EXAMINATION OF CHEMOSELECTIVE *N*-HETEROCYCLIC CARBENE-CATALYZED CROSS-BENZOIN REACTIONS AND EFFORTS TOWARDS A CONCISE TOTAL SYNTHESIS OF SPARTEINE

A Thesis Submitted to the College of
Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements
For the Degree of Doctor of Philosophy
In the Department of Chemistry
University of Saskatchewan
Saskatoon, Saskatchewan, Canada

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ABSTRACT

This thesis is broadly subdivided into two topics: the development and exploration of a methodology for catalyst-controlled chemoselective cross-benzoin reactions using *N*-heterocyclic carbenes, and efforts towards a concise and scalable total synthesis of sparteine.

The first chapter of this work begins with a brief overview of carbenes with an emphasis on *N*-heterocyclic carbenes (NHCs) and their applications in organocatalysis. Synthetic routes and considerations in the formation of NHCs for organocatalysis follow. A historical overview of the advances in first homo-benzoin and subsequently cross-benzoin reactions highlights current limitations with these systems, with an emphasis on the need for specific substrate functionalization to achieve high degrees of chemoselectivity. Finally, the chapter concludes with a discussion of experimental and computational studies on the mechanism of these reactions.

Chapter two contains a historical overview of sparteine, its isomers, and the practical uses for this natural product. Isolation techniques and a proposed biosynthesis precede reported partial and complete syntheses of sparteine, a potential synthetic precursor (anaferine), and a surrogate compound developed to replace sparteine in synthetic applications. A brief overview of amine-catalyzed Mannich reactions rounds out the chapter and provides context for the proposed synthetic route to sparteine.

A description of the development and exploration of chemoselective NHC-catalyzed cross-benzoin reactions is described in Chapter three. After illustrating that chemoselectivity is tied to ring size in the catalyst backbone, a broad range of substrates and reaction conditions are shown to be amenable to the new methodology. The method represents the first instance of chemoselectivity in cross-benzoin reactions between two aldehydes that does not rely on steric differences between the substrates for control. A detailed mechanistic study combining both computational and experimental results follows, highlighting those features of the catalyst leading to chemoselectivity. With ongoing efforts to add a high degree of enantioselectivity to the catalytic system, the chapter concludes with the development and application of a new approach for the synthesis of both achiral and chiral triazolium salts.

Returning to the total synthesis of sparteine, the fourth chapter of this thesis first outlines several possible synthetic routes to access sparteine through Mannich reactions with a precursor, anaferine. A substantial body of work covers

attempts to locate reproducible reaction conditions for a concise synthesis of this precursor. The chapter culminates in the completed four-step synthesis of anaferine and concludes with a discussion of how it could be used in the synthesis of sparteine and, eventually, its diastereomers genisteine and pusilline.

ACKNOWLEDGMENTS

Graduate studies would be a terrible thing without outside help and support. I'd like to start by thanking my supervisor Dr. Michel Gravel for his patience, support, motivation, and genuine love of the field. I chose this group to have him as a mentor, and have never been disappointed with his advice or demeanour.

Secondly, I would like to thank my Advisory Committee, Dr.'s S. Abrams, N. Low, and D. Ward, for their insightful comments and guidance during my studies. In particular, over my studies I've spent a lot of time talking to and learning from Dr. Ward on academic, professional, and personal matters. I am very grateful for all the effort each of you has put in to make my program especially enriching.

My coworkers in the Gravel group, both past and present, have been outstanding with their support and friendship over the course of my degree. From Karen and Eduardo acclimating me in my starting year, to Pouyan getting me to grow and try new things (and food), my peers have been a phenomenal group to work and learn with. Karen, Eduardo, Myron, Janice, Li, Pouyan, Christa, Venkata, Karn, Mehran, Hemkalyan, and all the undergrads, I had a blast working with you.

The faculty and staff in the department of chemistry have all been incredibly helpful during my time here. Dr. K. Brown, Dr. J. Zhu, Ken Thoms, and Leah Hildebrandt each deserve special mention for their work with me over the years. Additional thanks go to professors Dr. C. Y. Legault of the Université de Sherbrooke and Dr. I. Burgess of the University of Saskatchewan, who spent quite a bit of time teaching (and debating) me about computational and physical chemistry respectively.

My work was made possible with financial support from a wide array of sources: the Natural Sciences and Engineering Research Council (NSERC), the government of Saskatchewan, the Canada Foundation for Innovation, WestGrid, Compute Canada, Calcul Québec, the Université de Sherbrooke, and the University of Saskatchewan. Thanks to each of these institutions for backing my studies and professional career.

I'd like to thank my family, Mark, Sharon, and Kelly, for their emotional and financial support. I'm sure I wasn't always a ray of sunshine, so thanks for putting up with me. My friends, both in and out of grad school, helped make life

interesting, helped me focus (or unwind), and made sure I kept up personal growth along with my academic growth. Finally, a special thank-you to my partner Curtis Clavelle for feigning interest in my work. Being excited for and proud of my accomplishments made all the difference.

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LIST OF ABBREVIATIONS

Å	angstrom(s)
Ac	acetyl
Alk	alkyl
aq.	aqueous
Ar	aryl
BI	Breslow intermediate
Bn	benzyl
Boc	*tert*-butyloxycarbonyl
*n*Bu	*n*-butyl
*s*Bu	*sec*-butyl
*t*Bu	*tert*-butyl
°C	degrees Celsius
cal	calorie(s)
Cbz	carboxybenzyl
δ	chemical shift (in parts per million)
DBU	1,8-diazabicycl[5.4.0]undec-7-ene
DMAP	4-(dimethylamino)pyridine
DMF	*N*,*N*-dimethylformamide
DMSO	dimethyl sulfoxide
dr	diastereomeric ratio
EI	electron-ionization
equiv.	equivalent
er	enantiomeric ratio
ESI	electrospray ionization
Et	ethyl
FTIR	Fourier transform infrared
h	hour(s)
HPLC	high performance liquid chromatography
HRMS	high resolution mass spectrometry
Hz	hertz
J	coupling constant (spectral)

LAH	lithium aluminum hydride
lit.	literature
M	molar (moles/L)
Me	methyl
Mes	mesityl (2,4,6-trimethylphenyl)
min	minute(s)
mmol	millimole(s)
mol	mole(s)
m.p.	melting point
MS	molecular sieves
MTBE	methyl *tert*-butyl ether
m/z	mass-to-charge ratio
NHC	*N*-heterocyclic carbene
NMR	nuclear magnetic resonance
Ph	phenyl
PhH	benzene
PhMe	toluene
ppm	parts per million
*i*Pr	*iso*-propyl
*n*Pr	*n*-propyl
PTLC	preparatory thin-layer chromatography
pyr	pyridine / pyridyl
s	second(s)
t	time
Tfac	trifluoroacetate
THF	tetrahydrofuran
TLC	thin-layer chromatography
TS	transition state

PART I: INTRODUCTION

CHAPTER 1: HISTORICAL OVERVIEW OF N-HETEROCYCLIC CARBENE CATALYZED BENZOIN REACTIONS

1.1. NHCs as Organocatalysts

Carbenes are a class of molecules containing a neutral carbon atom with two substituents and two unshared valence electrons.[1] Whether these valence electrons are spin-paired and occupying the same molecular orbital (singlet state, Figure 1.1) or not (triplet state) has a profound effect on their reactivity. *N*-heterocyclic carbenes (NHCs) are a sub-class of these species wherein the carbene is housed in a nitrogen-containing cycle such that at least one nitrogen is adjacent to the carbene.[2] This proximity allows the nitrogen's lonepair to π-donate into the vacant *p*-orbital of the carbon, favouring the singlet state and increasing both the stability and nucleophilicity of the carbene.

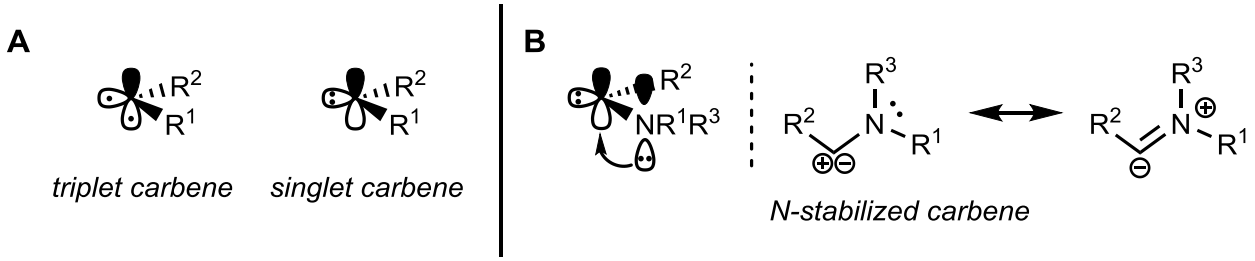
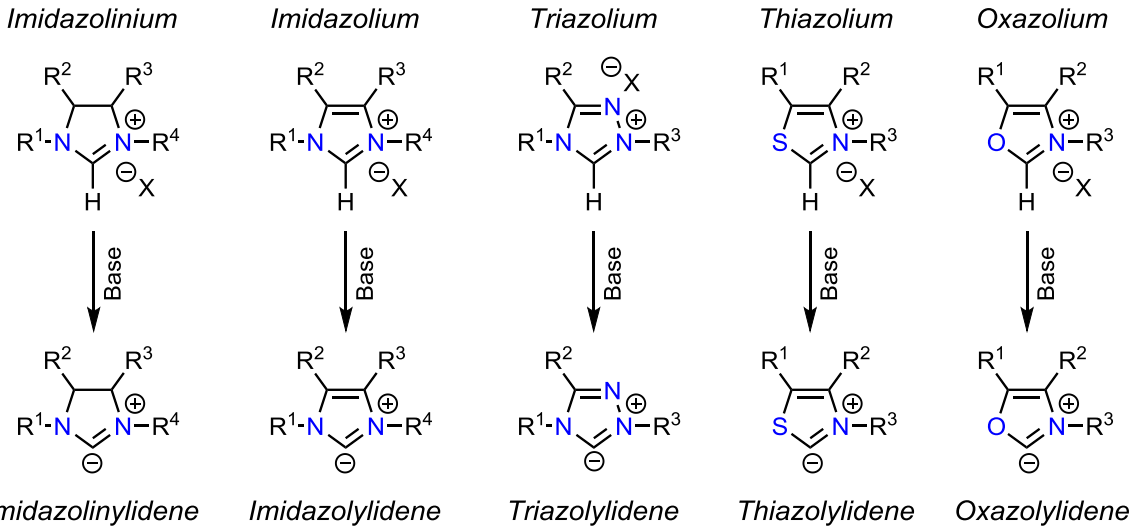


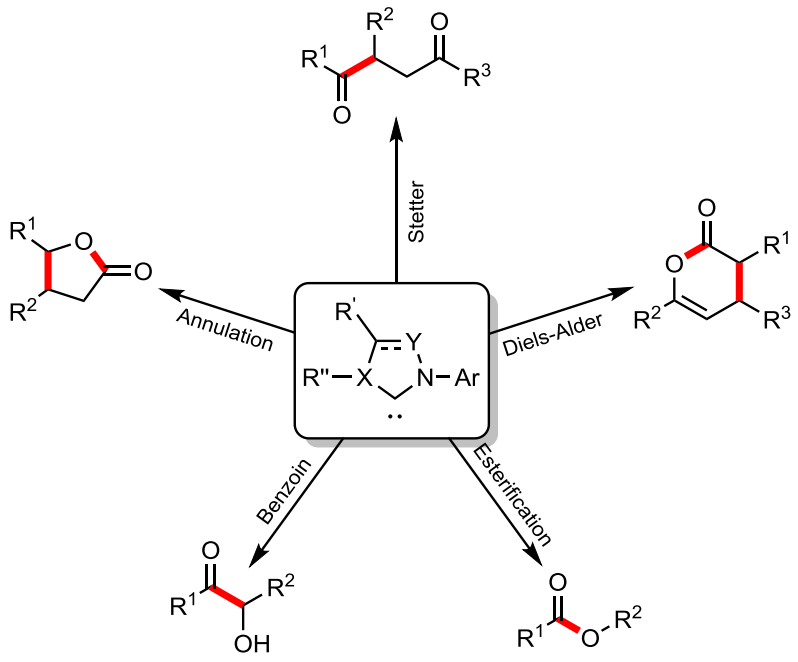
Figure 1.1 - Representations of carbenes showing (A) triplet and singlet states and (B) π-donation of an adjacent nitrogen to a carbene.

This enhanced nucleophilicity was put to use in 1943, when Ukai and coworkers demonstrated that a mixture of base and a thiazolium salt could catalyze homo-benzoin reactions of aromatic and heteroaromatic aldehydes.[3] This demonstration of organocatalytic potential was slowly followed with the development and diversification of NHC catalysts (Scheme 1.1), culminating in a period of rapid growth beginning in the 1990's with the introduction of triazolylidenes.[4]



Scheme 1.1 – Prototypical classes of NHCs and their parent azolium salts.

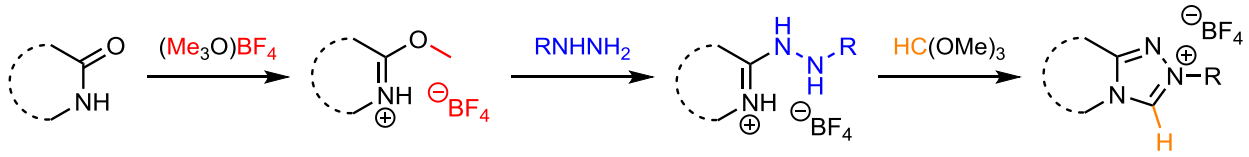
In addition to their applications in the benzoin reaction, the catalytic activity of NHCs has seen use in an assortment of other reactions (Scheme 1.2).[4] These transformations typically rely on the formation of a reactive acyl anion or acylazolium intermediate, though other nucleophilic and basic modes of catalysis have also been demonstrated.[4e]



Scheme 1.2 – Select examples of transformations catalyzed by NHCs.

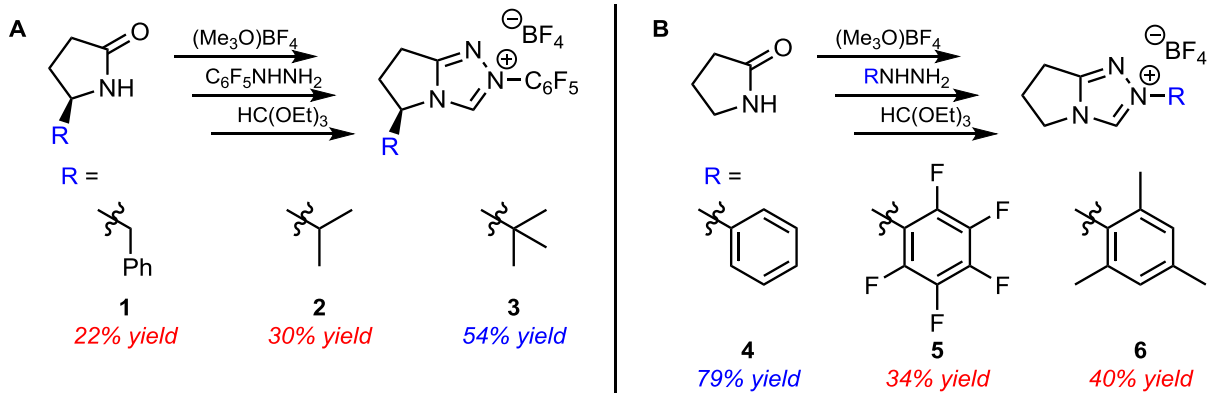
1.1.1. Triazolylidene Catalysts: Synthesis and Design

NHCs are typically accessed through the *in situ* deprotonation of an azolium salt.[5] With the variety of NHCs (Scheme 1.1) used in catalysis comes a variety of synthetic approaches used to access their parent azolium salts.[4e] However, syntheses of triazolium salts overwhelming proceed through the three-step sequence introduced by Leeper[6] and later modified by Rovis[7] (Scheme 1.3): methylation of an amide/lactam, followed by condensation with a hydrazine to form an amidrazonium salt, and subsequent cyclization with an orthoformate.



Scheme 1.3 – Typical procedure for the synthesis of triazolium salts.

This synthetic route has limitations. Yields, though typically reproducible, are highly dependent on both the catalyst backbone[8] and the *N*-substituent[9] (Scheme 1.4). A modified procedure in which the salt of the hydrazine is used must often be employed in cases where the parent hydrazine is unstable and/or electron-rich.[4e] Additionally, isolation of the final azolium salt from the mother liquor may be difficult, requiring extensive time, large volumes of solvent(s),[7] or affording low isolated yields despite high conversion.[10]



Scheme 1.4 – Yield variability in the synthesis of triazolium salts as a function of (A) catalyst backbone and (B) *N*-substituent.

Three basic elements of triazolylidenes may be modified to modulate reactivity: the catalyst backbone,[6, 11] the (other) *N*-substituent,[12] and the counterion.[13]

In 1997 Leeper proposed that tethering a *N*-substituent to form a bicyclic framework would restrict rotation, more effectively blocking one face at the active site and providing increased stereochemical control (Figure 1.2).[11a] With both Leeper[6] and Enders[11c] demonstrating the efficacy of these systems, the vast majority of all subsequent triazolylidenes have been synthesized as bicyclic species.

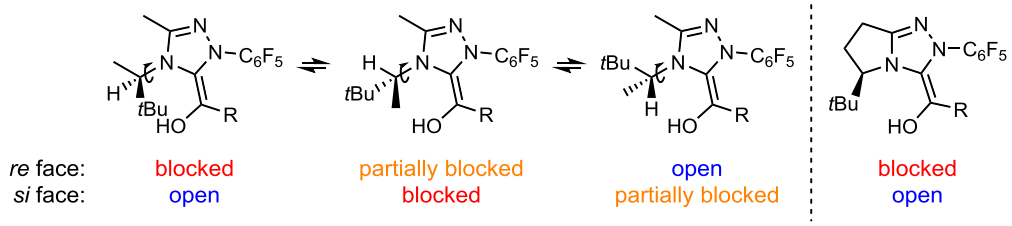
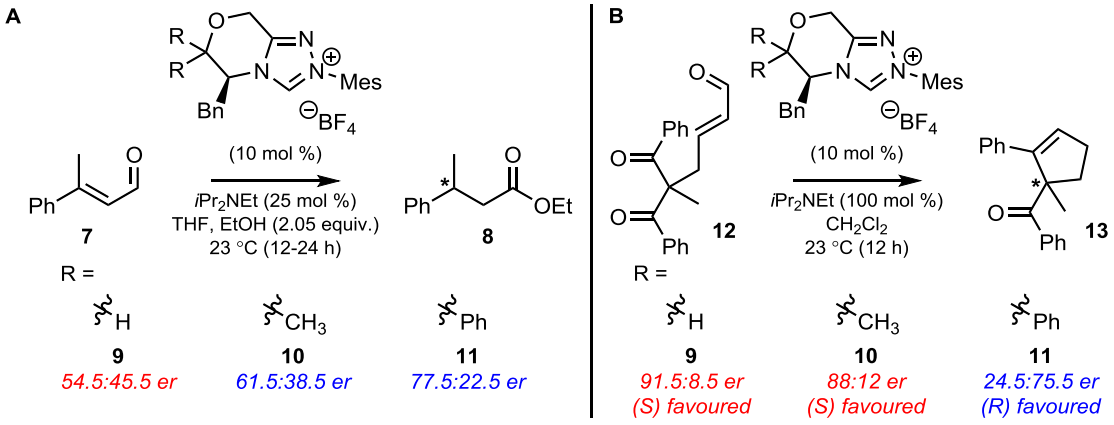


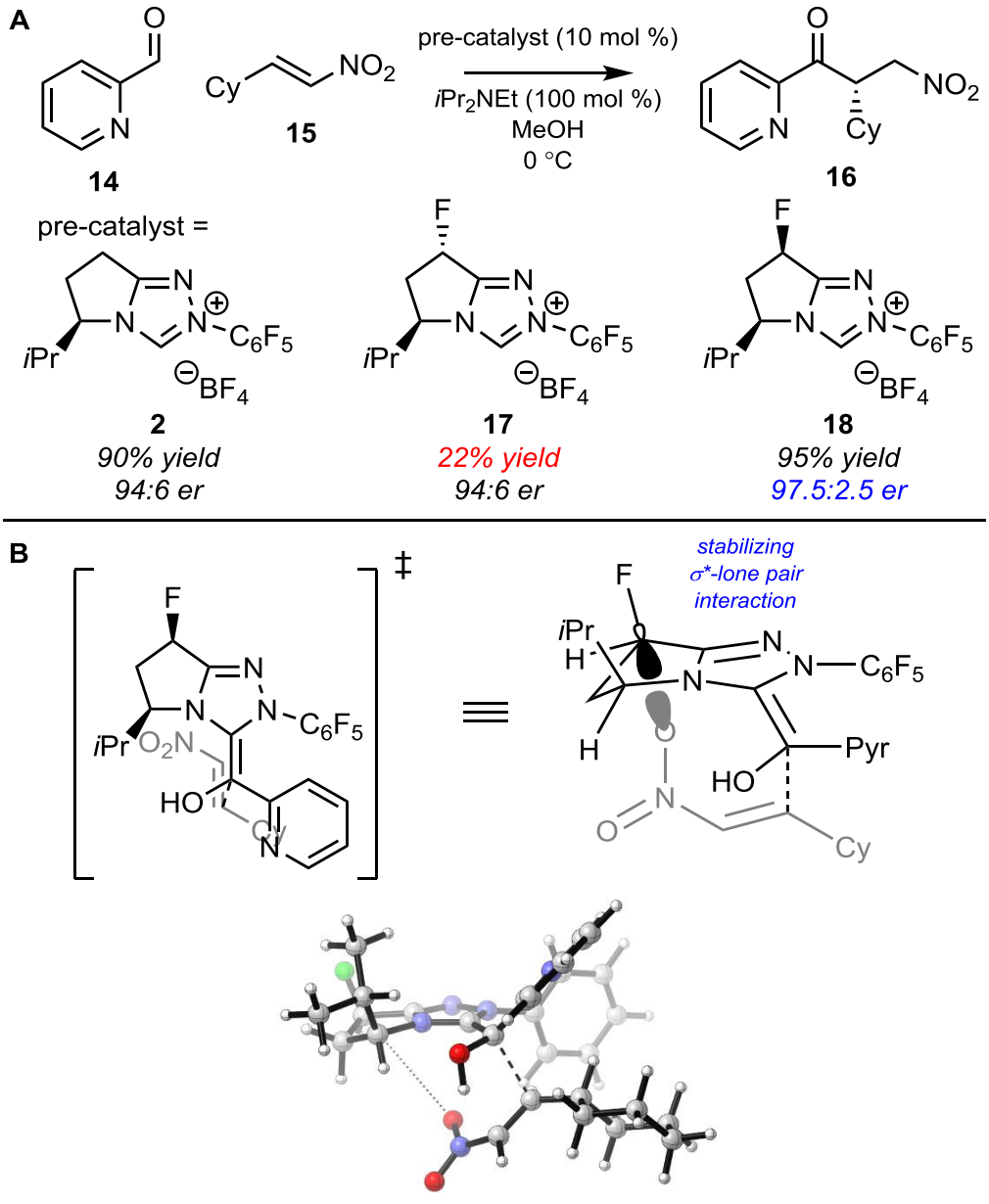
Figure 1.2 - Effect of restricting rotation through formation of a bicyclic system on triazolylidene-derived acyl anion equivalents.

In addition to the expected stereoinduction from steric bulk, substitution of the catalyst backbone may be used to modulate reactivity in non-intuitive ways. Addition of geminal disubstitution adjacent to the stereocentre (Scheme 1.5) has been variously shown to increase,[14] decrease,[15] or invert enantioselectivity,[16] in addition to lowering or halting catalytic activity.[15, 17]



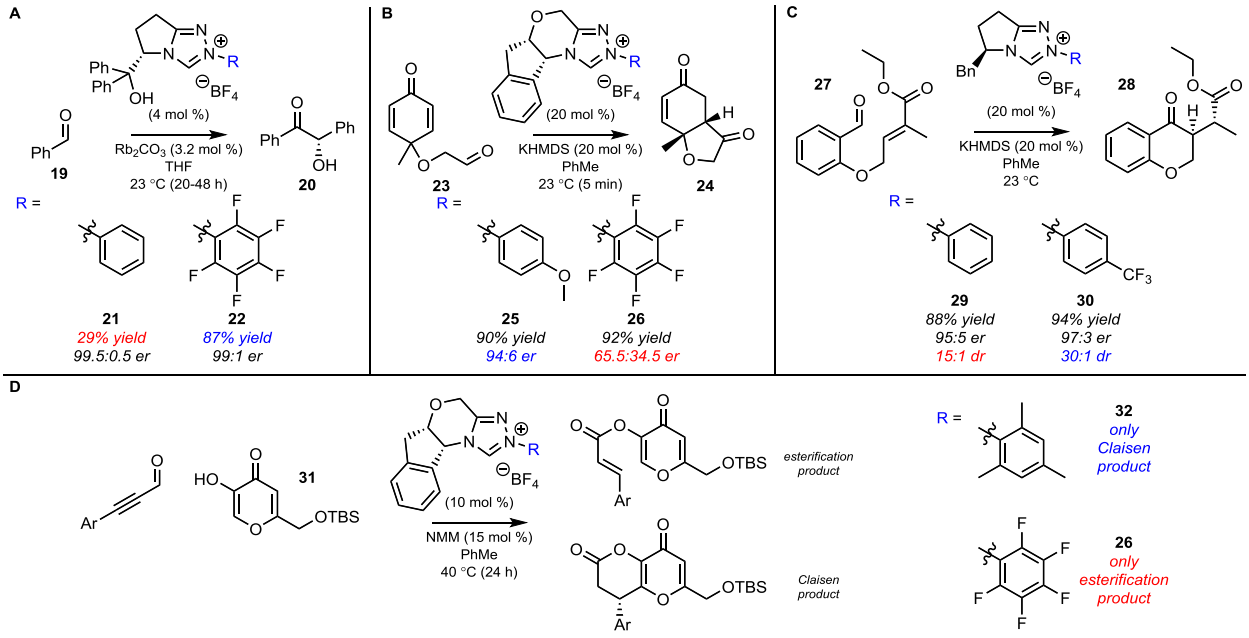
Scheme 1.5 – Examples of the effects of geminal disubstitution showing (A) increased and (B) decreased and inverted stereoselectivity.

Rovis *et al*. have demonstrated that stereoselective fluorination of the catalyst backbone may allow stereoelectronic factors to complement steric interactions and enhance enantioselectivity (Scheme 1.6).[8a, 18] It has also been suggested that stereoelectronic effects may alter the isomeric ratio of acyl anion intermediates formed from triazolylidenes, affecting the (stereo)chemical outcome of these reactions.[4a]



Scheme 1.6 – Example of stereoelectronic effects on enantioselectivity with (A) a comparison of catalysts and (B) the putative stereoelectronic interaction.

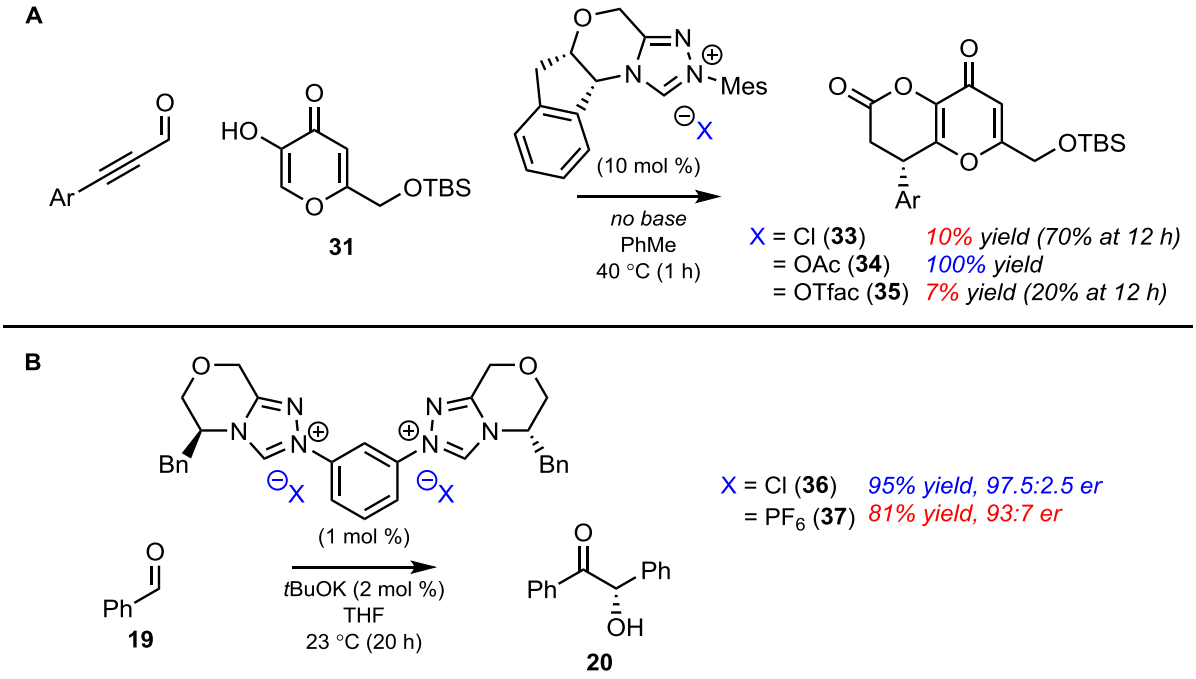
Judicious selection of the *N*-substituent is important for modulating both the steric and electronic parameters of triazolylidenes.[4e, 12g, 12i] For simplicity of synthesis and modification of electronic parameters, the majority of catalysts contain an aromatic *N*-substituent. However, both heteroaromatic[19] and aliphatic[12b, 12h, 20] *N*-substituents have been shown as effective, or superior, choices in several applications. The exact nature of the *N*-substituent has been shown to affect reaction yield/rate,[12m, 21] enantioselectivity,[22] diastereoselectivity,[23] and chemoselectivity[12d] (Scheme 1.7). Additionally, electronic effects from the *N*-substituent can adjust the acidity/basicity of the triazolium salt/triazolylidene, necessitating a change in reaction conditions and/or causing compatibility issues with substrates.[12g]



Scheme 1.7 – Examples of *N*-substituent effects on (A) reaction yields, (B) enantioselectivity, (C) diastereoselectivity, and (D) chemoselectivity.

Relatively little work has focused on counterion effects. It has been demonstrated that the choice of counterion can affect reaction rates,[13b] yields,[13d, 24] and enantioselectivities[13a] (Scheme 1.8). However, the mode by which the counterion alters the reactivity, and in particular the enantioselectivity, remains unknown. As some reactions do not exhibit a counterion effect,[15, 25] it is possible

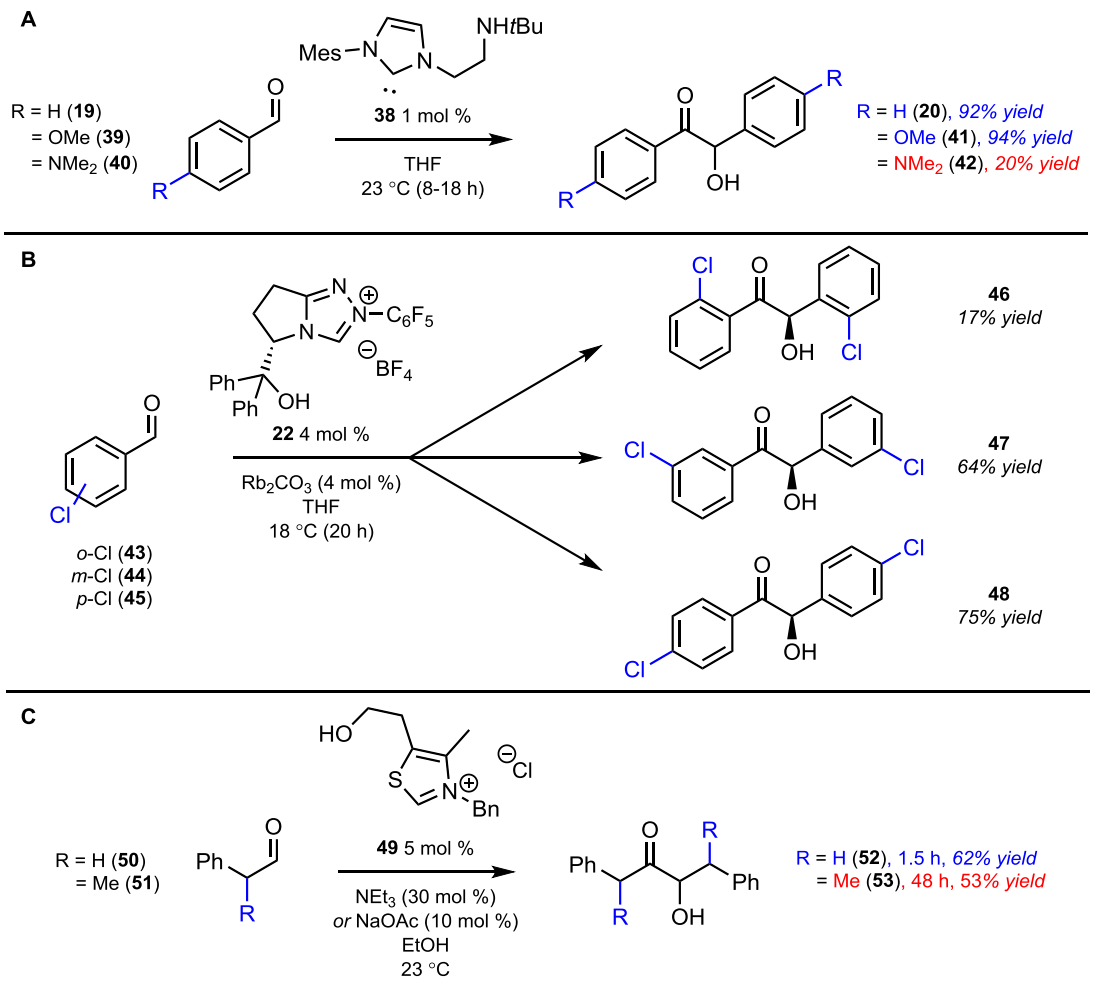
that counterions affect individual reaction pathways differently. Current approaches to vary the counterion beyond chloride and tetrafluoroborate are limited to late-stage modification or counterion-exchange.[15, 25] The additional step(s) may also adversely affect the overall yields of the triazolium salts; Rovis' two-step protocol for late-stage substitution of the counterion lowers the overall catalyst yield by 48 to 62%.



Scheme 1.8 – Examples of counterion effects on (A) reaction rate and (B) yield and enantioselectivity.

1.2. NHC-Catalyzed Homo-Benzoin Reactions

In 1832 Wöhler and Liebig demonstrated that potassium cyanide may be used to produce the compound benzoin, later determined to be the α-hydroxy ketone formed from the coupling of two molecules of benzaldehyde.[26] Both catalytic and stoichiometric variants of the benzoin reaction were subsequently developed.[4a, 27] Ronald Breslow subsequently combined Ukai's work (see Section 1.1), Lapworth's proposed mechanism for the cyanide-catalyzed reaction,[28] and a series of mechanistic experiments to propose the currently accepted mechanism for the NHC-catalyzed benzoin reaction (see Section 1.4).[29]



Scheme 1.9 – Select examples of homo-benzoin reactions highlighting substrate effects with (A) electron-rich aromatic aldehydes, (B) *o*-, *m*-, and *p*-substituted aromatic aldehydes, and (C) α-substituted aliphatic aldehydes.

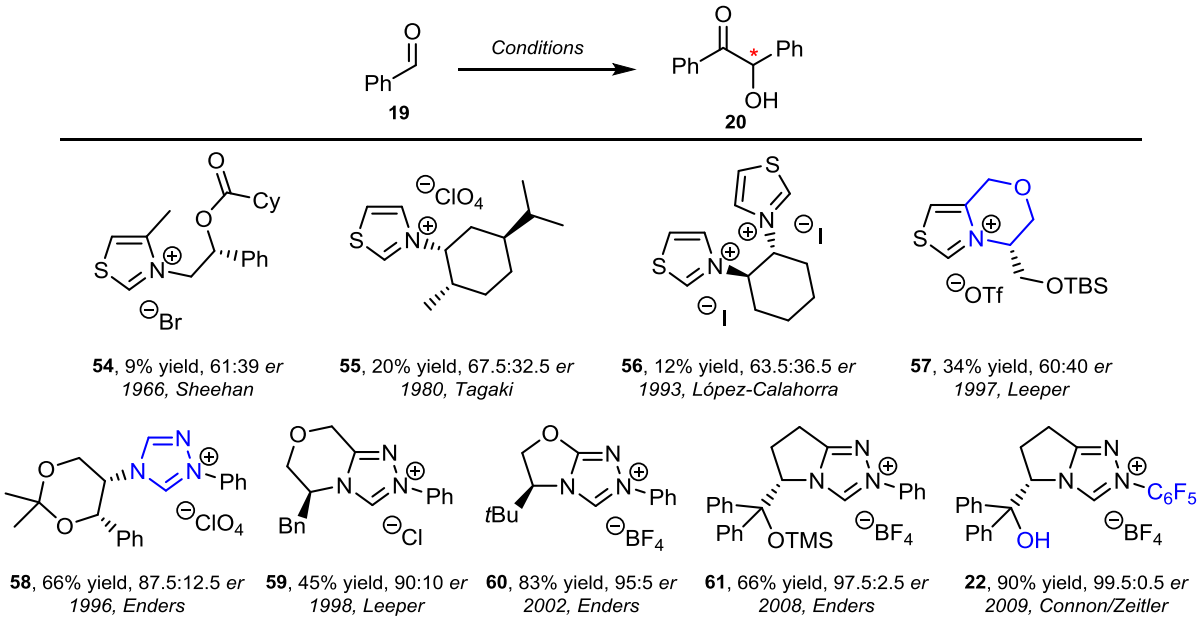
Each of the major classes of NHCs (thiazol-, imidazol-, imidazolin-, and triazol-ylidenes) has been employed as active catalysts in homo-benzoin reactions, although the majority of reports have focused on thiazol- and triazol-ylidene catalysts.[4a, 30] A broad range of solvents (protic and aprotic, polar and non-polar) may be used. Aromatic aldehydes bearing electron-withdrawing or donating groups may be employed, though highly electron-rich or -poor systems may be problematic (Scheme 1.9).[31] Substitution placement can negatively impact reaction rates and yields, with *para*/*meta*-substitution affording improved rates/yields over *ortho*-substituted substrates.[12m] Heteroaromatic aldehydes with the aldehyde functionality adjacent to the heteroatom often afford high product

yields.[32] Use of aliphatic aldehydes or formaldehyde is also possible, though these reactions often require modified reaction conditions.[32a, 33] Branching at the α-, and to a lesser extent β-, position of aliphatic aldehydes again has a negative impact on reaction rates and/or yields.[34]

1.2.1. NHC-Catalyzed Enantioselective Homo-Benzoin Reactions

A large body of work has focused on making NHC-catalyzed homo-benzoin reactions enantioselective.[4d, 4f, 30] From 1966 until 1996 efforts focused on using an assortment of chiral thiazolium salts, with limited success (Scheme 1.10). Combining the improvements afforded by triazolylidenes with their tethered *N*-substituent framework, Leeper *et al*. introduced the first bicyclic triazolylidene catalyst.[6, 11a]

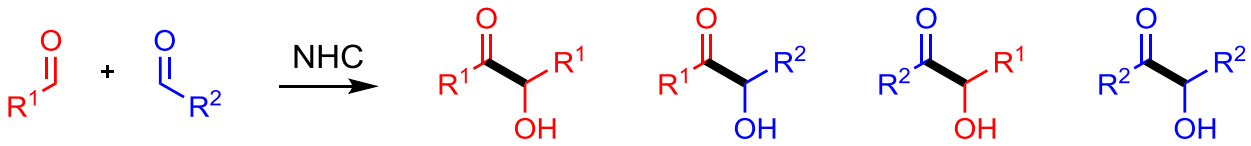
Enantioselectivity was sequentially improved through the addition of increased steric bulk and the presence of a H-bonding substituent. Notably, modification of the *N*-substituent from phenyl to its perfluorinated analogue was necessary to improve reaction yields (see Scheme 1.7A).[12m]



Scheme 1.10 – Select thiazolium and triazolium pre-catalysts for the enantioselective homo-benzoin reaction of benzaldehyde, highlighting key advances.

1.3. NHC-Catalyzed Cross-Benzoin Reactions

Cross-benzoin reactions introduce an additional level of complexity to the reaction in the form of chemoselectivity; when combining two different aldehydes there are multiple α-hydroxy ketone products which can be formed (Scheme 1.11).

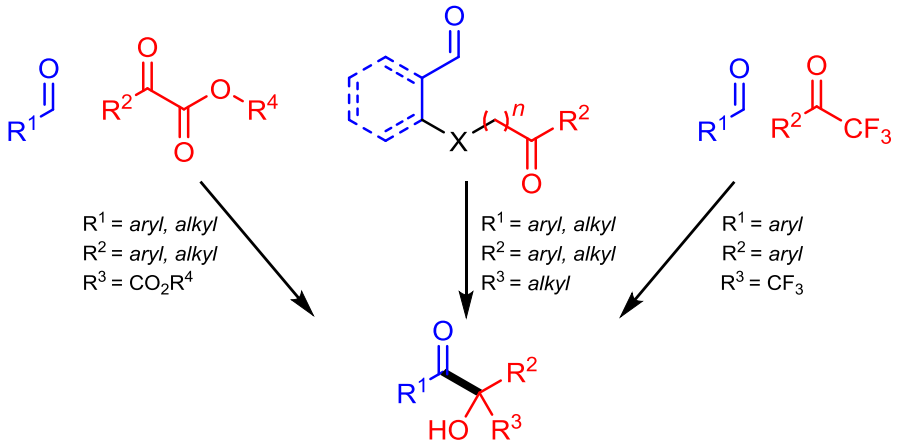


Scheme 1.11 – General form of a cross-benzoin reaction between aldehydes.

Attempts at performing chemoselective NHC-catalyzed cross-benzoin reactions may be broadly separated into two groups: reactions between an aldehyde and an electronically activated ketone, and reactions between two different aldehydes.

1.3.1. Cross-Benzoin Reactions Between an Aldehyde and a Ketone

Generally, attempting chemoselective cross-benzoin reactions between aldehydes is extremely difficult and/or substrate-dependent (see Section 1.3.2). However, the issue of chemoselectivity can be avoided by replacing one of the aldehydes with another carbonyl species. These approaches take advantage of the fact that only aldehydes can form the required acyl anion intermediate (see Section 1.4) for carbon-carbon bond formation. Consequently, the number of possible benzoin products decreases to two: a cross-benzoin product derived from the aldehyde reacting as the acyl anionic nucleophile, and the homo-benzoin product of the aldehyde. Further improving the overall chemoselectivity and yield, the homo-benzoin product can be suppressed by tethering the two functional groups, making the intramolecular benzoin reaction entropically favoured over the intermolecular one.[30]



Scheme 1.12 – Approaches to chemoselective NHC-catalyzed cross-benzoin reactions between aldehydes and ketones.

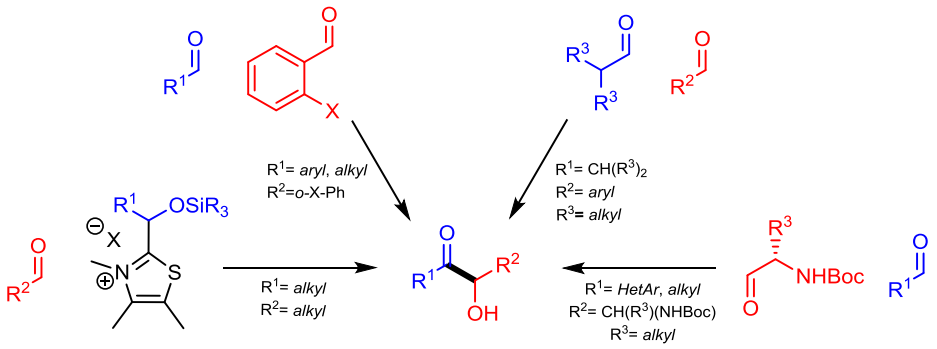
This tethering has the added benefit of lowering the electrophilic activation required for the partnering ketone, allowing intramolecular cross-benzoin reactions with simple aliphatic and aromatic ketones (Scheme 1.12).[35] In intermolecular cases more electrophilic carbonyls such as trifluoromethyl ketones[36] or α-keto esters[37] are required. Notably, moderate to high enantioselectivities are achievable with each of these substrate types.[17, 38]

1.3.2. Cross-Benzoin Reactions Between Two Aldehydes

Cross-benzoin reactions with both substrates as aldehydes are more complex:

> *The primary issue with chemoselectivity in cross-benzoin reactions [between aldehydes] is one of reactivity. Namely, in a typical reaction the acyl anion equivalent (Breslow intermediate) is formed faster with the most electrophilic aldehyde. Other factors remaining constant, it should thus prefer to attack another equivalent of the same aldehyde, leading to homo-benzoin products. If the electrophilicity of the two aldehydes is similar there is little impetus for selectivity and a statistical mixture is generally obtained. The issue of chemoselectivity is compounded by the commonly observed reversibility of the benzoin reaction. Achieving chemoselectivity via kinetic control therefore depends on the choice of substrates, catalyst, and reaction conditions.*[39]

Comparatively little work has demonstrated chemoselective NHC-catalyzed cross-benzoin reactions between aldehydes. Intramolecular reactions are typically poorly chemoselective and/or afford moderate yields.[40] The original study on intermolecular chemoselective cross-benzoin reactions between aldehydes was reported in the 1970's by Stetter and Dämbkes.[41] The authors reported that the use of either *ortho*-substituted aromatic aldehydes or α-substituted aliphatic aldehydes forms cross-benzoin products chemoselectively (Scheme 1.13).



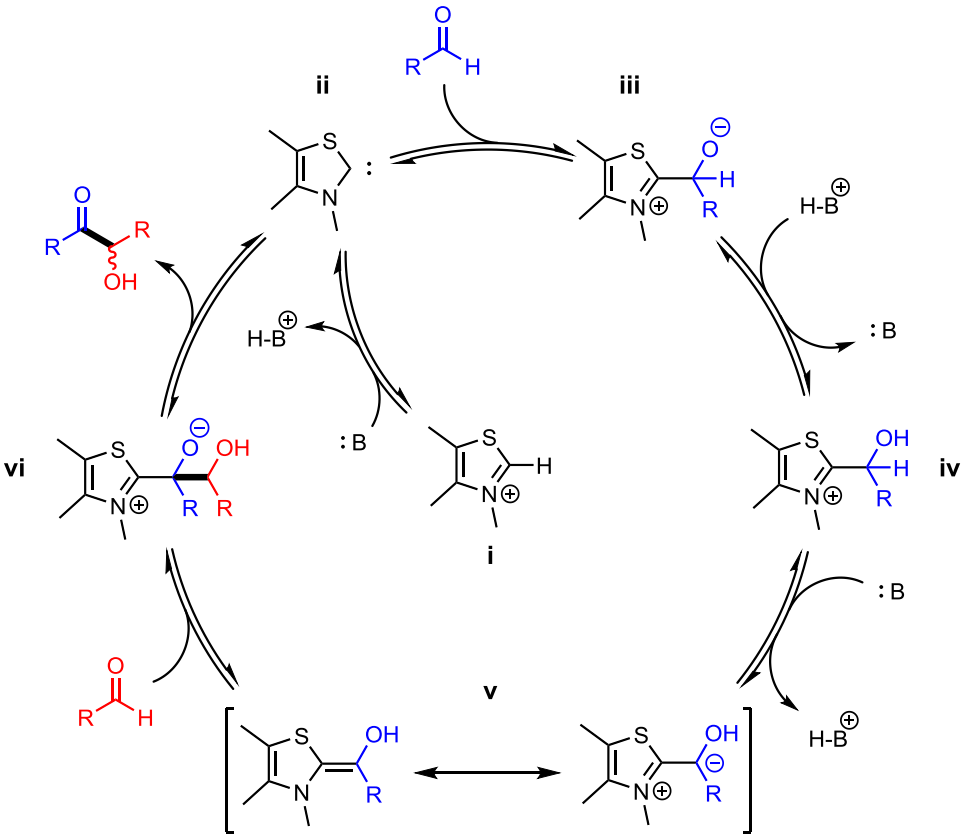
Scheme 1.13 – Effective substrate combinations for chemoselective NHC-catalyzed cross-benzoin reactions between two aldehydes.

Stetter and Dämbkes' work was subsequently expanded by both Connon/Zeitler[37] and Glorius[12l] to increase the substrate scope and afford improved product yields. It has recently been demonstrated that α-aminated, rather than α-alkylated, substrates afford the opposite regioisomer with high selectivity.[42] Chemoselectivity between cross-benzoin products may be induced by using a large excess of one aldehyde.[13d] In these cases the major cross-benzoin product is derived from the acyl anion equivalent formed by the aldehyde in excess. However, the requirement for a large excess of one substrate, as well as significant contamination from the homo-benzoin product of this aldehyde, may limit the synthetic utility of this approach. The sole approach able to afford chemoselective cross-benzoin reactions between two un-functionalized aliphatic aldehydes is not catalytic with respect to the NHC.[43] Instead this methodology relies on the pre-formation of a protected reaction intermediate, functionally

causing exclusive formation of the acyl anion intermediate with one of the two aldehydes.

1.4. Mechanism of NHC-catalyzed Benzoin Reactions

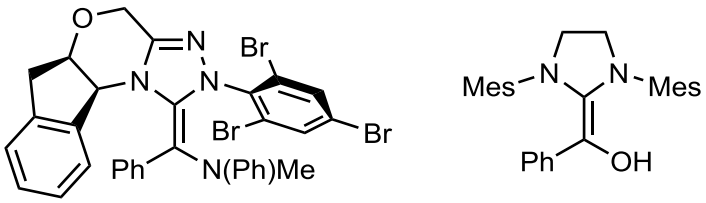
In 1958 Ronald Breslow published a single-author study on the mechanism of NHC-catalyzed benzoin reactions. Taking Lapworth's proposed mechanism for the cyanide-catalyzed benzoin reaction,[28] combined with a series of mechanistic experiments, Breslow proposed the currently accepted mechanism for the NHC-catalyzed benzoin reaction (Scheme 1.14).[29] Deprotonation of the azolium salt (**i**) initiates the cycle and forms the free carbene (**ii**). Nucleophilic attack on an aldehyde creates a new tetrahedral intermediate (**iii**), and sequential protonation of the alkoxide (**iv**) followed by deprotonation at the carbon forms a resonance-stabilized hydroxyenamine (**v**).



Scheme 1.14 – Currently accepted mechanism for the NHC-catalyzed benzoin reaction.

This species is crucial to the reactivity of NHCs, allowing a reversal of polarity (*umpolung*)[44] for the former carbonyl carbon; the acyl anion equivalent (**v**) makes the formerly electrophilic carbon nucleophilic. In recognition for his contribution to the area, this species has since come to be referred to as the 'Breslow intermediate' (BI). Nucleophilic attack onto another aldehyde molecule forms an unstable intermediate (**vi**) which collapses to eject the benzoin product.

Since Breslow's initial proposal, several alternative mechanisms have been suggested for the NHC-catalyzed benzoin reaction, although these have not gained widespread acceptance.[45] Some researchers have found components of Breslow's mechanism contentious. For example, formation of the Breslow intermediate may instead involve a 1,2-proton shift[46] or an additional epoxide intermediate.[47] Protonated tetrahedral intermediates have been observed under reaction conditions, adding credence to their role in the mechanism.[45a] Recent work has resulted in the isolation and characterization of a series of Breslow intermediates and related species (Figure 1.3), again supporting Breslow's proposed reaction pathway.[48] These compounds are highly oxygen sensitive, reaffirming the need for anaerobic conditions in many benzoin reactions. Very recently, evidence has been presented suggesting that the carbon-carbon bond formation step may proceed through sequential single-electron transfers.[45e]



62 **63**

Figure 1.3 - Examples of isolated (aza-)Breslow intermediates.

Through crossover experiments Connon and Zeitler's groups have determined that, under their reaction conditions, the NHC-catalyzed homo-benzoin reaction of aromatic aldehydes is variably reversible or irreversible depending on the substitution pattern of the aromatic ring(s).[49] Homo-benzoin products of unbranched aliphatic aldehydes were formed effectively irreversibly. Results with cross-benzoin products again suggested reversibility is dependent on the exact

aromatic aldehyde used. It is important to note that NHC-catalyzed homo-benzoin reactions have been variously reported as first- or second-order with respect to the aldehyde.[45b, 50] It is probable that the rate-limiting step depends on the choice of solvent, base/buffer, NHC, and the nature of the substrate.[50a]

It has been suggested that triazolylidene-derived Breslow intermediates are electronically suited to preferentially form the *E*-isomer.[4a] In cases where the catalyst backbone possesses a substituent adjacent to the active site the *E*-isomer is substantially preferred due to steric interactions (Figure 1.4).[51] Control of the *E*:*Z* ratio of the Breslow intermediate is important in achieving high enantioselectivity as it limits the number of possible transition states. The combination of preferential formation of the *E*-Breslow intermediate with restricted rotation of the catalyst's substituents (see Section 1.2.1) severely limits the number of possible transition states for carbon-carbon bond formation (the putative rate-limiting and stereo-determining step).[11a, 11b, 12a, 52]

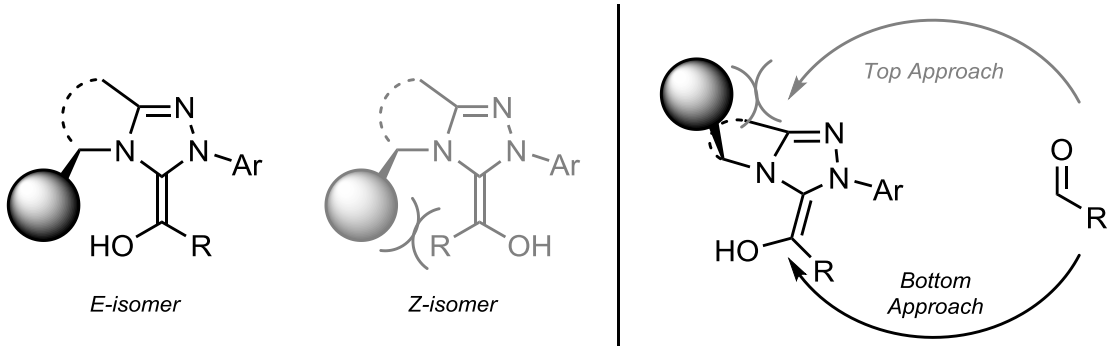


Figure 1.4 - Comparison of *E*- and *Z*-Breslow intermediates for triazolylidene-derived Breslow intermediates highlighting steric interactions.

1.4.1. Density Functional Theory Studies on NHC-Catalyzed Benzoin Reactions

Computational studies may be used to add support for mechanistic proposals and to explore chemical interactions not easily studied through traditional experiments. The majority of computational Density Functional Theory (DFT) studies on NHC catalysis have focused on the Stetter reaction.[53] Three reports examined NHC-catalyzed benzoin reactions with DFT calculations.

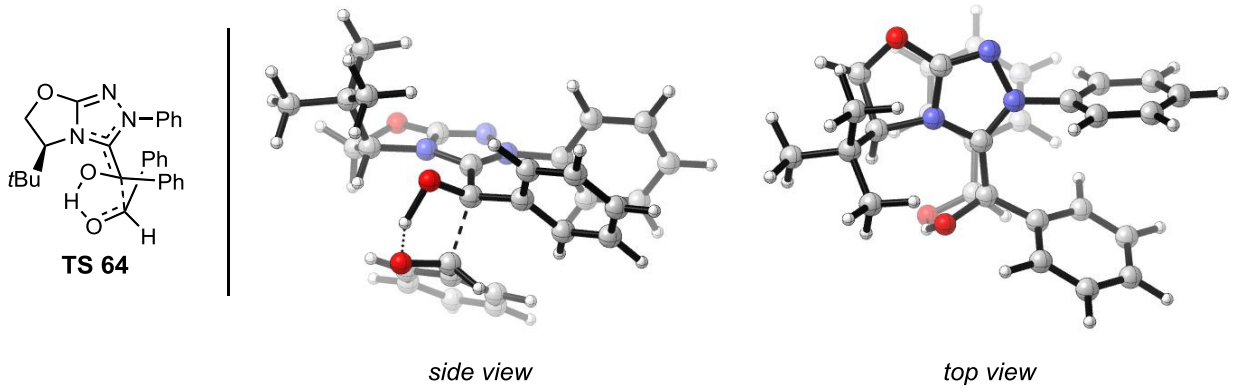


Figure 1.5 - Lowest energy transition state for carbon-carbon bond formation as calculated by Dudding and Houk in a homo-benzoin reaction catalyzed by a chiral catalyst.

In 2002 Enders *et al*. reported highly enantioselective NHC-catalyzed homo-benzoin reactions using a chiral bicyclic triazolylidene (see Section 1.2.1, Scheme 1.10).[11c] Following this success, Dudding and Houk published a computational study (using a variation of ONIOM (n-layered integrated molecular orbital method) with a combination of B3LYP/6-31G(d) and AM1) exploring the factors leading to the increased enantioselectivity.[51] This study focused exclusively on the carbon−carbon bond formation step. The calculated transition state energies support the reaction pathway proceeding preferentially through the *E*-isomer of the Breslow intermediate. However, the authors suggest two additional factors in achieving high enantioselectivity: a hydrogen bond between the Breslow intermediate and the incoming electrophile and a π-π interaction between the triazolium core and the aromatic substituent of the aldehyde (Figure 1.5). These additional stabilizing factors bias the possible approaches of the aldehyde, leading to increased stereoselectivity.

An *N*-ethyl triazolylidene catalyst was modeled for the homo-benzoin reaction of benzaldehyde (B3LYP/6-311+G(2d,p)//B3LYP/6-31+G(d)).[54] The rate-limiting step was determined to be a direct conversion of (cf. **iii**) to (cf. **v**) *via* a dimer-like transition state ($\Delta G^{\ddagger}$ = 28.8−30.9 kcal/mol). However, the possibility of a stepwise proton transfer mediated by the base/conjugate acid as proposed by Breslow (Scheme 1.14) was not explored. Formation of the alkoxide intermediate (cf. **iii**,

$\Delta G^{\ddagger}$ = 24.1 kcal/mol) and carbon-carbon bond formation (cf. **vi**, $\Delta G^{\ddagger}$ = 27.0 kcal/mol) were found to have the next highest barriers.

Finally, a brief study compared the self-consistent field (SCF) energies (using B3LYP/6-311+G**) of homo-benzoin reactions of acetaldehyde catalyzed by a thiazolylidene with a triazolylidene.[46] Again the rate-limiting step was found to be the direct formation of (cf. **v**) from (cf. **iii**), this time modeled as a 1,2-proton shift ($\Delta G^{\ddagger}$ = 45.7 kcal/mol). Interestingly, the study also found that the barrier for carbon−carbon bond formation catalyzed by triazolylidene is roughly 3 kcal/mol higher in energy than the catalyst ejection step. However, the situation is reversed for the same reaction catalyzed by thiazolylidene, where catalyst ejection is rate-limiting.

CHAPTER 2: HISTORICAL OVERVIEW OF SPARTEINE

2.1. Isomers and Properties

Simple alkaloids have a variety of applications in synthetic and medicinal chemistry.[55] An important example of these is sparteine, a bis-quinolizidine lupin alkaloid (Figure 2.1). Sparteine has two major conformers in solution, of which one is slightly (ca. 3 kcal/mol) higher in energy.[56]

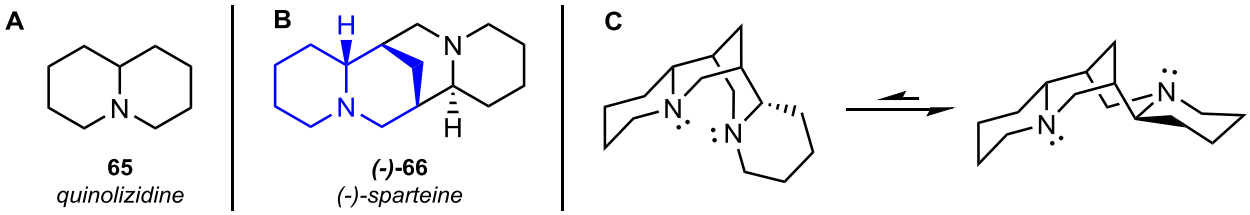


Figure 2.1 - Representations of (A) a quinolizidine system, (B) (-)- sparteine, and (C) the two major conformers of (-)-sparteine.

The fused tetracyclic carbon skeleton of sparteine allows for three diastereomers. Genisteine (α-isosparteine) and pusilline (β-isosparteine) are C_2-symmetric diastereomers of sparteine, each capable of adopting similar conformations (Figure 2.2).

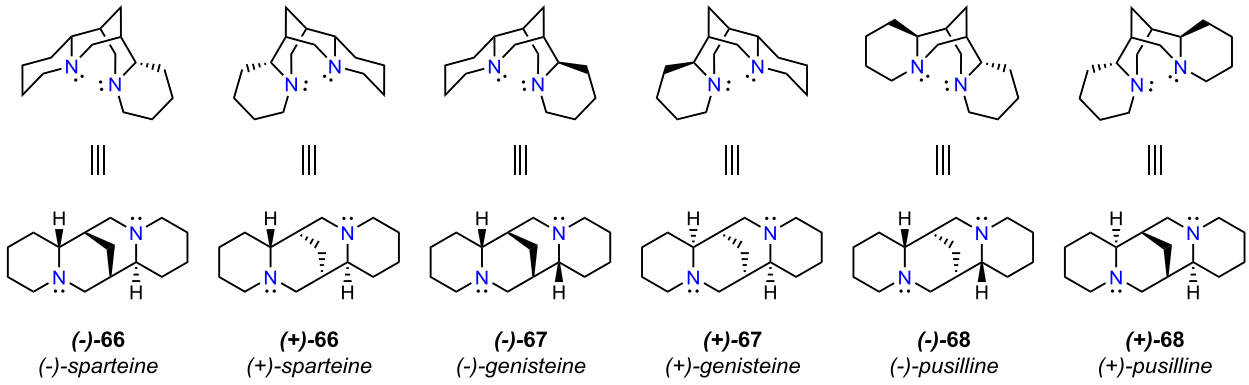


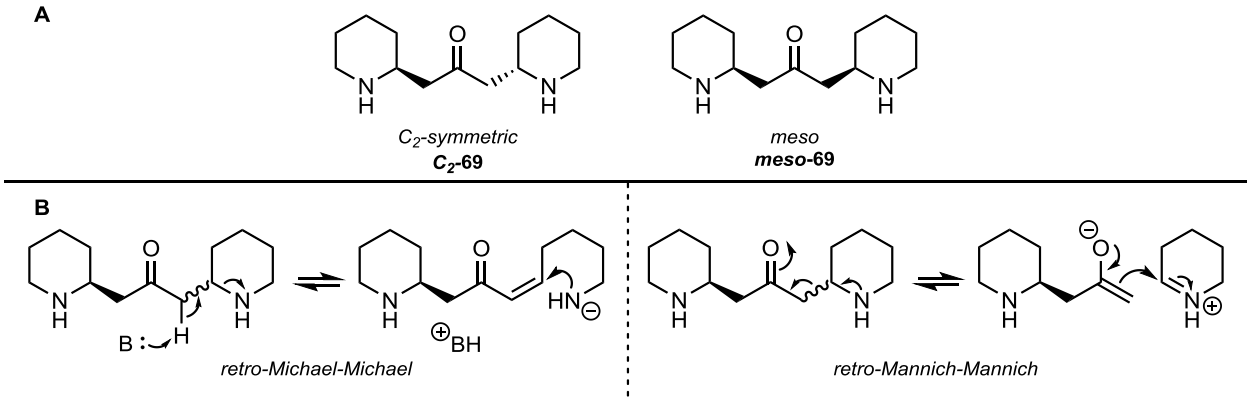
Figure 2.2 - Stereoisomers of sparteine.

Historically, sparteine and its stereoisomers have been characterized primarily through melting points, most commonly of the dipicrate salts.[57] Optical rotation and infrared spectra have also been used. Recent synthetic efforts (see Section

2.4.2) have included ^{1}H NMR and ^{13}C NMR spectra.[58] The diastereomers may be separated variously through fractional distillation, fractional crystallization with perchlorate, or most effectively through chromatography using activated alumina.[57e] Resolution of racemic sparteine may be accomplished through selective crystallization with enantioenriched β-camphor-10-sulfonic acid.[57d]

2.1.1. Anaferine

The simple alkaloid anaferine has been used in previous syntheses of sparteine isomers and derivatives.[57b, 57c, 59] Isolation of anaferine in the 1960's afforded a mixture of the C_2-symmetric and *meso* forms (Scheme 2.1).[60] However, the free base form of anaferine is not configurationally stable, interconverting between the two isomers *via* retro-Michael-Michael and/or retro-Mannich-Mannich reactions;[61] it is possible that only one of these isomers is produced naturally.[62]



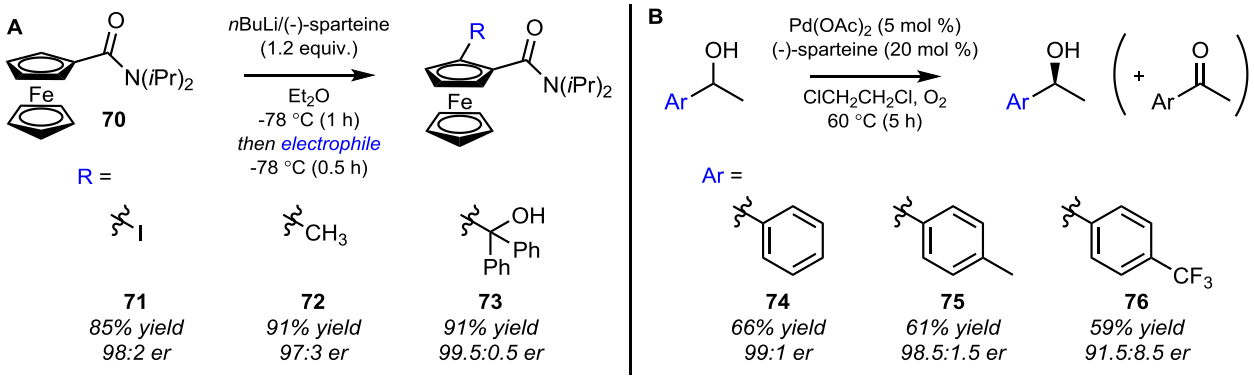
Scheme 2.1 – Graphical depictions of (A) the stereoisomers of anaferine and (B) the putative mechanisms for interconversion between these isomers.

Historically, anaferine has been characterized through melting points, most commonly of the dipicrate and dihydrochloride salts.[60a, 63] Synthetic efforts (see Section 2.4.4) have included ^{1}H NMR, ^{13}C NMR, and infrared spectra for both the free diamine and the dihydrochloride salt.[60a, 61a] The stereoisomers may be separated sequentially into *meso*-, (+)-, and (-)-anaferine through formation of their respective dimandelate salts using enantioenriched mandelic acid.[63a] These salts may be converted directly to their respective dipicrates.

2.2. Uses of Sparteine

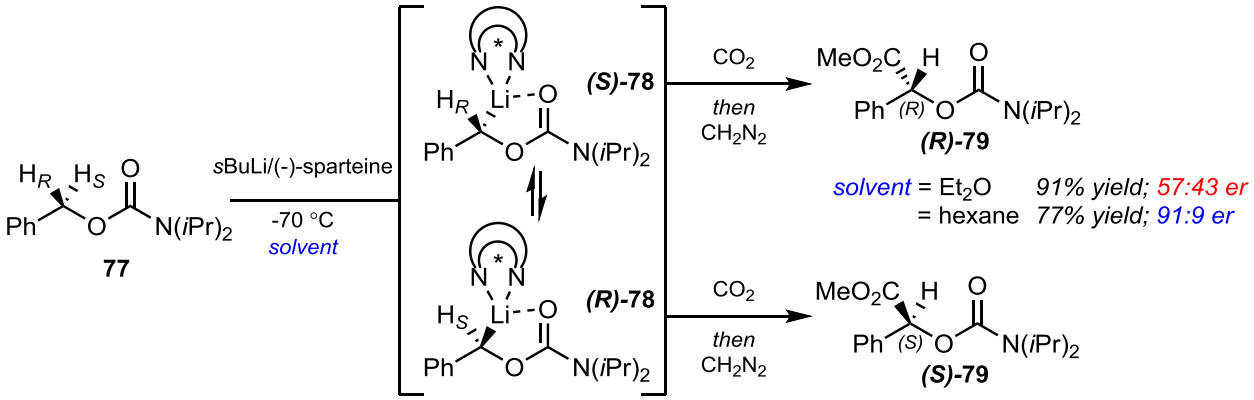
It has been suggested that sparteine, and quinolizidine alkaloids in general, are synthesized by lupins/legumes as a defence mechanism; quinolizidine alkaloids are bitter, deterring consumption, and are broadly toxic upon ingestion.[64] In particular, sparteine and related lupanine inhibit sodium and potassium channels, affecting the central nervous system. In small doses sparteine may act as a stimulant.[55d, 64] This has led to consideration of using sparteine and/or its sulphate salt to treat cardiac arrhythmia,[65] to induce and regulate labour,[66] and more recently as an anticonvulsant.[67] However, in larger doses sparteine causes paralysis of the autonomic nervous system, typically leading to asphyxiation.[55d, 68] During early applications in the medical industry it was found that roughly 10% of the general population is unable to properly metabolize sparteine, substantially increasing the risk of overdose.[65a] As a result sparteine has not been earnestly pursued in pharmaceutical applications.

Research with (-)-sparteine showed that one of its major conformers (Figure 2.1c) is a capable bidentate ligand in organometallic species, though initial applications were not promising.[69] Subsequent research improved its synthetic utility, with syntheses of isotactic polymers,[70] planar chiral ferrocenes,[71] and chiral bisphosphenes,[72] as well as palladium-catalyzed enantioselective oxidations[73] as recently as 2006 (Scheme 2.2).



Scheme 2.2 – Select examples of synthetic applications of (-)-sparteine in (A) the syntheses of planar chiral ferrocenes and (B) in palladium-catalyzed oxidations.

The principal synthetic application of sparteine is in the stereoselective formation of alkyl lithium species.[56a] In a typical example, an organolithium species and enantioenriched sparteine are combined with a prochiral species, undergoing a deprotonation. This leads to the formation of non-degenerate diastereomers. Subsequent equilibration favours the more thermodynamically stable epimer, with the attack on an electrophile thus generating a new stereocentre (Scheme 2.3). It is important to note that reaction conditions have a dramatic effect on enantioselectivity (14-90% ee), most likely by affecting the equilibrium ratio and/or the rate of equilibration. Kinetic deprotonations and dynamic kinetic resolutions are also common.[56a, 74]



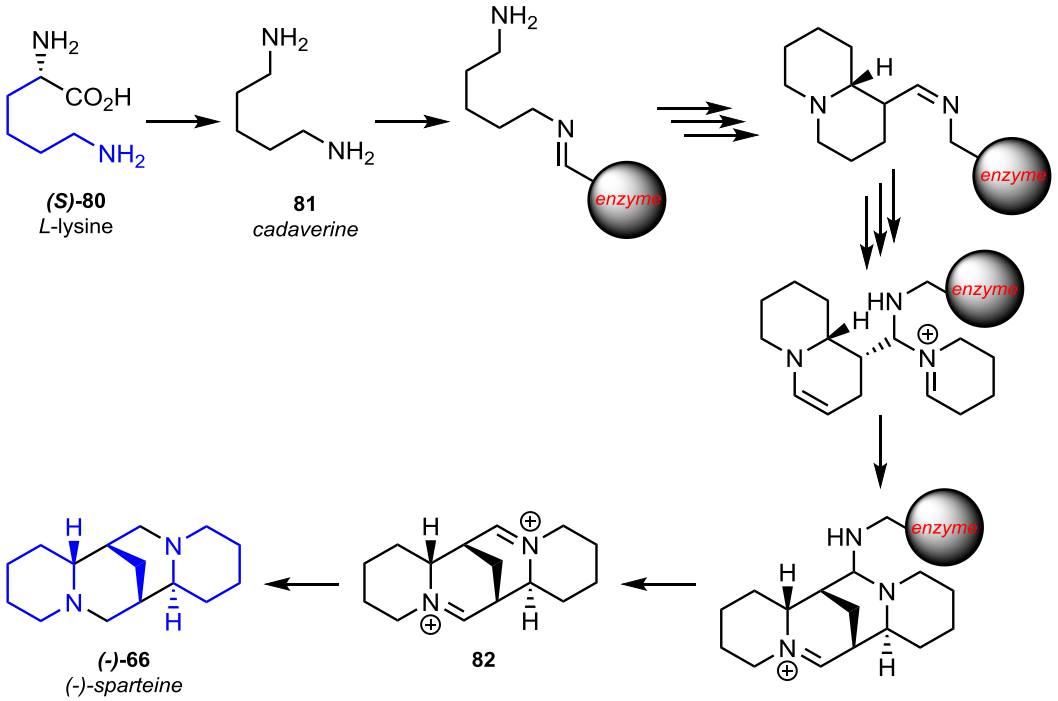
Scheme 2.3 – Example of the use of enantioenriched sparteine in the stereoselective formation of organolithium species.

2.3. Isolation and Biosynthesis

(-)-Sparteine was initially isolated in 1851 from Scotch Broom (*Cytisus scoparius*, also known as *Spartium scoparium*), a flowering leguminous shrub native to Western Europe.[75] Notably, the species has been exported globally and is now classified as a highly invasive noxious weed.[76] Both antipodes of sparteine may also be isolated from a variety of plants, primarily from the genus *Lupinus*, although (+)-sparteine is considerably rarer.[55a, 56a, 58d]

As confirmed by labelling studies,[58a, 77] sparteine is ultimately derived from three lysines (Scheme 2.4). Following decarboxylation of lysine to cadaverine, the oxidative formation of a series of imines/iminiums and enamines allows

successive cyclizations through Mannich reactions. Although originally proposed to occur on liberated species,[55d, 78] it is now thought that these reactions occur on enzyme-bound intermediates,[79] though exactly which enzymes are involved remains contentious.[55d]



Scheme 2.4 – Simplified putative mechanism for the biosynthesis of sparteine.

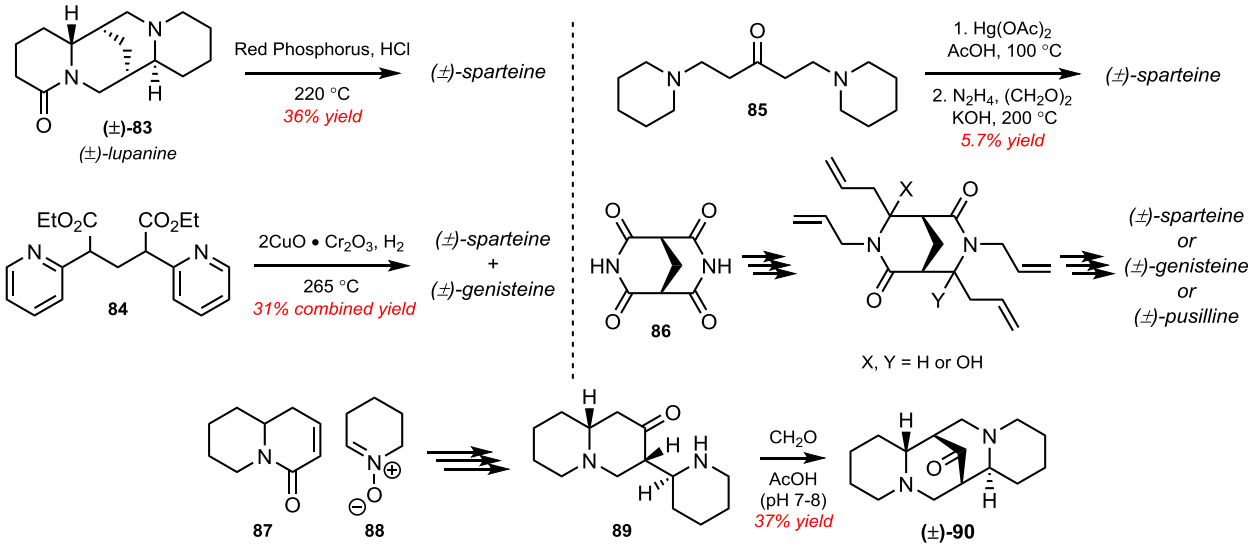
2.4. Syntheses of Sparteine

Largely due to its high synthetic utility, a number of syntheses of sparteine have been attempted with varying degrees of success.

2.4.1. Syntheses Affording Racemic Sparteine

A variety of partial and total syntheses of sparteine have been reported over the years. Overall step counts for these syntheses vary dramatically. For example, a partial synthesis in 1928 produced racemic sparteine from racemic lupanine by reduction (Scheme 2.5, 1 step and 36% yield overall).[80] Conversely, a recent ring-closing metathesis approach was used to generate all three diastereomers as

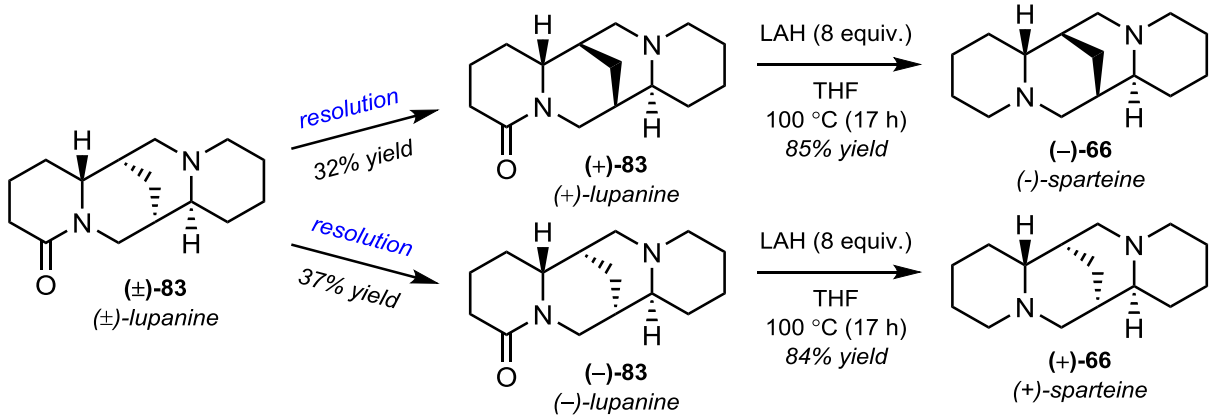
their racemates from a common precursor (9 steps and 2.5% yield overall for sparteine, 7 steps overall to each of genisteine and pusilline).[56b] Several other approaches have formed racemic sparteine with varying degrees of synthetic utility,[57a-c, 57e, 57f, 58b, 58c, 81] or have been formal syntheses.[82]



Scheme 2.5 – Select examples of partial, total, and formal syntheses of racemic sparteine.

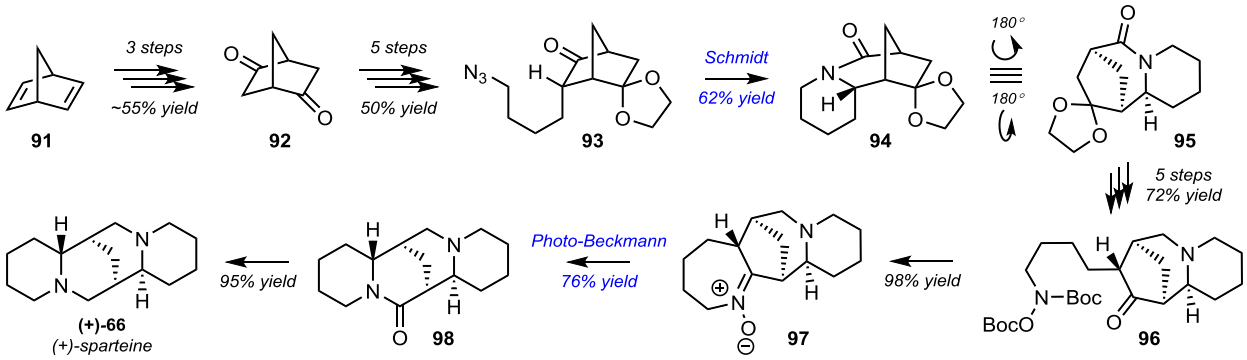
2.4.2. Syntheses Affording Enantioenriched Sparteine

Lupanine is abundant in nature as a racemate. Apparently unaware of Clemo's partial synthesis from racemic lupanine (Scheme 2.5),[80] and their subsequent work with enantioenriched lupanine,[83] Przybyl and Kubicki report a large scale partial synthesis of (+)-sparteine.[58g] Initial work improved the isolation of racemic lupanine from *Lupinus albus*, with 2.5 kg of seeds affording 10.3 g of (±)-lupanine (0.412% w/w). Resolution using enantioenriched dibenzoyltartaric acid affords either (-)-lupanine (37% yield) or (+)-lupanine (32% yield) in 99.9% *ee* (99.95:0.05 er) depending on which enantiomer of the acid is used. Reduction affords enantioenriched sparteine (99.5:0.5 er) in high yields (84-85% yield, Scheme 2.6).



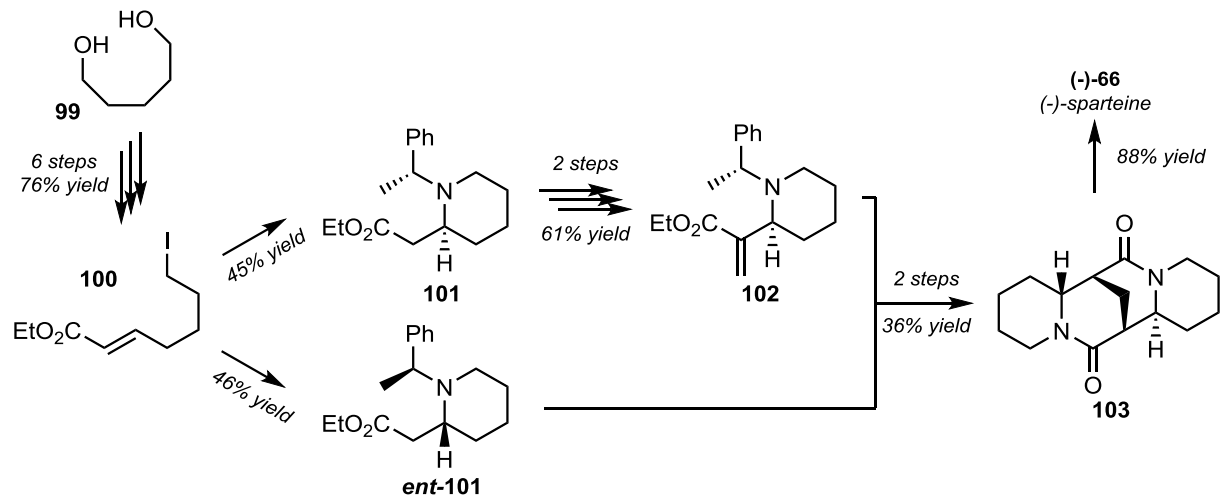
Scheme 2.6 – Partial synthesis of enantioenriched sparteine from enantioenriched lupanine.

In 2002 the first total synthesis of (+)-sparteine was reported by Aubé *et al*.[58d] The approach relies on nitrogen ring-expansion reactions (Schmidt and photo-Beckmann rearrangement) and produces (+)-sparteine in 18 steps and ca. 10% overall yield from norbornadiene (Scheme 2.7). Blakemore *et al*. note that this represents the first successful enantioselective total synthesis of any of the sparteine-type alkaloids.[56b]



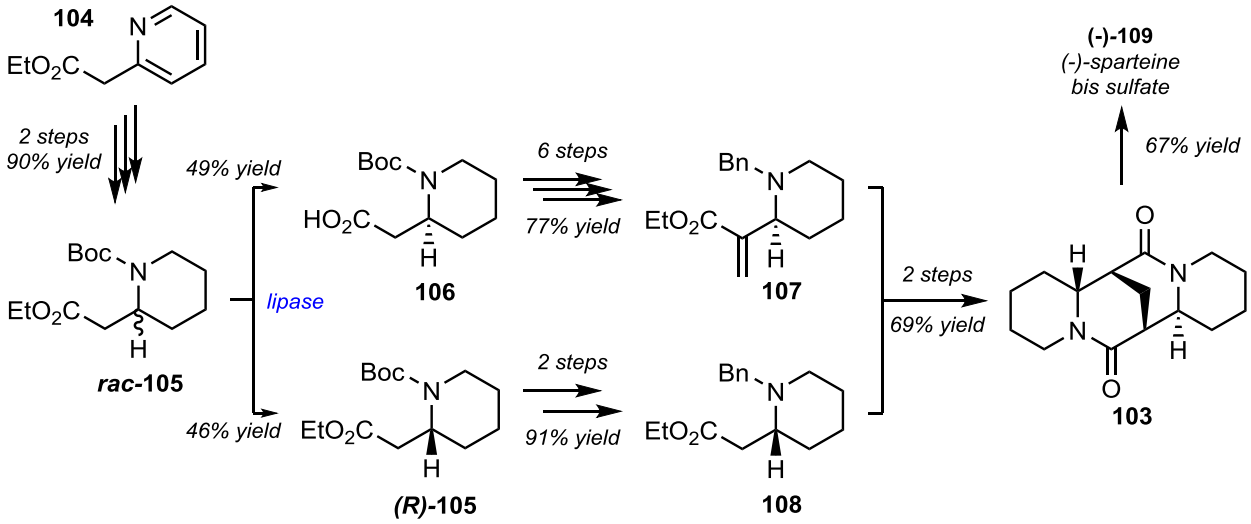
Scheme 2.7 – Total synthesis of (+)-sparteine from norbornadiene.

A subsequent total synthesis of (-)-sparteine reported by O'Brien *et al*. in 2004 shortened the synthesis at the cost of lowering the overall yield (10 steps and 4.4% overall yield, Scheme 2.8).[58f] Notably, this approach relies on the use of low-cost chiral auxiliaries, and could in principle be used to synthesize either enantiomer of sparteine.



Scheme 2.8 – Total synthesis of (-)-sparteine from 1,5-pentanediol.

This method was improved in 2018 through the use of an enzymatic resolution (Scheme 2.9).[58e] The second-generation synthesis increased the overall number of steps (16 total) and the overall yield of the product (14% overall).

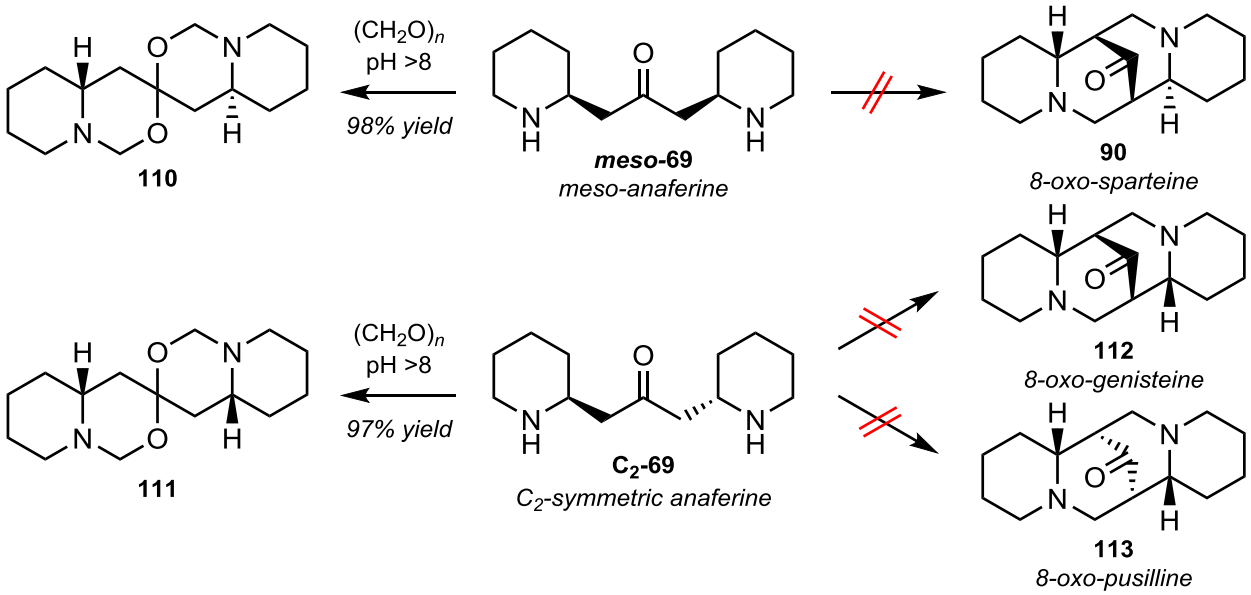


Scheme 2.9 – Total synthesis of (-)-sparteine from ethyl 2-pyridyl acetate.

Thus, despite the high synthetic utility of enantioenriched sparteine (see Section 2.2), only four routes have been reported leading to enantioenriched product.

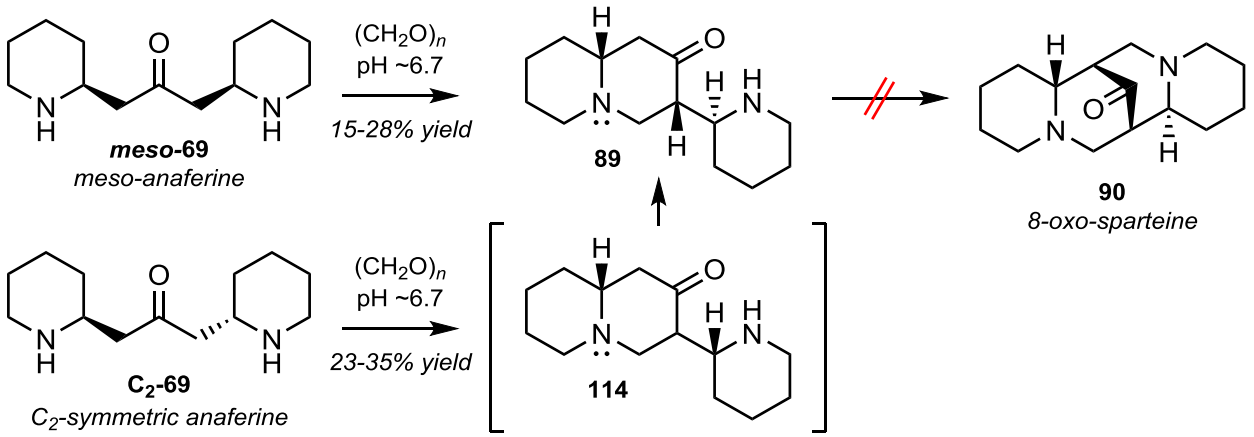
2.4.3. Schöpf's Attempted Synthesis

In 1971 Schöpf *et al*. published a trio of papers aimed at using a Mannich reaction to cyclize the *meso* and C_2-symmetric isomers of anaferine.[84] Initial attempts aimed to form a mixture of all diastereomers of sparteine, but instead resulted in the formation of spiro-acetals (Scheme 2.10).[84b] Incomplete iminium formation results in formation of a hemiaminal. Attack of the hemiaminal onto the ketone results in formation of a hemiketal, and subsequent ring closing leads to a stable tetracyclic system.



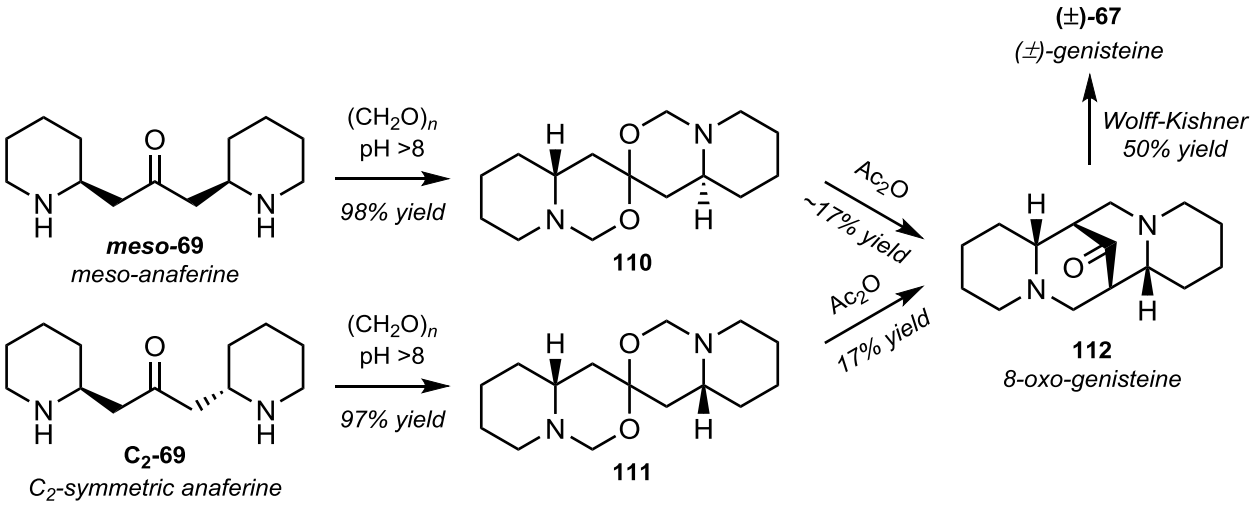
Scheme 2.10 – Cyclization of anaferine using formaldehyde affording spirocyclic compounds.

Slightly decreasing the pH of the solution allowed the first Mannich reaction to proceed (15-35% yield).[84c] However, the second ring does not close under their conditions (Scheme 2.11).[85] Interestingly, only the product with relative configuration deriving from the *meso* form of anaferine is obtained. The authors suggest that retro-Michael-Michael reactions allow the products to equilibrate to the more thermodynamically stable diastereomer.



Scheme 2.11 – Cyclization of anaferine under mildly acidic conditions using formaldehyde, affording a tricyclic intermediate.

In lieu of developing conditions to close the second ring, subjecting either of the spirocyclic diastereomers to acetic anhydride followed by Wolff-Kishner reduction results in the formation of (±)-genisteine (Scheme 2.12).[59] The authors note that this is only possible if epimerization of their material occurs; if the substrates are conformationally stable under the reaction conditions they should observe all three diastereomers. Genisteine is thought to be the thermodynamically most stable of the three.

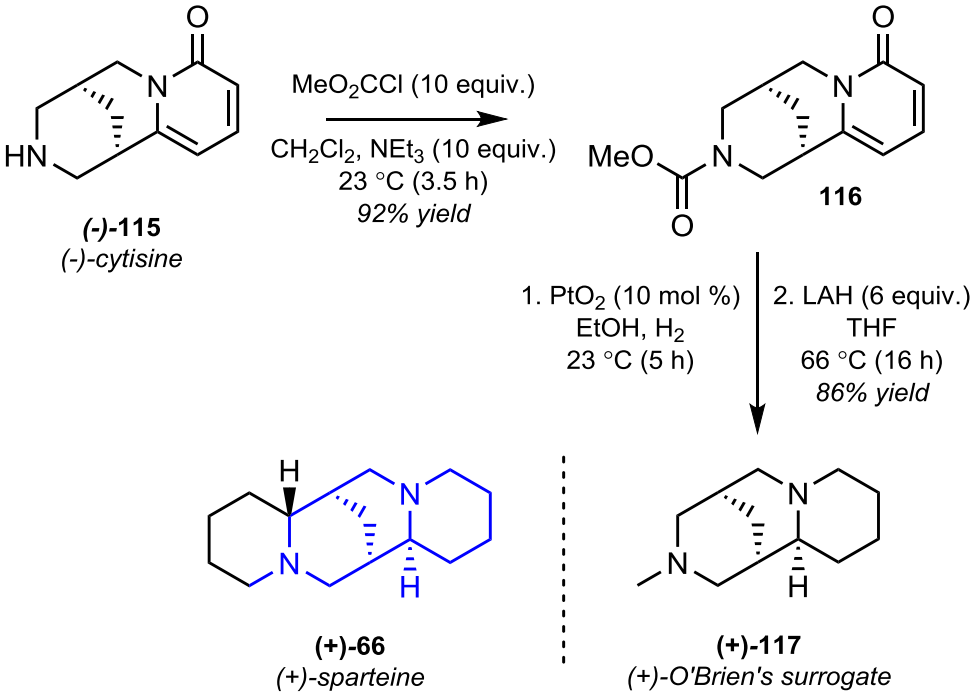


Scheme 2.12 – Conversion of spirocycles to racemic genisteine.

2.4.4. O'Brien's Surrogate

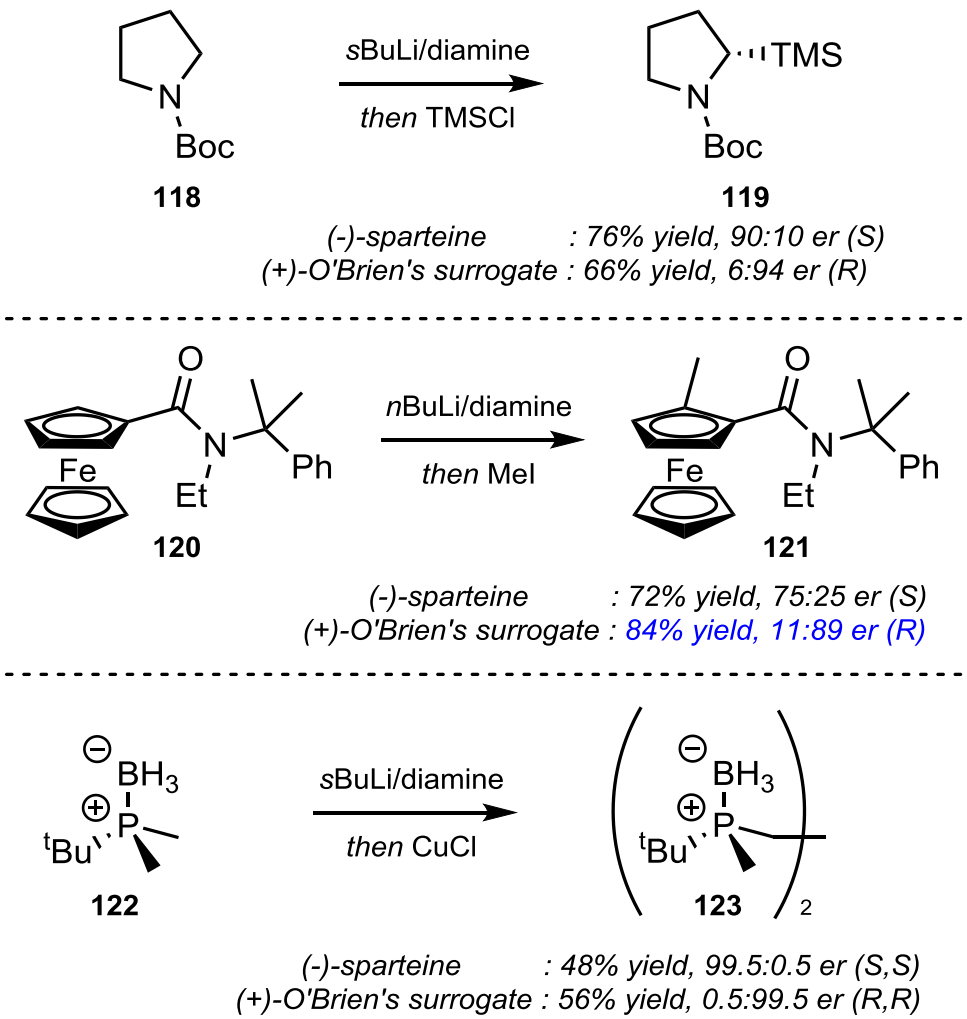
Given the lack of easy access to (+)-sparteine, and the increasing scarcity of (-)-sparteine,[86] several groups attempted to find substitutes for synthetic use.[87] In 2001 O'Brien *et al*. disclosed the most successful of these surrogate compounds.[88] Examination of computed transition states[89] suggested only three of sparteine's rings were necessary to achieve comparable enantioselectivity.

Initially, the syntheses of O'Brien's surrogates resulted in racemic products requiring resolution for use.[88, 90] Subsequent syntheses primarily relied on the commercially available alkaloid cytisine, which shares the majority of its skeletal structure and absolute configuration with sparteine.[91] It has been suggested that (-)-cytisine is derived biosynthetically from (+)-sparteine, though it is considerably more abundant.[55d] In a three step process cytisine can be converted to the sparteine surrogate with high efficiency (79% overall yield, Scheme 2.13). Recently an alternative synthesis from ethyl 2-pyridyl acetate has been reported (11 steps overall, 22% overall yield) due to concerns about long-term accessibility of cytisine *via* extraction from natural sources.[58e]



Scheme 2.13 – Synthesis of O'Brien's sparteine surrogate from cytisine.

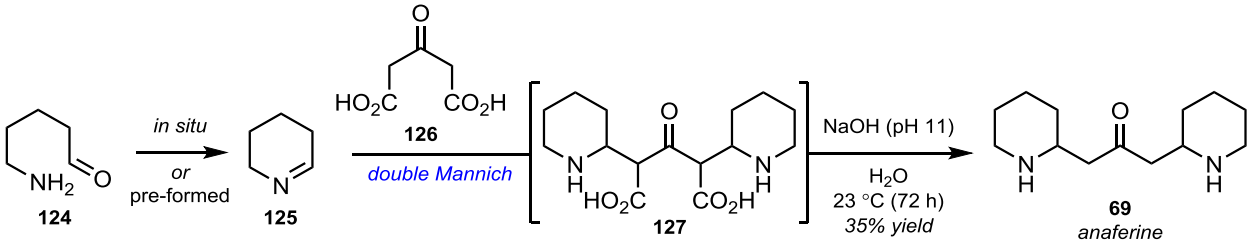
O'Brien's group has demonstrated that their surrogate is capable of enantioselective deprotonations[92] as well as stereoselectively generating ferrocenes and bisphosphenes[93] with yields and enantioselectivities comparable to those using (-)-sparteine (Scheme 2.14). Relative rates of reaction using the two ligands are not always similar. In particular, alkyl lithium complexes with the surrogate compound are substantially more reactive than their equivalent (-)-sparteine complexes, despite affording comparable yields and enantioselectivities.[94]



Scheme 2.14 – Selected examples of enantioselective reactions comparing the use of O'Brien's sparteine surrogate with that of sparteine.

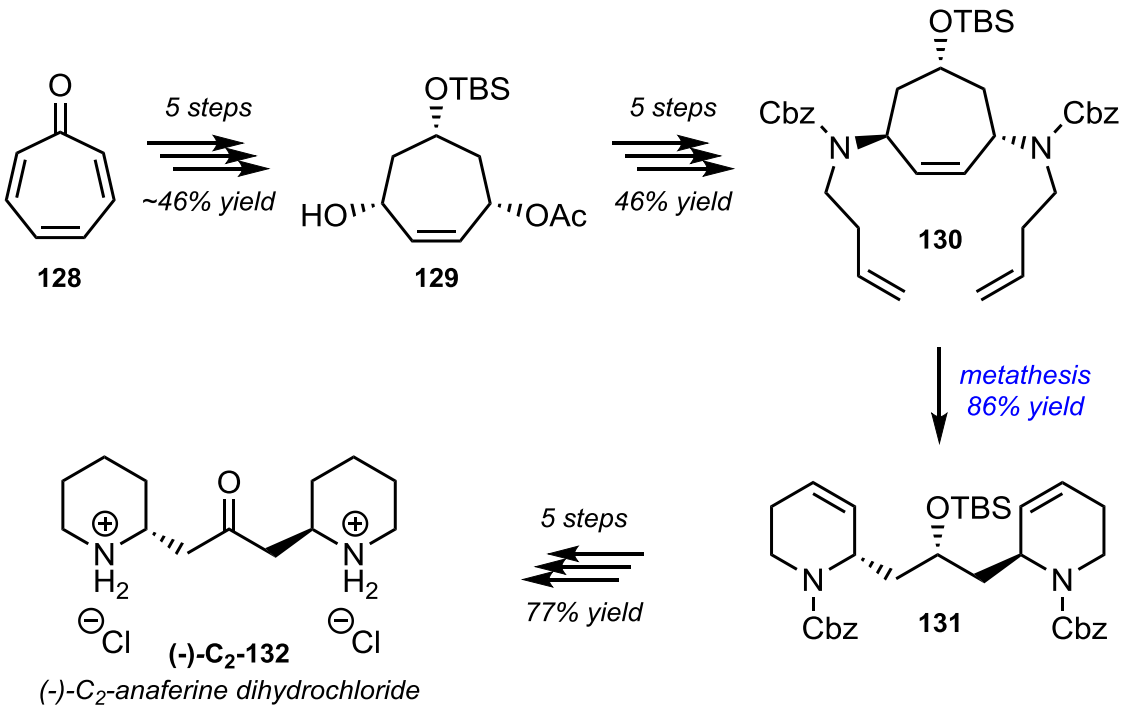
2.4.5. Previous Syntheses of Anaferine

Previous work by Anet,[57b, 57c] and later Schöpf,[84d, 95] shows that a mixture of *meso*- and C_2-symmetric anaferine can be obtained *via* a three-step synthesis (Scheme 2.15). Self-condensation of 5-aminopentanal (*in situ*[57b, 57c] or prior to the reaction)[84d, 95] followed by two Mannich reactions with 3-oxoglutaric acid produces a dicarboxylic acid. Under the basic reaction conditions (pH 11), double decarboxylation affords anaferine (35% yield) in a one-to-one mixture of isomers.[57c]



Scheme 2.15 – Three-step one-pot synthesis of anaferine as a mixture of diastereomers.

The first and only stereoselective synthesis of anaferine was reported in 2002 by Blechert and Stapper (Scheme 2.16).[61a] Beginning from tropone, the approach relies on an enzymatic desymmetrization and ring-rearrangement metathesis to afford (-)-anaferine in 16 overall steps and 14.1% overall yield. The authors note that many of the steps in the sequence are due to protecting group interconversions; it may be possible to substantially shorten this synthesis with more judicial selection of protecting groups.

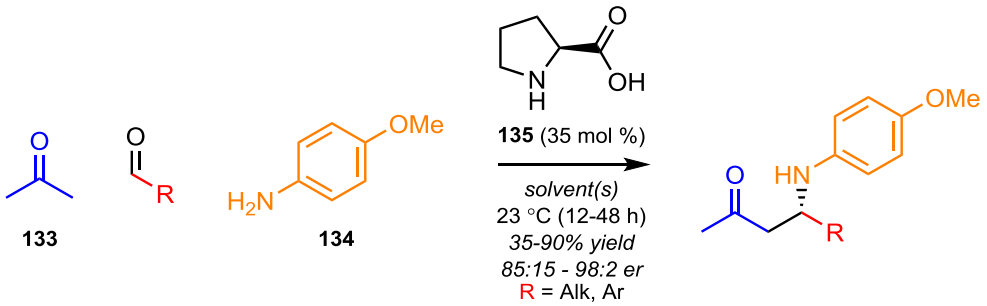


Scheme 2.16 – Total synthesis of (-)-anaferine from tropone.

2.5. Amine Catalysis of the Mannich Reaction

The Mannich reaction is a classic synthetic tool to generate β-aminoketones, esters, and aldehydes.[96] Historically, the reaction has been divided into indirect (i.e.: preformed imines/iminiums and/or enolate equivalents) and direct approaches. Other species such as *N*,*O*-acetals, aminals, and hydrazones have occasionally been employed as imine substitutes. Catalysis offers an attractive way to improve the scope of the Mannich reaction, particularly when enantioenriched products are desired. Although some impressive results have been achieved through organometallic species,[97] organocatalysis offers a robust and potentially cost-effective alternative, particularly with direct three-component Mannich reactions.

In the mid 1990's, few approaches to stereoselective Mannich reactions were reported,[98] and fewer still were catalytic.[99] In the later part of the decade several stereoselective and catalytic methods were described, culminating in a proline-catalyzed enantioselective three-component procedure by List in 2000 (Scheme 2.17).[100]



Scheme 2.17 – Original report of proline-catalyzed three-component Mannich reactions.

This was based on previous work with proline-catalyzed enantioselective aldol reactions,[101] as well as two assumptions: "(a) the nucleophilic addition of the proline enamine would be faster to an imine than to an aldehyde and (b) that imine formation with a primary amine would be faster than concurrent aldolization."[100] Initial results showed moderate to excellent yields and enantioselectivities (35-90% yield, 85:15-98:2 er). A model rationalizing the enantioselectivity was proposed (Figure 2.3, coordination to the enamine shown for clarity) as involving either a boat-like transition state and *E* enamine, or chair-like transition state with a *Z* enamine. Following this a number of secondary amine-catalyzed Mannich reactions were reported using a variety of catalysts, many of which are proline-derived.[97d]

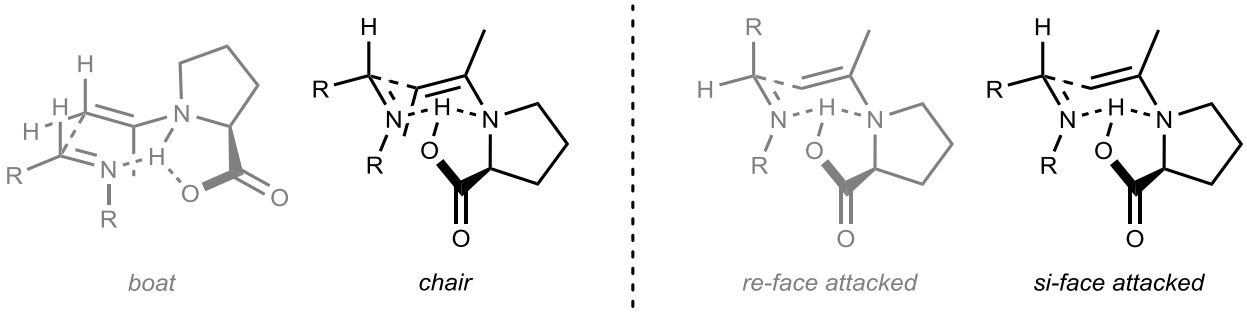
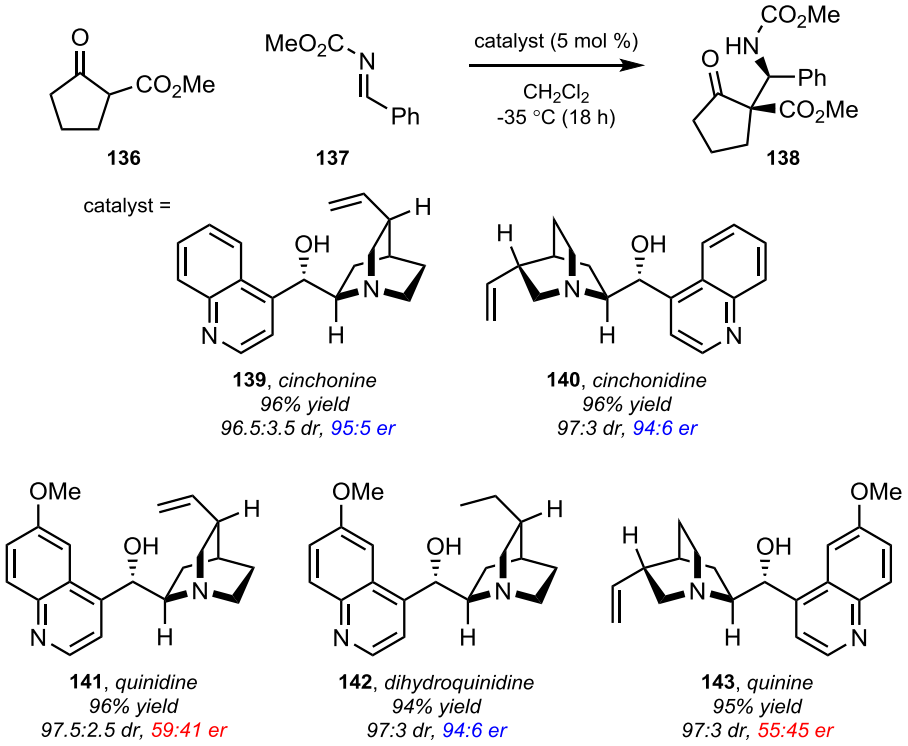


Figure 2.3 - Putative transition states for proline-catalyzed Mannich reactions.

A major limitation to secondary amine catalysis of the Mannich reaction lies in its minimal applications with ketones;[102] the majority of reactions employ aldehydes where one partner is non-enolizable and thus only able to serve as the

electrophile.[103] Primary amines have recently begun to see applications in catalysis with ketones in enantioselective aldol and Michael reactions,[104] capitalizing on List's second assumption above to generate chiral intermediates faster than the competing achiral ones. Concurrently, promising work comes from cinchona-family alkaloids[105] and their derivatives in enantioselective Mannich reactions of both aldehydes[106] and ketones[107] (Scheme 2.18). These systems are not based on enamine catalysis, but instead utilize the alkaloids as chiral Brønsted bases. Very recently, this approach has been extended to the use of cinchona-derived squaramides,[108] thioureas,[109] and other derivatives[110] as catalysts in Mannich reactions. Amine-containing cinchona-derived catalysts are also competent at enamine catalysis though no examples of Mannich reactions have been reported.[105b]



Scheme 2.18 – Example of cinchona alkaloid catalysis of Mannich reactions.

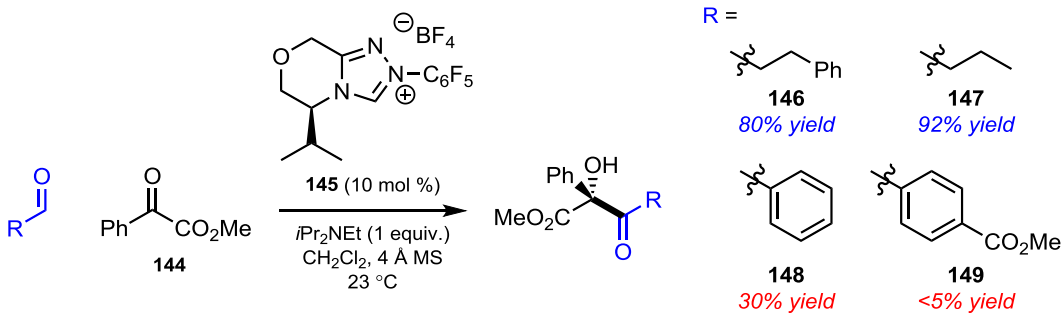
PART II: RESULTS AND DISCUSSION

CHAPTER 3: CHEMOSELECTIVE N-HETEROCYCLIC CARBENE CATALYZED CROSS-BENZOIN REACTIONS OF ALDEHYDES

3.1. Research Objective

Several methods have been reported for NHC-catalyzed cross-benzoin reactions of aldehydes (see Section 1.3). However, the conditions needed to achieve chemoselectivity, such as an *ortho*/α-substituent or the use of a large excess of one of the aldehydes, result in narrow substrate scopes and limited synthetic applicability. As a result of these restrictions, these approaches have limited synthetic utility.

During studies on cross-benzoin reactions between aldehydes and ketones the Gravel group noticed a difference in reactivity between aliphatic and aromatic aldehydes (Scheme 3.1).[10, 17] Using triazolylidene catalysts derived from morpholinones results in fast reactions and high yields with aliphatic aldehydes, while reactions with aromatic aldehydes are substantially slower and lower yielding. This contrasted strongly with contemporary results from Connon/Zeitler,[37] who reported fast reactions with high yields for both aliphatic and aromatic aldehydes. The major difference between these two reports is the presence of a fused *morpholine* ring in place of a *pyrrolidine* ring in the catalyst backbone. It was hypothesized that some aspect of the morpholine ring causes the catalyst to preferentially form Breslow intermediates with aliphatic aldehydes over aromatic aldehydes.



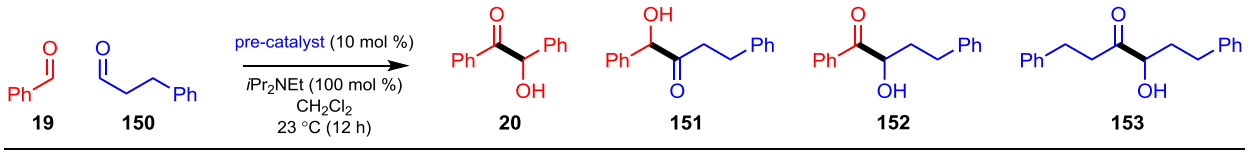
Scheme 3.1 – Difference in reactivity of aromatic and aliphatic aldehydes reported by Thai, Langdon, Bilodeau, and Gravel.

To address the current limitations of NHC-catalyzed cross-benzoin reactions, we sought to explore this effect of the catalyst backbone on chemoselectivity. The project aims to determine whether and which judicious modification(s) of the catalyst backbone can be used to improve chemoselectivity in cross-benzoin reactions of aldehydes. A thorough understanding of how the catalyst(s) afford improved chemoselectivity is also sought, to improve subsequent catalyst design. If possible, further improving the synthetic utility with catalysts affording both highly chemo- and enantioselective cross-benzoin reactions is also desired.

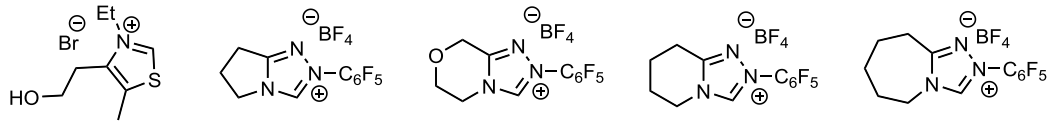
3.2. Catalyst Comparison

A series of cross-benzoin reactions between hydrocinnamaldehyde and benzaldehyde, prototypical aliphatic and aromatic aldehydes respectively, was used to gauge the effect of the catalyst backbone on chemoselectivity (Table 3.1).

Table 3.1 – Comparison of catalysts for a prototypical cross-benzoin reaction.



19 150 20 151 152 153



154 5 155 156 157

entry	pre-catalyst	product ratio (20 : 151 : 152 : 153)	yield of 151 (%)[a]
1[b]	154	6 : 12 : 21 : 61	2
2	5	2 : 59 : 25 : 14	43
3	155	2 : 93 : 0 : 5	19
4	156	2 : 94 : 0 : 4	16
5	157	21 : 68 : 9 : 2	26

a) Yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard. b) Performed using 5 mol % DBU.

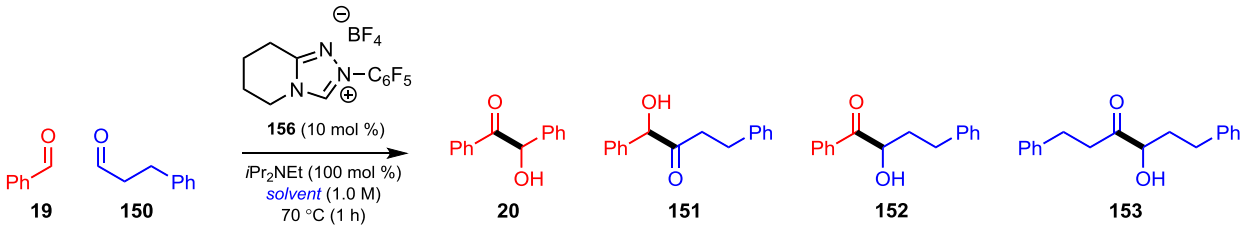
Use of a commonly employed thiazolylidene catalyst affords poor yield and chemoselectivity, with cross-benzoin product **152** being slightly preferred (entry 1). Although reactivity (*viz*. conversion) with this catalyst can be improved by modifying the reaction conditions, chemoselectivity remains poor. The pyrrolidinone-derived triazolylidene (entry 2) affords the best conversions but limited selectivity for **151**. Increasing the size of the fused ring (entries 3 and 4) substantially improves chemoselectivity at the cost of lowering conversion. As both piperidinone- and morpholinone-derived catalysts produce comparable results, it can be concluded that the presence of oxygen in the catalyst backbone is not a factor leading to improved chemoselectivity. Further increasing to a fused seven-membered backbone (entry 5) results in a loss of chemoselectivity. Notably, reactions using pre-catalyst **157** exhibit poor reproducibility; fluctuating chemoselectivities and yields, as well as variable formation of oxidized products (diketones), exclude salt **157** as a viable synthetic tool.

Synthesis of **155** proved highly problematic (see Section 3.7). Repeated attempts (five by S. Langdon, three by Dr. K. Thai, and one by Dr. M. Wilde) resulted in only one successful synthesis in poor yield (30 mg, 0.7% yield from morpholinone, Dr. K. Thai). As such, subsequent work focused on use of piperidinone-derived **156**.

3.3. Optimization of Reaction Conditions

Although the piperidinone-derived triazolylidene catalyst afforded excellent chemoselectivity, the initial yields of **151** were too low to be synthetically useful. Modifications to the reaction conditions were explored to attempt to improve these yields. Monitoring the initial rates of reaction by ^{1}H NMR showed that an increase of 10 °C in the reaction temperature affords a 2.5-2.6 fold increase in reaction rates (see Section 5.2.3). Both microwave and conventional heating afford comparable improvements. Conventional heating to 70 °C was adopted as heating beyond this point did not further improve yields.

Table 3.2 – Comparison of solvents for a cross-benzoin reaction.



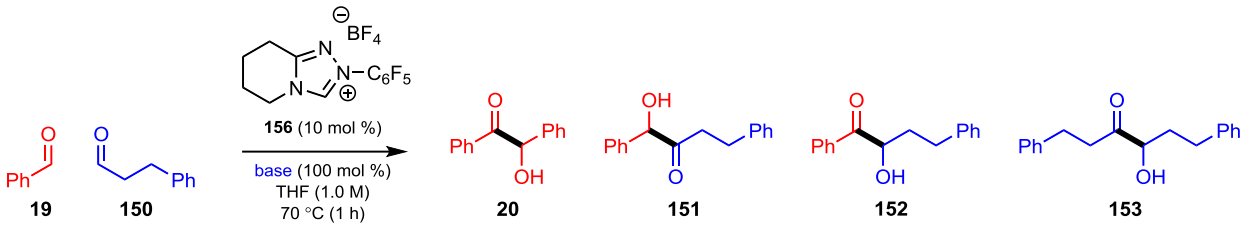
entry	solvent	product ratio (20 : 151 : 152 : 153)	yield of 151 (%)[a]
1	CH_2Cl_2	6 : 82 : 8 : 5	66
2	THF	6 : 88 : 3 : 3	69
3	PhMe	7 : 89 : 0 : 4	63
4	$ClCH_2CH_2Cl$	7 : 81 : 5 : 7	64
5	EtOH	50 : 50 : 0 : 0	10

a) Yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard.

Varying the solvent of the reaction (Table 3.2) did not afford any significant improvement. Protic solvents (entry 5) are not appropriate for the reaction, affording low (ca. 50%) consumption of starting materials and a large amount of oxidized diketone products. Ethereal (entry 2), halogenated (entries 1 and 4), and aromatic (entry 3) solvents all afford comparable chemoselectivity and yield. With a mild improvement in both, THF was used for further optimization.

Several commonly used bases were then screened (Table 3.3). Tertiary amine (entry 1) and acetate (entry 2) bases afford identical results. Similar results can be obtained using DBU (entries 3 and 4) though only at catalytic levels; use of stoichiometric amounts of DBU results in a complex mixture of non-benzoin products. Surprisingly, the use of a carbonate base (entry 5) results in a loss of both chemoselectivity and yield. It is not immediately apparent why this occurs. Switching from Cs_2CO_3 to K_2CO_3 restores both chemoselectivity and yield to levels comparable to *i*Pr_2NEt (entry 1), suggesting the caesium cation may be responsible.[111] However, the use of CsOAc in place of NaOAc (entry 2) does not alter the reaction outcome. It is possible that the increased hygroscopicity of Cs_2CO_3 relative to K_2CO_3 causes it to contaminate the system with water, which has a detrimental effect on both yield and chemoselectivity (see Table 3.5).

Table 3.3 – Comparison of bases for a cross-benzoin reaction.



19 150 20 151 152 153

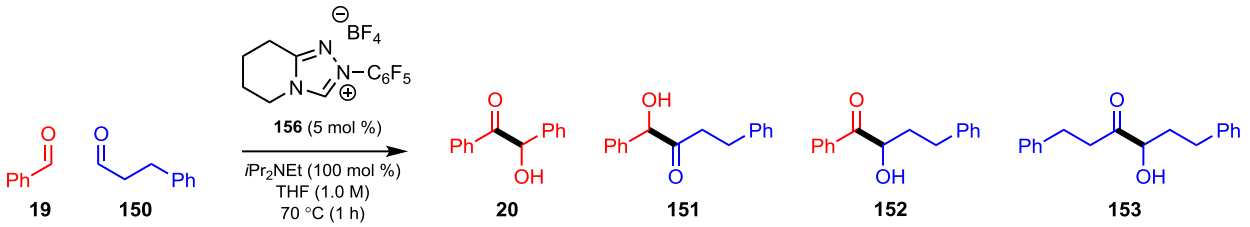
entry	base	product ratio (20 : 151 : 152 : 153)	yield of 151 (%)[a]
1	*i*Pr$_2$NEt	5 : 88 : 2 : 5	66
2	NaOAc	5 : 88 : 2 : 5	66
3	DBU	0 : 0 : 0 : 0	0
4	DBU[b]	3 : 86 : 8 : 3	63
5	Cs_2CO_3	8 : 37 : 51 : 4	22

a) Yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard. b) Performed using 5 mol% DBU.

Reaction yields were not significantly improved through varying the solvent or base employed. Thus several other variables were explored (Table 3.4). As lowering the catalytic loading to 5 mol % (entry 2) shows no loss of yield relative to the control (entry 1) all subsequent reactions were carried out with this loading. Further decreasing the catalytic loading to 1 mol % affords inconsistent yields of **151** (36-92% yield, 6 reactions), though without a loss of chemoselectivity. Neither increasing the concentration (entry 3) nor halving the reaction time (entry 4) had a significant effect. At high concentrations a slurry is formed. As this makes stirring difficult the molarity was not increased in the optimized conditions.

The Yang group has reported that using a large excess (10 equiv.) of one aldehyde may improve reaction yields in NHC-catalyzed cross-benzoin reactions.[13d] Increasing the amount of aliphatic aldehyde from 1 equiv. to 1.5 equiv. affords substantially improved yields of **151** (entry 5), although this slightly increases the amount of contaminating homo-benzoin product **153**.

Table 3.4 – Additional modified conditions for a cross-benzoin reaction.

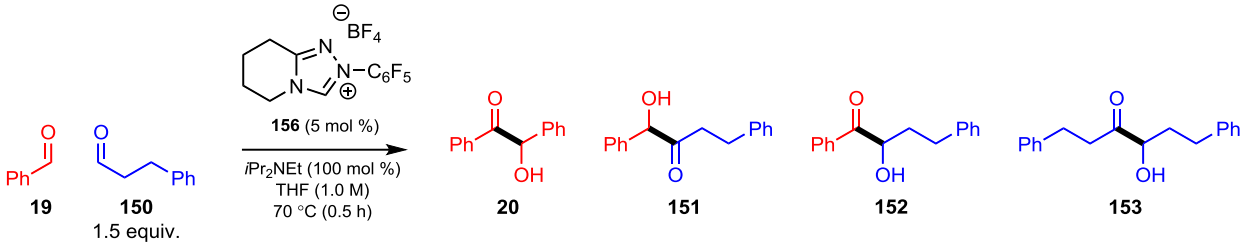


entry	modification	product ratio (20 : 151 : 152 : 153)	yield of 151 (%)[a]
1	*control* (10 mol % of **156**)	5 : 88 : 2 : 5	66
2	5 mol % of **156**	4 : 88 : 2 : 6	67
3	2.0 M	4 : 87 : 3 : 6	65
4	0.5 h	3 : 89 : 2 : 6	68
5	1.5 equiv. hydrocinnamaldehyde	1 : 86 : 2 : 11	80

a) Yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard.

It has been shown that the addition or removal of water can have a significant impact on yields in cross-benzoin reactions.[10, 17] Additional conditions were explored to determine the effect of water on the reaction (Table 3.5). The addition of 4 Å molecular sieves (entry 2) did not improve the selectivity or yield. Extraction and an aqueous workup are required to remove the base and (pre-) catalyst after the reaction. Returning the solvent to CH_2Cl_2 (entry 3) facilitates this extraction and brings a slight improvement in the yield. The addition of small amounts of water (entries 4 and 5) slows the reaction but does not adversely affect the chemoselectivity. However, introduction of a large amount of water (entry 6) results in both a slower reaction and a significant loss of chemoselectivity.

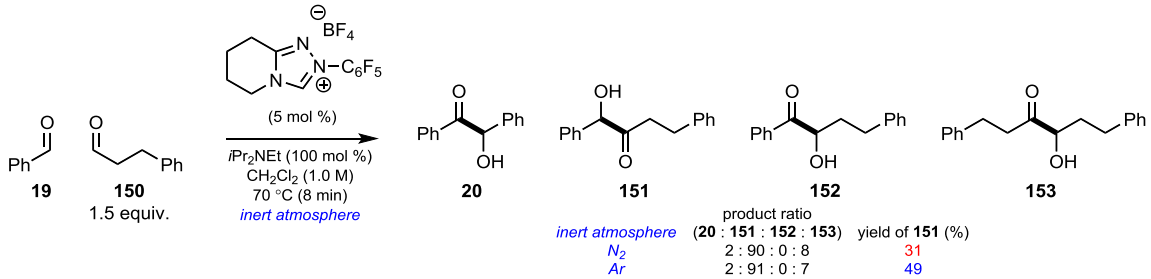
Table 3.5 – Effect of water on a cross-benzoin reaction.



entry	modification	product ratio (20 : 151 : 152 : 153)	yield of 151 (%)[a]
1	*control*	1 : 86 : 2 : 11	75
2	4 Å MS	1 : 83 : 2 : 14	72
3	CH_2Cl_2	1 : 84 : 5 : 10	82
4	CH_2Cl_2, 2 h 1 equiv. H_2O	2 : 83 : 0 : 15	86
5	CH_2Cl_2, 2 h 10 equiv. H_2O	6 : 84 : 0 : 10	51
6	1:1 CH_2Cl_2:H_2O, 2 h	12 : 51 : 16 : 21	15

a) Yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard.

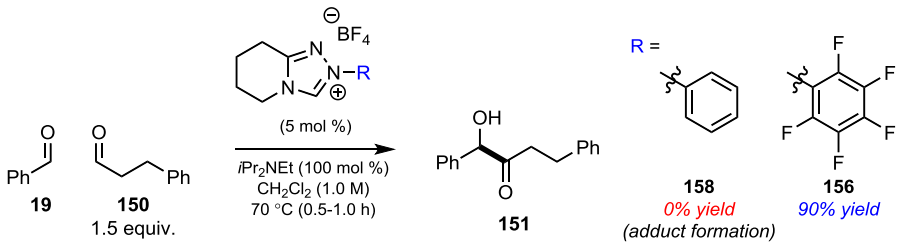
Switching the inert atmosphere from nitrogen to argon both improved the rate of reaction and minimized oxidized side products (Scheme 3.2). A separate experiment demonstrated that the addition of 20 mol % benzil, the diketone from the oxidation of **20**, causes a complete loss in reactivity under these conditions. The rigorous exclusion of oxygen thus has multiple favourable effects on the reaction.



Scheme 3.2 – Comparison of benzoin reactions under nitrogen and argon inert atmospheres.

Although conversions were high using these modified conditions, isolated yields were often significantly lower. Dr. M. Wilde contributed to the optimization by demonstrating that sealing the vessel brings isolated yields into agreement with ^{1}H NMR determined yields.[112] It is thought that, despite the use of a cold finger in the experimental setup, some of the starting material(s) were being lost to evaporation under the reaction conditions.

Piperidinone-derived triazolium salts bearing *N*-phenyl and *N*-mesityl groups, in place of the *N*-C_6F_5 group, were also synthesized (by S. Langdon and Dr. M. Wilde respectively; see Section 3.7). Use of the *N*-mesityl triazolylidene in cross-benzoin reactions (as Table 3.1) does not afford any benzoin product(s). While the use of the *N*-phenyl catalyst in homo-benzoin reactions of benzaldehyde affords trace amounts of benzoin, application of this pre-catalyst under the optimized reaction conditions in cross-benzoin reactions (Scheme 3.3) does not afford any benzoin product(s). Instead, the *N*-phenyl catalyst forms a long-lived, semi-stable, adduct with the aliphatic aldehyde (cf. Scheme 1.14, structure **iv**).



Scheme 3.3 – Homo- and cross-benzoin reactions catalyzed with *N*-phenyl and *N*-pentafluorophenyl substituted triazolylidenes.

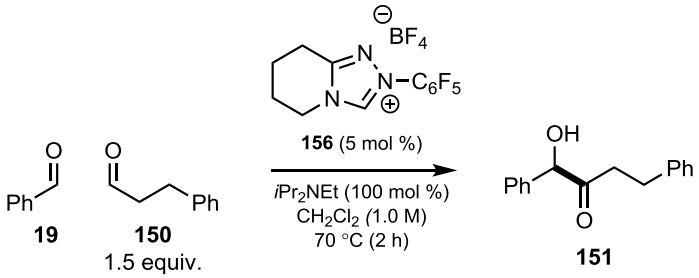
Optimization of the isolation and purification of the products was also required. During the elucidation of the substrate scope (see Section 3.4) it became apparent that many of the benzoin products were degrading during purification. Purification by flash column chromatography variably results in significant mass loss, decomposition, and/or isomerization to a mixture of cross-benzoin products. Dr. M. Wilde demonstrated that the source of the silica gel exacerbated these issues.[112] Distillation of the products also leads to partial isomerization. Quenching the reaction with acetic acid in place of dilute hydrochloric acid also has a detrimental effect on purification. Functionalization/protection such as

silylation (S. Langdon) or acylation (Dr. M. Wilde)[112] were explored. However, these reactions were incompatible with *in situ* conditions, did not proceed smoothly with crude reaction mixtures, and/or did not affect purification.

3.3.1. Other Additives

Over the course of the optimization, it was observed that control reactions carried out on sequential days afforded a noticeable variability, despite otherwise identical conditions. Examination of the conditions showed an additional variable: how recently the aldehyde(s) had been distilled. Taking this effect to its extreme (Table 3.6) suggests that it is significant. Notably, each reaction exhibited comparable levels of chemoselectivity, suggesting an effect on reaction rate rather than selectivity. When both aldehydes are freshly distilled the yield is substantially diminished (51% yield). Use of freshly distilled aliphatic aldehyde with previously distilled aromatic aldehyde affords an improvement (67% yield). However, as reactions employing previously distilled aliphatic aldehyde with either freshly distilled or previously distilled aromatic aldehyde afford comparable yields, the effect from the aliphatic aldehyde must be stronger.

Table 3.6 – Effect of time since distillation of the aldehydes on a cross-benzoin reaction.

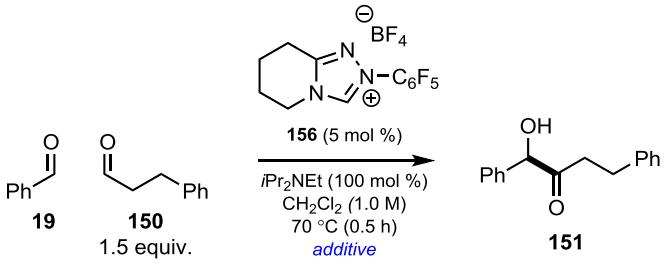


	"fresh" 19 (distilled <1 h ago)	**"old" 19** (distilled 7 d ago)
"fresh" 150 (distilled <1 h ago)	*51% yield of* ***151***	*67% yield of* ***151***
"old" 150 (distilled 7 d ago)	*77% yield of* ***151***	*76% yield of* ***151***

a) Yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard.

Use of additives bearing OH functionalities, notably catechol,[32d] has been shown to accelerate the Stetter reaction up to 400-fold. It was hypothesized that some impurity in the aldehydes improves the reaction rate. Impurities common in aldehydes include alcohols and carboxylic acids derived from the Cannizzaro reaction and/or air oxidation. A screening of additives with freshly distilled aldehydes was performed (Table 3.7).

Table 3.7 – Effect of additives on a prototypical cross-benzoin reaction.



entry	additive (mol %)	relative yield of 151 ([yield with additive]/[yield of control])
1	benzyl alcohol (1)	0.95
2	benzoic acid (1)	1.71
3	hydrocinnamic acid (0.1)	1.38
4	hydrocinnamic acid (1)	1.81
5	hydrocinnamic acid (5)	1.79
6	valeric acid (1)	1.86
7	acetic acid (1) (pKa = 4.76)	1.71
8	chloroacetic acid (1) (pKa = 2.87)	1.00
9	dichloroacetic acid (1) (pKa = 1.25)	1.09
10	trichloroacetic acid (1) (pKa = 0.77)	1.71
11	trifluoroacetic acid (1) (pKa = 0.23)	0.91
12	sodium acetate (1)	1.43
13	hydrochloric acid (1)	1.07
14	catechol (1)	1.00

a) Yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard.

Benzyl alcohol, which could arise from the Cannizzaro reaction of benzaldehyde, has no effect on the reaction (entry 1). However, benzoic acid

shows substantial improvement (entry 2). Initial screening of hydrocinnamic acid shows improvement even at 0.1 mol % loading (entry 3). This effect plateaus at 1 mol % (entry 4) and is maintained through 5 mol % loading (entry 5). Other aliphatic carboxylic acid additives produce an equivalent effect (entries 6 and 7). To gauge the effect of acidity (pKa) a series of acetic acid derivatives were screened (entries 7-11). However, no trend was observed. The addition of sodium acetate (entry 12) also showed improvement, suggesting a role for the carboxylate. Neither hydrochloric acid (entry 13) nor catechol (entry 14) affects the yield, supporting this hypothesis.

Although these effects were noteworthy, they were not always reproducible. For example, the addition of 1 mol % of hydrocinnamic acid variably decreased (0.85x) or increased (1.15x, 1.39x, 1.81x) the reaction yield. Chemoselectivity remained constant in all experiments carried out in CH_2Cl_2. However, in toluene the use of acid additives results in either no effect or a loss of chemoselectivity.

As models, homo-benzoin reactions are simpler to study. Assuming that NHC-catalyzed homo-benzoin reactions of aromatic and/or aliphatic aldehydes proceed through the same mechanism as cross-benzoin reactions, any rate enhancement due to acid additives should be observed in these systems as well. Repeated experiments comparing the rates of homo-benzoin reactions of benzaldehyde both with and without 1 mol % hydrocinnamaldehyde added show no effect on the reaction. An equivalent series of experiments using hydrocinnamaldehyde also shows no effect. Finally, a set of experiments monitoring reaction progress with ^{1}H NMR for both the homo-benzoin reaction of benzaldehyde and the cross-benzoin reaction of benzaldehyde with hydrocinnamaldehyde shows no change in reaction rate when performed with or without the acid additive.

Given the inconsistent nature of this effect, for optimal results with this reaction aromatic aldehydes should be freshly distilled and the aliphatic aldehydes should be used 1-3 days after distillation. Although this does not address *why* the yield improves with aged aldehyde(s), it allows for reproducible results across multiple experiments and experimenters.

3.4. Substrate Scope

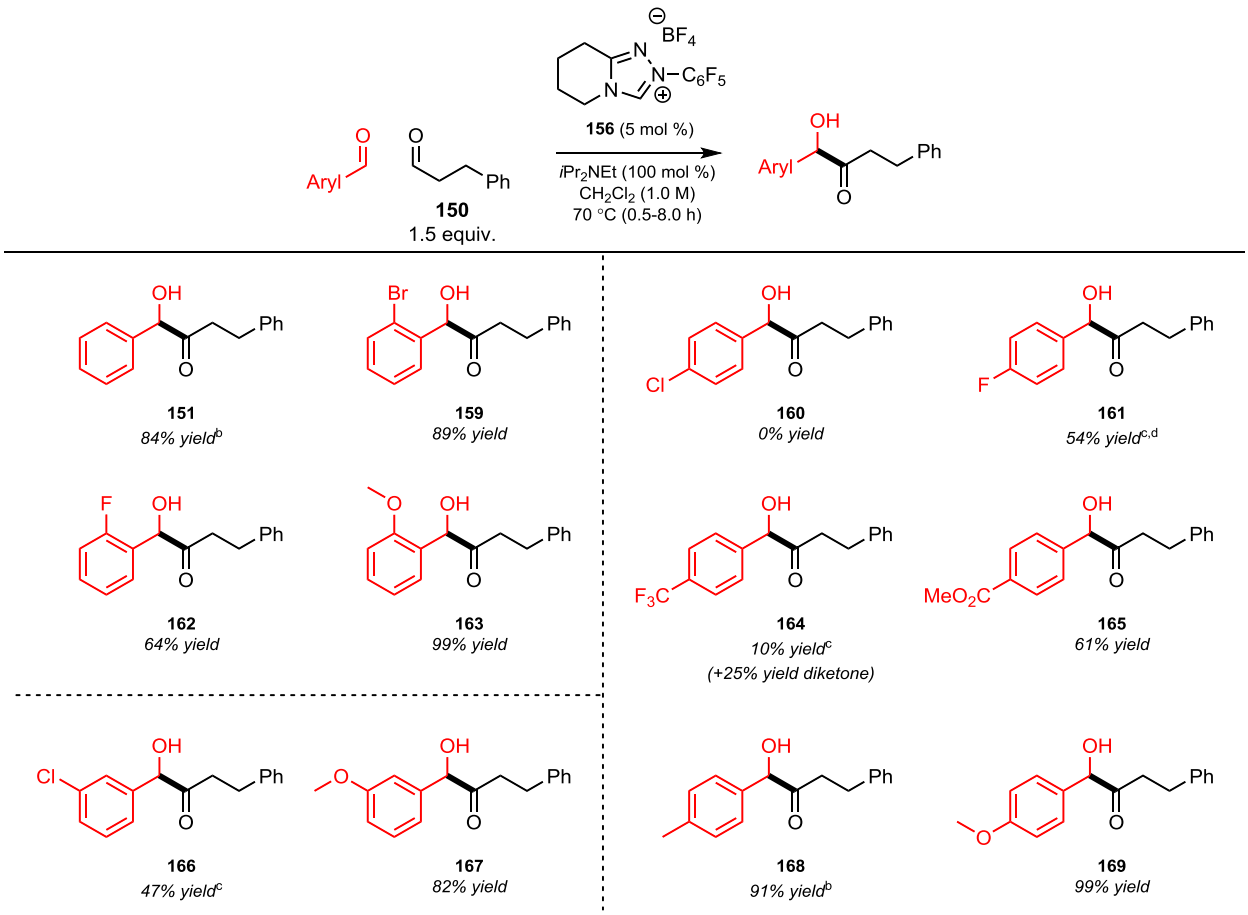
With both the reaction conditions and the isolation/purification of products optimized an exploration of the substrate scope was undertaken.

3.4.1. Division of Labour

The substrate scope was determined in tandem with Dr. M. Wilde. The majority of these reactions were performed in duplicate by both S. Langdon and Dr. M. Wilde, with the reaction less affected by purification issues (see Section 3.3)[112] presented. Reactions with acetaldehyde, *p*-CO_2Me benzaldehyde, *o*-OMe benzaldehyde (*o*-anisaldehyde), *o*-F benzaldehyde, and crotonaldehyde were performed exclusively by Dr. M. Wilde. Reactions with *m*-Cl benzaldehyde, *p*-Cl benzaldehyde, *p*-CF_3 benzaldehyde, *p*-F benzaldehyde, 2-furfuraldehyde, 2-phenylpropionaldehyde, and the functionalized aliphatic aldehydes (Section 3.4.3.1.) were performed exclusively by S. Langdon. In some instances the reactions were performed by S. Langdon and purified by Dr. M. Wilde (benzaldehyde, *p*-Me benzaldehyde (*p*-tolualdehyde), *o*-Br benzaldehyde, 2-pyridinecarboxaldehyde, and 3-pyridinecarboxaldehyde) either for the sake of speed or due to health concerns.

3.4.2. Substrate Scope: Aromatic Aldehydes

A wide array of aromatic aldehydes were subjected to the optimized reaction conditions to test their viability as substrates (Scheme 3.4). Hydrocinnamaldehyde was chosen as the model aliphatic aldehyde due to its ease of use (low volatility, low odour) and characterization (^{1}H NMR signals). Substitution at the *ortho* position (**159**, **162**, and **163**) is well tolerated, although **162** is produced in diminished yield. As all fluorinated substrates (**161**, **162**, and **164**) prove problematic it is probable that this is due to the highly electron-withdrawing nature of the fluorine rather than substitution at the *ortho* position. *Meta*-substitution (**166** and **167**) also affords chemoselectivity for cross-benzoin products. Again the more electron-rich substrate (**167**) affords higher product yields.



a) yield of isolated product after flash column chromatography; b) yield corrected from the mass of a known mixture of benzoin products; c) yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard; d) 1 mol % pre-catalyst loading

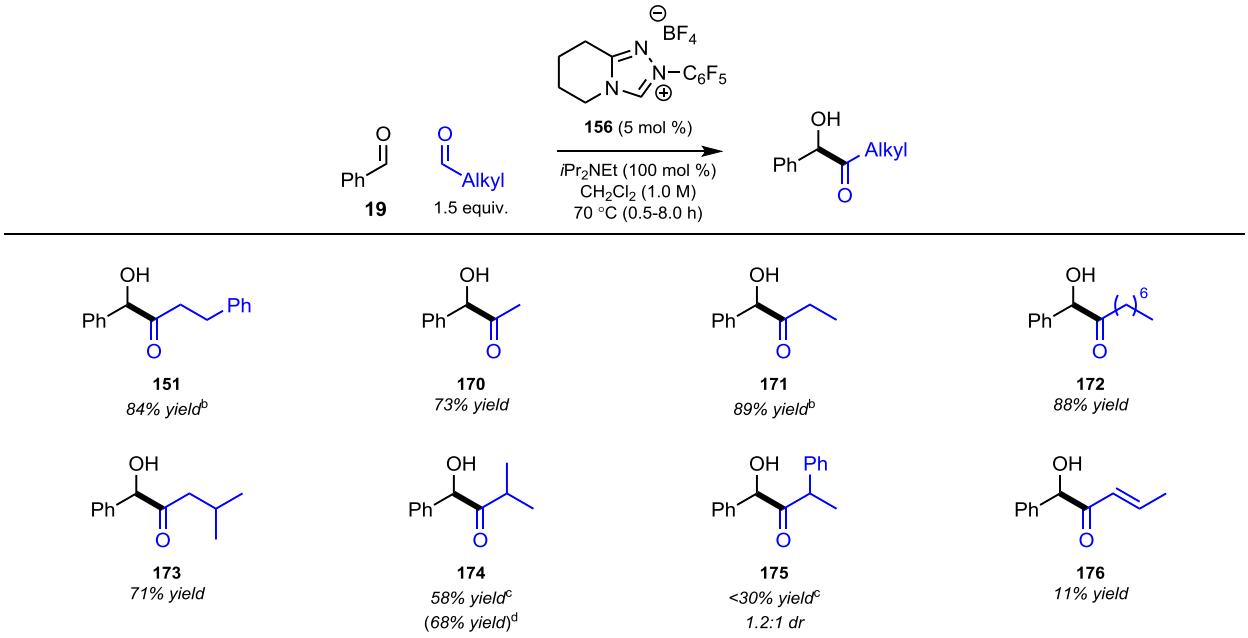
Scheme 3.4 – Explored substrate scope with respect to aromatic aldehydes for chemoselective NHC-catalyzed cross-benzoin reactions.

Without complicating steric interactions *para*-substituted substrates should provide a good indication of the role of electron-withdrawing/donating effects on the reaction. Halogen substituents (**160** and **161**) provide conflicting results. Use of *para*-chlorobenzaldehyde (**160**) affords only the homo-benzoin product of hydrocinnamaldehyde (**153**, quant.). The aromatic aldehyde remains unconsumed, forming neither homo- nor cross-benzoin products. This substrate has previously been shown effective in enantioselective homo-benzoin reactions under similar conditions,[12m] making this result surprising. Simple catalyst deactivation must be ruled out as the homo-benzoin reaction of hydrocinnamaldehyde still proceeds to completion. Repetition of the experiment

under otherwise identical conditions using the pyrrolidinone-derived triazolylidene catalyst affords both homo- and cross-benzoin products with high conversion, confirming that the aldehyde has not been modified/misassigned. Other electron-deficient substrates (notably **161** and **165**) and chlorinated substrates (**166**) remain reactive under these conditions. An explanation for the lack of reactivity can thus not easily be attributed to any single factor.

Substitution with a highly electron-withdrawing trifluoromethyl group (**164**) dramatically lowers the yield of the reaction. The diminished yield seems to be due to a substantially increased susceptibility to oxidation, as diketones from the oxidation of the cross-benzoin product(s) (25% yield) and the homo-benzoin product of the aromatic aldehyde (ca. 20% yield) are observed. More moderately electron-poor substrates afford moderate yields of their corresponding cross-benzoin products (**161** and **165**). Again the use of more electron-rich aromatic aldehydes affords substantially improved product yields (**168** and **169**).

3.4.3. Substrate Scope: Aliphatic Aldehydes



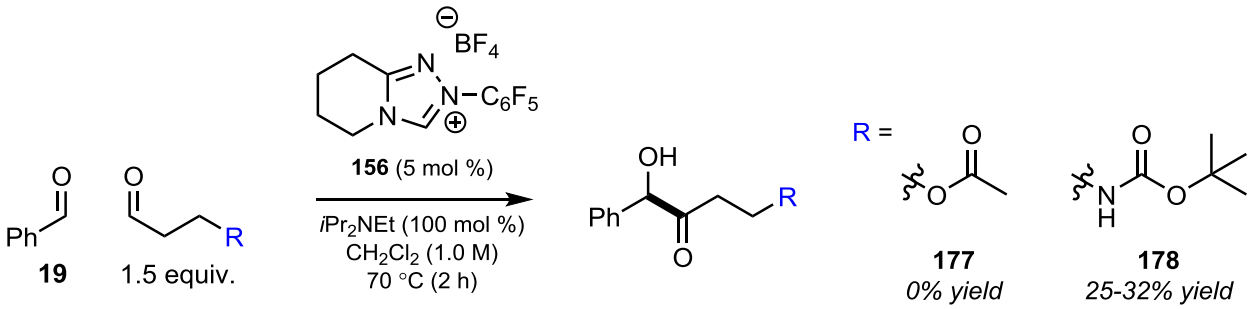
a) yield of isolated product after flash column chromatography; b) yield corrected from the mass of a known mixture of benzoin products; c) yield determined by ^{1}H NMR analysis using dimethyl terephthalate as an internal standard; d) 5 equiv. isobutyraldehyde

Scheme 3.5 – Explored substrate scope with respect to aliphatic aldehydes for chemoselective NHC-catalyzed cross-benzoin reactions.

An array of aliphatic aldehydes were subjected to the optimized reaction conditions to test their viability as substrates (Scheme 3.5). Benzaldehyde was chosen as the model aromatic aldehyde. Use of short- and long-chain unbranched aliphatic aldehydes affords excellent yields (**151**, **170**, **171**, and **172**). The addition of a β-substituent (**173**) does not adversely affect chemoselectivity, although extended reaction times are required. α-Substituents (**174** and **175**) result in dramatically decreased reactivity, requiring extremely long reaction times and/or a larger excess of aliphatic aldehyde for moderate yields. The additional stereocentre from 2-phenylpropionaldehyde (**175**) does not provide high diastereoselectivity, although this may be improved (3.2:1 dr) through the use of a chiral catalyst. Introduction of an α-β unsaturation (**170**) lowers both the chemoselectivity and yield of the reaction.

3.4.3.1. Substrate Scope: Functional Group Compatibility

Two aldehydes were synthesized to determine whether the reaction is tolerant to aliphatic aldehydes bearing esters or carbamates. Use of an aliphatic aldehyde bearing an acetylated alcohol (**177**) affords only the homo-benzoin product of benzaldehyde (**20**, quant.). Analysis of the ^{1}H NMR spectrum suggests that the aliphatic aldehyde remains unconsumed, forming neither homo- nor cross-benzoin products. As with *para*-chlorobenzaldehyde (see Section 3.4.2) the efficacy of another ester-containing substrate (**165**) means that an explanation for the lack of reactivity remains elusive.

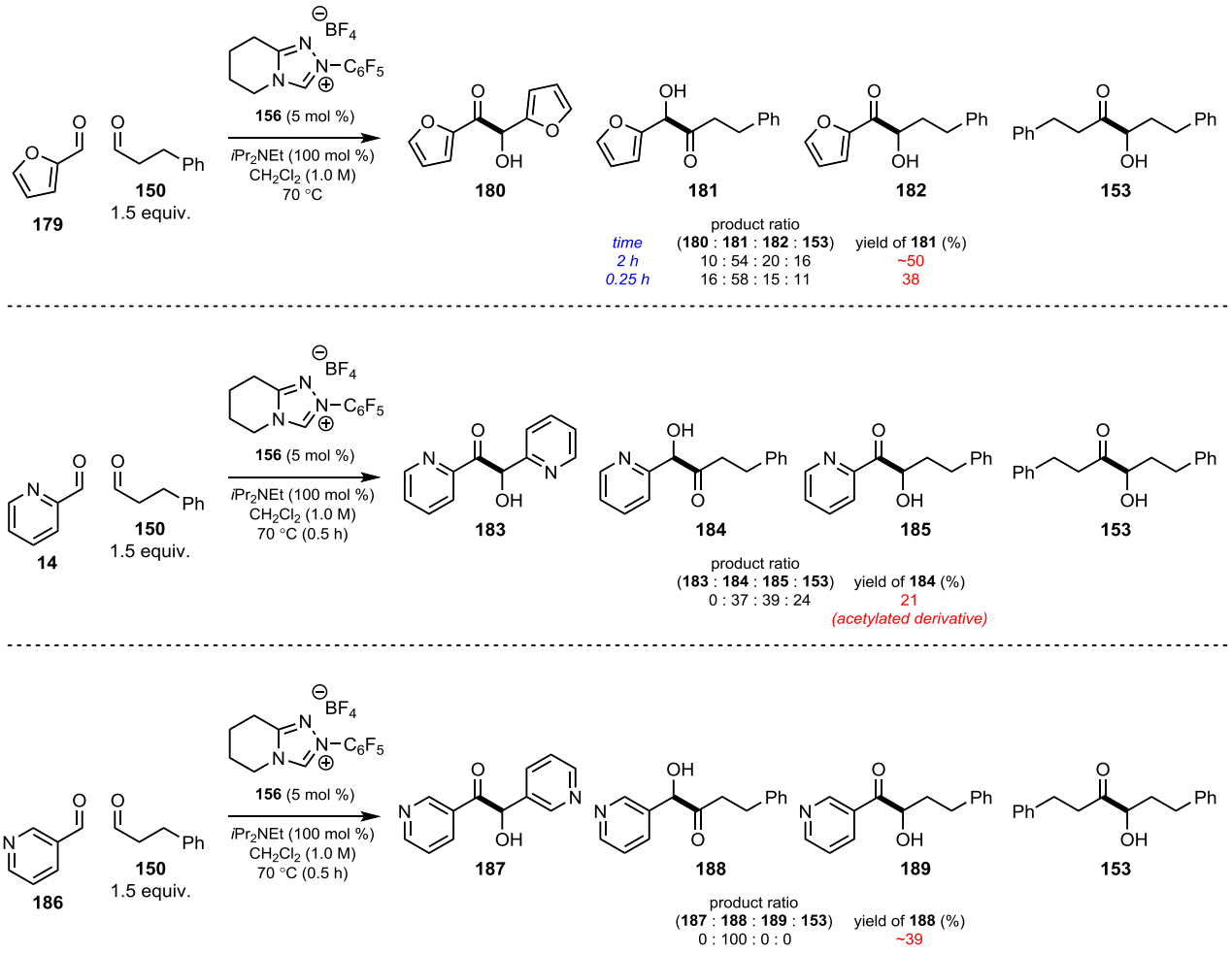


Scheme 3.6 – Attempted chemoselective NHC-catalyzed cross-benzoin reactions with functionalized aliphatic aldehydes.

Use of a Boc-protected amino aldehyde (**178**) again affords high chemoselectivity, but substantial degradation of the starting material results in low yields. Recent success with an isomer of this substrate suggests that it is not the functional group, but the position of the functional group, that is responsible for the low yield.[42]

3.4.4. Substrate Scope: Heteroaromatic Aldehydes

Three heteroaromatic aldehydes were subjected to the optimized reaction conditions to test their viability as substrates (Scheme 3.7).

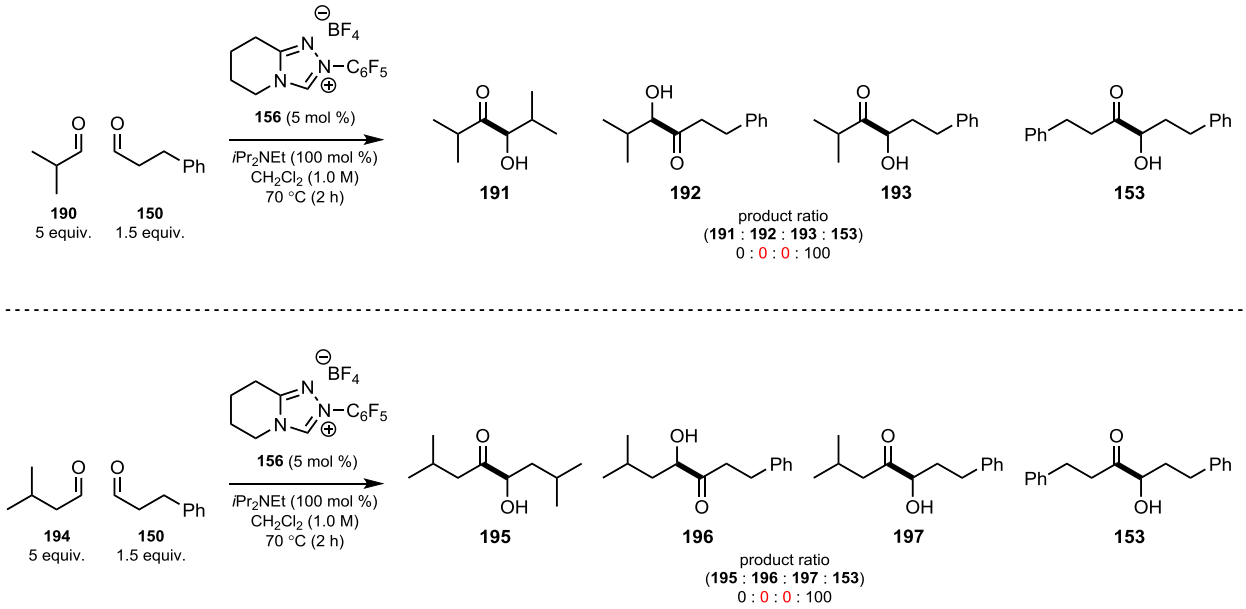


Scheme 3.7 – Explored substrate scope with respect to heteroaromatic aldehydes for chemoselective NHC-catalyzed cross-benzoin reactions.

When 2-furfuraldehyde is subjected to reaction conditions very limited chemoselectivity between cross-benzoin products is obtained. It was suspected that the product ratio may be initially high and decrease over time. Quenching the reaction after 15 minutes affords a similar product distribution, suggesting that either the reaction is not selective, or that thermodynamic equilibrium is established faster than the benzoin products accumulate.

Use of 2-pyridinecarboxaldehyde results in a loss of selectivity between cross-benzoin products (ca. 1:1), although they are formed preferentially over its homo-benzoin product (**183**). Analysis of the ^{1}H NMR spectrum suggests non-benzoin products, including diketones, are formed under the reaction conditions. Moving the heteroatom away from the aldehyde (3-pyridinecarboxaldehyde) restores chemoselectivity for a single cross-benzoin product but also shows evidence of non-benzoin product formation. Attempts to purify either of these mixtures using flash column chromatography result in oxidation to the corresponding diketones. Acetylation allows the protected compounds to be isolated, albeit in substantially diminished yields.[112]

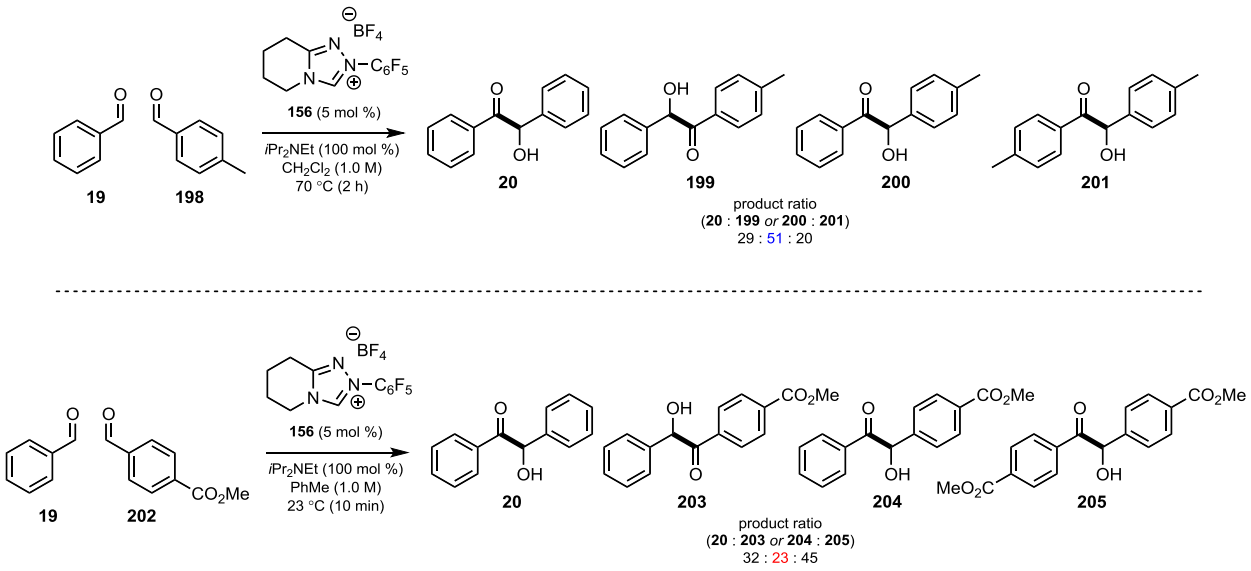
3.4.5. Other Cross-Benzoin Reactions



Scheme 3.8 – Attempted NHC-catalyzed cross-benzoin reactions between two aliphatic aldehydes.

All previous examples involved cross-benzoin reactions between two aldehydes with substantially different substituents (*viz*. (hetero)aromatic *vs*. aliphatic). When aliphatic aldehydes with α- or β-substituents were used a significantly extended reaction time was needed to reach high conversions. It was hypothesized that this difference in reactivity could be used to allow chemoselective cross-benzoin reactions between unbranched and branched aliphatic aldehydes. Subjecting hydrocinnamaldehyde to reaction conditions in the presence of either isobutyraldehyde or isovaleraldehyde fails to produce any cross-benzoin products (Scheme 3.8). Instead the homo-benzoin product of the unbranched aliphatic aldehyde (**153**) is obtained.

Following elucidation of the interaction(s) affording chemoselectivity (see Section 3.6.8) it was hypothesized that chemoselective cross-benzoin reactions between aromatic aldehydes may be possible under the optimized conditions, provided that the substrates were sufficiently distinct. Although chemoselective NHC-catalyzed cross-benzoin reactions between aromatic aldehydes have been reported,[12l, 49, 113] all examples involve the use of an *ortho*-substituted aromatic aldehyde to achieve chemoselectivity (see Scheme 1.13).



Scheme 3.9 – Chemoselective NHC-catalyzed cross-benzoin reactions between two aromatic aldehydes.

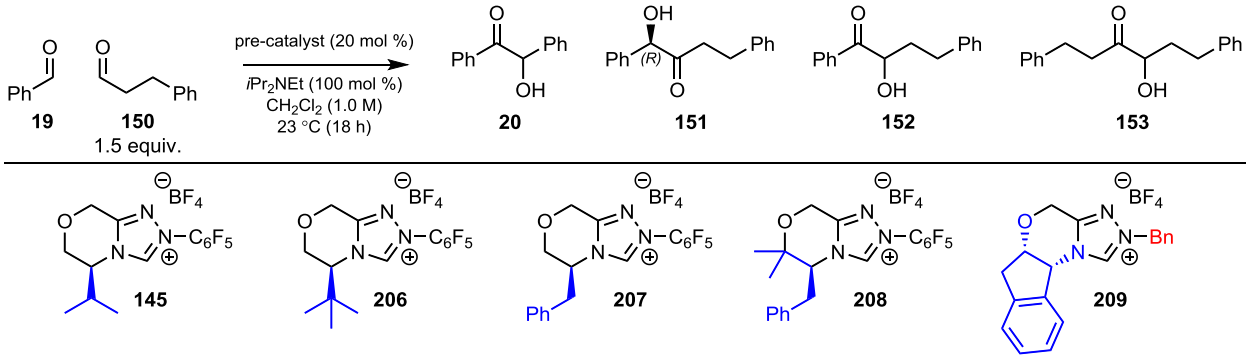
Subjecting benzaldehyde to reaction conditions in the presence of either electron-rich *p*-Me benzaldehyde (*p*-tolualdehyde) or electron-poor *p*-CO_2Me benzaldehyde (Scheme 3.9) affords promising results. Analysis of the ^{1}H NMR spectra for these reactions suggests the formation of a single cross-benzoin product in both cases. As these compounds are expected to have similar ^{1}H NMR chemical shifts, assignment of which cross-benzoin product is formed is not directly feasible. It is possible that the diagnostic signals for the cross-benzoin products in both cases (*viz*. **199** and **200**, **203** and **204**) have *very* similar chemical shifts to each other, overlapping and appearing to be a single compound. As the cross-benzoin products from coupling benzaldehyde and *p*-OMe benzaldehyde (*p*-anisaldehyde) are resolved in their ^{1}H NMR chemical shifts (see Sections 3.6.5 and 5.2.4) this seems improbable. Attempts to isolate and characterize the cross-benzoin product(s) from the reaction mixtures using flash column chromatography were unsuccessful; the putative cross-benzoin product co-elutes with the homo-benzoin products. Given the difficulties with isolation and poor material efficiency, additional examples were not pursued.

3.5. Enantio- and Chemoselective Cross-Benzoin Reactions

With the optimized conditions and substrate scope explored, focus shifted to adding a synthetically-useful degree of enantioselectivity to the methodology. A set of chiral morpholinone-derived triazolium salts were screened to determine the extent of enantioselectivity they could impart (Table 3.8).

The initial catalyst screened affords moderate enantioselectivity (entry 1, 70:30 er). This is in contrast to the high enantioselectivity (>95:5 er) obtained with this species under similar conditions with α-keto esters.[17] It was hypothesized that enantioselectivity with this catalyst could be improved by lowering the temperature of the reaction. Decreasing the reaction temperature to -26 °C or 0 °C respectively results in a complete or substantial loss in reactivity despite higher catalytic loading (30 mol %). This is likely due to the combination of a slowing of the reaction rate and a loss in catalyst solubility (see Section 3.6.9). Low yield and poor efficiency of isolation unfortunately meant that the enantiomeric ratio of **151** from the 0 °C reaction could not be determined.

Table 3.8 – Comparison of catalysts for an enantio- and chemoselective cross-benzoin reaction.



entry	pre-catalyst	product ratio (20 : 151 : 152 : 153)	er of 151 (*R*:*S*)[a]
1	**145**	2 : 77 : 0 : 21	70 : 30
2[b]	**206**	3 : 59 : 0 : 38	30.5 : 69.5
3	**207**	4 : 59 : 12 : 25	53.5 : 46.5
4[b]	**208**	5 : 58 : 0 : 37	65 : 35
5[c]	**209**	*n/a*	*n/a*

a) Absolute configuration assigned based on literature precedence;[114] b) Incomplete conversion by ^{1}H NMR analysis (<70%); c) No benzoin products detected by ^{1}H NMR analysis.

In order to determine if the enantiomeric excess decreases over time the experiment with **145** (entry 1) was repeated on large scale with aliquots taken at 1.5, 3, 4.5, and 24 hours into the reaction. The enantiomeric ratio remains constant (68:32 er) over time.

The effects of increasing and decreasing the steric bulk around the stereocentre were then explored. Increasing the steric bulk by substitution with a *tert*-butyl group in place of the isopropyl group (entry 2) affords an equivalent level of enantioselectivity. Substantially increasing the reaction temperature (70 °C) has no effect on the observed enantioselectivity. However, the preferred enantiomer is now of the opposite configuration. Computational modelling of transition states (by Dr. M. Gravel) for the chiral catalysts was explored, in part to attempt to understand this reversal. Unfortunately no transition state leading to **(*S*)-151** catalyzed by **206** could be located. Calculations with the other catalysts (**145**, **208**, and ***ent*-209**) uniformly suggest that **(*R*)-151** should be favoured.

Decreasing the steric bulk by substitution with a benzyl group in place of the isopropyl group (entry 3) lowers the obtained enantiomeric ratio, as expected. Interestingly this catalyst also shows diminished chemoselectivity. As its derivative (entry 4) retains chemoselectivity this is not readily explained. Based on literature precedence (see Scheme 1.5) a catalyst bearing geminal dimethyl substitution was explored to attempt to increase enantioselectivity. Although slight, an improvement was observed (entry 4).

Finally, use of amino indanol-derived **209** affords no benzoin products under reaction conditions (entry 5). This may be due to the substantial steric bulk of the substituent, the change to an *N*-benzyl group, or a combination of these factors. A pair of reactions were conducted with pyrrolidinone-derived catalysts bearing *N*-benzyl and *N*-C_6F_5 substitution. At room temperature these species afford, within error, identical conversions. Based on these experiments it is likely that the increased steric bulk is causing the loss in reactivity.

With the poor performance of available catalyst scaffolds, a novel catalyst backbone was designed and targeted for synthesis (see Section 3.7.1).

3.6. Mechanistic Study

Although excellent chemoselectivity and isolated yields are generally obtained with the new catalytic system, some limitations were observed (see Sections 3.4.2 to 3.4.5). Further development of NHC-catalyzed chemoselective cross-benzoin reactions required a detailed understanding of *how* chemoselectivity is obtained; it was hypothesized that expansion of the substrate scope and/or improvement of enantioselectivity may be possible depending on what factor(s) lead to chemoselectivity. Computational studies were pursued as a way to explore and quantify these parameter(s).

Additional experimental data was also sought as a way to support, refute, and/or supplement computational results. During the course of these studies an article was published describing a computational study of the mechanism for this methodology.[115] The experimental results, both in-depth and initial (see Section 3.6.1), are not in agreement with the conclusions of this study. This highlights the importance of including experimental results in mechanistic studies.

3.6.1. Initial Results

Thermodynamically-derived chemoselectivity would be highly limiting for both the substrate scope and the potential for enantioselectivity. Initial experiments aimed to rule out this possibility. Subjecting a mixture of **20** (the homo-benzoin product of benzaldehyde) and hydrocinnamaldehyde, or **153** (the homo-benzoin product of hydrocinnamaldehyde) and benzaldehyde, to reaction conditions results only in formation of **153** or **20**, respectively. This suggests that homo-benzoin products are formed irreversibly under the reaction conditions (see Sections 3.6.4 and 3.6.7). Considering the high isolated yields of cross-benzoin products (such as **151**), these results suggest that the cross-benzoin products are kinetically preferred over homo-benzoin products.

A set of ^{1}H NMR monitoring experiments were conducted to corroborate this. A comparison of cross-benzoin reactions as catalyzed by the pyrrolidinone- and piperidinone-derived triazolylidenes confirmed that the less sterically hindered catalyst catalyzes the reaction much faster than its piperidinone-derived equivalent. This had been suggested by the higher conversion when comparing catalysts at the project outset (Table 3.1). If the product distribution were governed by the thermodynamic stability of the products then the faster catalyst should provide high selectivity by reaching thermodynamic equilibrium faster. That chemoselectivity is lower with **5** suggested that the observed major cross-benzoin product is kinetically preferred.

Monitoring the homo- and cross-benzoin reactions over time confirmed that these reactions are higher than first order with respect to the aldehyde(s). However, these initial experiments introduced a new ambiguity: the data suggested that the cross-benzoin reaction may be *higher* than second order with respect to the aldehydes overall. This is not consistent with any of the steps in the accepted mechanism (Scheme 1.14) being rate-limiting.

Based on these initial experiments chemoselectivity is likely kinetically-controlled when using the piperidinone-derived catalyst. However, the origin of chemoselectivity was not established. As well, a more rigorous determination of the overall reaction order was required to rule out, or confirm, an exotic mechanism involving more than two aldehydes at the rate-limiting step.

3.6.2. Division of Labour

The computational study was performed jointly with Dr. M. Gravel. Initial computational results, including many obtained using the B3LYP functional (not discussed) were obtained by Dr. M. Gravel, who also assisted with/obtained some of the later computational results. The following computational components were obtained exclusively by S. Langdon: all results for all structures containing the BF_4 counterion (*viz*. all charged species), all single-point calculations, all results for all structures containing or derived from anisaldehyde, and all results for the caprolactam-derived (**157**-based) catalytic system. The majority of the Non-Covalent Interaction (NCI) calculations were also performed by S. Langdon. All Intrinsic Reaction Coordinate calculations were obtained exclusively by Dr. M. Gravel. The remaining calculations were performed in roughly equal proportions by both S. Langdon and Dr. M. Gravel. Dr. C. Legault assisted the project by consulting/advising on the computational studies, especially by providing technical assistance in performing the calculations. All non-computational results were obtained by S. Langdon.

3.6.3. Computational Methods

All calculations were performed with the Gaussian 09 software package.[116] The M06-2X exchange-correlation functional with the polarized diffuse split-valence 6-31+G(d,p) basis set was used for all geometry optimizations (including those with constraints), transition state calculations, infrared frequency calculations, and IRC calculations. This level of theory was chosen as it is both commonly utilized and accounts for non-covalent interactions (London dispersion forces, π interactions, and others) which may have a pronounced effect on the calculated energy.[117] Subsequent single-point energies were determined using the same functional with the corresponding triple-ζ 6-311+G(d,p) basis set. Solvent effects were added using the integral equation formalism model (IEFPCM)[118] with radii and nonelectrostatic terms for Truhlar and co-workers' SMD solvation model (CH_2Cl_2).[119]

For each species a broad conformational search was performed using the MMFF94 force field. Additional conformers were generated by hand as needed. The lowest energy structures (typically 20−30) were carried forward for full optimization. The conformer with the lowest energy had its vibrational frequencies computed using the same level of theory to confirm that it was a stationary point and to evaluate its zero-point vibrational energy (ZPVE) and thermal corrections at 298.15 K.

Transition states were found using a similar conformer search, but with a single constrained interatomic distance. The lowest energy conformations found with this process were optimized without the constraint and confirmed to be first-order saddle points by harmonic vibrational frequency analysis (*viz*. they contain only one imaginary frequency). The imaginary frequency was inspected to ensure it represented the desired reaction coordinate/transition state. This process was repeated for each diastereomeric species (*E*/*Z* Breslow intermediate attacking the *re*/*si* face of the incoming aldehyde). The pathway proceeding through the lowest overall barrier (Minimum Energy Pathway, MEP) is described in detail herein. For key transition states the intrinsic reaction coordinate (IRC) was followed to ensure it connects the reactants and products.

Non-covalent interactions (NCIs) were plotted using NCIPLOT version 1.0 with the coordinates from the corresponding structure/transition state.[120] Other three-dimensional representations were generated using CYLview.[121]

Energy differences between half-chair conformers on the catalyst backbone were typically found to be within the error of the calculation (usually ∼0.5 kcal/mol) and are excluded from discussion (in Section 3.6.11.). Counterion (BF_4^-) placement was found to have a substantial effect on the energy of all charged species. The counterion was manually placed in several likely locations and each of these complexes was then optimized as above.

For simplicity trimethylamine was modeled as a Hünig's base equivalent. Propionaldehyde was chosen for modelling as a prototypical aliphatic aldehyde. Benzaldehyde was chosen for modelling as an electron-neutral aromatic aldehyde. All discussion of relative facial selectivity, such as attack of a Breslow intermediate onto an aldehyde, is considered from the same perspective (*viz*. the *re* face of *Z*-Breslow intermediates and the *si* face of *E*-Breslow intermediates.

3.6.4. Aliphatic Homo-Benzoin Reaction

The homo-benzoin reaction of aliphatic aldehydes is presented first for clarity. Figure 3.1 outlines the energy profile for this process. Deprotonation of the azolium salt is barrierless, and the resulting carbene is slightly higher in energy (+1.4 kcal/mol). An attack on propionaldehyde should generate an alkoxide intermediate, which should then be protonated. Several attempts were made to model the initial attack, though none converged to the appropriate saddle point.

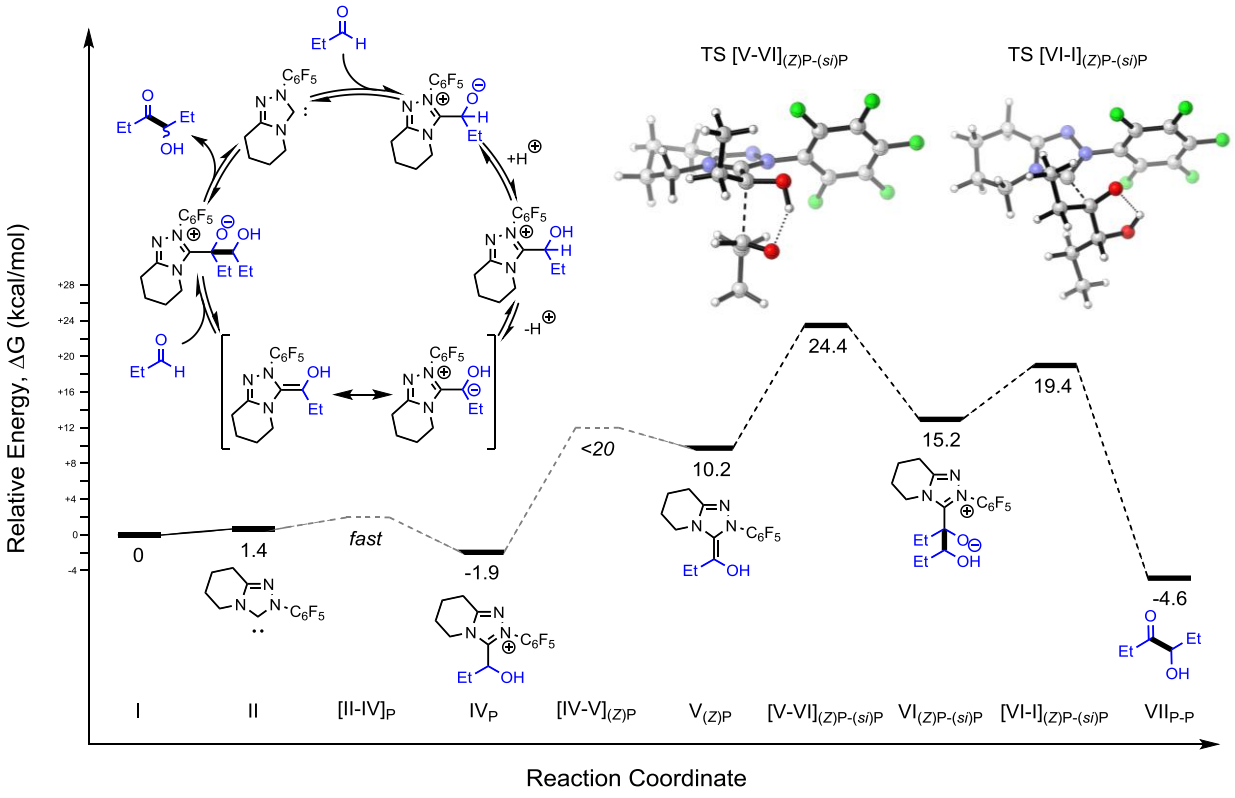
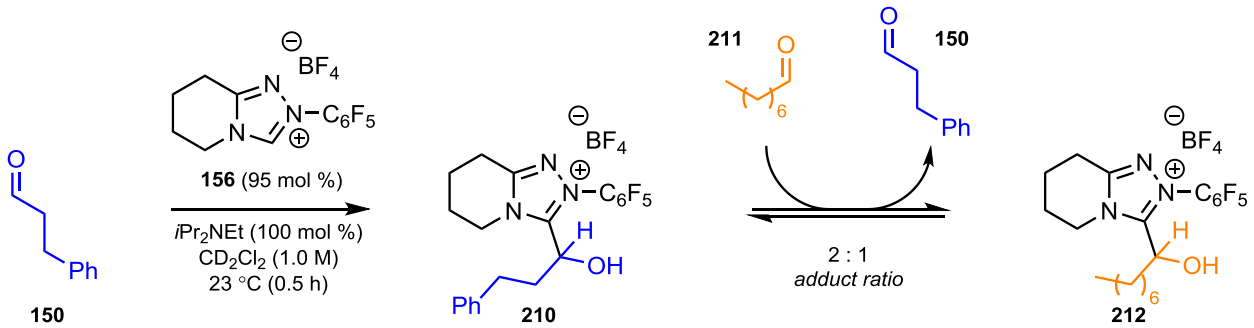


Figure 3.1 - Computed reaction coordinate for the NHC-catalyzed homo-benzoin reaction of propionaldehyde.

An experiment was performed with high catalytic loading and monitored by ^{1}H NMR (Scheme 3.11). Formation of the protonated intermediate is nearly instantaneous, occurring quantitatively within the first minute of the reaction. Stoichiometric addition of a second aldehyde, octanal, results in exchange and equilibration to a mixture of protonated tetrahedral intermediates prior to

formation of any benzoin product(s). Rapid formation of this intermediate is also observed when toluene is used as the solvent, suggesting that this reactivity is unchanged when different (*viz*. less polar) solvents are used. Thus the barrier for addition is relatively low, and protonation is concomitant, barrierless, or possesses a lower barrier than that for addition. The computed energy difference between the starting materials and the protonated intermediate (-2.0 kcal/mol) suggests that >95% of the catalyst should be occupied as the intermediate once equilibrium is achieved (*viz*. a resting state is formed). This is consistent with the observed speciation by ^{1}H NMR.



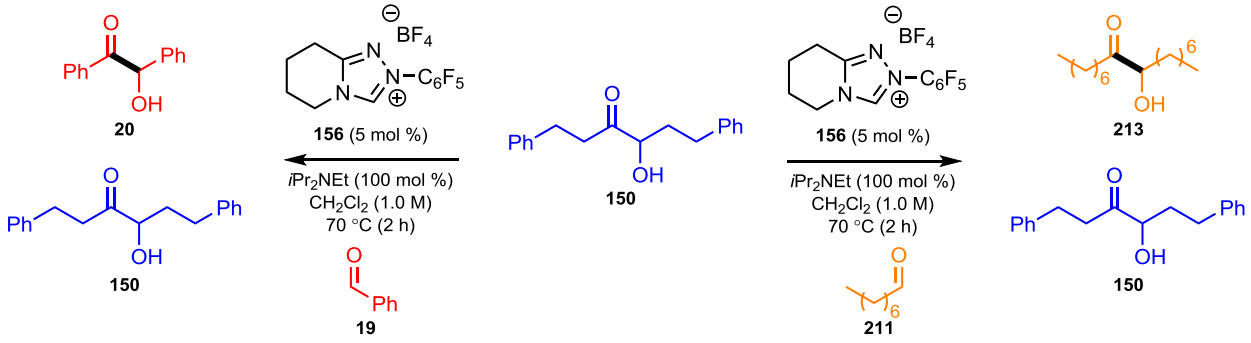
Scheme 3.11 – Formation of protonated NHC-aldehyde adducts with aliphatic aldehydes.

Subsequent deprotonation leads to the formation of the Breslow intermediate. Although this transition state could also not be located, previous studies suggest that it is not rate-limiting.[45b] It is possible that this transition state proceeds through a non-classical mechanism (*viz*. proton tunnelling). Monitoring the NHC-catalyzed homo-benzoin reaction of hydrocinnamaldehyde by ^{1}H NMR confirmed that the reaction is second order with respect to the aldehyde. Although it is possible that the barrier for Breslow intermediate formation is competitive as a rate-limiting step, taken together the data suggests that the formation of the Breslow intermediate is not rate-limiting and likely possesses a barrier at or below +20 kcal/mol (see Section 3.6.5).

The computed *E* and *Z* isomers of this Breslow intermediate have, within error, the same energy (+9.9 and +10.2 kcal/mol respectively). Attack of the *E* Breslow intermediate on the *re* face of propionaldehyde also has, within error, the same

overall barrier (+24.3 kcal/mol) as the attack of the *Z* Breslow intermediate on the *si* face of propionaldehyde (+24.4 kcal/mol). The latter is discussed here to facilitate comparison with the corresponding cross-benzoin reaction (see Section 3.6.5). Notably, attacks from the *Z* Breslow intermediate on the *re* and *si* faces of propionaldehyde are very similar energetically (+24.9 and +24.4 kcal/mol respectively). The proton transfer is concomitant and asynchronous, appearing as a "hidden" transition state in the IRC (see Section 3.6.5).

The new tetrahedral intermediate collapses comparatively quickly, ejecting the homo-benzoin product with a barrier of +19.4 kcal/mol. The resulting α-hydroxy ketone is considerably stabilized relative to the starting materials (−4.6 kcal/mol). A pair of crossover experiments were performed to determine whether these products are formed reversibly under the reaction conditions (Scheme 3.12). No detectible amount of cross-benzoin product(s) was formed. This suggests that the formation of homo-benzoin products from aliphatic aldehydes is effectively irreversible under these conditions.



Scheme 3.12 – Crossover experiments between the homo-benzoin product of hydrocinnamaldehyde with aromatic and aliphatic aldehydes.

3.6.5. Aliphatic-Aromatic Cross-Benzoin Reaction

If the Breslow intermediate derived from the aliphatic aldehyde instead attacks an aromatic aldehyde, a cross-benzoin reaction occurs. This corresponds to the major cross-benzoin product observed when using the piperidinone-derived catalyst. Initial results (see Section 3.6.1) confirmed that the rate of this reaction is first order with respect to aliphatic aldehyde by simply using the integrated rate

law and observing the rate of consumption using ^{1}H NMR spectroscopy. This approach was ambiguous when determining the order with respect to aromatic aldehyde, suggesting that it may be a non-integer value (1.5-1.6). A more thorough use of the method of initial rates confirmed that the reaction is, within error, first order with respect to the aromatic aldehyde (see Section 5.2.3.1). This allowed the study to focus on the traditional mechanistic proposal, rather than a more exotic one to account for the reaction order. The energy profile for this transformation is depicted in Figure 3.2.

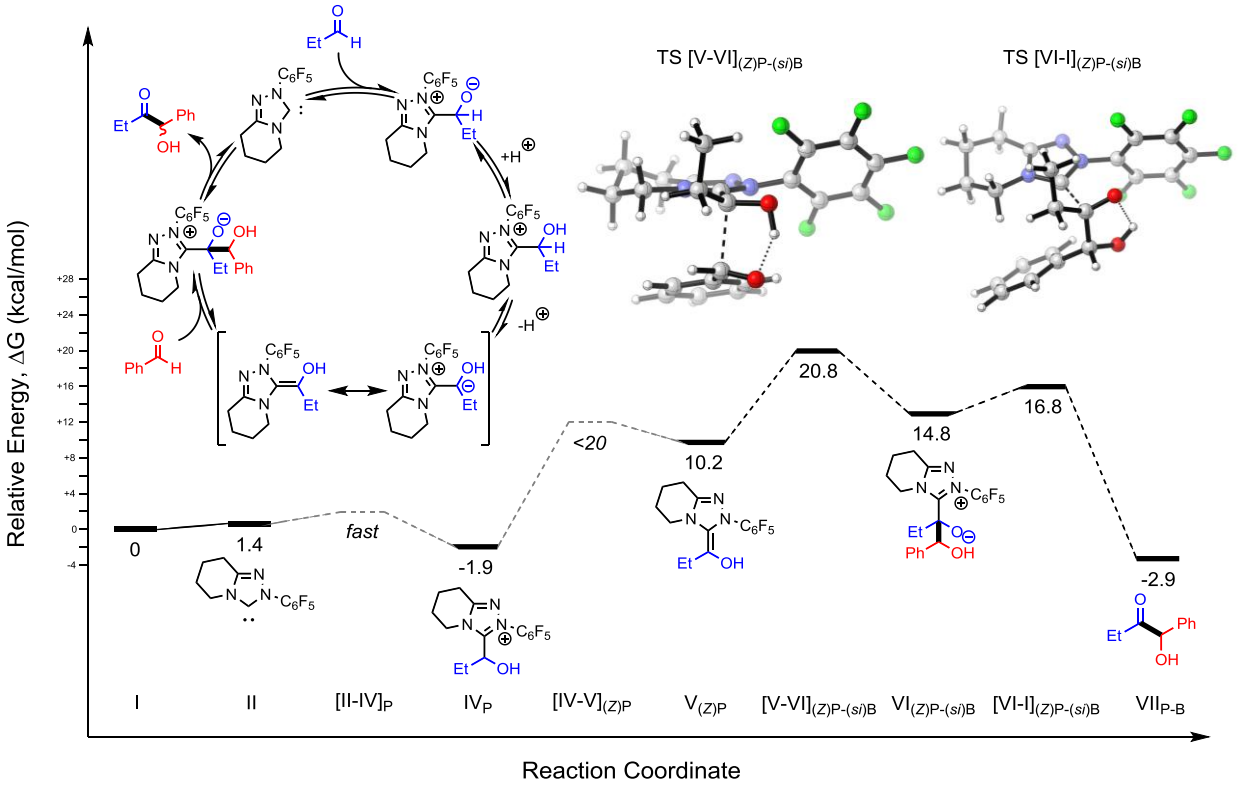


Figure 3.2 - Computed reaction coordinate for the NHC-catalyzed cross-benzoin reaction of propionaldehyde with benzaldehyde.

The reaction proceeds along the same coordinate as before (see Section 3.6.4) until the carbon-carbon bond formation step ([V-VI]$_{(Z)P}$). In contrast to the homo-benzoin reaction of aliphatic aldehydes one diastereomeric transition state (attack of the *E* Breslow intermediate onto the *si* face of benzaldehyde) is heavily

favoured, being more than 2 kcal/mol lower than all other diastereomeric transition states.

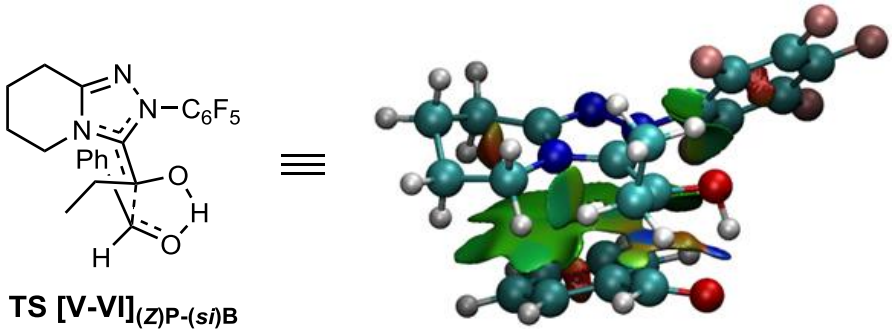


Figure 3.3 - Plot of non-covalent interactions for the MEP carbon-carbon bond formation step of the NHC-catalyzed cross-benzoin reaction of propionaldehyde with benzaldehyde.

Examination of these transition states suggests this diastereoselectivity is governed by a competition between a stabilizing π-π/π-cation interaction between the approaching aromatic ring and the triazole/triazolium, and steric repulsion between the incoming aldehyde and the pentafluorophenyl group. The preferred diastereomeric transition state allows the best overlap of the π systems without excessive steric interactions. Plotting the non-covalent interactions supports this hypothesis (Figure 3.3).

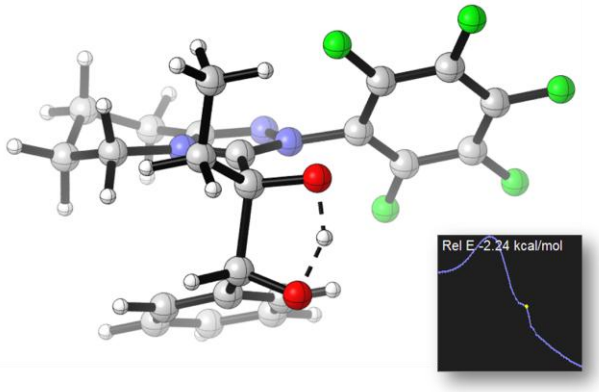
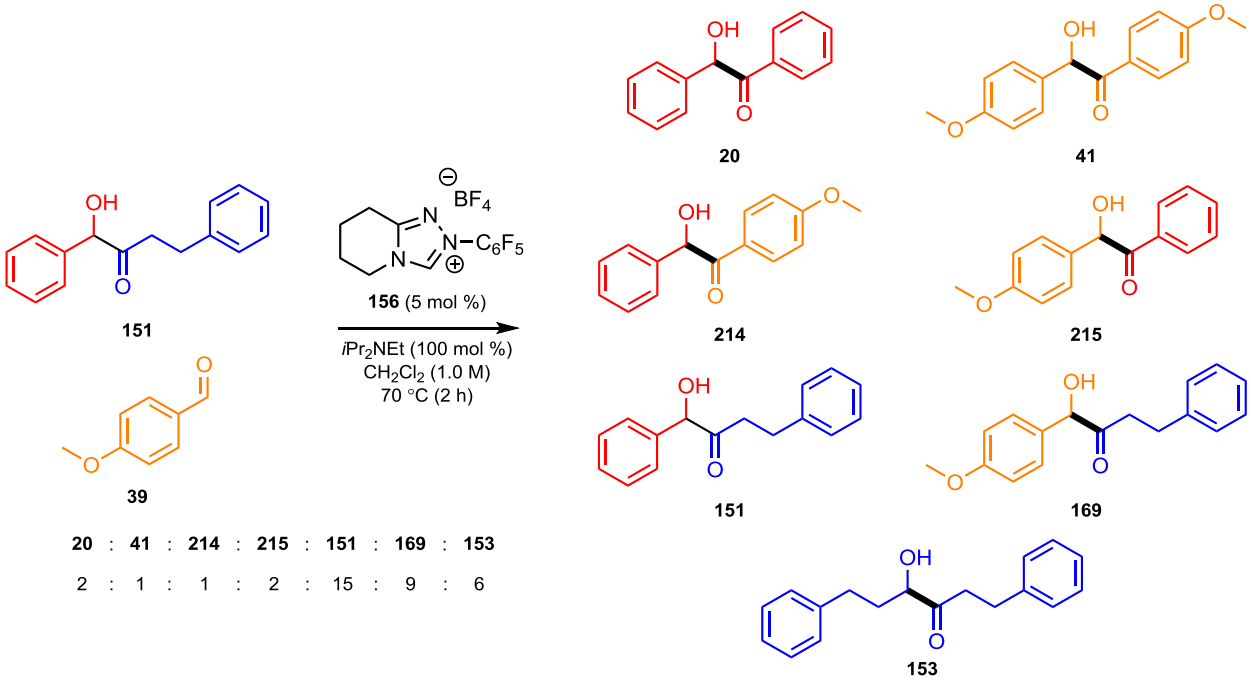


Figure 3.4 - Hidden transition state for proton transfer during the carbon-carbon bond formation step of the NHC-catalyzed cross-benzoin reaction of propionaldehyde with benzaldehyde.

Again the proton transfer is concomitant and asynchronous, appearing as a "hidden" transition in the IRC (Figure 3.4). Both the new tetrahedral intermediate (**Int. VI$_{(Z)P\text{-}(si)B}$**) and the transition state for product ejection (**TS [VI-I]$_{(Z)P\text{-}(si)B}$**) show similar stabilizing π-π/π-cation interactions to the carbon-carbon bond formation step. This may account for their lower energies relative to their equivalent species in the homo-benzoin reaction of aliphatic aldehydes. The resulting α-hydroxy ketone is again stabilized relative to the starting materials (−2.9 kcal/mol). A crossover experiment was performed on the cross-benzoin product of hydrocinnamaldehyde and benzaldehyde (Scheme 3.13). As the formation of the homo-benzoin product of hydrocinnamaldehyde (in addition to the other benzoin products) is observed, each step in this process must be reversible. Repetition of the experiment using hydrocinnamaldehyde in place of *p*-anisaldehyde affords no new cross-benzoin products (see 3.6.7.)



Scheme 3.13 – Crossover experiment between the cross-benzoin product of hydrocinnamaldehyde with benzaldehyde and an aromatic aldehyde.

3.6.6. Aromatic-Aliphatic Cross-Benzoin Reaction

The opposite cross-benzoin product is formed in only trace amounts under reaction conditions. Attack of the carbene onto benzaldehyde and subsequent protonation result in the formation of a tetrahedral adduct (IV_B, Figure 3.5).

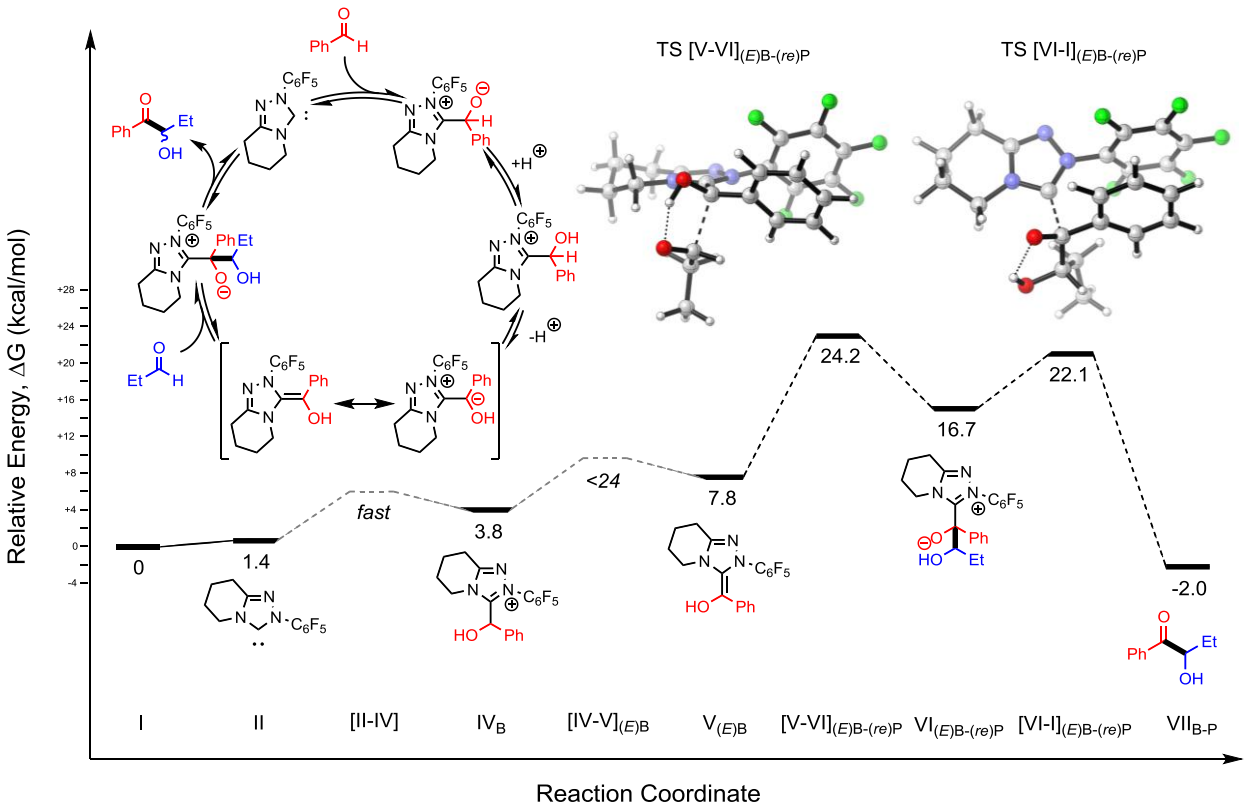
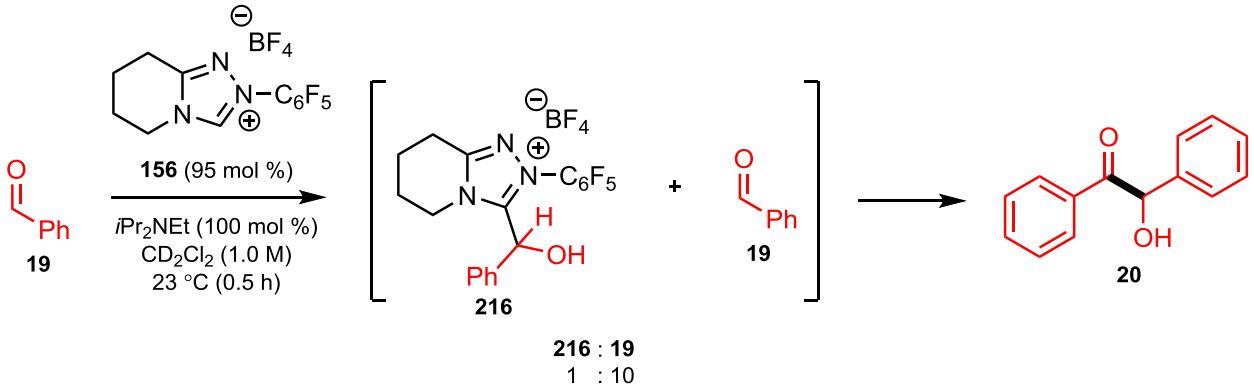


Figure 3.5 - Computed reaction coordinate for the NHC-catalyzed cross-benzoin reaction of benzaldehyde with propionaldehyde.

Unlike the protonated adduct with an aliphatic aldehyde, the adduct with the aromatic aldehyde is higher in energy than the corresponding starting materials (+3.8 kcal/mol). During formation of the adduct with the aliphatic aldehyde no conjugated system is altered. However, formation of the adduct with an aromatic aldehyde lowers the extent of the conjugation from eight to six π electrons. This may account for some of the energetic differences.

As with the adduct of the aliphatic aldehyde, attempts to find a transition state leading to the formation of this adduct were unsuccessful. An equivalent

experiment was performed to probe this step (Scheme 3.14). As before, within the first minute adduct was visible. The ratio of adduct to aldehyde remains relatively constant over time despite steady consumption of both species to form the corresponding homo-benzoin product. This ratio (1:10 adduct:aldehyde) corresponds to an energy difference of +1.4 kcal/mol between the adduct and the starting materials, suggesting that the computed energy of this adduct may be overestimated.



Scheme 3.14 – Formation of protonated NHC-aldehyde adducts with aliphatic aldehydes.

No transition state for the formation of the Breslow intermediate could be found. During the cross-benzoin reaction a detectable amount of the homo-benzoin product from the aromatic aldehyde (cf. **20**) is observed, while typically no aromatic-aliphatic cross-benzoin product is formed. Based on evidence from the homo-benzoin reaction of benzaldehyde, both computational and experimental, the formation of this Breslow intermediate has a barrier at or below 24 kcal/mol (see Section 3.6.7). For this cross-benzoin reaction it may be competitively rate-limiting.

Despite the additional π-π interaction between the phenyl and pentafluorophenyl rings (see inset, Figure 3.5) the *Z* isomer of the Breslow intermediate is slightly more stable than the *E* isomer (7.6 and 7.8 kcal/mol respectively). Although the *Z* isomer may proceed through a reaction coordinate with a comparable rate-limiting barrier (see Section 3.6.8), attack of the *E* isomer onto the *re* face of propionaldehyde is both slightly favoured energetically and

offers a better comparison to the homo-benzoin reaction of benzaldehyde (see Section 3.6.7).

Carbon–carbon bond formation is again the rate-limiting step. There is a substantial preference for attack on the *re* face of propionaldehyde. This likely results from the increased steric interactions (between the ethyl chain and the phenyl ring) required for an attack on the *si* face. Subsequent collapse and ejection releases the cross-benzoin product, which is 2.0 kcal/mol more stable than the starting materials.

3.6.7. Aromatic-Aromatic Homo-Benzoin Reaction

The reaction coordinate for the homo-benzoin reaction of benzaldehyde is significantly different than those of the other benzoin reactions. The energy profile for the minimum energy pathway is shown in Figure 3.6.

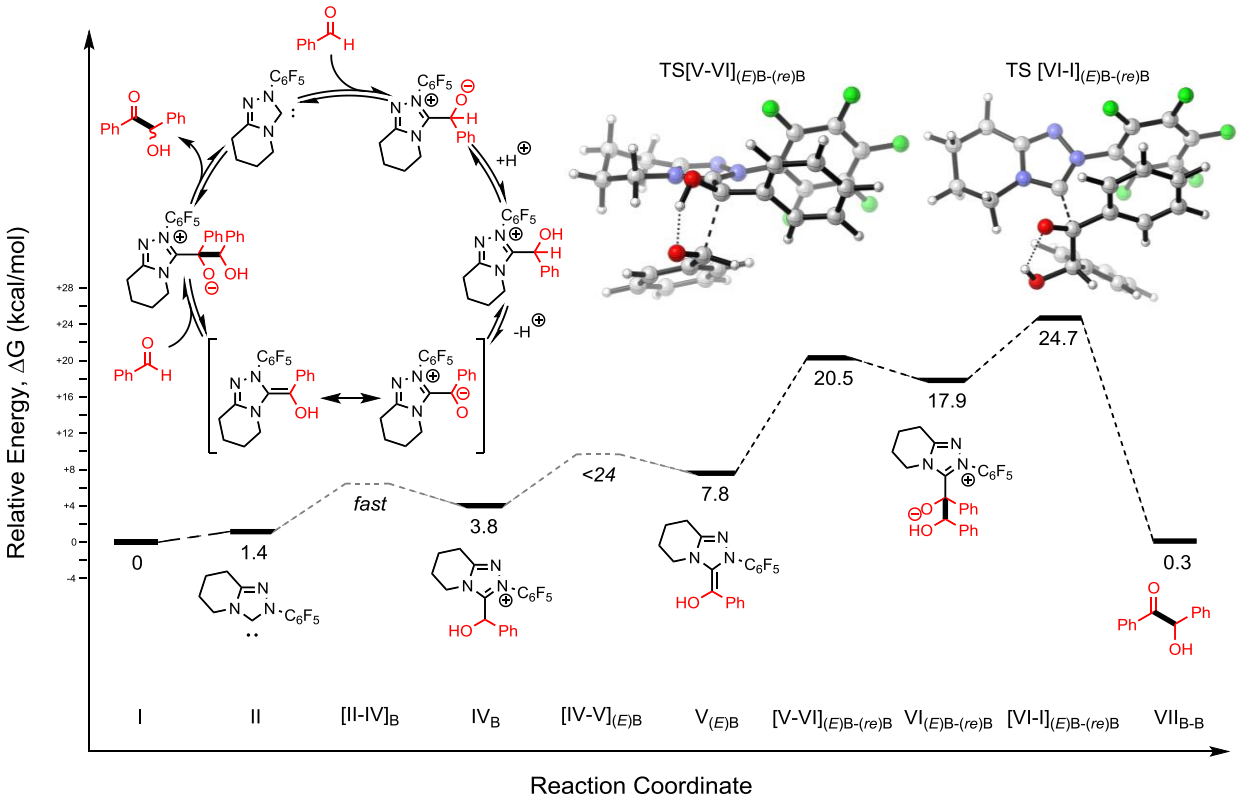


Figure 3.6 - Computed reaction coordinate for the NHC-catalyzed homo-benzoin reaction of benzaldehyde.

The reaction proceeds through formation of the aromatic aldehyde-derived Breslow intermediate as before (see Section 3.6.6). Of the four possible diastereomeric pathways, those proceeding from the *Z* isomer follow similar coordinates to the other benzoin reactions (see Section 3.6.8); a rate-limiting carbon-carbon bond formation followed by a relatively quick product ejection, with overall barriers higher than that of the major cross-benzoin pathway (see Section 3.6.5). However, pathways proceeding through the *E* isomer of the Breslow intermediate, and importantly the minimum energy pathway through attack on the *re* face of benzaldehyde, break this trend. The carbon-carbon bond forming transition state benefits from the same π-π/π-cation interaction as the favoured cross-benzoin pathway (Figure 3.7) in addition to a second π-π interaction between the pentafluorophenyl ring and the adjacent phenyl ring. Consequently this transition is substantially more energetically stable (>3.8 kcal/mol) than any of its diastereomers.

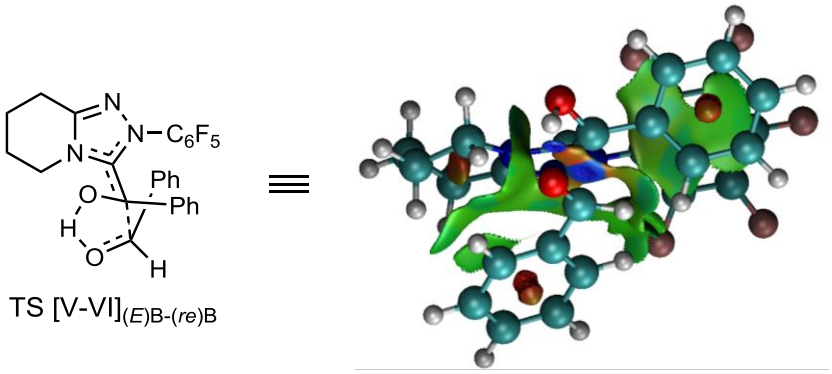


Figure 3.7 - Plot of non-covalent interactions for the MEP carbon-carbon bond formation step of the NHC-catalyzed homo-benzoin reaction of benzaldehyde.

The new tetrahedral intermediate must undergo a rotation around the newly formed carbon−carbon bond to allow efficient product ejection. This rotation breaks the π-π/π-cation interaction. The loss of this stabilizing interaction was unexpected, prompting a more in-depth exploration of potential conformers for the ejection transition state (Figure 3.8).

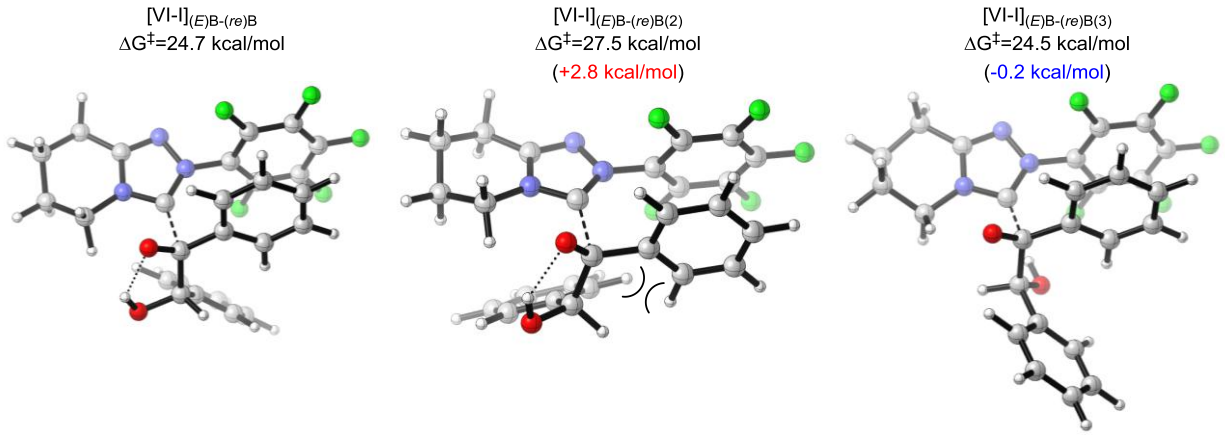
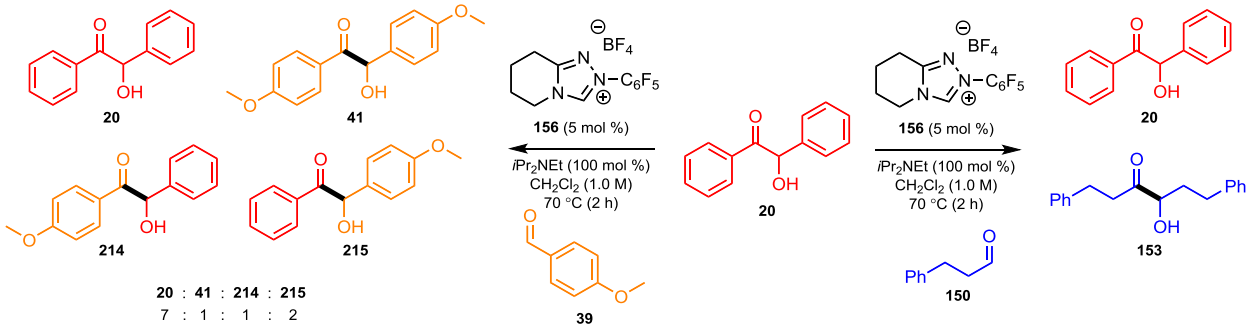


Figure 3.8 – Select alternate conformers examined for the product ejection step of the NHC-catalyzed homo-benzoin reaction of benzaldehyde.

If the rotation does not occur (**TS [VI-I]$_{(E)B\text{-}(re)B(2)}$**) the π-π/π-cation interaction is retained but the *ortho* protons of the two phenyl rings come relatively close (2.03 Å), resulting in a significant increase in energy. As this interaction develops in the carbon-carbon bond-formation step rotation may be asynchronous but concomitant to accommodate the growing strain. Based on the IRC for this step, it would follow proton transfer (*viz*. be very late in the transition). Interestingly, if the rotation is taken further a non-hydrogen-bonded ejection transition state can be located (**TS [VI-I]$_{(E)B\text{-}(re)B(3)}$**). The loss of the hydrogen bonding is mitigated by π-stacking between all three aryl rings. Based on the energy of this transition state, it is possible that the reaction proceeds with this rotation, although the energetic difference is within the error of the calculation.

The product is higher in energy (+0.3 kcal/mol) relative to the starting materials. This reaction is known to proceed under a variety of conditions; the products must be more stable than starting materials. Recalculating using a higher level of theory (CCSD(T)/LPNO-CEPA/1 extrapolation using the cc-PV(D/T)Z basis set; by Dr. C. Legault) did not remove this discrepancy. Use of Grimme's D3 correction lowers this energy to -0.29 kcal/mol, though this value is likely still overestimated.[122]



Scheme 3.15 – Crossover experiments between the homo-benzoin product of hydrocinnamaldehyde with aromatic and aliphatic aldehydes.

A pair of crossover experiments were performed to determine whether the product is formed reversibly under the reaction conditions (Scheme 3.15). In the presence of *p*-OMe benzaldehyde (*p*-anisaldehyde) both possible cross-benzoin products are formed. This confirms that the reaction is reversible up-to and including the carbon-carbon bond formation step. It is therefore likely that the reaction is completely reversible.

No detectible amount of cross-benzoin product(s) is formed in the presence of hydrocinnamaldehyde. This contradicts a similar experiment performed using the pyrrolidinone-derived catalyst,[49] and the result using *p*-OMe benzaldehyde. The conflict is resolved by considering the catalyst adduct with the aliphatic aldehyde as a resting state. As deprotonation forms the active carbene it rapidly forms the more stable resting state. Based on the computed energy difference (see Section 3.6.4) over 95% of the catalyst should be occupied in this form. The adduct slowly proceeds along its preferred reaction coordinate leading to the formation of the homo-benzoin product of hydrocinnamaldehyde. Only after the aliphatic aldehyde is consumed is there sufficient carbene in solution to catalyze the retro-benzoin reaction of the homo-benzoin product of benzaldehyde. As homo-benzoin products of aliphatic aldehydes are formed irreversibly under the conditions (see Section 3.6.4) there is then no aliphatic aldehyde in solution for the cross-benzoin reaction(s) to proceed.

Monitoring the consumption of benzaldehyde by ^{1}H NMR confirms that, under these conditions, the homo-benzoin reaction of benzaldehyde is second order with respect to the aldehyde. This is consistent with either carbon-carbon bond

formation or product ejection being rate-limiting. The rate-limiting steps for at least two of the diastereomeric pathways are in close energetic proximity to each other (see Section 3.6.8). It is probable that these steps are competitively rate-limiting for this transformation.

3.6.8. Overall Picture

An overlay of the presented pathways highlights the relative rate-limiting barriers for these reactions (Figure 3.9). The active catalyst initially forms a protonated tetrahedral intermediate with either an aliphatic or aromatic aldehyde. The adduct with the aliphatic aldehyde may be considered a catalyst resting state. While this step is not rate-limiting (*viz*. chemoselectivity determining) it has important consequences for crossover experiments.

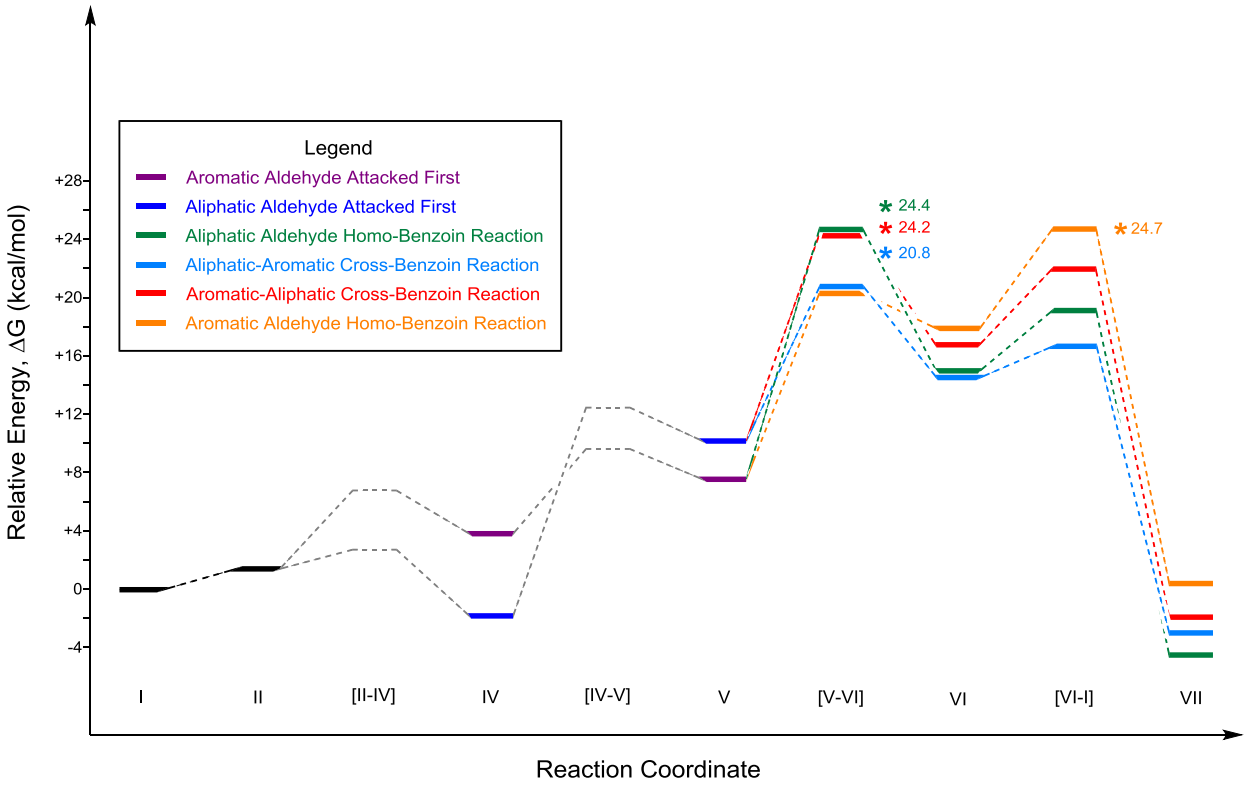


Figure 3.9 - Graphical overlay of the computed reaction coordinates for the NHC-catalyzed homo- and cross-benzoin reactions of benzaldehyde with propionaldehyde using the piperidinone-derived catalyst.

These adducts must cross a (potentially) high, though not rate-limiting, barrier as they form their respective Breslow Intermediates. The Breslow intermediates then attack another molecule of aldehyde. Both these Breslow intermediates strongly favour subsequent attacks on aromatic aldehydes due to a strong π-π/π-cation interaction. This step is typically rate-limiting, although in homo-benzoin reactions of aromatic aldehydes ejection of the product may be competitively rate-limiting.

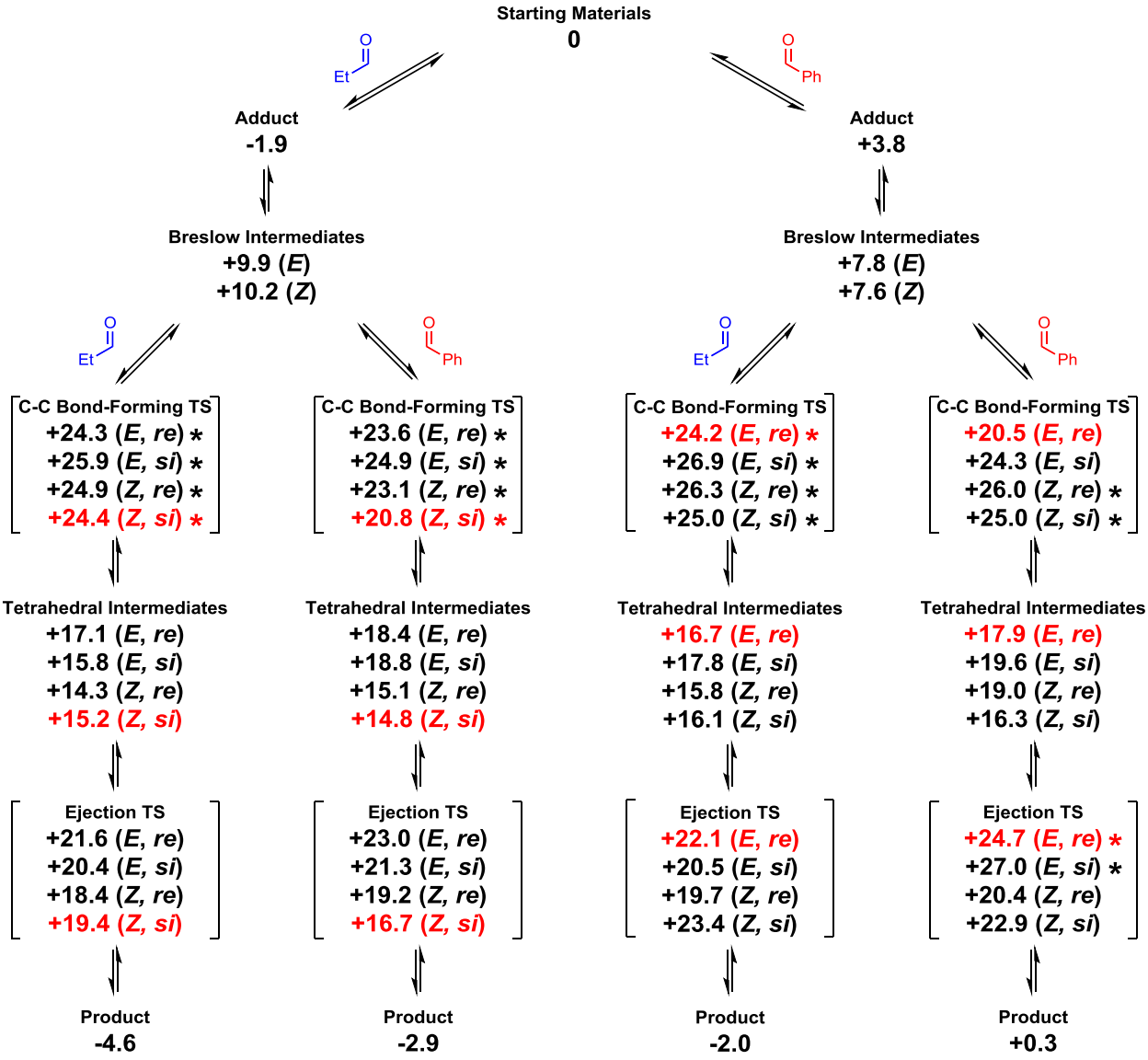
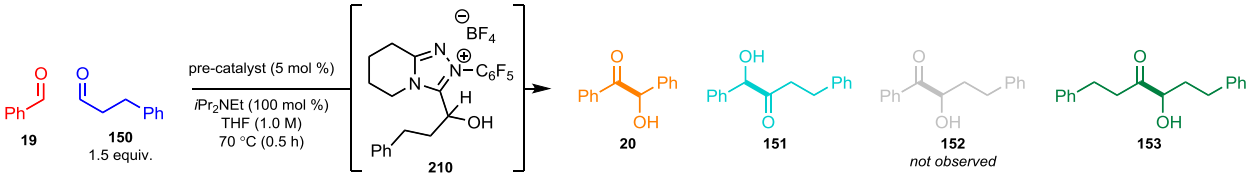
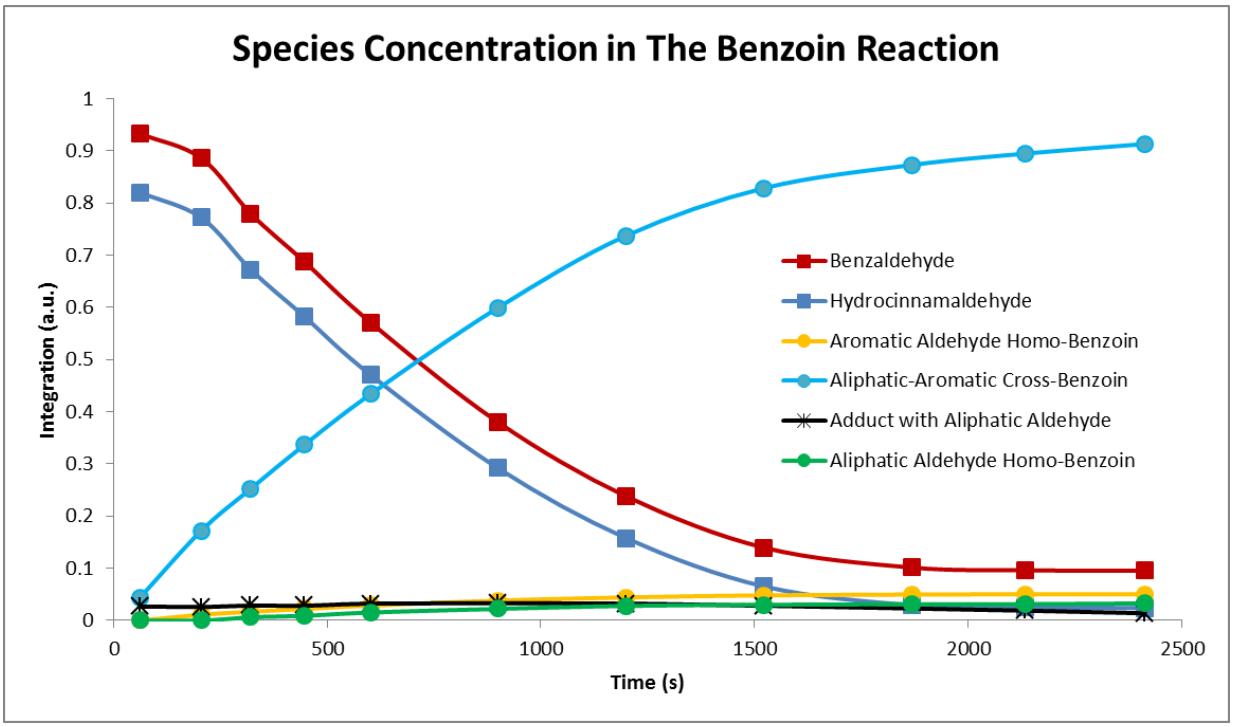


Figure 3.10 – Numerical summary of the computed reaction coordinates for the NHC-catalyzed homo- and cross-benzoin reactions of benzaldehyde with propionaldehyde using the piperidinone-derived catalyst.

With the reaction coordinate computed a final experiment was conducted to monitor the relative concentrations of all detectible species over time using ^{1}H NMR spectroscopy (Scheme 3.16). This confirmed both that the product is kinetically favoured and that the catalyst is only present in detectible amounts as the protonated adduct with the aliphatic aldehyde.

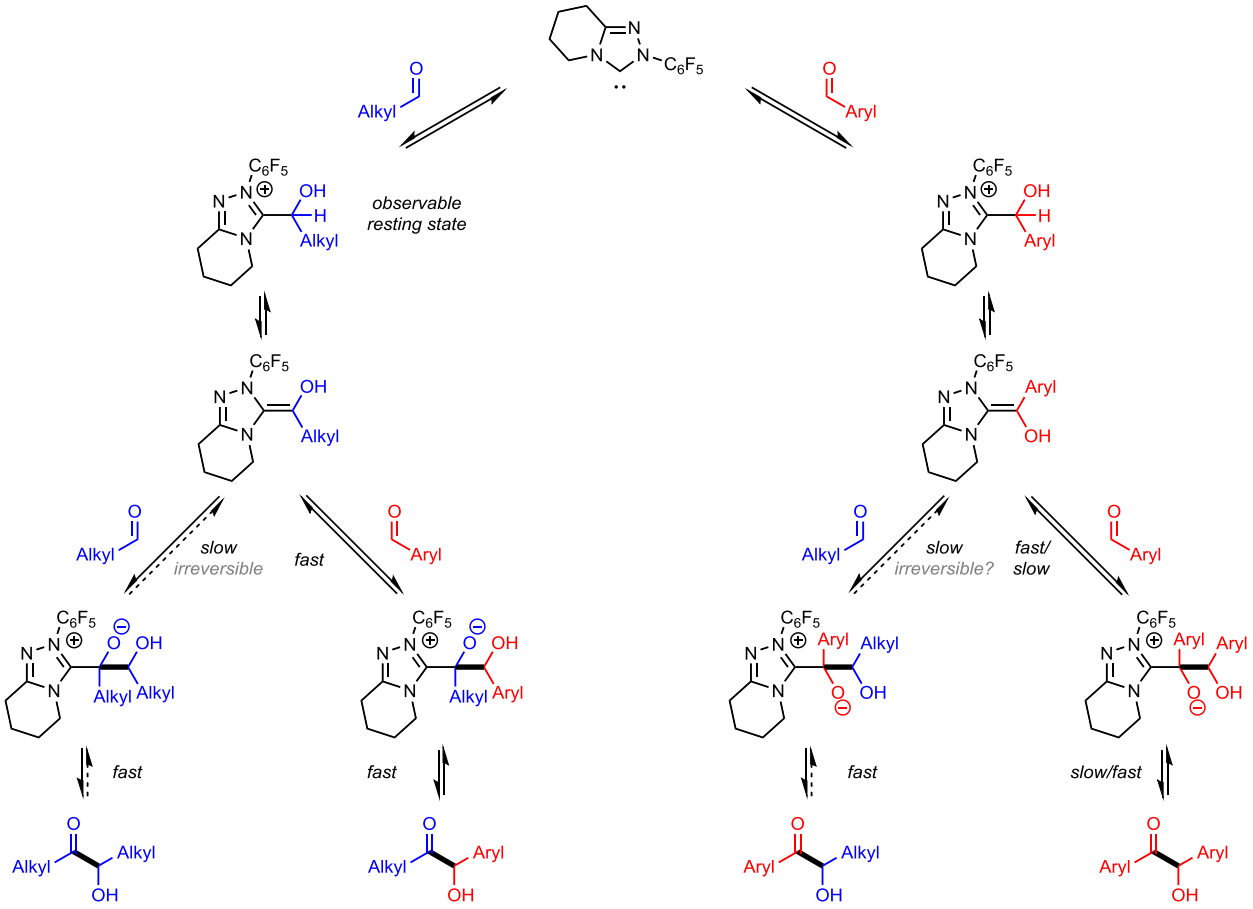




Scheme 3.16 – Monitoring the concentration of all detectible species in the chemoselective NHC-catalyzed cross-benzoin reaction of hydrocinnamaldehyde with benzaldehyde using the piperidinone-derived catalyst.

The experimental results can be summarized by describing the reversibility of steps in the system (Scheme 3.17). Formation of all species up to, and probably including, the Breslow Intermediates is completely reversible. Based on crossover experiments the formation of homo-benzoin products from aliphatic aldehydes proceeds irreversibly, with either (or both) the carbon-carbon bond formation

and/or ejection step(s) being irreversible. From the calculated barriers for this path, it is more likely to be the carbon-carbon bond formation step. An additional crossover experiment confirms that the major cross-benzoin product is formed completely reversibly. Homo-benzoin reactions of aromatic aldehydes also proceed with reversibility, though it is not possible to definitively say they are completely reversible. Formation of the minor cross-benzoin product (Figure 3.5) could not be probed to determine its reversibility. The calculated overall barrier for this process is of a similar magnitude to that of the irreversible homo-benzoin reaction of aliphatic aldehydes. The product is likely formed irreversibly, again with a probable irreversible carbon-carbon bond formation.



Scheme 3.17 – Schematic summary of the NHC-catalyzed cross-benzoin reaction of an aliphatic aldehyde with an aromatic aldehyde using the piperidinone-derived catalyst.

3.6.8.1. Modified System: Anisaldehyde

Electron-rich anisaldehydes afford their respective cross-benzoin products in near-quantitative yields (see Section 3.4.2). It was suggested that some structural feature of these aldehydes may be leading to the improved yields. Transition states for the carbon-carbon bond formation and product ejection steps were recalculated using *p*-OMe benzaldehyde (*p*-anisaldehyde). The cross-benzoin pathway continues to have the lowest rate-limiting barrier, though it and all transitions involving the anisaldehyde are slightly higher in energy than their benzaldehyde equivalents (Figure 3.11).

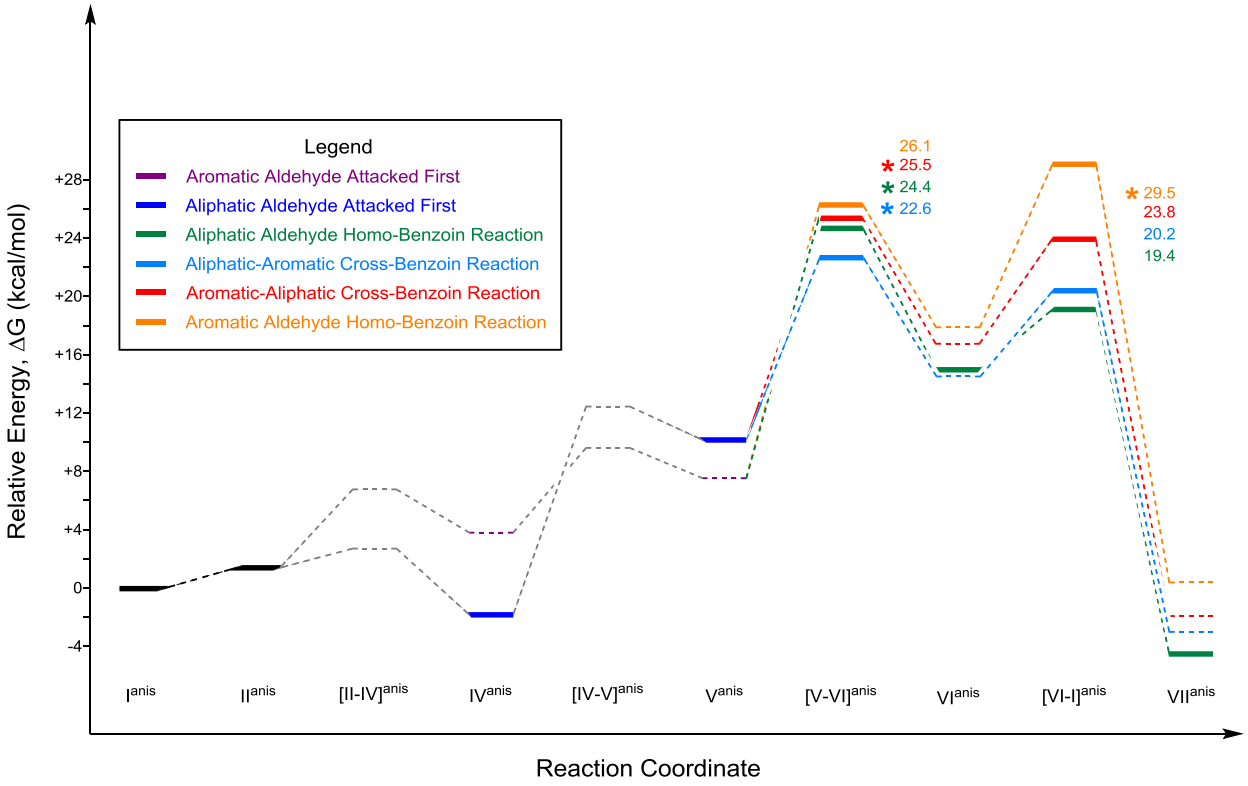


Figure 3.11 - Graphical overlay of the computed reaction coordinates for the NHC-catalyzed homo- and cross-benzoin reactions of *p*-anisaldehyde with propionaldehyde using the piperidinone-derived catalyst.

The improved yield may best be attributed to the sizable increase in the energy of the rate-limiting step of the homo-benzoin reaction of *p*-anisaldehyde. The π-π interactions between the electron-rich aromatic ring and the electron-poor *N*-C_6F_5

ring are likely substantially stronger than in the previous case, raising the energy of ejection. A plot of the non-covalent interactions shows this, a positive interaction between the methoxy and fluorine substituents, and a π-F interaction, though the degree to which each of these affects the transition state is not obvious (Figure 3.12). Monitoring this reaction by ^{1}H NMR shows that the reaction proceeds roughly half as quickly (0.41x) as the reaction between benzaldehyde and hydrocinnamaldehyde, consistent with an increased energy for the rate-limiting step. The homo-benzoin product of *p*-anisaldehyde is not observable at any point during or after the transformation.

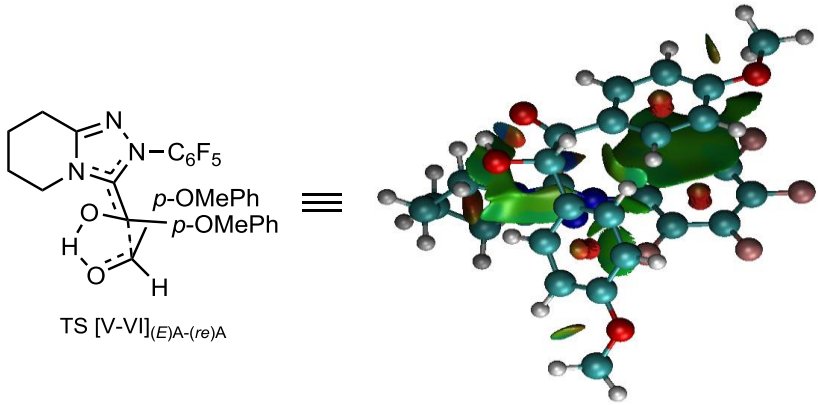


Figure 3.12 - Plot of non-covalent interactions for the carbon-carbon bond formation step of the NHC-catalyzed homo-benzoin reaction of *p*-anisaldehyde.

3.6.9. Pyrrolidinone-Derived Catalytic System

Calculations suggested features of the piperidinone-derived triazolylidene that lead to kinetic selectivity, notably a resting state with aliphatic aldehydes and a stabilizing π-π/π-cation interaction which favours attack of all Breslow intermediates onto aromatic aldehydes. However, these effects do not obviously derive from the size of the fused catalyst backbone; how this catalyst affords improved selectivity over the pyrrolidinone- and caprolactam- derived catalysts was not explained. The same reaction pathways were thus explored for the pyrrolidinone-based catalyst (Figure 3.13).

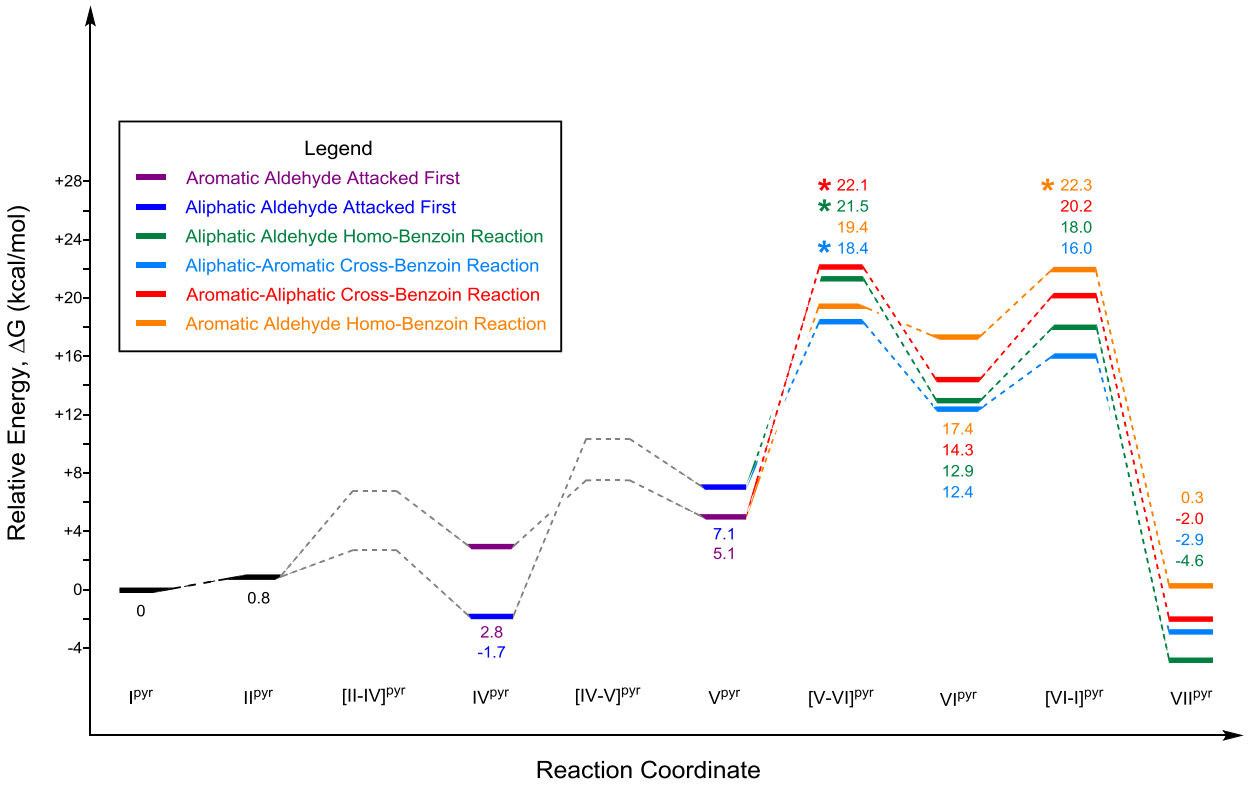
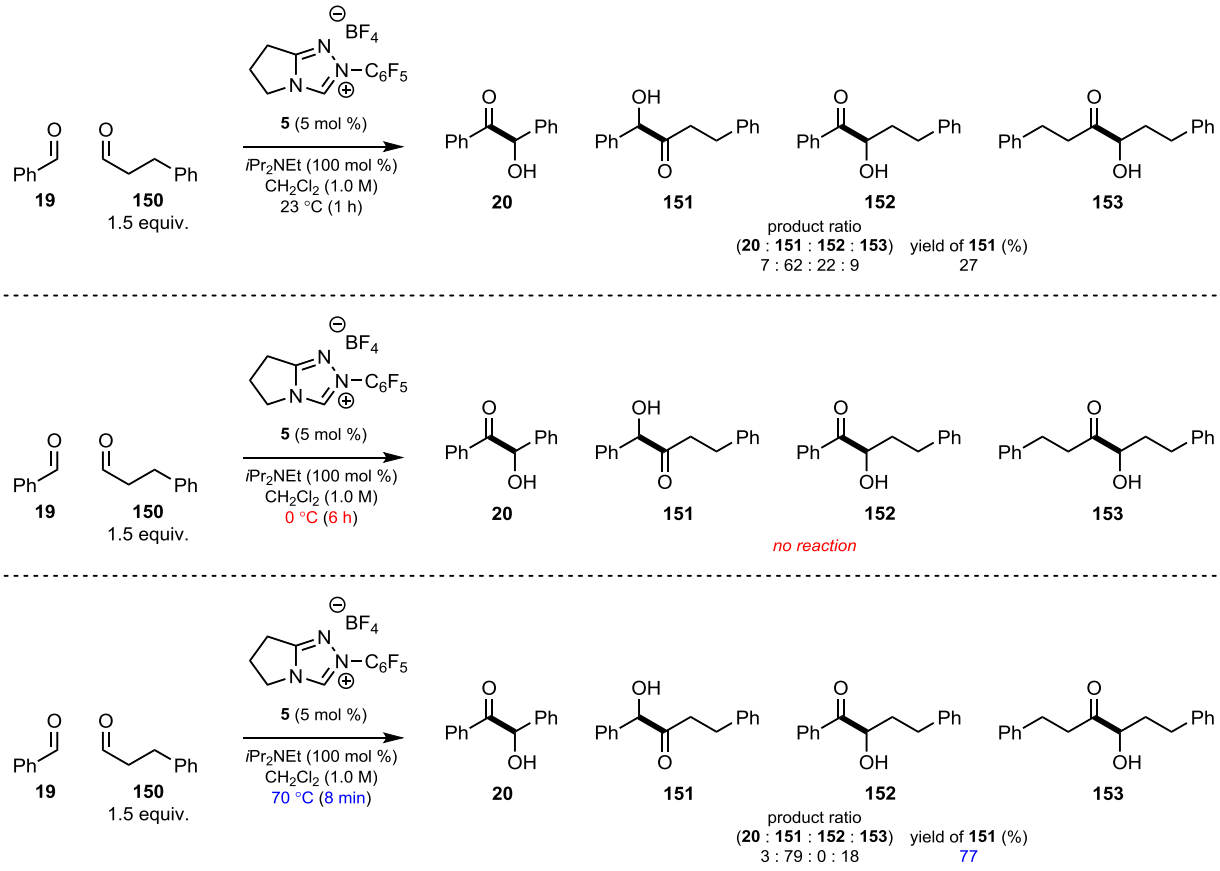


Figure 3.13 - Graphical overlay of the computed reaction coordinates for the NHC-catalyzed homo- and cross-benzoin reactions of benzaldehyde with propionaldehyde using the pyrrolidinone-derived catalyst.

The computed reaction coordinate is strikingly similar to that of the piperidinone-derived system (see 3.6.8.). However, the energies of all transition states, and most species, have been decreased. The decrease in $\Delta G^{\ddagger}$ is accompanied by a decrease in $\Delta\Delta G^{\ddagger}$, which may explain the lower chemoselectivity observed under reaction conditions. This suggests that the pyrrolidinone-based catalyst should display high chemoselectivity under modified (*viz*. kinetically controlled) conditions. At room temperature this reaction exhibits only a slight preference for the aliphatic-aromatic cross-benzoin product (Scheme 3.18). To account for the lowered $\Delta\Delta G^{\ddagger}$(s) the temperature was decreased. This results in a loss of reactivity rather than improved chemoselectivity. If the temperature is instead increased a high degree of chemoselectivity is obtained.



Scheme 3.18 – Comparison of cross-benzoin reactions at different temperatures using the pyrrolidinone-derived catalyst.

The lack of reactivity at low temperature was surprising; the computed barriers suggest that *some* conversion should still occur at 0 °C. The intensity of the UV absorbance of the free carbene, a proxy for concentration, was monitored as a function of temperature (Figure 3.14). This suggests that below 30 °C the amount of catalyst in solution is strongly dependent on the reaction temperature. This severely restricts applications of the pyrrolidinone-derived catalyst where chemoselectivity may be kinetically controlled.

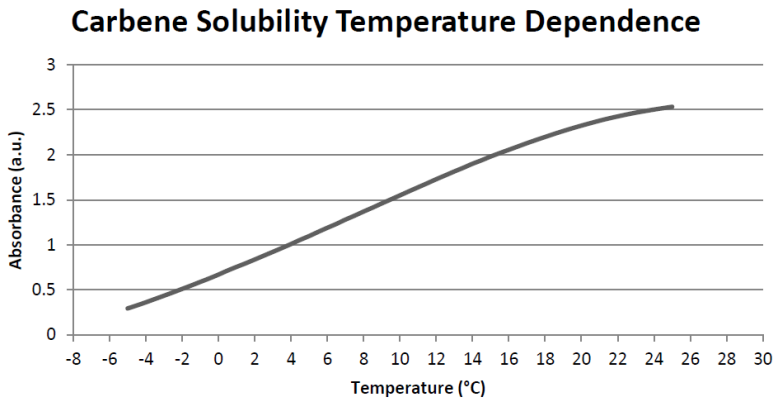
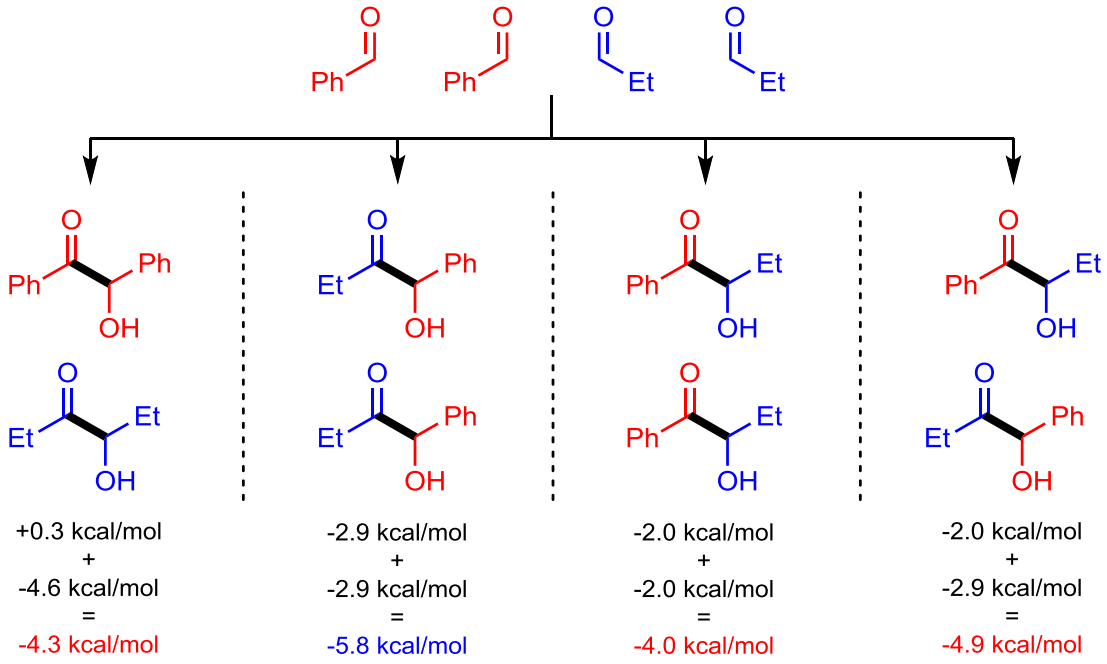


Figure 3.14 – Solubility of the pyrrolidinone-derived triazolylidene as a function of temperature.

Using elevated temperatures affords comparable yield and chemoselectivity to the piperidinone-derived catalyst. This was initially surprising, but may be explained by considering the thermodynamics of the system. For simplicity the most basic system, two molecules of benzaldehyde and two molecules of propionaldehyde, is considered.



Scheme 3.19 – Comparison of cross-benzoin reactions at different temperatures using the pyrrolidinone-derived catalyst.

Assuming these aldehydes undergo benzoin reactions to completion there are only four possible outcomes (Scheme 3.19). They may form: a set of the two homo-benzoin products (-4.3 kcal/mol), a pair of the aliphatic-aromatic cross-benzoin products (-5.8 kcal/mol), a pair of the aromatic-aliphatic cross-benzoin products (-4.0 kcal/mol), or one each of the two cross-benzoin products (-4.9 kcal/mol). Of these possibilities the pair of aliphatic-aromatic cross-benzoin products is the most stable. This means that the kinetically favoured product is also the thermodynamically favoured product. A crossover experiment confirms that formation of the homo-benzoin product of hydrocinnamaldehyde is reversible under these reaction conditions, allowing full equilibration. This contrasts with the same reaction catalyzed using the piperidinone-derived catalyst (Scheme 3.12). Taken together, these experiments suggest that the pyrrolidinone-derived catalyst is able to achieve chemoselectivity by reaching thermodynamic equilibrium. While this may have synthetic applications it is likely not applicable to potential enantioselective cross-benzoin reactions, which must rely on kinetic control.

A summary of the full computed reaction coordinate for each diastereomer of each benzoin reaction follows (Figure 3.15).

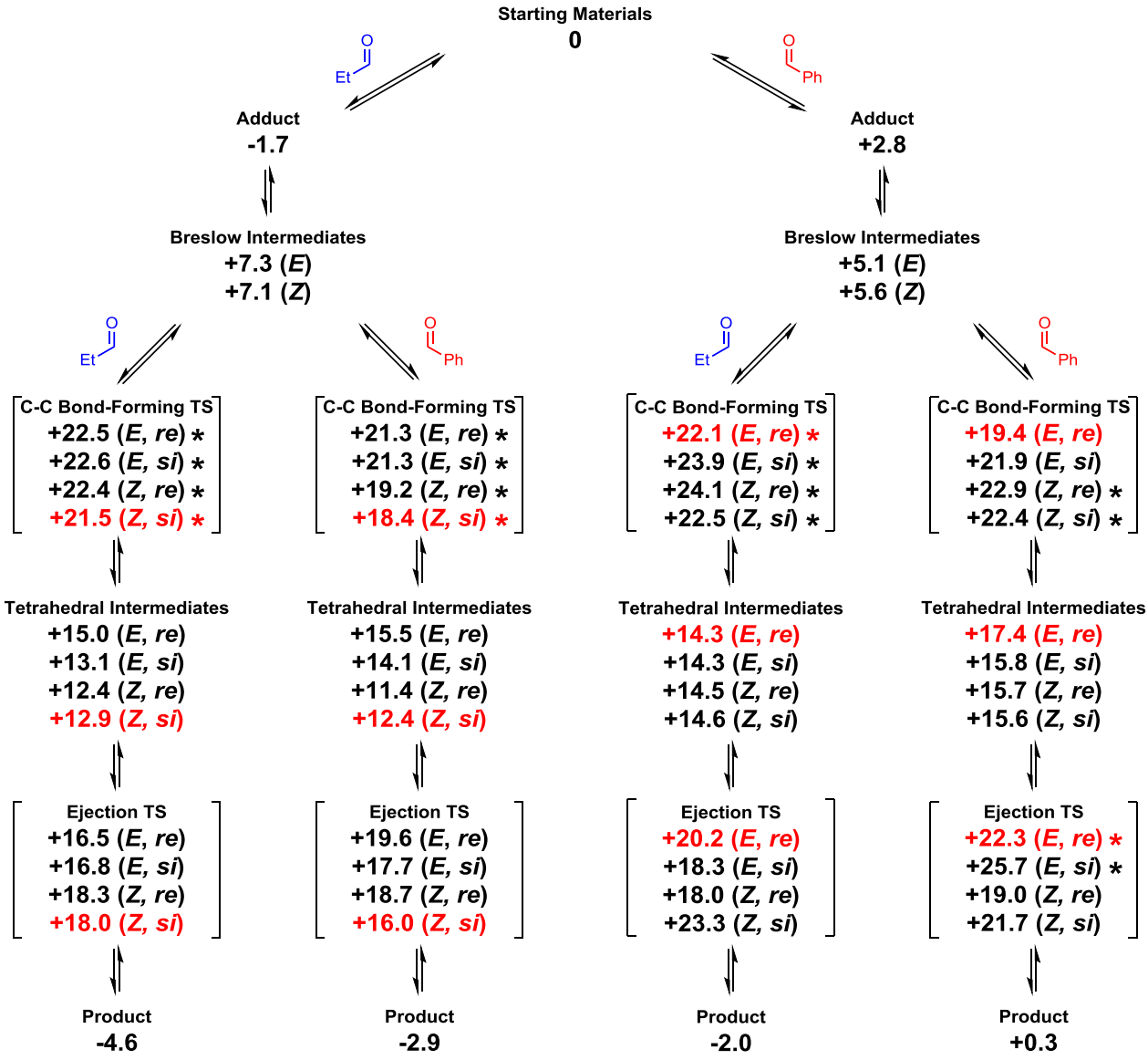


Figure 3.15 – Numerical summary of the computed reaction coordinates for the NHC-catalyzed homo- and cross-benzoin reactions of benzaldehyde with propionaldehyde using the pyrrolidinone-derived catalyst.

3.6.10. Caprolactam-Derived Catalytic System

The transition state for carbon-carbon bond formation in the major cross-benzoin pathway as catalyzed by the caprolactam-based triazolylidene was also modeled. The barrier for this transition state is calculated at 23.5 kcal/mol. Initial catalyst screening showed poor chemoselectivity relative to that of the

piperidinone-derived triazolylidene (see Section 3.2). The reaction (Table 3.1, entry 5) was repeated with extra care taken in the experimental setup (vacuum dry triazolium salt, flame-dried vessel, double purging with argon) and chemoselectivity was comparable to that obtained with the piperidinone-derived catalyst. However, additional experiments under modified conditions suggest that the result is variable. For example, reactions carried out side-by-side, under identical conditions, and with comparable levels of care taken in the experimental setup afford similar levels of chemoselectivity but substantially different conversions. These results suggest that reactions using this catalyst are significantly affected by trace moisture/oxygen (see Table 3.5), which may be exacerbated by the extended reaction times.

3.6.11. Comparison of Catalytic Systems

Three ^{1}H NMR monitoring experiments of the cross-benzoin reaction between benzaldehyde and hydrocinnamaldehyde, as catalyzed by the pyrrolidinone-, piperidinone-, and caprolactam-derived catalysts, were carried out under otherwise identical conditions. Special care was taken in the experimental setup to ensure that each reaction was thoroughly purged of moisture/oxygen. Using an average initial rate (see Section 5.2.3) the relative reaction rates were determined. The pyrrolidinone-derived catalyst has the fastest reaction rate and a computed reaction barrier of 18.4 kcal/mol for the rate-limiting step of the cross-benzoin reaction (see Section 3.6.9). The piperidinone-derived catalyst has a reaction rate roughly 1/5th (0.21x) as fast. Using the Arrhenius equation, and assuming the pre-exponential terms are identical, this translates to an increase in the activation energy of +1.03 kcal/mol. The equivalent computed barrier is 20.8 kcal/mol (+2.4 kcal/mol higher). The caprolactam-derived catalyst has a reaction rate roughly 1/25th (0.038x) as fast. Using the Arrhenius equation, and assuming the pre-exponential terms are identical, this translates to an increase in the activation energy of +1.98 kcal/mol. The equivalent computed barrier is 23.5 kcal/mol (+5.1 kcal/mol higher).

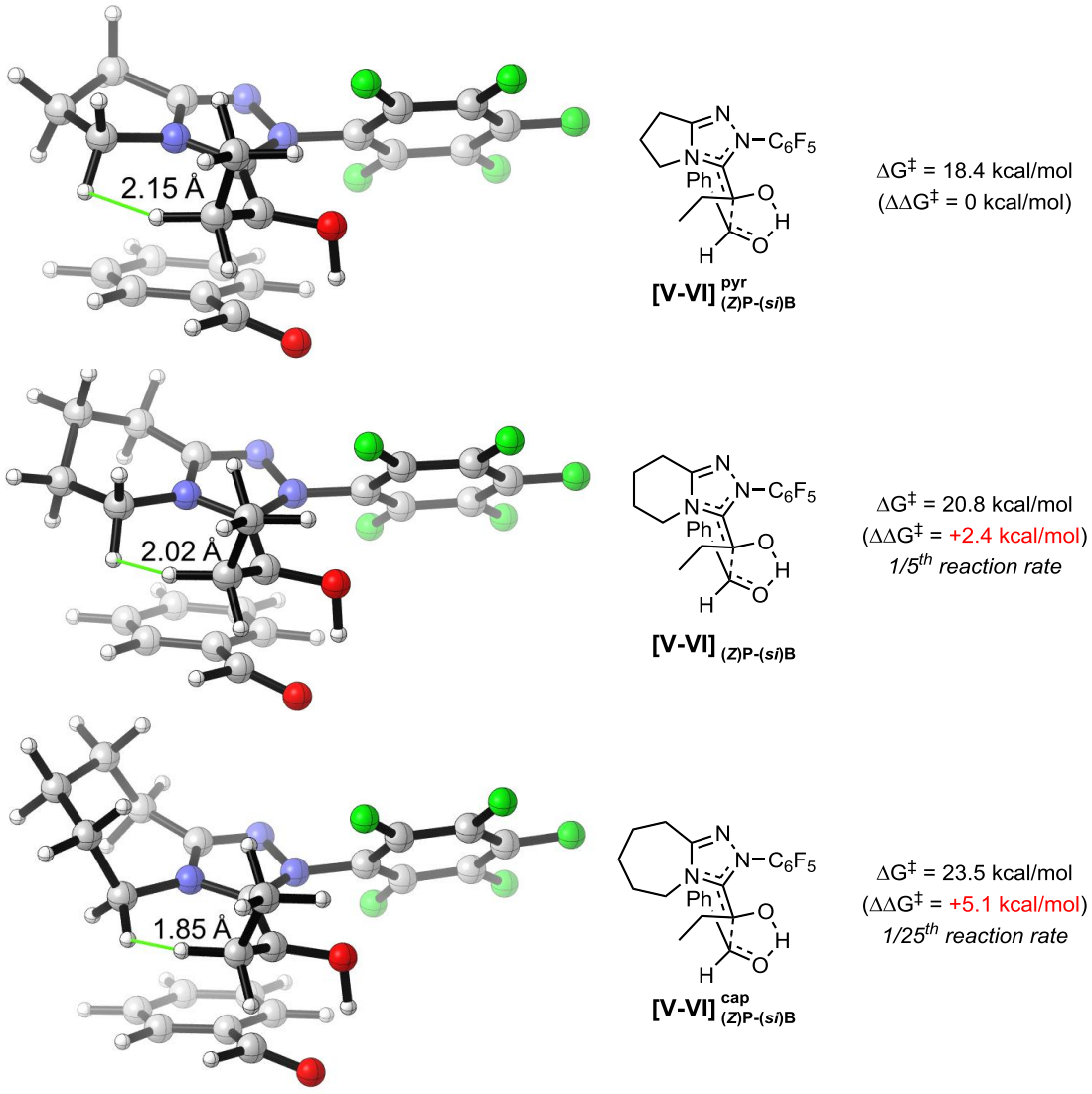


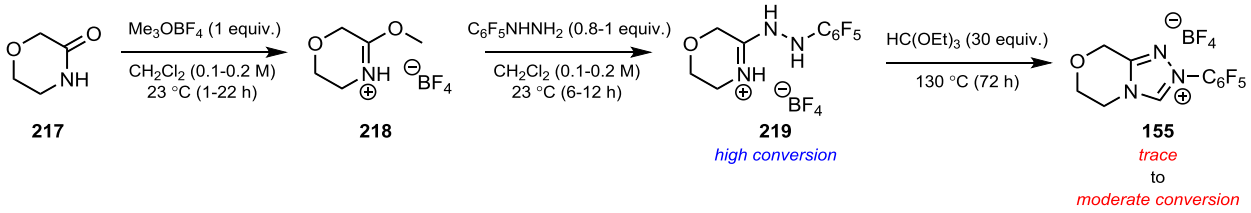
Figure 3.16 – Comparison of computed rate-limiting transition states for the NHC-catalyzed cross-benzoin reactions of propionaldehyde with benzaldehyde using the pyrrolidinone-, piperidinone-, and caprolactam-derived catalysts.

These results are consistent with the computed trend but may suggest a systematic overestimation in the computed barriers as the catalyst backbone increases. Alternatively, the steric parameter (ρ) of the pre-exponential term in the Arrhenius equation may be increasing by a factor of ca. 2.5 for each additional methylene unit. Comparing the rate-limiting transition states for these reactions (Figure 3.16) suggests that the increasingly close methylene protons of the catalyst backbone may be the source of the increased activation barriers. The

differences in chemoselectivity at room temperature (see Section 3.2) are likely a function of the relative positions of these barriers. The pyrrolidinone-derived catalyst has a low activation energy, but also has a diminished $\Delta\Delta G^{\ddagger}$ relative to the rate-limiting steps for the other possible benzoin pathways. This lowers chemoselectivity under non-equilibrating conditions. Conversely, the caprolactam-derived catalyst should afford high kinetically-controlled chemoselectivity. However, the higher barrier requires extended reaction times. This increases sensitivity to trace oxygen/moisture, making chemoselectivity and/or conversion difficult to reproduce.

3.7. Catalyst Syntheses

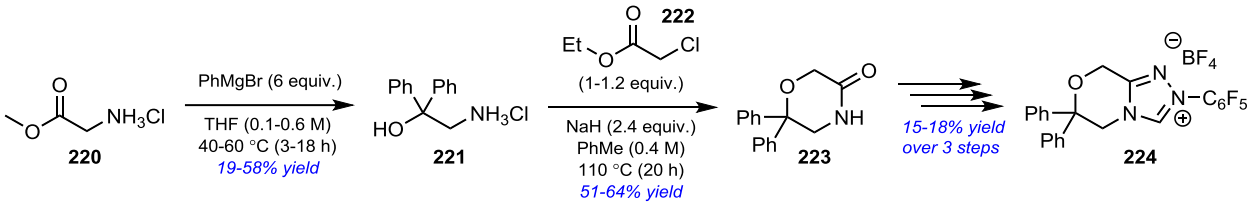
During the initial catalyst screening (see Section 3.2) access to the achiral, unsubstituted morpholinone-derived triazolium salt was required. Five separate attempts to access the catalyst all resulted in no isolated product (Scheme 3.20). Aliquot sampling confirmed that both methylation of the lactam and formation of the amidrazonium salt proceed with high efficiency/conversion. Analysis of ^{1}H NMR spectra of the crude reaction mixtures for the cyclization step shows that in all cases at least a trace amount of compound is formed. Isolation of this azolium salt is non-trivial. The sole successful isolation (30 mg, 0.7% yield from morpholinone, Dr. K. Thai) retains a noticeable amount of the product in the mother liquor, reaffirming the challenges of isolation.



Scheme 3.20 – Attempts to synthesize an unsubstituted morpholinone-derived triazolium salt.

The piperidinone-derived azolium salt was synthesized by Dr. M. Wilde. During this time access to an equivalent achiral morpholinone-derived triazolium salt was

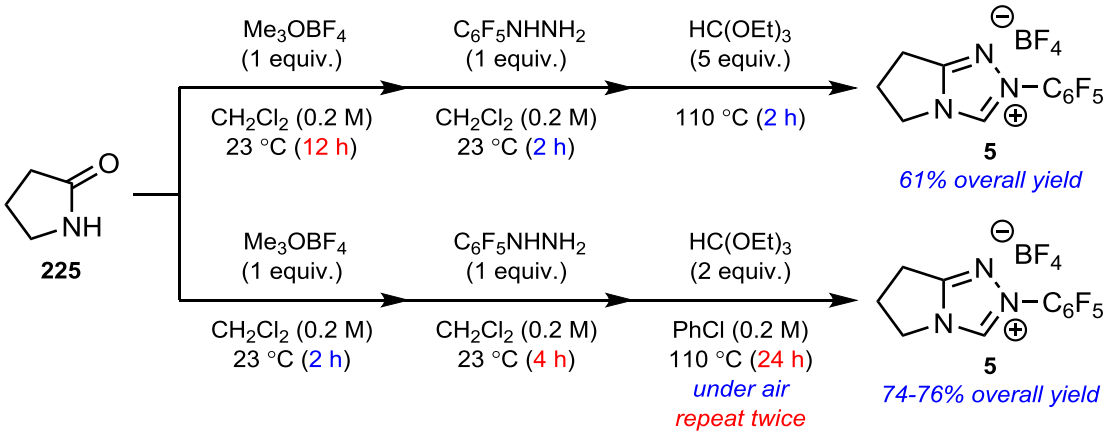
sought. Given the difficulties with isolation, it was hypothesized that additional crystallinity/bulk might aid in the isolation. The addition of a geminal diphenyl group distal to the active site was targeted (Scheme 3.21).



Scheme 3.21 – Synthesis of an achiral morpholinone-derived triazolium salt with geminal diphenyl substituents.

Increasing the concentration, temperature, and time for the Grignard addition to the ester improves yields. Conversion of the morpholinone to the azolium salt proceeds with moderate efficiency; isolation is substantially facilitated but conversion is lowered relative to the synthesis of **155**. Cross-benzoin reactions conducted using this pre-catalyst afford comparable yields and chemoselectivities to equivalent reactions catalyzed by the piperidinone-derived triazolylidene.

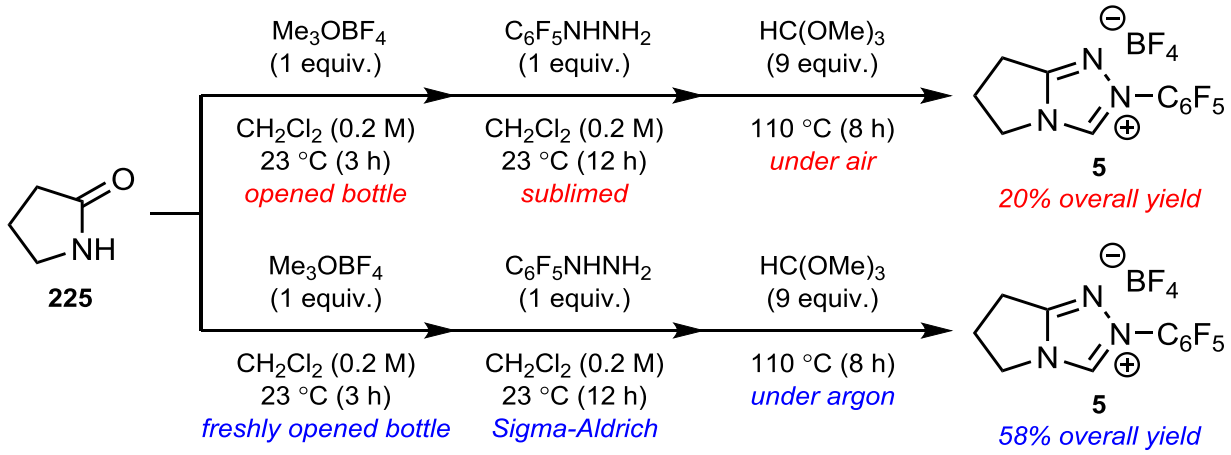
While exploring chemoselective cross-benzoin reactions (see Sections 3.2 to 3.6.11 inclusive) access to a large quantity of the pyrrolidinone-derived triazolium salt was required. The synthesis of this compound has been reported in high yield under multiple conditions by the Rovis group (Scheme 3.22).[7, 123]



Scheme 3.22 – Synthetic routes to a pyrrolidinone-derived triazolium salt reported by Rovis *et al*.

However, other groups generally report substantially lower yields (34-48% from pyrrolidinone) using similar/identical procedures.[9b, 124] Multiple syntheses of this compound by Gravel group members (Dr. E. Sanchez-Larios, Dr. K. Thai, Dr. M. Wilde, Dr. P. Haghshenas, S. Langdon) have never achieved isolated product yields above 36%.

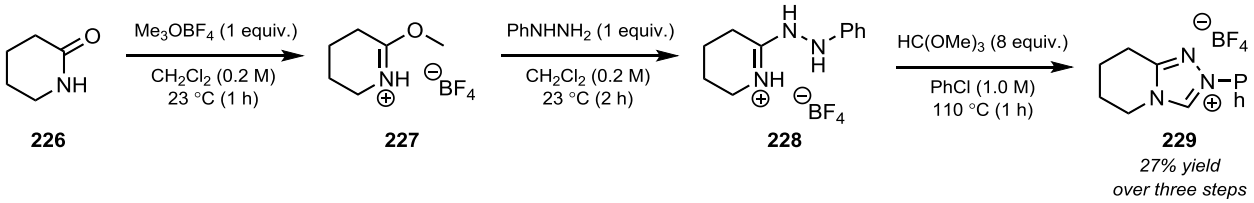
A series of control experiments were performed to probe the low yield in this synthesis. As discussed in Rovis' later work,[7] a fresh source of trimethyloxonium tetrafluoroborate is required for high yields. Careful storage of this salt under an argon atmosphere in a desiccator only moderately extends the compound's usable lifetime. Varying the source (*viz*. chemical supplier) did not have an effect on the yield. Conversely, the source of the hydrazine did affect the overall yield. As suggested by Rovis,[7] use of hydrazine acquired from Sigma-Aldrich affords the highest yields. Hydrazine from other sources may be sublimed before use, which results in improved but sub-optimal overall yields. The use of inert atmosphere during the cyclization stage is not required but substantially increases long-term reproducibility and ease of isolation. This is likely due to variable amounts of atmospheric moisture, which may react with the orthoformate over the extended reaction times. Applying these modifications has a substantial impact on the overall product yield (Scheme 3.23)



Scheme 3.23 – Comparison of synthetic procedures to a pyrrolidinone-derived triazolium salt.

Finally, product purification may be improved through the use of activated charcoal; following initial filtration, passing the mother liquor through activated charcoal followed by condensation and filtration affords more, and purer, product than directly condensing and filtering the mother liquor. This was determined in collaboration with Dr. P. Haghshenas. Alternatively, if the temperature for the orthoformate cyclization is decreased (70 °C) then no coloured impurities are formed and purification is substantially simplified (55% yield from amidrazonium).

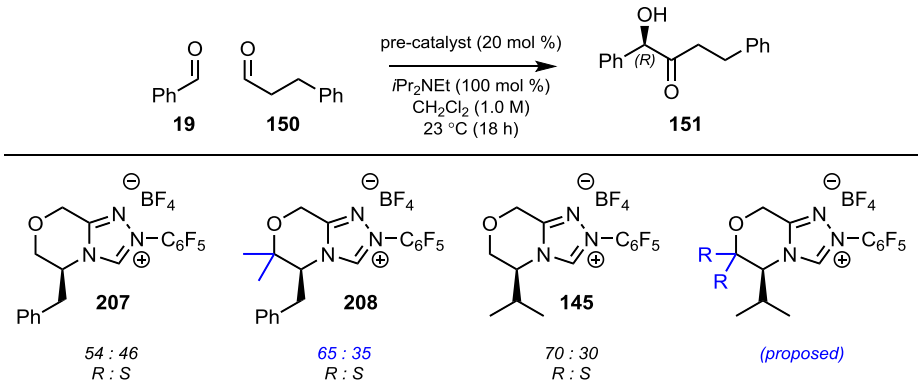
During the catalyst screening process (see Section 3.2) the substituent on the nitrogen was varied from pentafluorophenyl to phenyl to gauge what effect this would have on the reaction. Synthesis of this derivative followed an unoptimized variant of the standard protocol (Scheme 3.24).



Scheme 3.24 – Synthesis of an *N*-Ph analogue of the piperidinone-derived triazolium salt.

3.7.1. Efforts to Synthesize New Chiral Catalysts

Use of pre-existing chiral triazolylidene catalysts in chemo- and enantioselective cross-benzoin reactions affords minimal enantioselectivity (see Section 3.5). The observation that adjacent geminal disubstitution affords improved enantioselectivity prompted consideration of a class of catalyst derivatives (Scheme 3.25).



Scheme 3.25 – Highlighted examples from the comparison of catalysts for an enantio- and chemoselective cross-benzoin reaction.

The rate-limiting step in cross-benzoin reactions between aliphatic and aromatic aldehydes is carbon-carbon bond formation (see Section 3.6.5). Consequently enantioselectivity must be determined at (or after) this step. Consideration of potential transition states (Figure 3.17) suggests that this class of catalysts should be highly restricted with respect to approach to the aldehyde. This suggests high enantioselectivity may be obtainable with one of these derivatives.

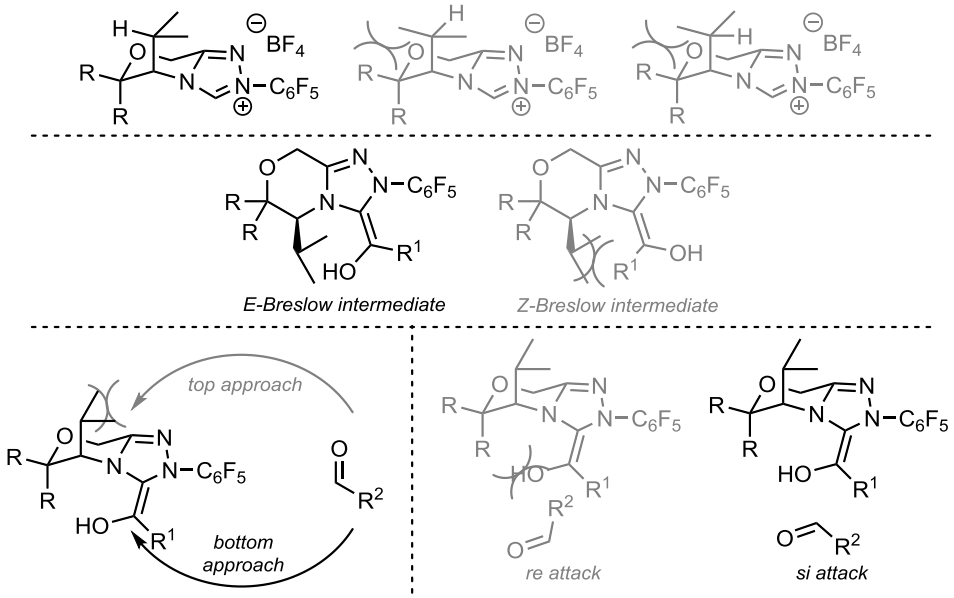
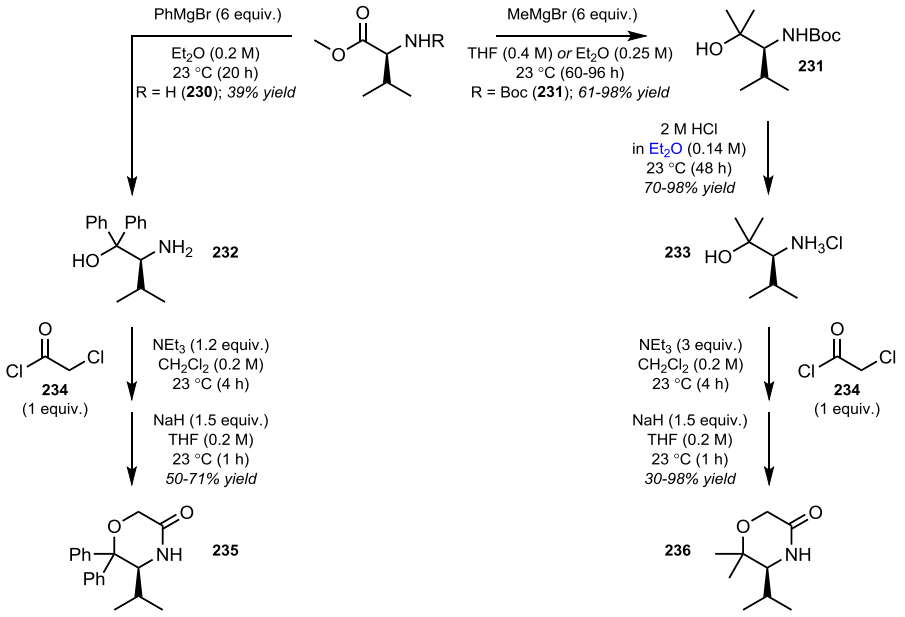


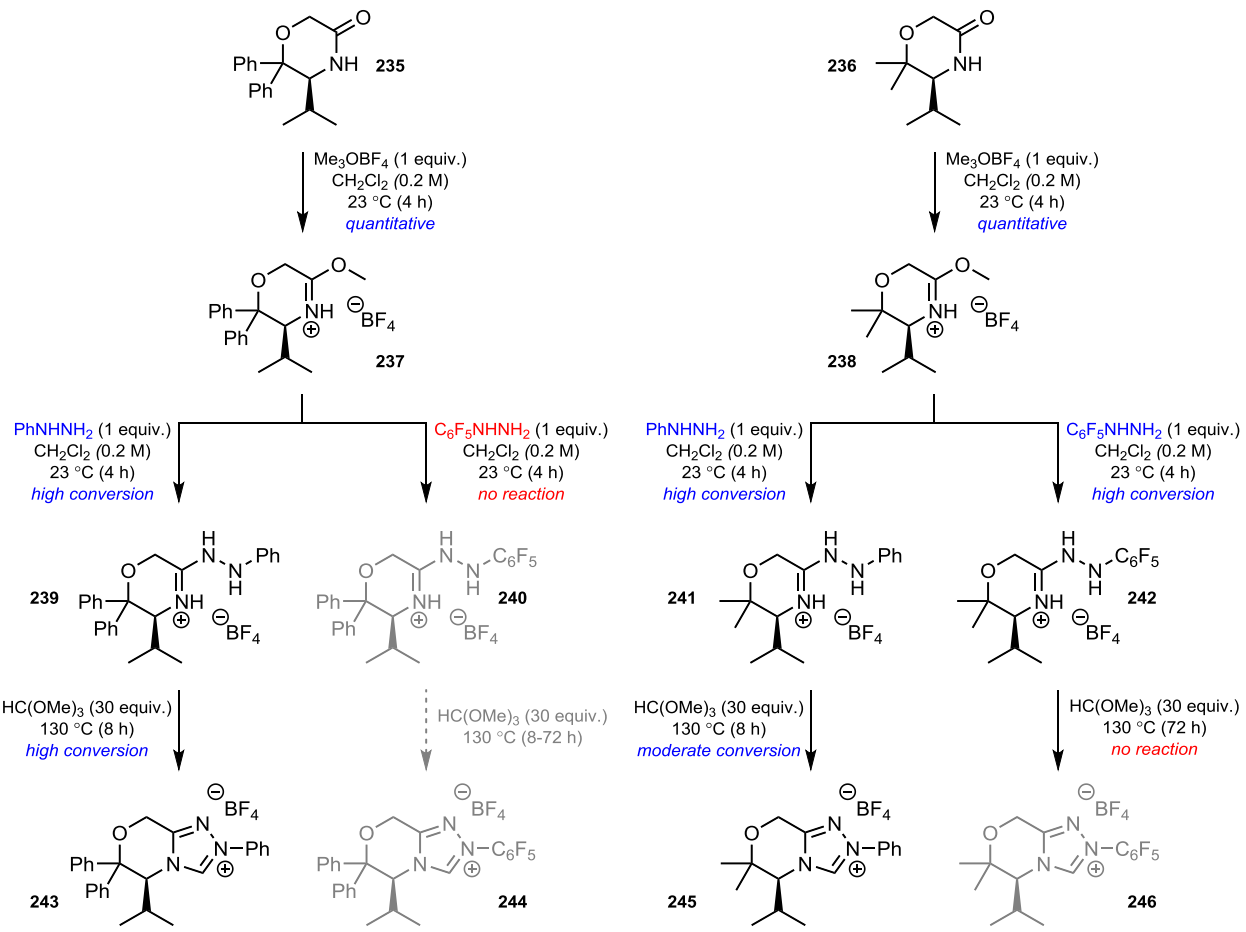
Figure 3.17 – Comparison of conformers, isomers, and transition states for enantioselective NHC-catalyzed benzoin reactions using morpholinone-derived catalyst with both isopropyl and geminal disubstitution.

Based on the literature (see Scheme 1.5)[14-17] two derivatives bearing geminal dimethyl and diphenyl substituents were targeted. Grignard additions to the methyl ester of *L*-valine proceed with moderate to high efficiency (Scheme 3.26). For reactions with methyl magnesium bromide protection of the amine was also required; in the absence of the Boc protecting group reactions with MeMgBr afford very low yields (0-13% yield). Removal of this protecting group is highly solvent-dependent. Use of dioxane, methanol, or ethyl acetate in place of diethyl ether results in decomposition rather than deprotection. Attempts to form the morpholinones using ethyl chloroacetate (see Scheme 3.21) were unsuccessful, with the respective starting materials recovered. Using a modified two-step sequence designed for the synthesis of sterically hindered morpholinones affords the respective compounds in good to excellent yields.[15]



Scheme 3.26 – Syntheses of chiral morpholinones with geminal dimethyl or diphenyl substituents.

These morpholinones were subjected to the standard conditions for the synthesis of triazolium salts (see Sections 1.1.1 and 3.7; Scheme 3.27). Analysis of the ^{1}H NMR spectra of the crude reaction mixtures for these reactions suggested that no azolium salts were formed. Aliquot sampling confirmed that methylation of the lactams proceeded quantitatively.



Scheme 3.27 – Attempted syntheses of chiral morpholinone-derived triazolium salts with geminal dimethyl or diphenyl substituents.

Formation of the amidrazonium salt proceeds with high efficiency/conversion for the morpholinone with geminal dimethyl substitution (**242**). However, no reaction is observed under cyclization conditions with orthoformate, with the starting material recovered instead. Basic extraction of the amidrazonium salt affords the corresponding amidrazone in moderate yield (52% yield).

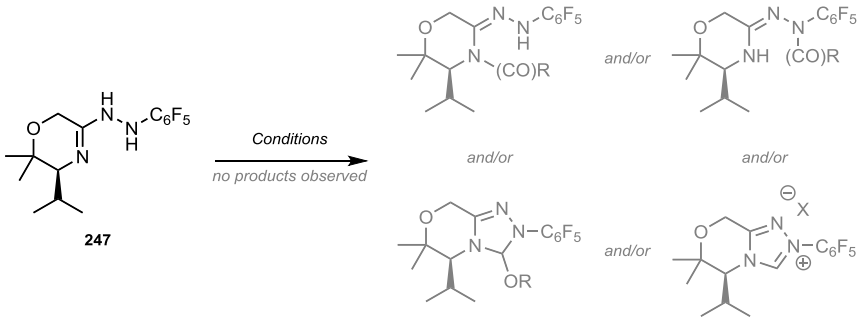
No amidrazonium salt is observed for the morpholinone bearing geminal diphenyl substitution (**240**), with the starting material recovered instead.

A pair of small-scale reactions were carried out using phenyl hydrazine in place of pentafluorophenyl hydrazine. Analysis of the ^{1}H NMR spectra of the crude reaction mixtures for these transformations confirms moderate to high conversion to the corresponding azolium salts in both cases. This suggests that the electronic nature of the nitrogen substituent affects triazolium salt yields (see

Scheme 1.4) primarily by hindering cyclization. As catalysts with *N*-Ph substitution are not appropriate for chemoselective cross-benzoin reactions (see Section 3.2) these species were not isolated.

The isolated amidrazone (**247**) was subjected to a wide range of reaction conditions to effect cyclization/formylation/amidation (Table 3.9). In all cases no product(s) from the amidrazone is observed, with the starting material remaining untouched.

Table 3.9 – Screened reaction conditions for functionalization of a chiral amidrazone with geminal dimethyl substitution.

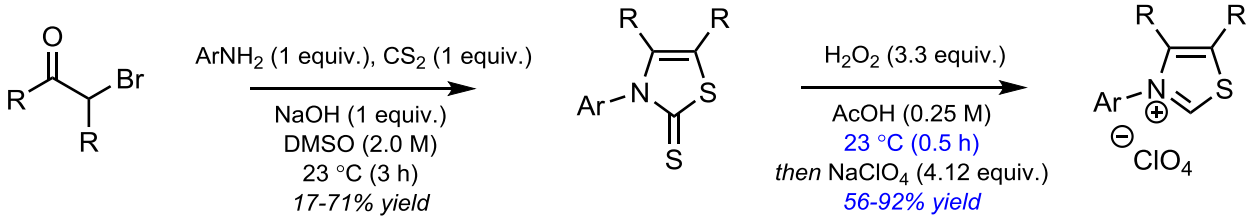


entry	conditions
1	$HC(OMe)_3$ (10 equiv.); PhCl (1.0 M); 120°C (6 h)
2	$HC(OMe)_3$ (20 equiv.); PhCl (1.0 M); 120°C (6 h)
3	$HC(OMe)_3$ (8 equiv.); HCl (2 equiv.); PhCl (1.0 M); 120°C (12 h)
4	$HC(OMe)_3$ (8 equiv.); BF_3 (2 equiv.); PhCl (1.0 M); 120°C (12 h)
5	HCO_2Me (1.0 M); 32°C (12 h)
6	HCO_2Me (1.0 M); 32°C (72 h)
7	HCO_2H (3 equiv.); $ZnCl_2$ (0.1 equiv.); 70°C (12 h)
8	HCO_2H (1.2 equiv.); PhMe (1.0 M); 110°C (12 h)
9	$HC(OMe)_2(NMe_2)$ (8 equiv.); HCl (3 equiv.); PhCl (1.0 M); 120°C (12 h)
10	$HC(OMe)_2(NMe_2)$ (8 equiv.); HCl (3 equiv.); PhCl (1.0 M); 23°C (12 h)
11	$HC(OMe)_2(NMe_2)$ (32 equiv.); HCl (3 equiv.); PhCl (1.0 M); 120°C (96 h)
12	$HC(OMe)_2(NMe_2)$ (75 equiv.); HCl (3 equiv.); 23°C (96 h)
13	$HC(OMe)_2(NMe_2)$ (8 equiv.); AcOH (3 equiv.); PhCl (1.0 M); 120°C (12 h)
14	$HC(OMe)_2(NMe_2)$ (8 equiv.); AcOH (3 equiv.); PhCl (1.0 M); 23°C (12 h)
15	$POCl_3$ (1.5 equiv.); DMF (5 equiv.); 23°C (12 h)

3.7.2. New Method for Syntheses of Triazolium Salts

Syntheses of triazolium salts suffer from several limitations (see Section 1.1.1) and yields are highly substrate-dependent. Subjecting highly hindered morpholinones to standard conditions for triazolium salt formation fails when the chosen nitrogen substituent is pentafluorophenyl (see Section 3.7.1), but is successful if the substituent is instead phenyl. The synthesis of an achiral morpholinone-derived triazolium salt (**155**, see Sections 3.2 and 3.7) proceeds with high conversion based on ^{1}H NMR analysis but affords very low yields (0.7% yield) after isolation. The desire to access a highly sterically hindered triazolium salt bearing an *N*-C_6F_5 substituent for application in chemo- and enantioselective cross-benzoin reactions prompted consideration of alternative routes to these species. Ideally, the new route would proceed with highly reactive reagents, allowing functionalization of the hindered lactam/amidrazone/amidrazonium. Additionally purification/isolation should be simplified to improve overall yields.

In 2011 Glorius *et al*. reported the syntheses of thiazolium salts from the oxidation of dithiocarbamate intermediates (Scheme 3.28).[12l, 125] This avoids the use of orthoformates for cyclization, potentially simplifying the isolation of the resulting azolium salts (see Section 1.1.1). In most cases the pre-catalysts were directly isolated by vacuum filtration. Application of these azolium salts in a series of benzoin reactions confirmed that these pre-catalysts afford identical reactivity to those synthesized by other routes.

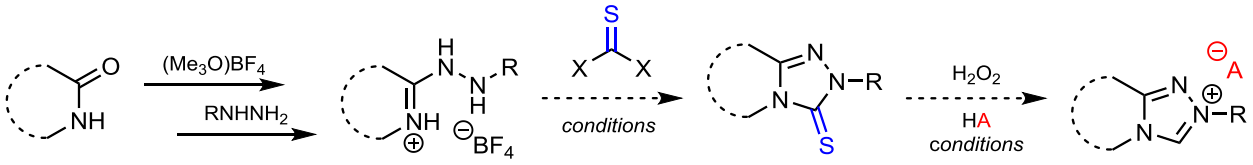


Scheme 3.28 – Syntheses of thiazolium salts through oxidation of thiocarbonyl-containing intermediates reported by Glorius *et al*.

Although no examples of triazolium salts were shown, it was surmised that this method should be applicable in their syntheses. Additionally, the ease of

counterion selection through either salt metathesis from the acetate or judicious selection of the acid during the oxidation phase would allow rapid access to a library of catalysts differing only in their counterion. Counterions have been shown to affect reaction rates and product enantioenrichment (see Section 1.1.1). This may assist in increasing enantioselectivity in chemo- and enantioselective cross-benzoin reactions.

Use of CS_2 for the synthesis of triazolium salts *via* the proposed route is not appropriate/possible. Based on previous experiments (see Sections 3.7 and 3.7.1) conversion of lactams to amidrazonium salts generally proceeds with high efficiency. Access to the 1,2,4-triazole-3-thione core should be possible by reacting a thiocarbonylating reagent with the appropriate amidrazonium (Scheme 3.29).

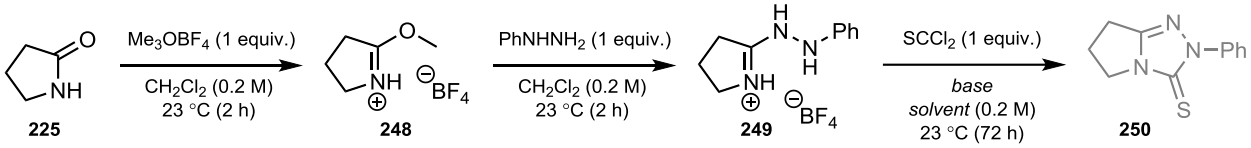


Scheme 3.29 – Proposed syntheses of triazolium salts through oxidation of thiocarbonyl-containing intermediates.

3.7.2.1. Optimization of Reaction Conditions

Conditions for the formation of the 1,2,4-triazole-3-thione core were explored first. Thiophosgene, both highly reactive and easily available, was chosen for initial optimization. Pyrrolidinone was chosen as a model substrate. It was assumed that substrates with electron-poor (*viz*. pentafluorophenyl-containing) nitrogen substituents would react slower than more electron-rich species. Although *N*-C_6F_5 substituted azolium salts were targeted for application in cross-benzoin reactions, a broad range of viable nitrogen substituents was desired to maximize potential applications. Based on these considerations phenyl hydrazine was chosen for initial optimization. Subjecting thiophosgene and amidrazonium salts to a wide range of reaction conditions (Table 3.10) does not afford any 1,2,4-triazole-3-thione containing compounds.

Table 3.10 – Screened reaction conditions for cyclization of an amidrazone with *N*-Ph substitution using thiophosgene.



225 248 249 250

entry	solvent	base (equiv.)
1	CH_2Cl_2	NEt_3 (4)
2	CH_2Cl_2	pyr (4)
3	THF	NEt_3 (4)
4	THF	pyr (4)
5	CH_2Cl_2	pyr (1)
6	CH_2Cl_2	pyr (3)
7	CH_2Cl_2	DMAP (3)
8	CH_2Cl_2	imidazole (3)
9	CH_2Cl_2	CsOAc (3)
10	CH_2Cl_2	K_2CO_3 (3)

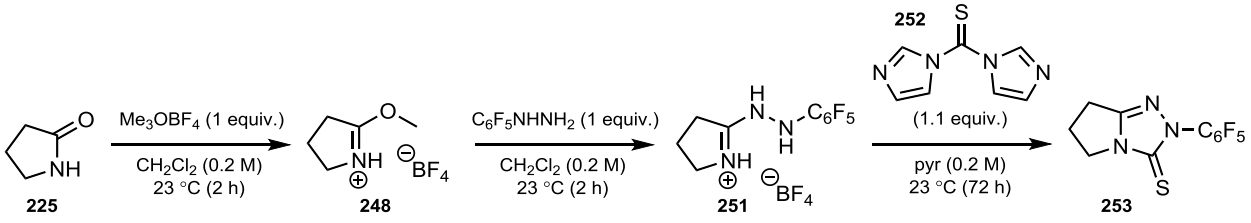
Altering the nature of the base or solvent (entries 1-4) does not afford any of the desired product. A complex mixture containing some of the amidrazone and several unidentified products is obtained. It was hypothesized that the protonation state of the amidrazonium may dictate which nitrogen is the most nucleophilic, which may alter the reactivity. Entries 1-4 were repeated with the opposite order of addition for the reagents (first $SCCl_2$, then base after 10 min). This did not afford any desired product. Repetition of entries 1 and 3 with substantially shorter reaction times for the cyclization step (8 h) showed lower consumption of the amidrazone. Decreasing the amount of base (entry 5) to attempt to stop the reaction after a single nucleophilic attack was not successful. Use of stoichiometric, rather than excess, base (entry 6) had no effect on the outcome.

Each of these reactions (entries 1-6) was repeated substituting pentafluorophenyl hydrazine for phenyl hydrazine. They were also repeated with elevated reaction temperature (40 °C). No desired product is formed under any of

these conditions. A broader scope of bases was examined (entries 7-10). The desired product is not formed under these conditions. In some cases the amidrazone was observed as the major product after the reaction, suggesting that the base may be reacting with the thiophosgene.

It was hypothesized that thiophosgene may be *too* reactive, causing a large number of side reactions to occur. Thiocarbonyldimidazole (TCDI) was chosen as an easily available and less reactive equivalent. To offset this diminished reactivity the reaction was run using pyridine as the solvent so that it may accelerate the reaction through nucleophilic catalysis. A test reaction using phenyl hydrazine afforded no desired product. Repeating the experiment with pentafluorophenyl hydrazine provided surprising results (Table 3.11).

Table 3.11 – Optimization of reaction conditions for cyclization of an amidrazone with *N*-C_6F_5 substitution using thiocarbonyldiimidazole.



225 248 251 252 253

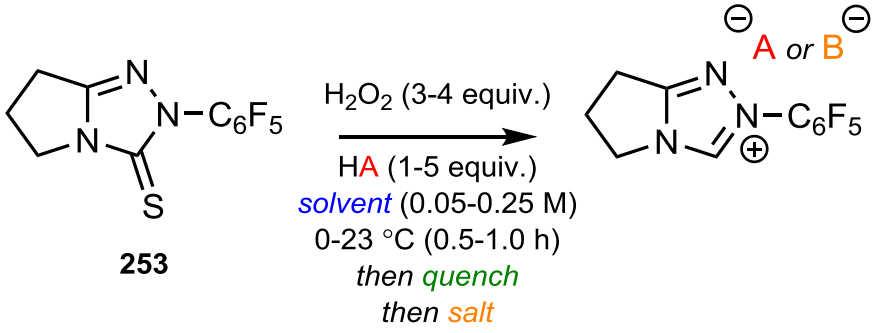
entry	modification	yield of 253 (%)
1	none	31
2[a]	isolate/purify amidrazonium	54[b]
3	72 h → 24 h	67
4	TCDI (1.1 equiv.) → $SCCl_2$ (1 equiv.)	0

a) amidrazonium salt isolated by filtration and purified by trituration with Et_2O (74% yield); b) yield from pyrrolidinone; 73% yield from isolated amidrazonium.

Initial yields using pentafluorophenyl hydrazine were promising (entry 1). Analysis of the crude ^{1}H NMR spectrum of the reaction suggested high conversion to the desired thione. Purifying the product using FCC resulted in substantial product loss due to tailing. Isolation of the amidrazonium prior to subjection to reaction conditions (entry 2) suggests that this reaction proceeds cleanly and confirms high conversion to the desired product. Purification was substantially

improved by very thoroughly removing pyridine *via* co-evaporation. This removed all tailing and allowed use of a silica plug rather than full FCC for purification. Decreasing the reaction time and more thoroughly removing CH_2Cl_2/MeOH *via* co-evaporation prior to thiocarbonylation (entry 3) further improves the reaction. Use of thiophosgene in place of thiocarbonyldiimidazole under otherwise identical conditions (entry 4) affords no desired product. This confirms that it is not the altered conditions but the altered reagent which is responsible for product formation. Pre-mixing thiophosgene and imidazole (6 equiv.) for several hours prior to the reaction may be used to form thiocarbonyldiimidazole *in situ*. This approach affords slightly diminished yields of the thione (59% yield).

Oxidation of the 1,2,4-triazole-3-thione to its corresponding azolium salt was then optimized. Initial attempts focused on the conditions of Glorius *et al.*[12l] and those of Wilde and Gravel (Scheme 3.30).[112]



Scheme 3.30 – General reaction for the synthesis of triazolium salts through oxidation of thiocarbonyl-containing intermediates.

Analysis of the ^{1}H NMR spectra of the crude reaction mixtures for these reactions showed extremely high conversion to the desired triazolium salt; neither the starting thione nor any side products are detectable in the reaction mixture. However, all samples obtained using these conditions are highly susceptible to decomposition from either heat (≥40 °C) or under the low pressures (≤1 torr.) required to remove solvent from the sample. Additionally, recrystallization of these samples is problematic, affording substantial mass loss and/or decomposition of the sample. The susceptibility to decomposition is independent of how the excess peroxide is quenched (no quench, SMe_2, Na_2SO_3,

Clear Eyes® Pt catalyst, Pt wire), solvent (AcOH, THF), the salt used for metathesis (none, $NaClO_4$, NH_4BF_4), the acid used (AcOH, HCl, $HClO_4$, HBF_4), or the equivalents of acid used (1 equiv., moderate excess, super-stoichiometric/solvent).

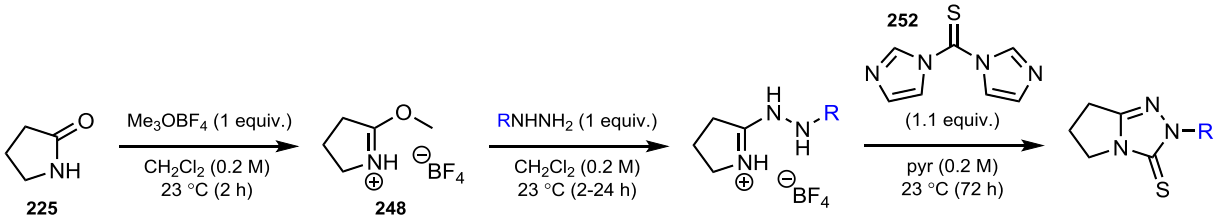
Changing the solvent to Et_2O and using only a stoichiometric (3 equiv.) amount of H_2O_2 completely removed all decomposition issues, improved the morphology (fluffy white solid), removed the need for a quenching reagent, and improved the isolated yield. The exact reason for the improvement when using Et_2O is not clear. As both THF and AcOH are more hygroscopic than Et_2O it was hypothesized that more residual water remains in the sample when these solvents are used. The additional water may lead to decomposition under heating and/or at high concentrations (*viz*. under low pressure with other solvents removed). Samples of the *N*-C_6F_5 pyrrolidinone-derived azolium salt (**5**) prepared using the traditional method (see Sections 1.1.1 and 3.7) were suspended in toluene at elevated temperatures (40-50 °C) and under low pressures (50-60 torr.) to simulate the conditions observed leading to decomposition during purification. No effect was observed, even after the addition of H_2O or H_2O_2 solutions. This suggests a trace impurity or reaction by-product is responsible for the decomposition when AcOH or THF is used as the solvent.

The experiment with optimized conditions was repeated several times with slight modifications to the work up. Analysis of the ^{1}H NMR spectra for these reactions showed an appreciable amount of water was retained regardless of the work up procedure used. As even trace water may significantly affect NHC-catalyzed reactions a considerable effort was made to remove the moisture. Extended periods under low pressure (1 torr. for 12 h), exposure to Na_2SO_4 and/or $MgSO_4$, recrystallization, the use of azeotropes, and the use of a lyophilizer all failed to remove the observed water. A series of ^{1}H NMR experiments confirmed that the observed water is present in the d_6-DMSO at time of purchase. The ratio of water:d_6-DMSO in the spectrum of the pure solvent was, within error, identical to that observed in the spectrum of a sample of the azolium salt prepared at the same time; all observed water in the isolated compounds thus derives from the deuterated solvent.

3.7.2.2. Substrate Scope

To explore the potential scope of the nitrogen substituent a series of hydrazines were subjected to the optimized reaction conditions (Table 3.12).

Table 3.12 – Explored substrate scope with respect to hydrazines for syntheses of 1,2,4-triazole-3-thiones using thiocarbonyldiimidazole.

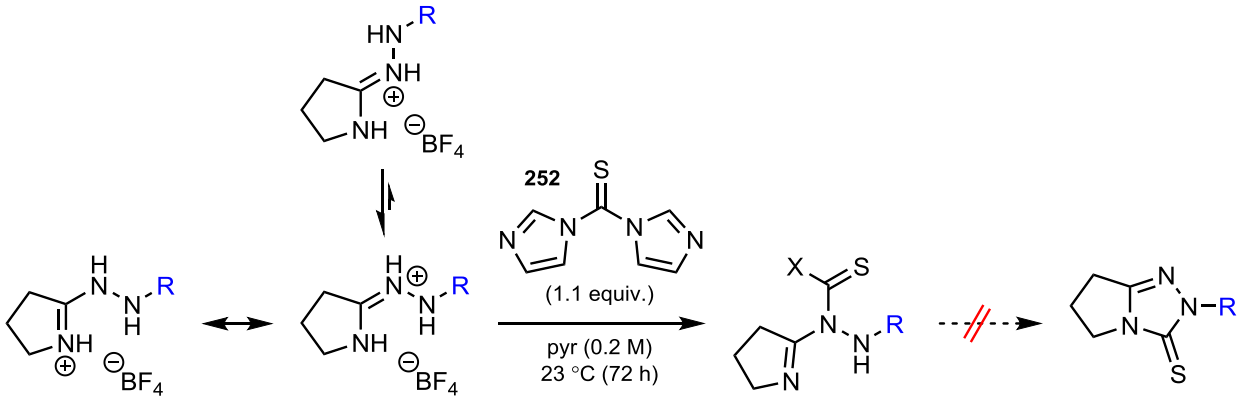


entry	hydrazine substituent (R)	yield of thione (%)
1	pentafluorophenyl	67
2	phenyl	0
3	2,4,6-trimethylphenyl (mesityl)	0
4	2,6-dichlorophenyl	0
5	benzyl	0

Under optimized conditions use of phenyl hydrazine still does not afford the cyclized thione (entry 2). The use of electron-rich (entry 3) or electron-poor (entry 4) aromatic substituents other than pentafluorophenyl does not afford cyclized products. Aliphatic substituents (entry 5) also prove unreactive. In all cases (entries 2-5) the corresponding amidrazone is detected in the crude reaction mixture. This suggests that the cyclization with thiocarbonyldiimidazole is problematic.

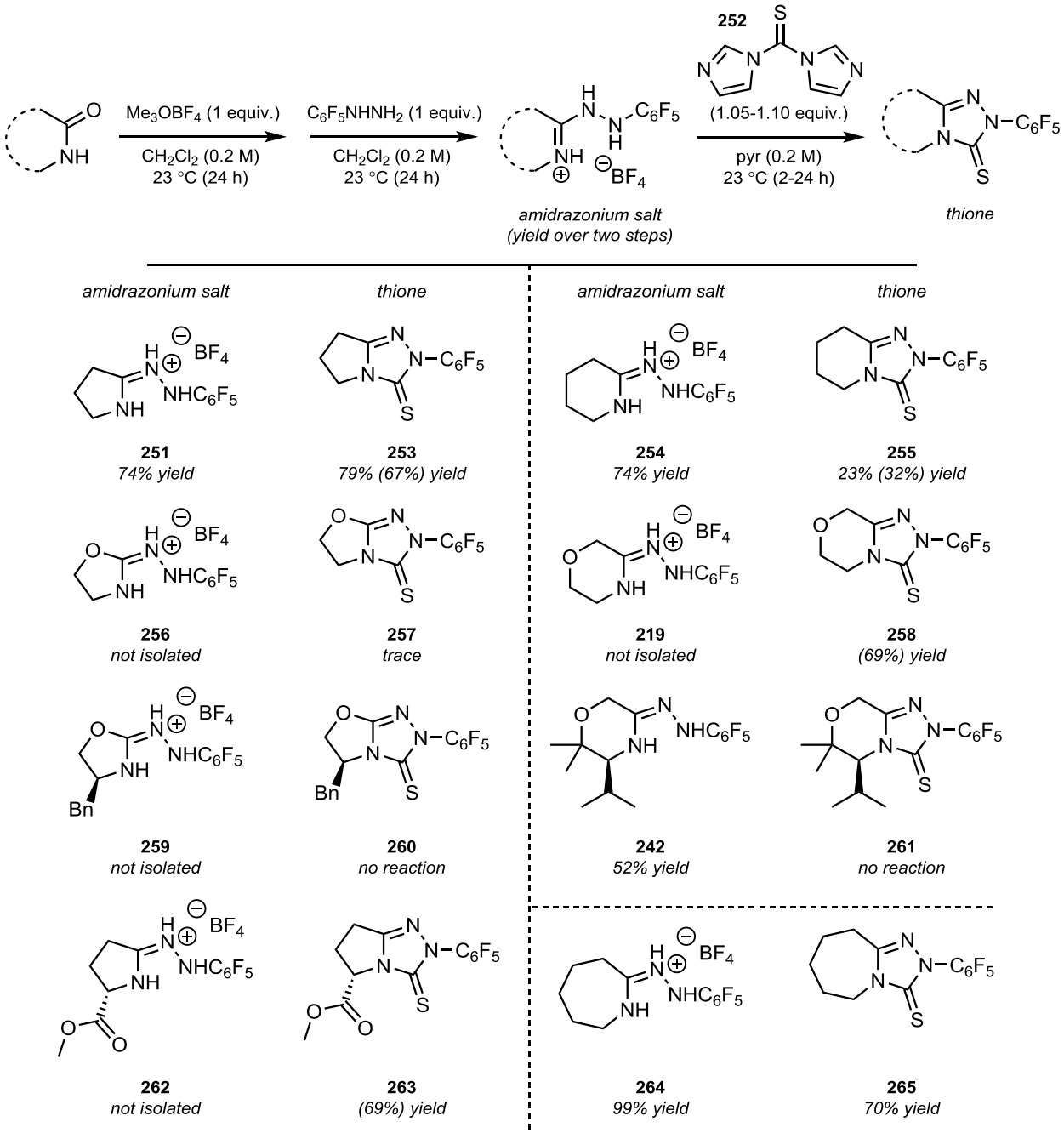
This outcome was unexpected; under cyclization conditions with orthoformates (see Section 3.7) the use of electron-rich aromatic groups typically proceeds with shorter reaction times (*viz*. faster conversion) and affords higher isolated yields than equivalent reactions with pentafluorophenyl hydrazine. It was hypothesized that the *N*-substituent may have an effect on the favoured tautomer/isomer of the amidrazone. This may preclude/inhibit cyclization depending on which tautomer/isomer is preferred. Low-level calculations (HF/STO-3G) suggest that

the expected *Z*-amidrazone is preferred over the *E*-amidrazone with either phenyl or pentafluorophenyl substitution (by 21.2 and 1.98 kcal/mol respectively), and substantially (3.83-16.6 kcal/mol) more than any other isomeric/tautomeric form. It is possible that the nitrogen at the future 1-position is the most nucleophilic in non-pentafluorophenyl substituted amidrazones. This would result in a non-productive adduct (Scheme 3.31). Visualization of the HOMOs for these species does not support this; the highest electron density is located on the future 2-position nitrogen in both cases. Additionally, analysis of ^{1}H NMR spectra confirms that the amidrazones remain largely untouched after subjection to reaction conditions. The origin of the stark difference in reactivity between amidrazones remains unclear.



Scheme 3.31 – Putative competitive reaction during the cyclization of amidrazones with non-pentafluorophenyl nitrogen substituents using thiocarbonyldiimidazole.

A variety of lactams were subsequently subjected to reaction conditions for the formation of their corresponding thiones (Scheme 3.32). Use of pyrrolidinone affords roughly 70% overall yield for the corresponding thione. Methyl *L*-pyroglutamate is also a suitable substrate for this transformation. This substrate was selected as it presents an opportunity for late stage diversification, potentially shortening the synthesis of its functionalized derivatives by 2-3 steps.



a) isolated yields after flash column chromatography; yields in brackets are from reactions where the amidrazonium was not isolated (yield over three steps).

Scheme 3.32 – Explored substrate scope with respect to lactams for syntheses of 1,2,4-triazole-3-thiones using thiocarbonyldiimidazole.

Oxazolidinone-derived thiones are not formed under these conditions. A set of test reactions were carried out with these substrates. Under the standard

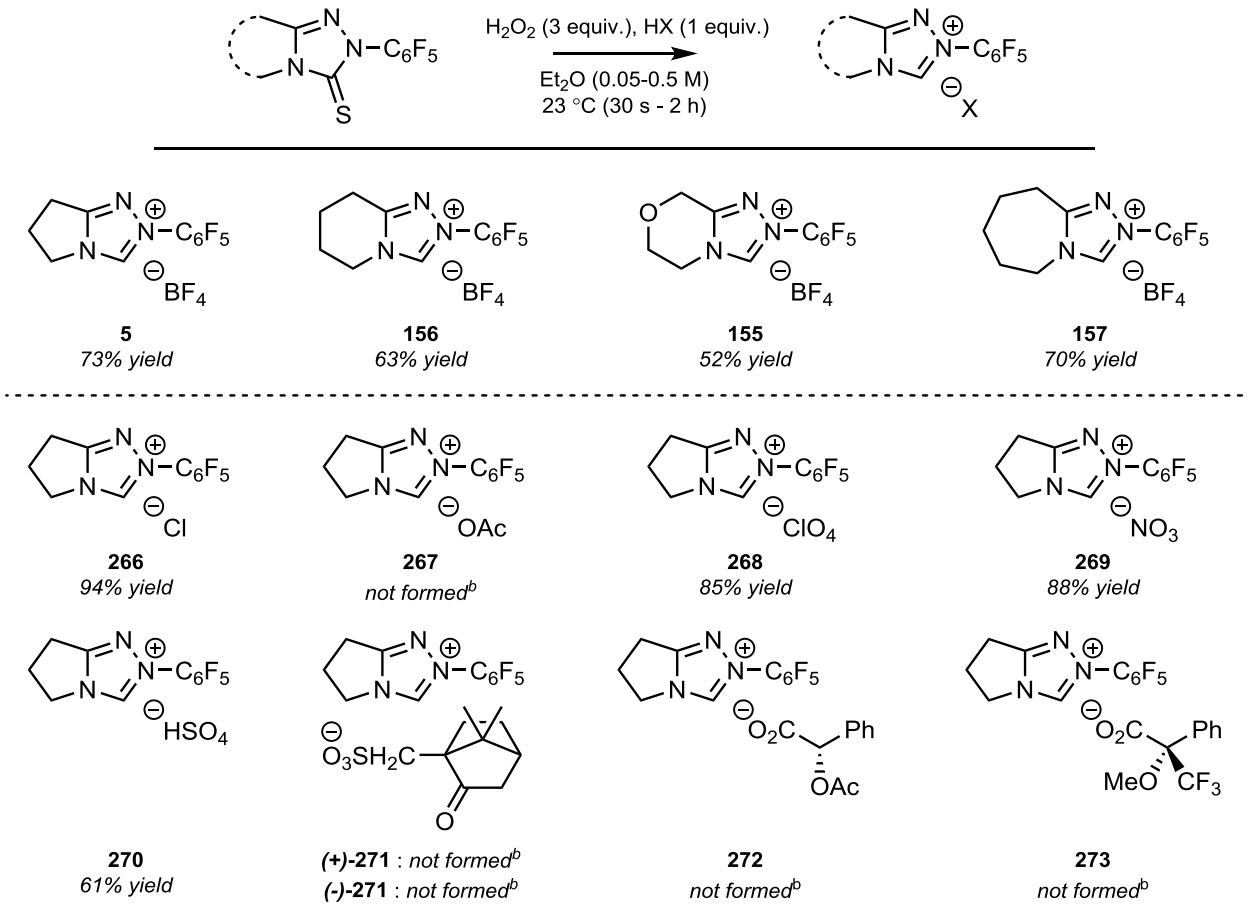
orthoformate cyclization conditions (see Section 3.7) no azolium salts are formed from either of the corresponding oxazolidinone-derived amidrazoniums. No *N*-C_6F_5 oxazolidinone-derived triazolium salts have been reported in the literature; it is possible that these species are particularly unreactive towards cyclization.

The use of piperidinone is problematic, with substantially lower yields for the formation of its thione (**255**) relative to similar species. Additionally, the synthesis of its amidrazonium produces a relatively high number of side products. Use of morpholinone, another six-membered ring, also affords its amidrazonium with a variable amount of impurities. In order to obtain a high yield of the corresponding thione purification of the amidrazonium must be avoided. It was hypothesized that increasing ring size may hinder formation of the amidrazonium and thione species. However, use of caprolactam affords the corresponding amidrazonium in quantitative yield, in addition to a high yielding cyclization. Based on these results the size of the lactam ring plays a non-obvious role in the formation of these species. Subjecting a sterically hindered geminally disubstituted morpholinone to the thiocarbonylation conditions does not produce any of the desired product, with the amidrazone remaining intact.

Under the optimized reaction conditions the 1,2,4-triazole-3-thiones were converted into their respective azolium salts (Scheme 3.33). Moderate to excellent yields are obtained for tetrafluoroborate salts. The caprolactam-based system displays an unusually high reactivity; complete conversion to the azolium salt occurs in less than one minute. Overall yield of the morpholinone-derived triazolium salt (36% from the lactam) is substantially improved over the previous synthesis (0.7% overall yield). The relative integrations for signals in the ^{19}F NMR spectrum were used to confirm that the desired tetrafluoroborate counterion is obtained, within error, in a one-to-one ratio with the triazolium cation.

Other possible counterions were also explored. When the counterion is derived from a strong acid the azolium salt is obtained in excellent yields. Whereas azolium cations with the chloride and hydrogen sulphate counterions require several triturations to obtain a solid, analysis of the ^{1}H NMR spectra of the crude reaction mixture for these reactions suggests high conversion to the desired product with no noticeable side products. Conversely, multiple attempts to generate the acetate salt formed several unidentified by-products which require

numerous triturations and recrystallizations to minimize. The desired counterion, acetate, is observed in neither the ^{1}H NMR nor the ^{13}C NMR spectra. This necessitates that an alternate counterion be present.



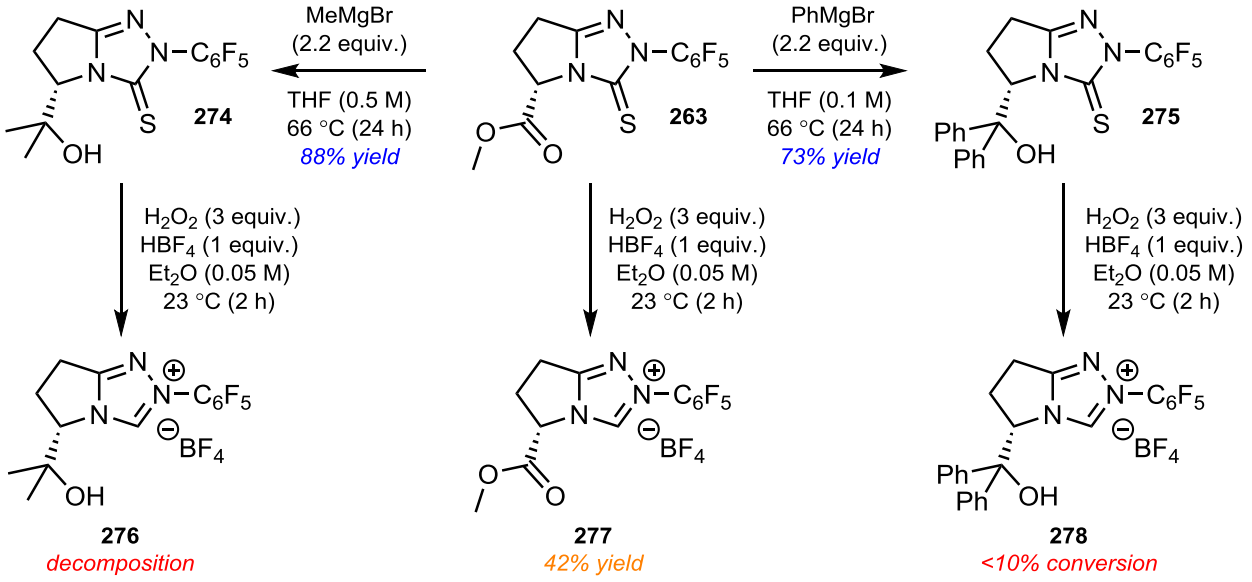
a) isolated yields after flash column chromatography; yields in brackets are from reactions where the amidrazonium was not isolated (yield over three steps).

Scheme 3.33 – Explored substrate scope with respect to lactams and acids for syntheses of triazolium salts from 1,2,4-triazole-3-thiones.

Counterions have been shown to have an effect on enantioselectivity in NHC catalysis (see Section 1.1 and Scheme 1.8). Several chiral acids were used to determine if enantioselectivity could be obtained from the use of a chiral counterion. In each case an oil is formed, which ^{1}H NMR analysis suggests is the desired product. However, extensive attempts to precipitate these compounds result instead in isolation of azolium salts whose counterion(s) are not visible by ^{1}H NMR spectroscopy.

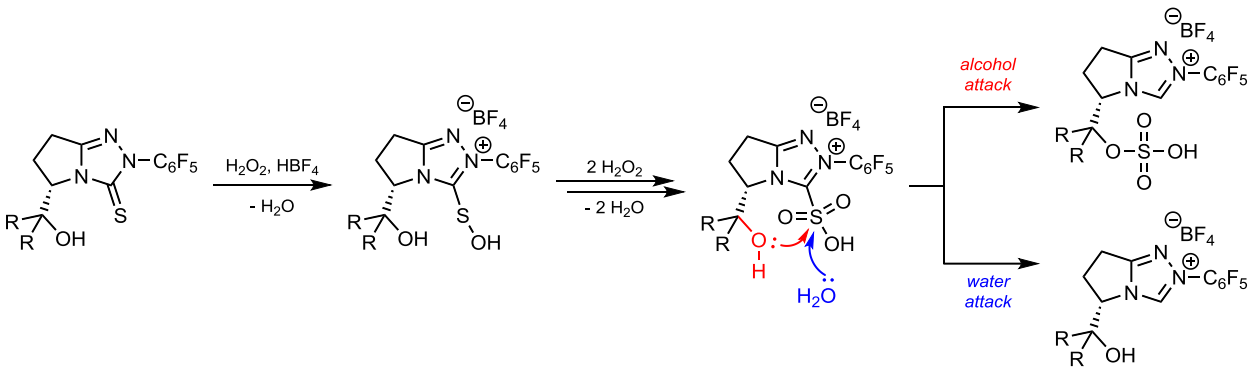
Based on these results, in instances where the acid is insufficiently strong an alternate counterion(s) is obtained. The most likely counterions are sulphate, the by-product of the oxidation of thiones with H_2O_2, and its protonated form (hydrogen sulphate). Melting points of salts formed using acetic acid and sulphuric acid differ substantially, suggesting that the hydrogen sulphate counterion is not obtained. It is thus likely that either the SO_4^{2-} salt or a mixture of the HSO_4^- and SO_4^{2-} salts are formed in these cases.

Functionalization of the pyroglutamate-derived thione proceeds with high yields (Scheme 3.34). Conversion of the parent ester-containing thione to the corresponding triazolium salt affords diminished but appreciable yield.



Scheme 3.34 – Transformations of a pyroglutamate-derived thione.

However, subjecting either of the derivatives to oxidation conditions results in decomposition and/or very low conversion. It is probable that the alcohols require protection to avoid reacting with the *in situ* formed sulphonate adduct (Scheme 3.35).[126] This may also explain the tempered yield with the ester substituent.

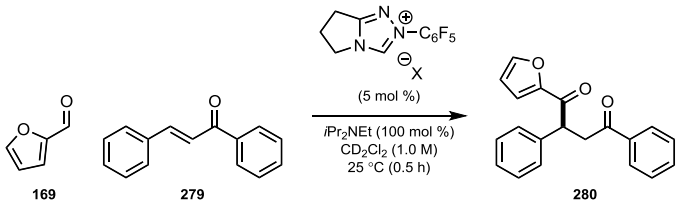


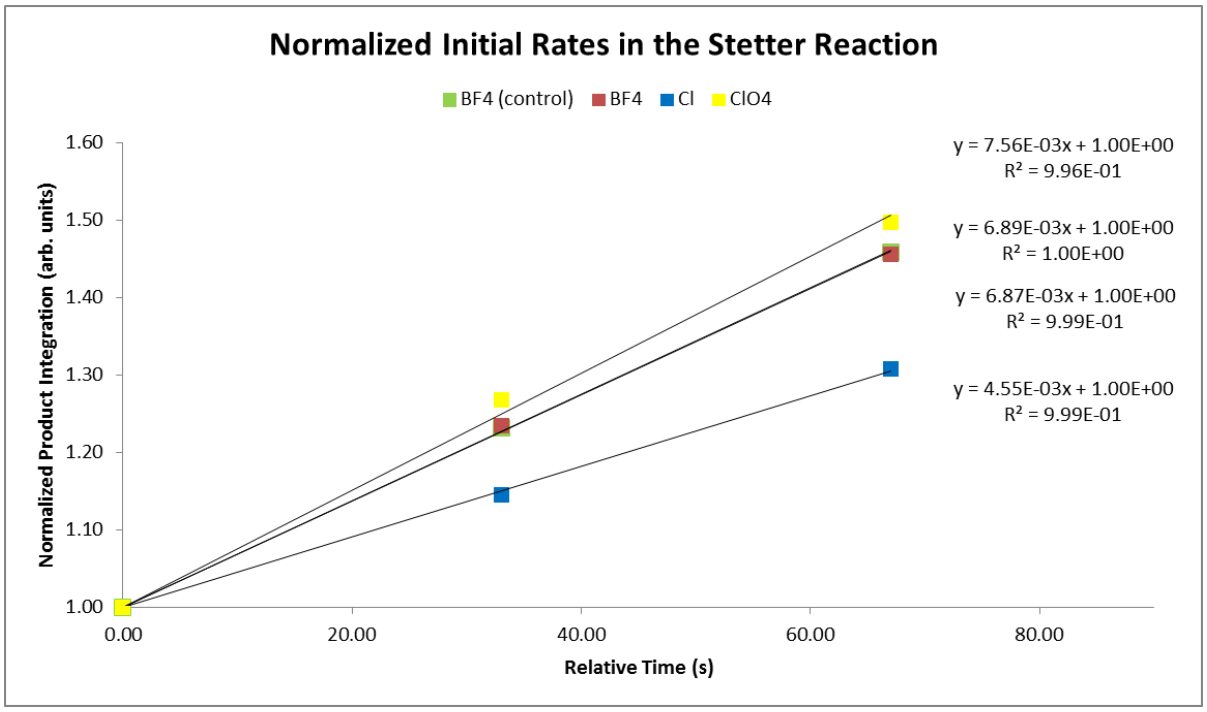
Scheme 3.35 – Putative competitive reaction during the oxidation of thiones with alcohol substituents using hydrogen peroxide.

3.7.2.3. Measured Counterion Effect

Two prototypical NHC-catalyzed reactions were chosen to explore counterion effects in: the Stetter and cross-benzoin reactions. A series of reactions as catalyzed by pyrrolidinone-derived triazolylidenes were monitored by ^{1}H NMR spectroscopy. These reactions differ only in the counterion of the azolium salt.

The Stetter reaction of 2-furfuraldehyde with *trans*-chalcone shows a counterion dependence on the rate of reaction (Scheme 3.36). For clarity only the first few data points are shown, though calculated relative initial rates are comparable up to 200 s into the reaction (see Section 5.2.3.2). Tetrafluoroborate salts prepared using the standard orthoformate route (control) and using the new thiocarbonylation-oxidation procedure afford, within error, the same reaction rates. This confirms that the new route affords product with the same purity/catalytic activity. Use of an azolium salt with perchlorate counterion in place of tetrafluoroborate mildly accelerates (1.1x) the reaction rate, though this may be within the error of the measurement. Conversely, use of the chloride salt substantially slows the reaction rate (0.6-0.7x) relative to use of the tetrafluoroborate salt. While it is possible that the rate change is due to difference in solubility in dichloromethane, this would be surprising; typically chlorides are more soluble than tetrafluoroborates.[127] It is therefore likely that there is a non-intuitive effect of the counterion on the Stetter reaction.

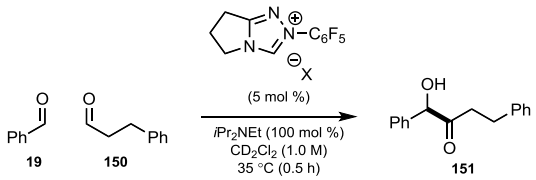


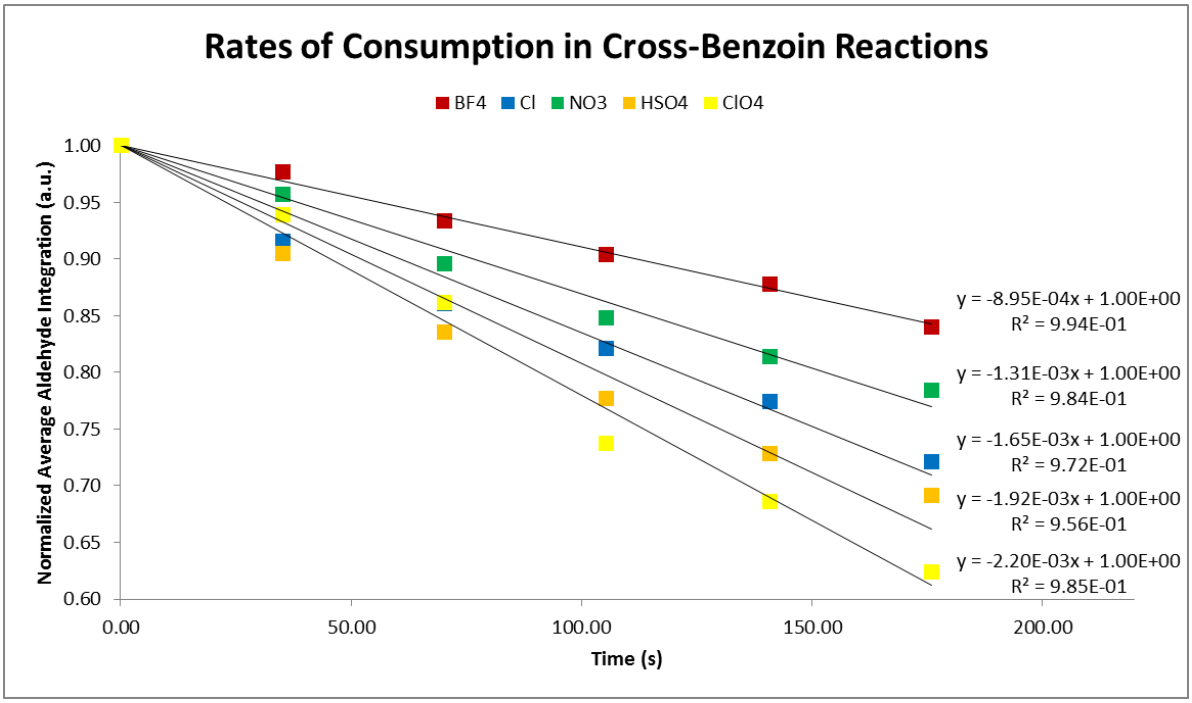


Scheme 3.36 – Normalized initial rates in the NHC-catalyzed Stetter reaction of 2-furfuraldehyde with *trans*-chalcone using pyrrolidinone-derived catalysts with different counterions.

Counterion effects in the cross-benzoin reaction between benzaldehyde and hydrocinnamaldehyde were also explored. Chemoselectivity was not noticeably impacted by the counterion. The relative rates of these reactions are determined by comparing the rates of consumption of the starting aldehydes (Scheme 3.37). This avoids issues with proximity/overlap between the diagnostic ^{1}H NMR signal for the major cross-benzoin product with the residual solvent signal. Use of the tetrafluoroborate salt was problematic. Although monitored rates of consumption across multiple experiments are consistently *linear*, the relative rates of these reactions with respect to those using other salts were highly variable; reactions using the tetrafluoroborate salt were variably the fastest or slowest compared to

their peers. Relative rates between reactions using all other salts remained consistent. For this reason relative rates are discussed with respect to those with the chloride counterion.





Scheme 3.37 – Normalized initial consumption rates in the NHC-catalyzed cross-benzoin reaction of benzaldehyde with hydrocinnamaldehyde using pyrrolidinone-derived catalysts with different counterions.

Use of the nitrate salt affords the slowest reaction rates (ca. 0.8x). Conversely, having hydrogen sulphate as the counterion mildly accelerates the rate (ca. 1.10x). Although the relative rate of this reaction with respect to that catalyzed using the chloride salt is consistent across multiple experiments (1.15x, 1.12x) this difference may be within the error of the experiment. As with the Stetter reaction, use of the perchlorate salt affords the fastest reaction rates (ca. 1.3-1.4x).

A separate series of reactions were carried out to determine whether these counterion effects could be mimicked/replicated by adding an excess (5 equiv. relative to the azolium salt) of a sodium salt with the appropriate anion. Cross-benzoin reactions between benzaldehyde and hydrocinnamaldehyde catalyzed using a triazolylidene were quenched prior to complete consumption and compared to a control reaction with no salt added. The addition of NaCl affects neither the chemoselectivity nor yield of the major cross-benzoin product. However, the addition of $NaClO_4$ significantly lowers the yield (*viz*. reaction rate) relative to the control (45% as much product). This contradicts the observed rate acceleration when using the perchlorate salt of the triazolium (see Scheme 3.35). It was hypothesized that addition of the salts may be introducing a significant amount of moisture, which has previously been shown to negatively affect the reaction rate (see Table 3.5). The tetraphenylborate anion has been used in other azolium and bis(amino)cyclopropenium salts, including those with demonstrated activity in Stetter and benzoin reactions.[112, 128] In addition, $NaBPh_4$ is minimally hygroscopic. Addition of $NaBPh_4$ completely suppresses all catalytic activity. This suggests that the difference is not due to added moisture. These experiments confirm that the counterion effect cannot be mimicked by simple addition of a sodium salt and reaffirm that anions in solution affect NHC-catalyzed reactions in indirect ways.

3.8. Conclusions and Future Work

Modification of the traditional catalyst backbone has allowed NHC-catalyzed cross-benzoin reactions between aromatic and aliphatic aldehydes that do not rely on steric differences between the substrates to afford high chemoselectivity. An assortment of electron-rich and electron-poor aromatic aldehydes have been shown as acceptable substrates. Both linear and branched aliphatic aldehydes are tolerated. Chemoselectivity and yield are largely invariant to choice of base and solvent, allowing a broad range of conditions to be used.

Currently the method is limited to chemoselective cross-benzoin reactions between aliphatic and aromatic aldehydes. Preliminary results have shown that chemoselectivity may be retained in cross-benzoin reactions between two

aromatic aldehydes without relying on steric differences (*viz*. ortho-substituents). Issues with isolation have so far precluded these reactions from thorough exploration. As the three major products (one cross-benzoin and two homo-benzoin compounds) necessarily have similar interactions with silica gel a more comprehensive approach may be useful in remedying this issue; application of non-chromatographic purification techniques and/or selective derivatization may be used to improve separation and allow isolation of pure compounds.

A detailed mechanistic study confirmed the presence of a catalyst resting state. This exists as a tetrahedral adduct selectively formed with aliphatic rather than aromatic aldehydes. Chemoselectivity is likely determined at the carbon-carbon bond formation step, with attacks on aromatic aldehydes being substantially favoured due to a stabilizing π-π/π-cation interaction between the approaching aromatic ring and the triazole/triazolium. The catalyst backbone affects transition states through a minor steric interaction between methylene protons. When the ring is small (five-membered) the interaction is very small and transition states have low $\Delta G^{\ddagger}$ values. However, this does not affect all transition states equally and consequently lowers the $\Delta\Delta G^{\ddagger}$ between products, lowering kinetic chemoselectivity under the reaction conditions. When the ring is large (seven-membered) the interaction becomes more pronounced and transition states have high $\Delta G^{\ddagger}$ values. The extended reaction times required to compensate for this allow competitive reactions and/or degradation to occur, lowering chemo-selectivity and yield.

Initial attempts at chemo- and enantioselective cross-benzoin reactions have afforded poor to moderate results. A novel catalyst was designed and targeted for synthesis. When both conventional and unconventional conditions failed to afford the desired azolium salt a novel approach for the synthesis of triazolium salts was developed. Although this also failed to produce the desired chiral triazolium salt the method allowed access to a series of achial azolium salts differing only in their counterions. A series of experiments have demonstrated that counterion selection may be important in accelerating, or decelerating, reaction rates in NHC-catalyzed processes.

All synthetic attempts have focused on generating the desired chiral morpholinone-derived triazolium salt with a pentafluorophenyl nitrogen

substituent. Catalysts with other *N*-substituents (Ph, Mes, Bn) are not viable for the cross-benzoin reaction, with either no catalytic activity under the reaction conditions or a substantial loss in chemoselectivity. Very recent work in the Ukaji group has shown that chiral pyrrolidinone-derived triazolylidenes bearing *N*-pyridyl substituents may catalyze these reactions. Major cross-benzoin products are isolated in moderate yields and with moderate enantioselectivities (23-69% yield, 70:30-88:12 er), although no mention is made of product distribution. Additionally, a pyrrolidinone-derived triazolylidene bearing *N*-Ph substitution demonstrated catalytic activity, although poor yields were obtained even under forcing conditions (14% yield of B, 70 °C for 24 h).

Cyclization of the *N*-Ph derivative (**245**, Figure 3.18) has already been demonstrated on small scale. Synthetic efforts should be made to access triazolium salts with the desired catalyst backbone but without *N*-C_6F_5 substitution. With the goal of enantio- and chemoselective cross-benzoin reactions, initial efforts should focus on *N*-phenyl and *N*-pyridyl substituted species. As it is probable that an electron-poor nitrogen substituent will afford higher catalytic activity (see Scheme 1.10)[12m] other electron-poor aromatic and non-aromatic substituents should be explored.

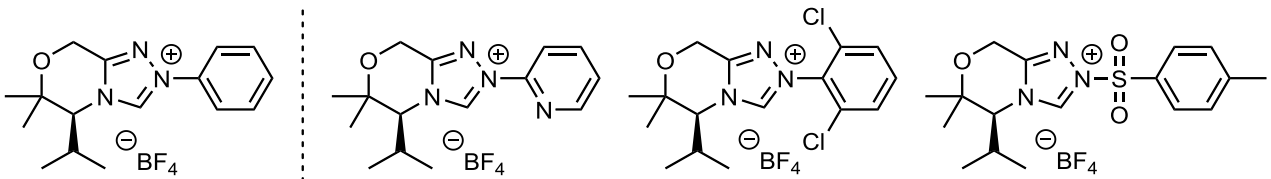


Figure 3.18 – Proposed nitrogen substituents for morpholinone-derived catalysts with both isopropyl and geminal dimethyl substitution.

A small but appreciable counterion effect has been demonstrated for NHC-catalyzed Stetter and benzoin reactions. An obvious potential source for this effect is solubility of either/both the azolium salt and the *in situ* formed ammonium species (*viz*. the conjugate acid of the base). The relative solubilities of each of these species may be determined and compared with the relative rates of reaction to determine if the effect may be easily attributed. Alternatively, the

degree of ion association may affect the energy of charged species, including the rate-limiting transition state. This may also be explored, though the method to determine this parameter is substantially more complex.[129]

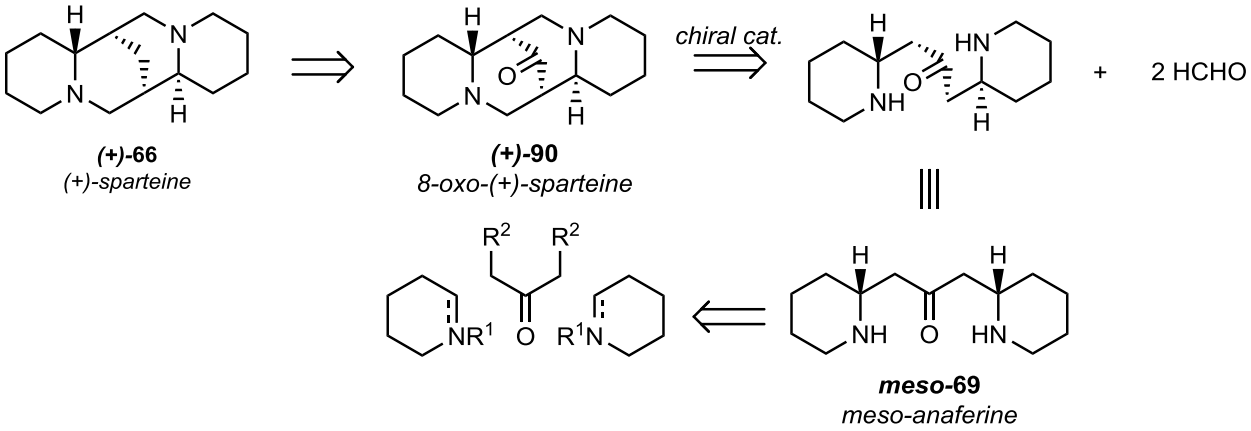
CHAPTER 4: EFFORTS TOWARDS A CONCISE ENANTIOSELECTIVE TOTAL SYNTHESIS OF SPARTEINE

4.1. Research Objective

With a variety of useful applications, especially in synthetic chemistry (see Section 2.2), enantioenriched sparteine would be a useful commodity chemical. At the outset of this work only one large-scale (multi-gram) synthesis of enantioenriched sparteine had been reported. Even this synthesis relied on isolation of a very late-stage intermediate from natural sources (lupanine (**83**), see Section 2.4.2) for which long-term high-volume supply may be a concern.[58e]

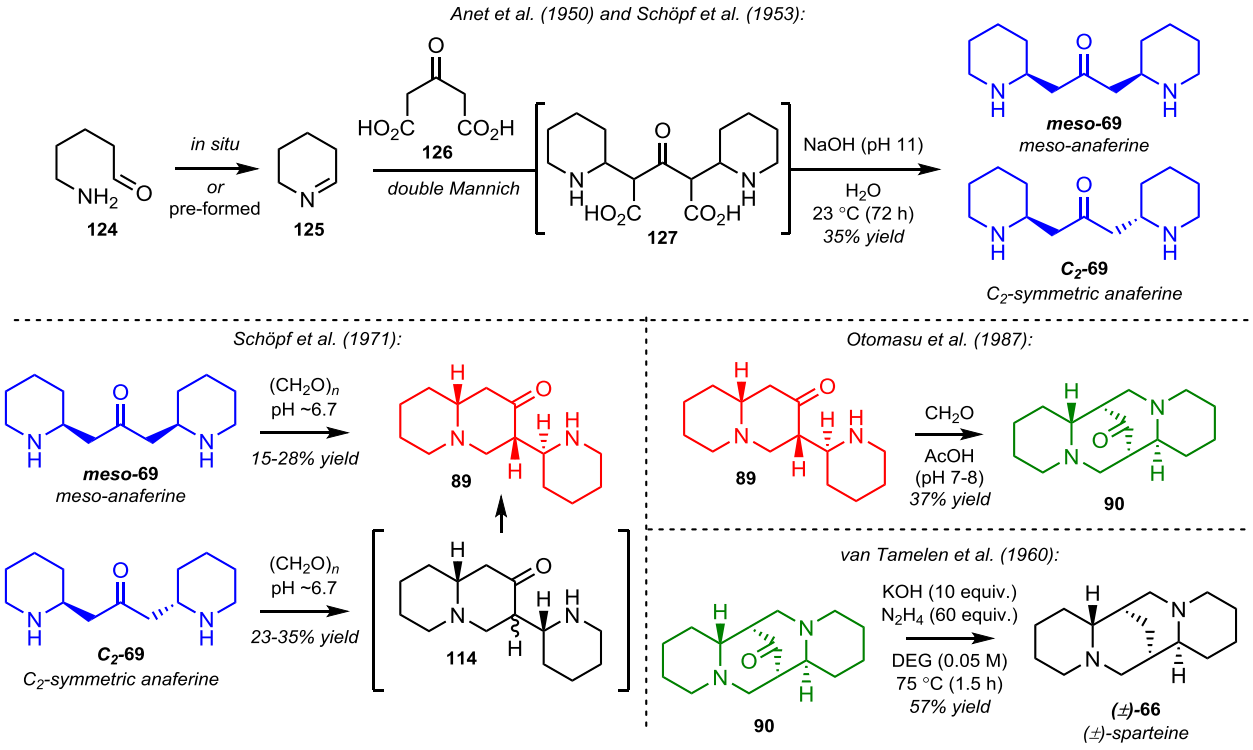
To address this supply problem we sought to develop a scalable and concise synthesis of enantioenriched sparteine. The project aims to access enantioenriched sparteine by modifying and combining known reactivities with organocatalysis to offer a low step count and high overall yield. Reliable access to anaferine on large-scale is required for the project (see Section 4.2). Following this, a sequential (or tandem) set of Mannich reactions and known high-yielding deoxygenation would be explored to furnish the desired compound. If possible, further exploration of the cyclization conditions would be used to afford any of sparteine, genisteine, and/or pusilline enantioselectively.

4.2. Synthetic Plan



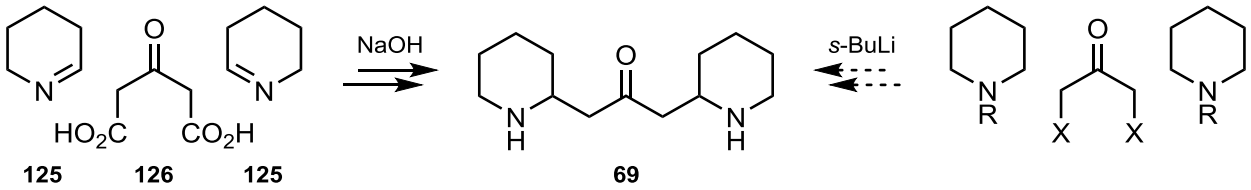
Scheme 4.1 – Original synthetic plan for a concise enantioselective synthesis of sparteine (dextrorotatory isomer shown).

The initial synthetic plan involves synthesis of anaferine followed by stereoselective double Mannich cyclization and deoxygenation to afford enantioenriched sparteine (Scheme 4.1). Examination of the literature showed that this had previously been attempted by Schöpf with poor results (see Section 2.4.3). However, since that work a number of additional studies have been reported. Individually, these reports demonstrate reactions which, when combined, effect the desired overall transformation (Scheme 4.2). This is a good indication that the proposed route would be effective and substantially lower the overall number of steps required for the total synthesis. Amine-containing cinchona-derived catalysts are effective at enamine catalysis (see Section 2.5) though no examples of Mannich reactions have been reported. Their application in this regard would be a natural extension of reported enamine activity and add some novelty to the synthesis.



Scheme 4.2 – Literature precedence for individual steps in the total synthesis of sparteine.

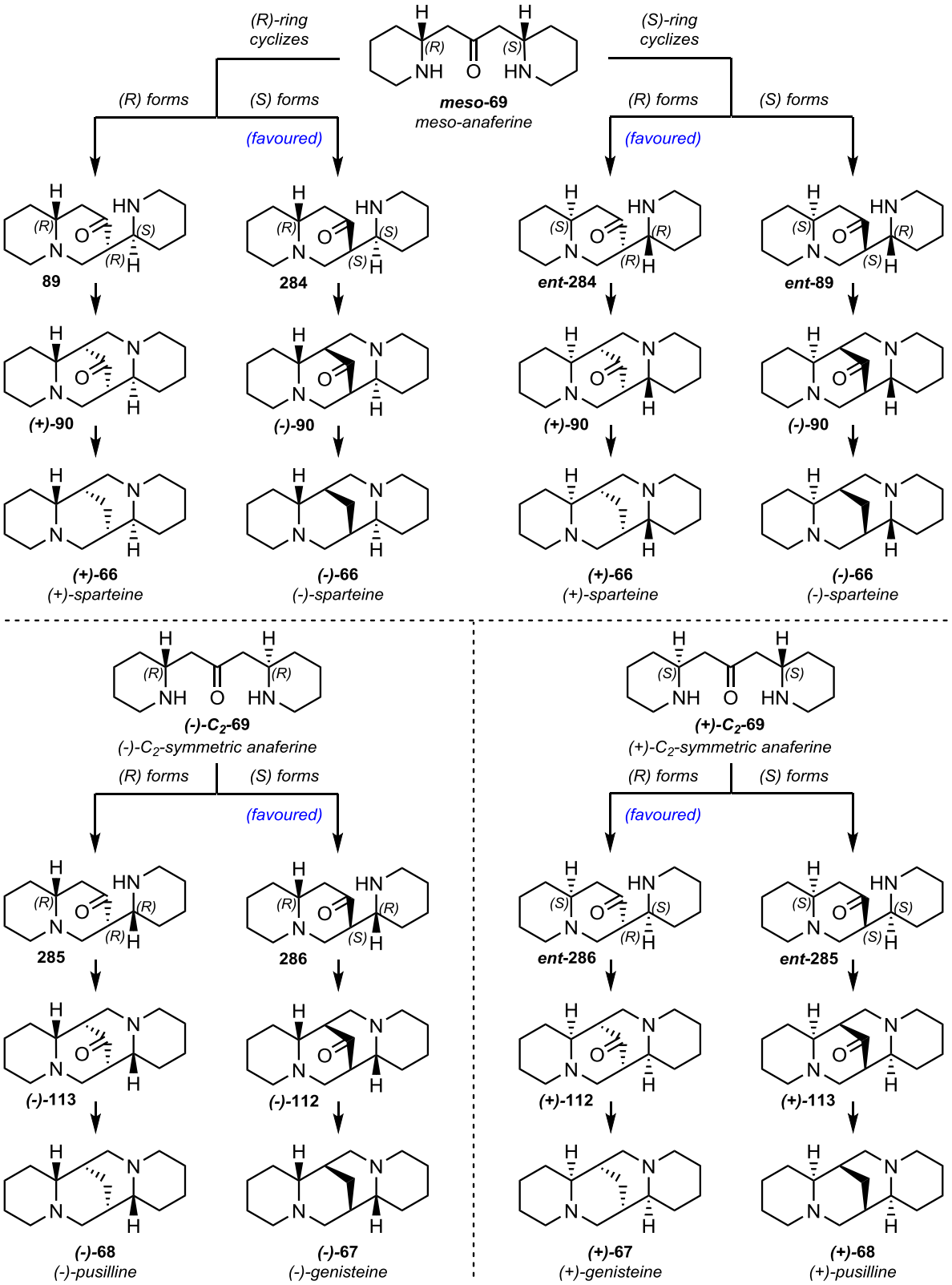
Initial work would target anaferine. Anet's and Schöpf's groups have shown that a mixture of the *meso* and C_2-symmetric forms of anaferine may be accessed *via* a double Mannich reaction with 3-oxoglutaric acid.[57b, 57c, 84d] In these reactions the imine is generated from the self-condensation of 5-aminopentanal. However, no reliable commercial source for this compound could be located. All reported syntheses of this compound rely on biotransformations, typically from lysine, and do not report isolated yields.[130] As a result, alternate routes to anaferine may have to be considered (Scheme 4.3).



Scheme 4.3 – Concise potential routes to anaferine.

Subsequent work demonstrated that both isomers of anaferine converge to the same diastereomer after the first ring-closing Mannich reaction.[84c] However, this may be condition-specific and outside the appropriate conditions for primary amine catalysis. Given that anaferine is not configurationally stable under neutral or basic conditions (see Section 2.1.1) it may still be possible to use a mixture of isomers and perform a dynamic kinetic resolution. Alternatively the two isomers can be resolved prior to use, with the C_2-symmetric form being used in related syntheses of genisteine and/or pusilline.

Diastereoselectivity in Schöpf's first ring-closing reaction is high. Since isomerization occurs under these conditions selectivity must be thermodynamically based. The configuration at the future bridgehead position dictates which enantiomer is formed during the second ring-closing reaction (Scheme 4.4). The catalyst must be relied on to afford both enantio- and diastereoselectivity if isomerizing/epimerizing conditions are not used. Assuming a similar diastereomeric bias to Schöpf's and non-isomerizing conditions, the C_2-symmetric form of anaferine should preferentially form genisteine. Any potential synthesis of pusilline would require overcoming this bias in addition to enantioselectivity.



Scheme 4.4 – Possible stereochemical outcomes from cyclization of anaferine to sparteine and its isomers.

4.2.1. Preliminary Computational Results

In order to gauge whether amine catalysis is feasible for the ring-closing step(s) several species were modelled computationally. All calculations were performed using the Gaussian 09 software package. The M06-2X exchange-correlation functional with the polarized diffuse split-valence 6-31+G(d,p) basis set was used for all geometry optimizations (including those with constraints), transition state calculations, and infrared frequency calculations.

Epimerization occurred during Schöpf's synthesis,[59] leading both the *meso* and C_2-symmetric forms of anaferine to eventually produce genisteine. Consequently transition states for the second ring-closing step leading to both 8-oxo-sparteine and 8-oxo-genisteine were considered (Figure 4.1). Un-catalyzed (*via* enol) and catalyzed (*via* pyrrolidine or methyl amine) transition states were explored. The difference between the two main conformers of sparteine (Figure 2.1c) was determined to be 2.3 kcal/mol, with the chelating conformer higher in energy. Transition states leading to both of these conformers were then modelled. Note that these correspond to attacks on the *si* and *re* faces of the iminium. For genisteine only transition states leading to the chelating conformer were considered as it is substantially (>5.1 kcal/mol, HF/STO-3G) lower in energy than all other conformers. Transition states in the methylamine-catalyzed reactions may orient the methyl group either *syn* or *anti* to the alkene. In all modelled systems the methyl preferred to be oriented towards the alkene (*syn*), presumably due to decreased steric hindrance on that side. The difference in energy between these two forms is approximately 3 kcal/mol for most transition states.

For the un-catalyzed reactions a barrier of 20-28 kcal/mol (relative to anaferine) was calculated. The transition state leading to 8-oxo-genisteine is >5.9 kcal/mol lower than either of those leading to 8-oxo-sparteine. If epimerization is fast relative to this step, then epimerizing conditions should form 8-oxo-genisteine exclusively (>99.99:0.01). This is consistent with Schöpf's results.

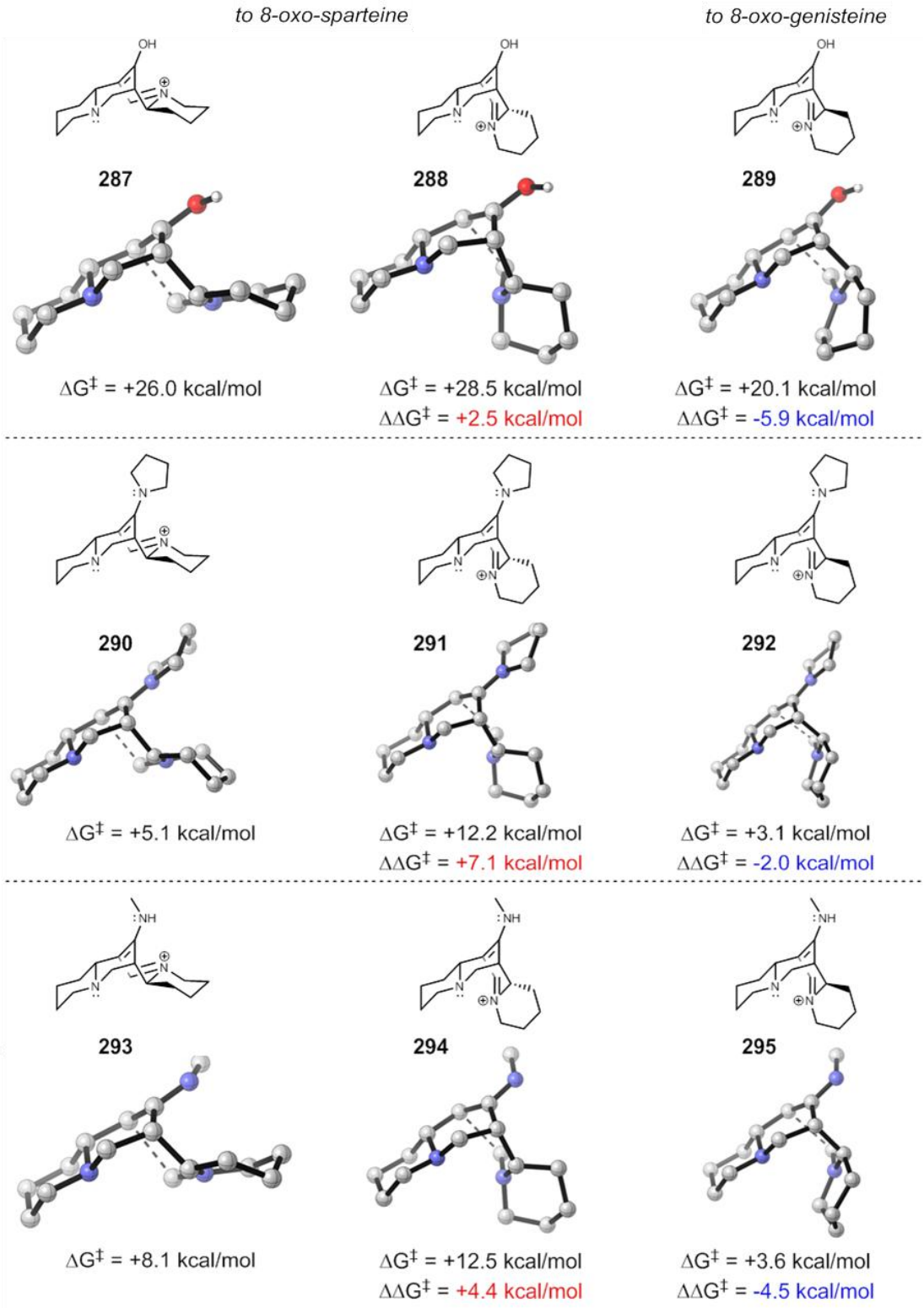


Figure 4.1 – Computed transition states for un-catalyzed, pyrrolidine-catalyzed, and methylamine-catalyzed Mannich reactions affording 8-oxo-sparteine and 8-oxo-genisteine (Hydrogen atoms omitted).

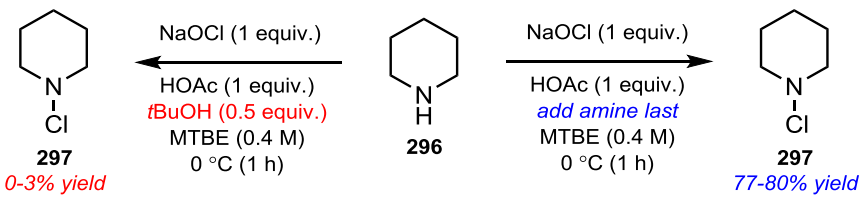
Secondary amine catalysis (pyrrolidine) significantly lowers the energies for all transition states. Importantly, the transition state leading to 8-oxo-genisteine (**292**) is now only 2.0 kcal/mol lower than that leading to 8-oxo-sparteine (**290**). This shows that secondary amine catalysis, while unlikely to lead to high enantioselectivity (see Section 2.5), preferentially lowers the barrier for 8-oxo-sparteine relative to 8-oxo-genisteine. Methylamine also significantly lowers the transition state energies, though the effect is lessened. As with pyrrolidine, methylamine favours lowering the activation energy for the transition state leading to 8-oxo-sparteine relative to 8-oxo-genisteine, though this effect is less pronounced; although methylamine catalysis decreases the $\Delta\Delta G^{\ddagger}$ between paths leading to 8-oxo-sparteine relative to 8-oxo-genisteine, the latter should still be substantially preferred (99.95:0.05).

4.3. Accessing Anaferine

Several routes were explored to reliably afford anaferine on gram scale.

4.3.1. Imine Acceptor Approach

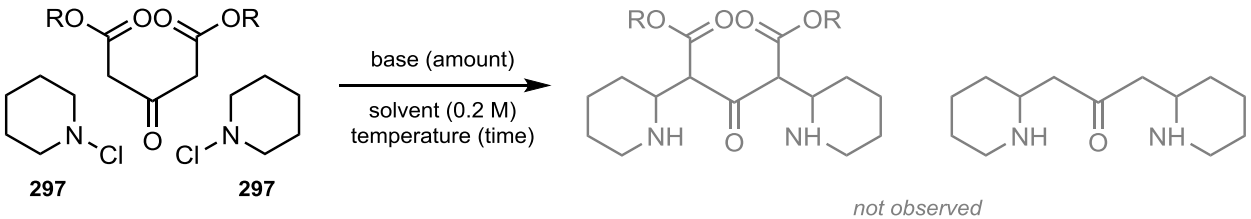
Initial efforts focused on replicating the syntheses of anaferine by Anet and Schöpf. Given the difficulty in obtaining 5-aminopentanal, access to the imine was instead pursued through elimination from *N*-chloropiperidine. Following a reported procedure affords none of the desired compound (Scheme 4.5).[131] Instead, the acetate salt is formed in high yield. Removing the *tert*-butanol from the reaction conditions furnishes the product in moderate yield (37% yield). However, both this and a change from the reported order of addition are required to obtain the compound in high yields.



Scheme 4.5 – Effect of reaction conditions in the synthesis of *N*-chloropiperidine.

In situ generation of the imine followed by reaction with 3-oxoglutaric acid or its dimethyl ester does not afford the desired product, nor any of its derivatives, under a series of reaction conditions (Table 4.1). Under all of these conditions a similar major product is formed. A series of control experiments were performed where reagents were systematically excluded from the reaction. Based on these experiments the major product is derived solely from 3-oxoglutaric acid. The exact identity of this compound remains unknown. It is possible that the desired imine is not formed, or formed too slowly, under the reaction conditions; it has been suggested that extended reaction times (24 h at 23 °C) may be needed for this elimination to proceed to high conversions.[132] However, other reports suggest rapid formation (10 min at 23 °C) of the imine under similar conditions.[133]

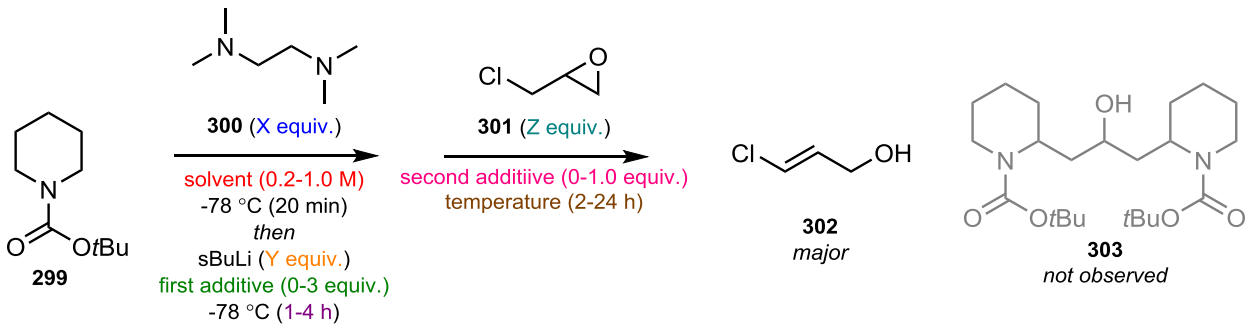
Table 4.1 – Screened reaction conditions for formation of anaferine using Mannich reactions.



entry	R	base (amount)	solvent	temperature (time)
1	H (**126**)	NaOH (to pH ca. 13)	H_2O	23 °C (72 h)
2	H (**126**)	NaOH (to pH ca. 13)	H_2O	100 °C (1 h)
3	Me (**298**)	NaOH (to pH ca. 13)	H_2O	23 °C (24 h)
4	Me (**298**)	NaOH (to pH ca. 13)	H_2O	50 °C (2 h)
5	Me (**298**)	DBU (2.1 equiv.)	CH_2Cl_2	23 °C (24 h)
6	Me (**298**)	DBU (5 equiv.)	CH_2Cl_2	23 °C (24 h)

4.3.2. Alkyl and Allylic Halide Acceptor Approaches

Concurrent work explored applying Beak's α-lithioamine chemistry to accessing anaferine.[134] Initial efforts aimed at coupling *N*-Boc piperidine with epichlorohydrin (Scheme 4.6).



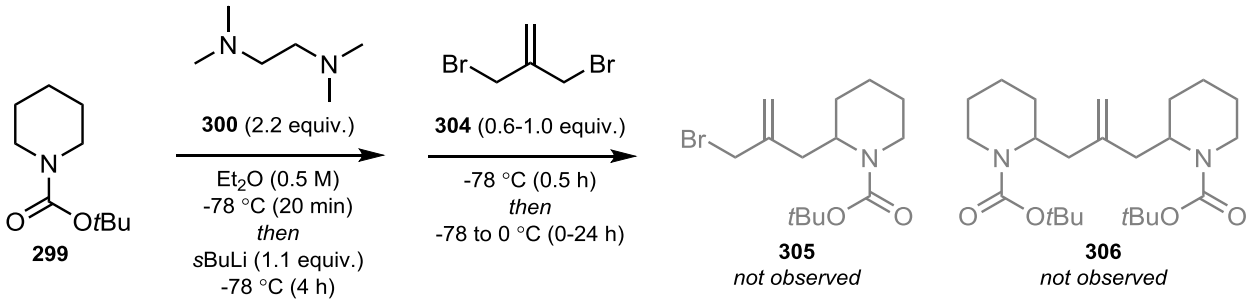
Scheme 4.6 – General form of conditions screened for the synthesis of an anaferine precursor through reaction of α-lithioamines with epichlorohydrin.

Regardless of reaction times (1-24 h), solvent (THF, Et_2O), concentration (0.2-1.0 M), stoichiometry of reagents (excess *N*-Boc piperidine relative to epichlorohydrin (4 equiv.), excess epichlorohydrin relative to *N*-Boc piperidine (1.4 equiv.), excess TMEDA relative to *s*BuLi (2.1 equiv.), sub-stoichiometric sBuLi relative to *N*-Boc piperidine (0.7 equiv.)), or the use of additives (CuI or LiCl (1.1 equiv.), BF_3 (0.6 equiv.), $ZnCl_2$ + CuCN/LiCl (1.3, 1.2, and 2.4 equiv. respectively)) neither the desired product nor its intermediates were observed. In all attempts the major product resulted from conversion of the epoxide to the allylic alcohol.

Beak reports that the deprotonation of *N*-Boc piperidine is substantially slower and less reliable than the deprotonation of *N*-Boc pyrrolidine.[135] *N*-Boc piperidine was subjected to the standard deprotonation conditions and subsequently quenched using D_2O. Incorporation of deuterium was, within error, quantitative. This suggests that the alkyl lithium species is formed quantitatively under the reaction conditions. Gilman titration of the *s*BuLi solution revealed the presence of a large amount of non-alkyl lithium base(s).[136] In some instances the molarity of contaminating base(s) exceeded that of the *s*BuLi. The contamination was independent of reagent age. It is possible that these bases lead to the decomposition of epichlorohydrin before it is able to react with the desired nucleophile. However, even when excess epichlorohydrin relative to the base is used no desired mono- or di-alkylation is observed. Based on these results epichlorohydrin is not an appropriate electrophile for this reaction.

Under similar conditions the reaction between *N*-Boc pyrrolidine and allyl bromide affords moderate (ca. 30-40%) yields of the allylated product.[134-135] 3-

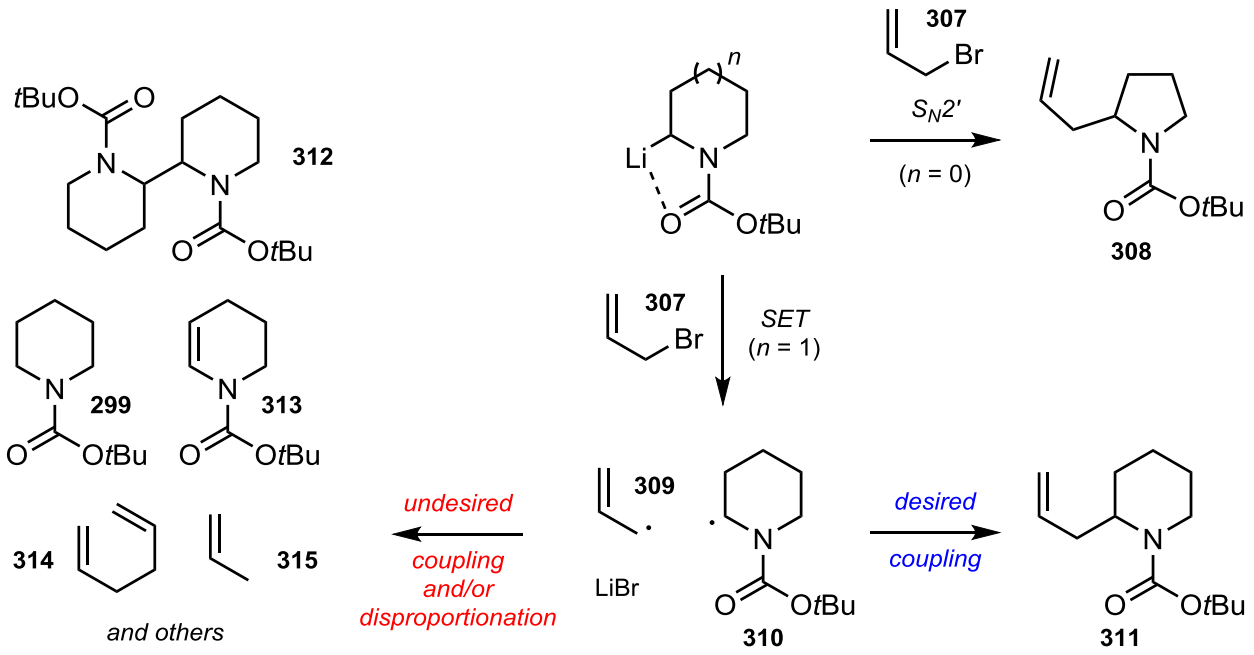
Bromo-2-(bromomethyl)prop-1-ene was used to attempt an equivalent transformation (Scheme 4.7). These experiments again failed to furnish either the mono- or di-functionalized products.



Scheme 4.7 – Attempted synthesis of an anaferine precursor through reaction of α-lithioamines with 3-bromo-2-(bromomethyl)prop-1-ene.

The prototypical coupling of allyl bromide with *N*-Boc piperidine (as Scheme 4.7) was carried out to probe potential reasons for the lack of reactivity. Extensive variation of solvent, time, rate of addition, and stoichiometry, as well as varying degrees of stringency in Schlenk technique and purification of all reagents, afforded a wide array of outcomes with no discernable pattern. It has been demonstrated that transmetalation to the cuprate substantially improves the reaction between *N*-Boc pyrrolidine and allyl bromide (>99% yield).[137] The reported optimal salt for this purpose is CuCN·2LiCl (0.5-1.0 equiv.). Use of this additive did not consistently improve the reaction.

A thorough re-examination of the literature suggested an explanation for the inconsistent results. Allyl bromide is a competent electrophile under the standard and modified conditions when *N*-Boc pyrrolidine is used. However, the results are highly variable when using *N*-Boc piperidine instead.[138] Increasing the ring size from 5 to 6 induces a change to a single-electron transfer mechanism for alkyl and allyl bromide electrophiles under these conditions (Scheme 4.8).[139]



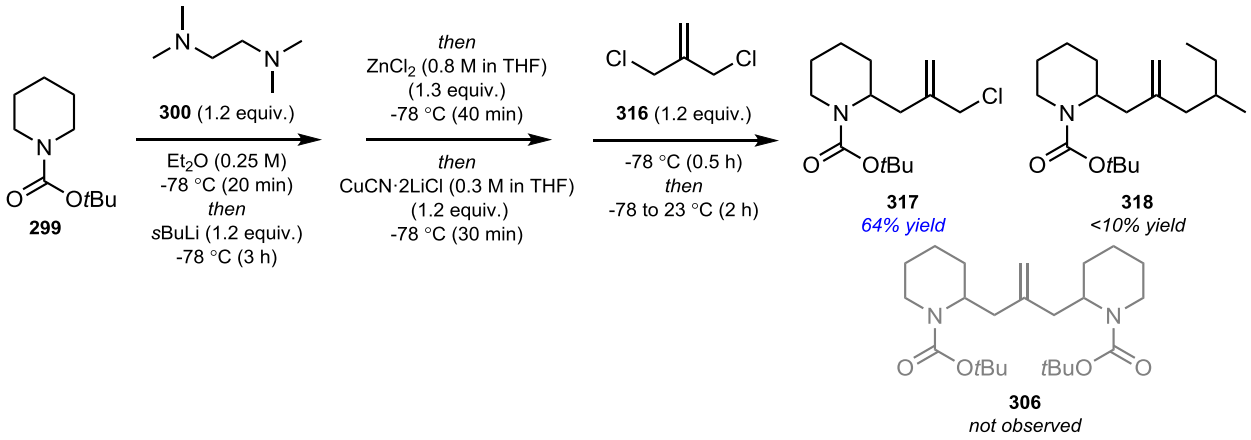
Scheme 4.8 – Comparison of reactivity with allyl bromide between α-lithioamines derived from *N*-Boc pyrrolidine and *N*-Boc piperidine.

Use of a specifically optimized protocol for the coupling of allyl halides and *N*-Boc piperidine improved yields and reproducibility.[138a] The protocol consists of sequential transmetalation through the alkyl zinc and alkyl cuprate species (see Scheme 4.9). A series of control experiments were performed where the zinc, copper, and lithium salt additives were systematically excluded from the reaction. The absence of any of the salts leads to generally lower yields and difficulties with reproducibility. This is in agreement with the original report.[138a] The exact amounts of the salts do not seem to affect the reactivity over the ranges explored (0.5-4.0 equiv.). Reversing the order of addition or adding both solutions simultaneously removes the beneficial effect. The origin of the improved reactivity is unclear, though the authors do note that a change in mechanism (S_N2 *vs.* S_N2') occurs depending on exactly which salts are used.[138a]

Switching the acceptor from allyl bromide to allyl chloride slightly lowers conversion but minimizes side reactions; analysis of the ^{1}H NMR spectra of crude reaction mixtures from reactions using allyl chloride suggests that, within error, only unreacted *N*-Boc piperidine and the desired allylated compound are present.

A control experiment confirmed that the modified conditions are required for both improved conversion and high selectivity with allyl chloride.

3-Chloro-2-(chloromethyl)prop-1-ene was used under the modified conditions (Scheme 4.9). Despite repeated attempts, use of 3-chloro-2-(chloromethyl)prop-1-ene affords only the single-addition product even when sub-stoichiometric amounts of it are used (0.3 equiv.).



Scheme 4.9 – Synthesis of an anaferine precursor through reaction of α-lithioamine with 3-chloro-2-(chloromethyl)prop-1-ene.

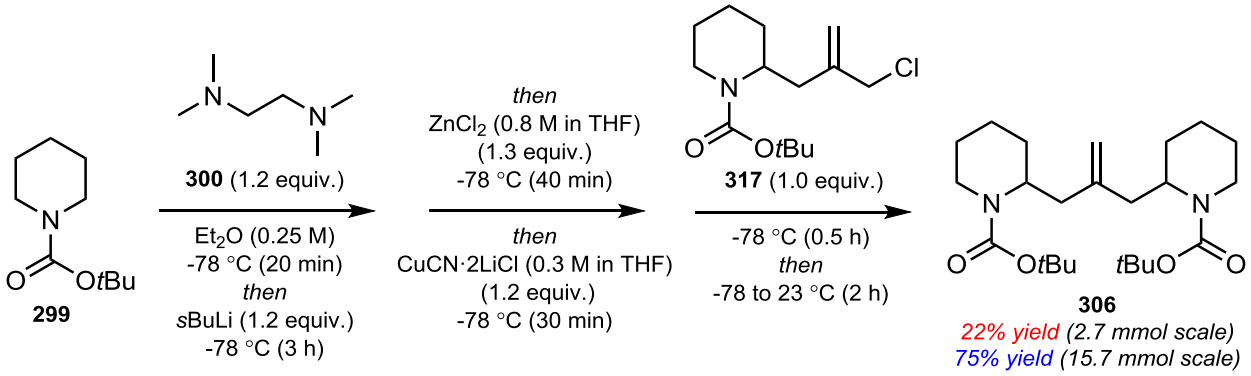
It was hypothesized that aggregation of the single-addition product as a lithium salt complex may inhibit the second nucleophilic attack from α-lithio *N*-Boc piperidine. Both TMEDA and LiCl have been suggested to affect the aggregation state of organolithium species.[140] Increasing the amounts of TMEDA or LiCl additive (10 equiv.) did not afford any of the double-addition product.

A minor impurity in the reaction derives from addition of unreacted *s*BuLi to the single-addition product. Given the apparent difficulty of a second nucleophilic attack from α-lithio *N*-Boc piperidine, it was hypothesized that increasing the steric bulk of the organolithium species would inhibit this side-reaction. Use of *t*BuLi inhibits formation of the equivalent side product (cf. **318**). However, the isolated product yield is not improved. As *t*BuLi is both challenging and hazardous to use on large scale, this modification was not employed.

Increasing the reaction scale decreases the isolated yield (4.26 g, 40% yield of **317**). Analysis of the ^{1}H NMR spectrum for this reaction suggests that a substantial

amount of unreacted *N*-Boc piperidine remains. Based on the success of other large scale reactions under these conditions (*vide infra*) the diminished yield may simply result from the quality of the *s*BuLi reagent used. The single-addition product completely degrades on contact with silica gel. Distillation may be used to remove the main impurity, residual *N*-Boc piperidine.

Re-subjecting the isolated single-addition product to reaction conditions as the electrophile affords the desired double-addition compound (Scheme 4.10). The relatively low isolated product yield (22% yield) was initially attributed to the second addition being challenging due to steric interactions. However, increasing the reaction scale substantially improves the isolated yield (4.96 g, 75% yield). Based on this high yield it is unclear why this compound is not formed directly from double addition onto 3-chloro-2-(chloromethyl)prop-1-ene.



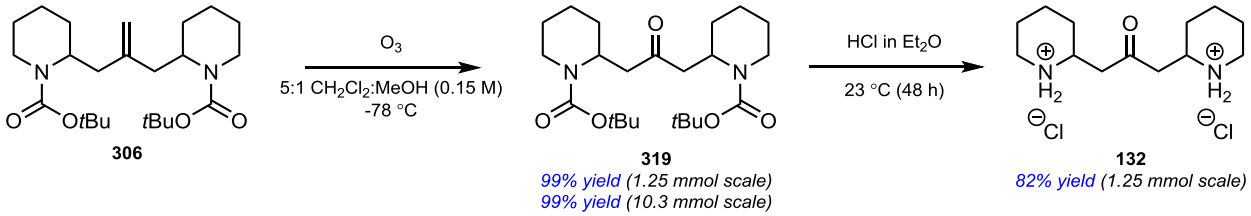
Scheme 4.10 – Synthesis of an anaferine precursor through reaction of α-lithioamine with an allylic chloride intermediate.

The dramatic improvement upon increasing the reaction scale may be due to a number of factors. Alternatively, that the product yield increased on large scale may be coincidental. The large-scale reaction necessitated that a new bottle of *s*BuLi be used. The contents of each bottle are titrated before use. However, initial screening of reaction conditions did not suggest the amount of non-alkyl lithium base(s) in solution affects reactions of *N*-Boc piperidine with allyl bromide (*vide supra*). Consequently, a full double titration was not performed with either bottle. It is possible that contaminating base(s) do play a role when the optimized reaction conditions are used.

The double-addition product is stable to silica gel and may be purified by passing the mixture through a short plug of silica gel (removing the single-addition product) followed by distillation to remove unreacted *N*-Boc piperidine. Analysis of the ^{1}H NMR spectrum of the purified compound suggests that it is either formed as a single diastereomer or that its C_2-symmetric and *meso* forms have identical/overlapping ^{1}H NMR chemical shifts.

4.3.3. Ozonolysis and Deprotection

Ozonolysis under standard conditions affords di-Boc anaferine in quantitative yields on both small and large scale (Scheme 4.11). The C_2-symmetric isomer of this compound (**C_2-319**) has been synthesized before.[61a] The authors report isolation using flash column chromatography on silica gel. However, use of either silica gel or elevated (>40 °C) temperatures for purification lead to significant decomposition. It is possible that the source of the silica gel has an effect on this.[112]



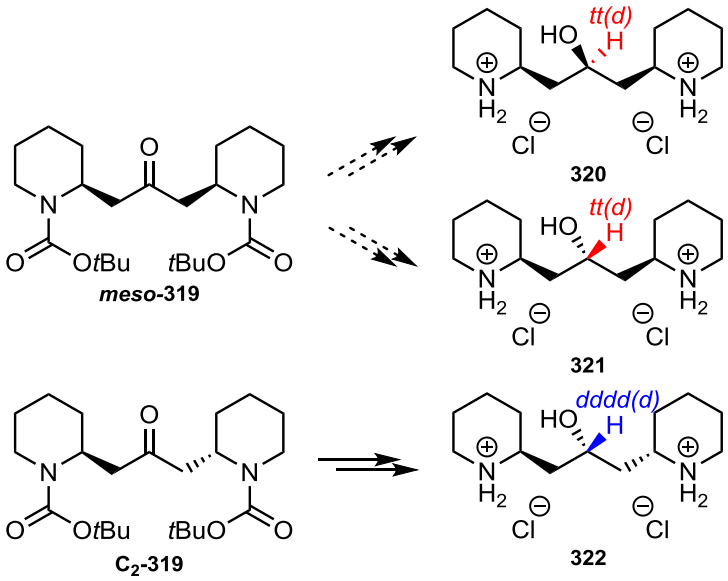
Scheme 4.11 – Ozonolysis and deprotection of an anaferine precursor to afford the dihydrochloride salt of anaferine.

Directly removing the Boc groups without purification affords the dihydrochloride salt in high yield. This compound did not require purification, alleviating the need to find conditions for purification of the protected compound. Again the C_2-symmetric isomer of this compound has been fully characterized.[61a] All signals in the ^{1}H NMR spectrum show a slight downfield shift relative to those of the reported C_2-symmetric species. A series of control experiments demonstrated that this shift is not concentration-dependent. This

initially suggested that the compound was either the *meso*-isomer or a mixture of the two forms.

Analysis of the ^{13}C NMR spectrum of the crude di-Boc anaferine mixture reveals the presence of ten signals. This suggests that a single diastereomer (*meso* or C_2-symmetric) is formed.

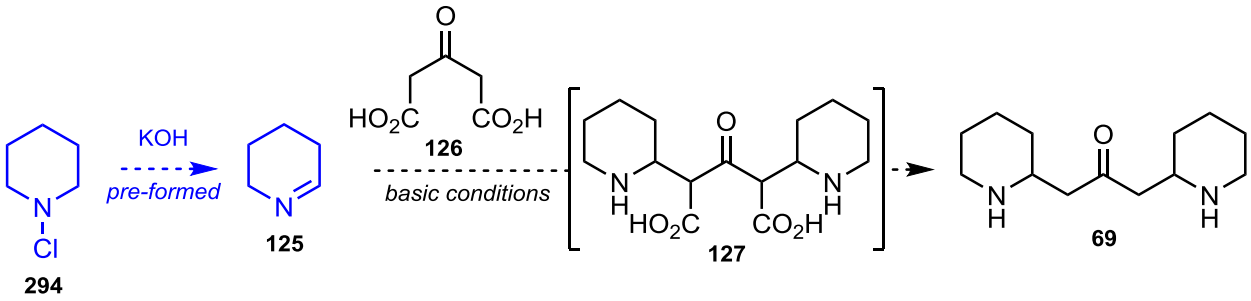
Reduction of the carbonyl in the C_2-symmetric isomer of anaferine should afford a single diastereomer (Scheme 4.12). Conversely, reduction of the carbonyl in the *meso*-isomer of anaferine should afford two diastereomers. A small scale reduction of the crude di-Boc anaferine mixture was carried out. Analysis of ^{1}H NMR spectra of the crude reaction mixture did not allow successful identification, regardless of solvent or temperature used. Subsequent deprotection affords the dihydrochloride salt and improves resolution of the spectra. The multiplicity and shape of the ^{1}H NMR signal for the central proton of the compound (app. tt) is unable to definitively allow assignment; with sufficiently similar coupling constants a *dddd* may appear as a *tt*. However, the presence of another, smaller signal (app. *tt*) in the same region may indicate that a mixture (*viz*. **320** and **321**) has been formed. The origin of the high diastereoselectivity in the formation of **306** remains unclear.



Scheme 4.12 – Potential diastereomers and multiplicities for the characteristic ^{1}H NMR signal from the reduction of an anaferine precursor.

4.4. Conclusions and Future Work

A substantial body of work has gone into accessing anaferine as the precursor to sparteine. Initial work aimed to replicate previous synthetic routes to anaferine using more accessible starting materials. These approaches invariably did not form anaferine, nor any of its precursors. If access to anaferine *via* this route is desired, it may be beneficial to repeat the experiments with pre-formed imine acceptor (Scheme 4.13) rather than *in situ* generation. This would ensure conditions are as similar as possible to those of the known synthetic route.[57b, 57c, 84d, 95]



Scheme 4.13 – Proposed modification of reaction conditions in the synthesis of anaferine from *N*-chloropiperidine.

Subsequent work targeted coupling allylic halides with α-lithioamines. The increased ring size of piperidine relative to pyrrolidine presumably induces a change in the mechanism for this transformation, making results using the standard protocol(s) highly variable. A specific mixture of zinc, copper, and lithium salts, added in a specific order, is required to achieve consistently high product yields. Use of 3-chloro-2-(chloromethyl)prop-1-ene under these conditions affords the single-addition product in moderate/high yield. Re-subjecting this compound to reaction conditions affords the desired double-addition product in excellent yield, even on large scale.

Ideally, both additions would occur in a single-step one-pot transformation. It remains unclear why this does not occur. It has been demonstrated that the coordinating solvent tetrahydrofuran (THF) disrupts aggregation of organolithium species.[140c] This may occur competitively, cooperatively, or in the absence of

N,N,N′,N′-tetramethylethylenediamine (TMEDA). Following the addition of the zinc, copper, and lithium salt solutions THF comprises roughly 60% of the solvent mixture. The addition of excess TMEDA to the reaction did not improve conversion nor afford any of the double-addition product (see Section 4.3.2). However, a related experiment where the reaction is carried out in the absence of TMEDA was not performed. If aggregation is the cause of the inactivity, and THF affects aggregation in this system differently that TMEDA, then this may allow the transformation to proceed.

Ozonolysis and subsequent deprotection of this compound both proceed well, affording the dihydrochloride salt of anaferine in high yield. Subsequent characterization suggests the formation of a single diastereomer. Attempts to elucidate which diastereomer is formed have remained inconclusive. The origin of the high diastereoselectivity remains unclear.

Subjecting the C_2-symmetric isomer to the proposed reaction sequence will not afford sparteine under non-epimerizing conditions (see Scheme 4.4). Based on preliminary computational results (see Section 4.2.1) the use of epimerizing conditions will likely favour formation of genisteine over sparteine. Depending on which diastereomer has been formed it may be necessary to access the *meso*-isomer of anaferine. As anaferine is not configurationally stable under neutral or basic conditions it is possible to use the synthesized sample to afford *meso*-anaferine, albeit in reduced yield or over many sequential isomerization-separation steps, even if the C_2-symmetric isomer has been formed.

CHAPTER 5: Experimental Details

5.1. General Methods

Most anhydrous solvents (dichloromethane (CH_2Cl_2), diethyl ether (Et_2O), toluene (PhMe), tetrahydrofuran (THF)) were dried using a Braun Solvent Purification System and stored under argon over 3 or 4 Å molecular sieves. Moisture content for these solvents was analyzed using a C20 Karl Fischer Coulometer. Moisture content did not exceed 15 ppm prior to use. Dimethyl formamide (DMF) and acetonitrile (MeCN) were dried using distillation over calcium hydride (CaH_2). Methanol (MeOH) and ethanol (EtOH) were dried using distillation over magnesium (Mg). Unless otherwise noted all reactions were performed under an inert atmosphere of argon (4.8 grade). Reaction concentrations (molarities) are reported with respect to the limiting (*viz*. 1.00 equiv.) reagent.

Thin layer chromatography (TLC) and preparative thin layer chromatography (PTLC) was performed using Merck Silica Gel 60 F_{254}. Visualization was typically performed with UV light (254 nm) and occasionally permanganate ($KMnO_4$), *p*-anisaldehyde, or iodine (I_2) stains. Silica gel 60 (40-63 μm) used for flash column chromatography (FCC) and silica plugs was purchased from EMD Millipore or Silicycle Chemical Division.

NMR spectra were measured primarily in deuterated chloroform ($CDCl_3$). Some spectra were instead measured in deuterated water (D_2O), methanol (CD_3OD), dichloromethane (CD_2Cl_2), acetonitrile (CD_3CN), dimethyl sulfoxide ($(CD_3)_2SO$), or acetone ($(CD_3)_2CO$) as needed. Proton (^1H) NMR spectra were obtained at 500 or 600 MHz. Carbon (^{13}C) NMR spectra were obtained at 125 MHz. The residual solvent protons (^1H) or carbon(s) (^{13}C) were used as internal standards for chemical shifts.[141] ^1H solvent residual signals used (δ): $CDCl_3$ = 7.26; D_2O = 4.79; CD_3OD = 3.31; CD_2Cl_2 = 5.32; CD_3CN = 1.94; $(CD_3)_2SO$ = 2.50; $(CD_3)_2CO$ = 2.05. ^{13}C solvent residual signals used (δ): $CDCl_3$ = 77.2; CD_3OD = 49.0; CD_2Cl_2 = 53.8; CD_3CN = 118.3; $(CD_3)_2SO$ = 39.5; $(CD_3)_2CO$ = 29.8.

High resolution mass spectra (HRMS) and low resolution mass spectra (LRMS) were obtained using a VG 70E double focusing high resolution spectrometer.

Electron impact (EI) ionization was accomplished at 70 eV. Chemical ionization (CI) was accomplished at 50 eV with ammonia as the reagent gas. Spectra obtained with electrospray ionization (ESI) were instead obtained using a Qstar XL LC-MS/MS time-of-flight (TOF) high resolution spectrometer.

Infrared (IR) spectra were typically performed on a Fourier transform interferometer using a diffuse reflectance cell (DRIFT). Only diagnostic and/or intense peaks are reported. Spectra obtained using this method are typically acquired from samples prepared as thin-films on potassium bromide (KBr) pellets, or as suspended solids in a KBr pellet matrix. Some spectra were instead obtained using a Bruker ALPHA I Fourier transform attenuated total reflectance (FT-ATR) spectrometer. Spectra obtained using this method are acquired using the neat compound, which must be a solid.

Optical rotations were determined from an average of 16 measurements at ambient temperature using a 1 mL, 10 dm cell. The units are 10^{-1} deg cm^2 g^{-1}, while the concentrations (*c*) are reported in units of g/100 mL. All optical rotations and concentrations for said rotations are rounded to two significant figures. Enantiomeric excess was assessed using am Agilent Technologies 1200 series HPLC with the CHIRALPAK IA, IB, IC, or ASH columns.

Melting points were determined using a Stanford Research Services MPA160 'DigiMelt' melting point apparatus.

5.2. Experimental Procedures for Chemoselective Cross-Benzoin Reactions of Aldehydes

Aldehydes which are solid at room temperature (23 °C) were used directly without prior purification. Aldehydes which are liquid at room temperature were distilled prior to use. Two aldehydes (see Section 3.4.3.1) were synthesized and purified according to literature procedures.[142] Unless otherwise stated all azolium pre-catalysts used in these reactions were prepared using slightly modified variations of the standard conditions[7] by S. Langdon, Dr. M. Wilde, or Dr. P. Haghshenas. All amine bases were distilled prior to use. Tertiary amines (triethylamine (NEt_3), *N*,*N*-diisopropylethylamine (colloquially Hünig's base; DIPEA; *i*Pr_2NEt)) were stored over 4 Å molecular sieves prior to use. 1,8-

Diazabicyclo[5.4.0]undec-7-ene (DBU) was either used immediately after distillation or stored over potassium hydroxide (KOH) prior to use.

Benzoin products were found to be unstable to flash column chromatography if the silica was too acidic in nature. Columns performed with silica gel obtained from Silicycle Chemical Division (or other sources) gave diminished yields as well as oxidized material. Use of 1% *v*/*v* triethylamine (NEt_3) in the eluent solution mitigated this for some compounds. Unless otherwise noted all flash column chromatography with benzoin products was carried out using silica gel obtained from EMD Millipore.

^{13}C NMR signals for carbons in pentafluorophenyl rings are not typically observed due to coupling and relaxation effects.

5.2.1. General Procedures for Cross-Benzoin Reactions

General Procedure:

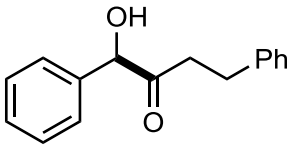
The azolium salt was added to a test tube with a Schlenk take-off. If one or more of the aldehydes is also a solid then they were added with the azolium salt. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Liquid aldehyde(s) and the anhydrous solvent were then added. Lastly the base was added and the septum quickly exchanged for a cold finger while a mild positive pressure of argon gas flows. The flask was then sealed and brought to the desired temperature. The reaction mixture was stirred for the desired amount of time and was then quenched by washing with 2 M HCl. The organic component was dried over Na_2SO_4. Volatiles were then removed *in vacuo* (ca. 50 torr.). In cases where the isolated compound was desired (*viz.* a ^1H NMR yield was insufficient) the crude reaction mixture was immediately purified by flash column chromatography.

Optimized Procedure:

The piperidinone-derived triazolium salt (**156**, 0.05 equiv.) was added to a test tube with a Schlenk take-off. If one or both aldehydes was/were also a solid then they were added with the azolium salt. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon)

atmosphere. Liquid aldehyde(s) were then added. The aromatic aldehyde (1.00 equiv.) and aliphatic aldehyde (1.50 equiv.) were rinsed to the bottom of the vessel as the anhydrous solvent (CH_2Cl_2 (1.0 M)) was added. Lastly *i*Pr_2NEt (1.00 equiv.) was added and the septum quickly exchanged for a cold finger while a mild positive pressure of argon gas flowed. The flask was then sealed and brought to 70 °C. The reaction mixture was stirred for the desired amount of time, typically 30 min. and was then quenched by washing with 2 M HCl. The organic layer was dried over Na_2SO_4. Volatiles were then removed *in vacuo* (ca. 50 torr.). The crude reaction mixture was immediately purified by flash column chromatography.

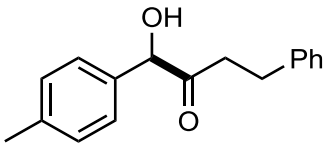
1-Hydroxy-1,4-diphenylbutan-2-one (151):



Following the *Optimized Procedure* using benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 0.5 h. Reaction carried out on 1.00 equiv. = 0.50 mmol scale. Purification (FCC; 8% EtOAc + 92% hexanes; R_f = 0.22) performed by Dr. M. Wilde affords 118 mg of the product contaminated 13% by mass of the homo-benzoin product of hydrocinnamaldehyde and 3% by mass with of the homo-benzoin product of benzaldehyde as a white solid.[112] Computed yield: 84% All spectra are consistent with those previously reported.[49]

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43-7.36 (m, 3H), 7.36-7.29 (m, 2H), 7.29-7.24 (m, 2H), 7.24-7.18 (m, 1H), 7.08 (d, *J* = 7.2 Hz, 2H), 5.07 (d, *J* = 3.9 Hz, 1H), 4.43 (d, *J* = 3.2 Hz, 1H), 2.96-2.88 (m, 1H), 2.86-2.78 (m, 1H), 2.78-2.64 (m, 2H).

1-Hydroxy-4-phenyl-1-(*p*-tolyl)butan-2-one (168):

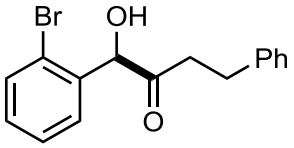


Following the *Optimized Procedure* using *p*-Me benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.50 mmol scale. Purification (FCC; 10% EtOAc + 90% hexanes; R_f =

0.25) performed by Dr. M. Wilde affords 132 mg of the product contaminated 14% by mass of the homo-benzoin product of hydrocinnamaldehyde as a white solid.[112] Computed yield: 91%

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.25-7.18 (m, 2H), 7.20-7.14 (m, 5H), 7.05 (d, *J* = 7.0, 2H), 5.00 (d, *J* = 4.3 Hz, 1H), 4.26 (d, *J* = 4.3 Hz, 1H), 2.95-2.85 (m, 1H), 2.82-2.74 (m, 1H), 2.74-2.59 (m, 2H), 2.62 (s, 3H).

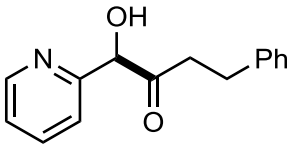
1-(2-Bromophenyl)-1-hydroxy-4-phenylbutan-2-one (159):



Following the *Optimized Procedure* using *o*-Br benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.50 mmol scale. Purification (FCC; 10% EtOAc + 90% hexanes; R_f = 0.22) performed by Dr. M. Wilde affords 141 mg (89% yield) of the product as a white solid.[112] All spectra are consistent with those previously reported.[49]

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.61 (d, *J* = 7.9 Hz, 1H), 7.30-7.22 (m, 3H), 7.22-7.16 (m, 3H), 7.09 (d, *J* = 7.3 Hz, 2H), 5.59 (d, *J* = 4.1 Hz 1H), 4.45 (d, *J* = 4.2 Hz, 1H), 2.98-290 (m, 1H), 2.90-2.80 (m, 2H), 2.72-2.64 (m, 1H).

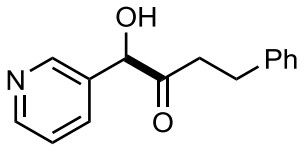
1-(2-Pyridyl)-1-hydroxy-4-phenylbutan-2-one (184):



Following the *Optimized Procedure* using 2-pyridinecarboxaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.36 mmol scale. Attempts at purification (FCC) performed by Dr. M. Wilde result in degradation of the products. Yield by ^{1}H NMR spectroscopy: 21% (internal standard = bibenzyl).[112]

Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 5.23 (s, 1H).

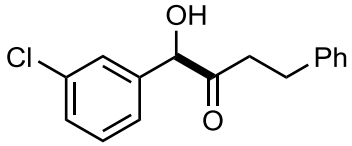
1-(3-Pyridyl)-1-hydroxy-4-phenylbutan-2-one (188):



Following the *Optimized Procedure* using 3-pyridinecarboxaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.36 mmol scale. Attempts at purification (FCC) performed by Dr. M. Wilde result in degradation of the products. Yield by ^{1}H NMR spectroscopy: 39% (internal standard = bibenzyl).[112]

Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 4.98 (s, 1H).

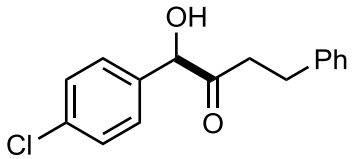
1-(3-Chlorophenyl)-1-hydroxy-4-phenylbutan-2-one (166):



Following the *Optimized Procedure* using *m*-Cl benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.27 mmol scale. Yield by ^{1}H NMR spectroscopy: 47% (internal standard = bibenzyl).

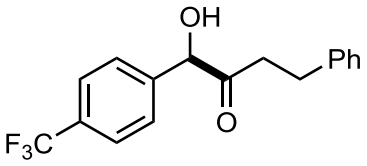
Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 5.03 (s, 1H).

1-(4-Chlorophenyl)-1-hydroxy-4-phenylbutan-2-one (160):



Following the *Optimized Procedure* using *p*-Cl benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.27 mmol scale. Yield by ^{1}H NMR spectroscopy: *not detected* (internal standard = dimethylterephthalate).

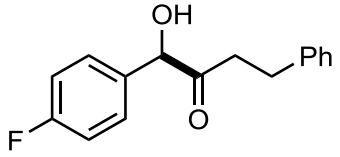
1-Hydroxy-4-phenyl-1-(4-(trifluoromethyl)phenyl)butan-2-one (164):



Following the *Optimized Procedure* using *p*-CF_3 benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 0.5 h. Reaction carried out on 1.00 equiv. = 0.27 mmol scale. Yield by ^{1}H NMR spectroscopy: 10% (internal standard = dimethylterephthalate).

Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 5.09 (s, 1H).

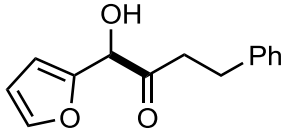
1-(4-Fluorophenyl)-1-hydroxy-4-phenylbutan-2-one (161):



Following the *Optimized Procedure* using *p*-F benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). 0.01 equiv. of azolium salt used. Reaction time = 8 h. Reaction carried out on 1.00 equiv. = 0.27 mmol scale. Yield by ^{1}H NMR spectroscopy: 54% (internal standard = dimethylterephthalate).

Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 5.11 (s, 1H).

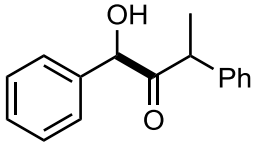
1-(Furan-2-yl)-1-hydroxy-4-phenylbutan-2-one (181):



Following the *Optimized Procedure* using 2-furfuraldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 15 min. Reaction carried out on 1.00 equiv. = 0.27 mmol scale. Yield by ^{1}H NMR spectroscopy: 38% (internal standard = bibenzyl).

Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 5.12 (s, 1H).

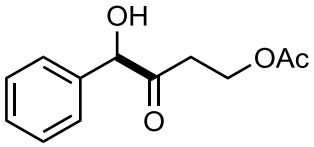
1-Hydroxy-1,3-diphenylbutan-2-one (175):



Following the *Optimized Procedure* using 2-furfuraldehyde (1.00 equiv.) and 2-phenylpropionaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.41 mmol scale. Yield by ^{1}H NMR spectroscopy: <30% (internal standard = bibenzyl). dr = 1.2 : 1.

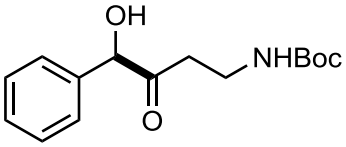
Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signals at δ 5.22 (s, 1H; *major*), 5.08 (s, 1H; *minor*).

4-Hydroxy-3-oxo-4-phenylbutyl acetate (177):



Following the *Optimized Procedure* using benzaldehyde (1.00 equiv.) and 3-oxopropyl acetate (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.41 mmol scale. Yield by ^{1}H NMR spectroscopy: *not detected* (internal standard = dimethylterephthalate).

***tert*-Butyl (4-hydroxy-3-oxo-4-phenylbutyl)carbamate (178)**:



Following the *Optimized Procedure* using benzaldehyde (1.00 equiv.) and *tert*-butyl (3-oxopropyl)carbamate (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.50 mmol scale. Yield by ^{1}H NMR spectroscopy: 25%, 32% (multiple experiments; internal standards = dimethylterephthalate, bibenzyl).

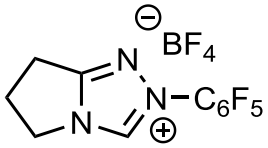
Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 5.11 (s, 1H).

5.2.2. General Procedures for Syntheses of Triazolium Salts

Modified Standard Procedure:[7]

The lactam (1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous dichloromethane (CH_2Cl_2 (0.2 M)) was added. Trimethyloxonium tetrafluoroborate (1.00 equiv.) was added while a mild positive pressure of argon gas flows. The mixture was then stirred for 3-4 h at room temperature (23 °C) under the argon atmosphere. A mono-substituted hydrazine (1.00 equiv.), typically pentafluorophenyl hydrazine, was added in one portion and stirring continued for 8-12 h. The solvent was evaporated *in vacuo* (ca. 50 torr.) thoroughly. Co-evaporation with trimethyl or triethyl orthoformate was occasionally employed. Trimethyl or triethyl orthoformate (8-9 equiv.) was added. Occasionally chlorobenzene (1.0 M) was added as a co-solvent. The mixture was refluxed open to air for 8-72 h. If there was a solid suspension it was filtered prior to removal of volatiles *in vacuo* (ca. 50 torr.). Trituration of the resulting oil, typically with diethyl ether or ethyl acetate, resulted in formation of (additional) solid which was then filtered. This process may be repeated up to three times to afford additional solid. All solids were combined and, if required, triturated from diethyl ether to remove coloured impurities.

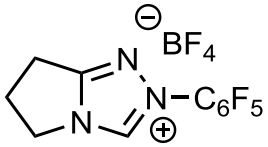
Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5*H*-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (5):



Following the *Modified Standard Procedure* using pyrrolidinone as the lactam. 3 h stirring with trimethyloxonium tetrafluoroborate. 12 h stirring with pentafluorophenyl hydrazine. Pentafluorophenyl hydrazine was sublimed prior to use. 8 h stirring with trimethyl orthoformate (9 equiv.) at 130 °C. Chlorobenzene was not used. Reaction carried out on 1.00 equiv. = 14.7 mmol scale. Affords 1.07 g (20% yield over three steps) of the product as a tan solid. All spectra are consistent with those previously reported.[7]

^{1}H NMR (500 MHz, d_6-DMSO) δ 10.55 (s, 1H), 4.47 (t, *J* = 7.0 Hz, 2H), 3.24 (t, *J* = 8.0 Hz, 2H), 2.75 (dt, *J* = 15.0, 7.5 Hz, 2H).

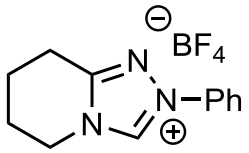
***Optimized Procedure For Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate* (5):**



Pyrrolidinone (4.00 mL, 52.6 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous dichloromethane (263 mL (0.2 M)) was added. Trimethyloxonium tetrafluoroborate (7.78 g, 52.6 mmol, 1.00 equiv.) from a freshly-opened bottle was added while a mild positive pressure of argon gas flows. The mixture was then stirred for 3 h at room temperature (23 °C). Pentafluorophenyl hydrazine (10.41 g, 52.6 mmol, 1.00 equiv.) was added in one portion and stirring continued for 12 h. The solvent was evaporated *in vacuo* (ca. 50 torr.) thoroughly. Co-evaporation with trimethyl orthoformate was employed. The vessel was fitted with a condenser and septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Trimethyl orthoformate (52.0 mL, 473 mmol, 9.00 equiv.) was added. The mixture was heated to 110 °C for 8 h. The solid suspension was filtered prior to removal of volatiles *in vacuo* (ca. 50 torr.). Trituration of the resulting oil with diethyl ether resulted in formation of additional solid which was then filtered. This process was repeated two times to afford additional solid. All solids were combined and triturated from diethyl ether to remove coloured impurities. Affords 2.76 g (58% yield over three steps) of the product as a white solid. All spectra are consistent with those previously reported.[7]

^{1}H NMR (500 MHz, d_6-DMSO) δ 10.55 (s, 1H), 4.47 (t, *J* = 7.0 Hz, 2H), 3.24 (t, *J* = 8.0 Hz, 2H), 2.75 (dt, *J* = 15.0, 7.5 Hz, 2H).

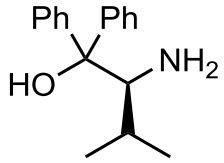
Synthesis of 2-phenyl-6,7,8,9-tetrahydro-5*H*-[1,2,4]triazolo[4,3-a]azepin-2-ium tetrafluoroborate (158):



Following the *Modified Standard Procedure*, using 2-piperidinone as the lactam. 3h stirring with trimethyloxonium tetrafluoroborate. 2 h stirring with phenyl hydrazine. 1 h stirring with trimethyl orthoformate at 130 °C. Chlorobenzene was used. Reaction carried out on 1.00 equiv. = 10.08 mmol scale. Affords 0.767 g (27% yield over three steps) of the product as a tan solid.

White solid (0.767 g, 27% yield). **m.p.**: 159.9-160.4 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3140, 2962, 1585, 1032, 761, 686, 520; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 10.74 (s, 1H), 7.88 (d, *J* = 7.8 Hz, 2H), 7.70 (app. t, *J* = 7.6 Hz, 2H), 7.63 (app. t, *J* = 7.5 Hz, 1H), 4.31 (t, *J* = 5.8 Hz, 2H), 3.09 (t, *J* = 6.5 Hz, 2H), 2.08-1.95 (m, 4H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 153.3, 140.7, 135.0, 130.4, 130.3, 120.4, 45.4, 20.7, 20.6, 18.3; **HRMS** (ESI) *m*/*z* calculated for $C_{12}H_{14}N_3$ $[M]^+$: 200.1188; found: 200.1177.

Synthesis of (*S*)-2-amino-3-methyl-1,1-diphenylbutan-1-ol (232):[143]

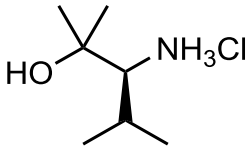


(*S*)-1-methoxy-3-methyl-1-oxobutan-2-aminium chloride (the hydrochloride salt of *L*-methyl valine) (10 g, 59.7 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous diethyl ether (299 mL (0.2 M)) was added. The mixture was cooled to 0 °C. Phenylmagnesium bromide (119 mL of 3.0 M solution in Et_2O, 358 mmol, 6.00 equiv.) was added dropwise while stirring. The mixture was then stirred for 20 h at room temperature (23 °C). The reaction was then quenched by addition of 3 M HCl until all visible solid dissolved. The aqueous layer was washed two times using dichloromethane. The aqueous layer was then basified to pH = 12 using 2 M NaOH solution. The aqueous layer was then extracted five times using dichloromethane. Care must be used to avoid formation of a semi-stable emulsion; the extraction must be performed without excessively vigorous shaking. The organic layers were combined, dried over Na_2SO_4, and all volatiles

were removed *in vacuo* (≤1 torr.). Affords 6.00 g (39% yield) of the product as a white solid. All spectra are consistent with those previously reported.[143]

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.56 (dd, *J* = 60.3, 7.4 Hz, 4H), 7.40-7.22 (m, 4H), 7.22-7.17 (m, 2H), 4.44 (be. s, 2H), 3.85 (br. s, 1H), 1.79-1.60 (m, 1H), 1.30-1.00 (m, 1H), 0.94 (d, *J* = 5.3 Hz, 3H), 0.88 (d, *J* = 6.8 Hz, 3H).

Synthesis of (*S*)-2-hydroxy-2,4-dimethylpentan-3-aminium chloride (233):[144]



Method 1:

Methyl (*tert*-butoxycarbonyl)-*L*-valinate (17.34 g, 75 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous tetrahydrofuran (188 mL (0.4 M)) was added. The mixture was cooled to 0 °C. Methylmagnesium bromide (100 mL of 3.0 M solution in Et_2O, 300 mmol, 4.00 equiv.) was added dropwise while stirring. The mixture was then stirred for 96 h at room temperature (23 °C). The reaction was then cooled to 0 °C and quenched by addition of aqueous $NH_4Cl_{(sat).}$ until all visible solid dissolved. The aqueous layer was extracted three times using dichloromethane. Care must be used to avoid formation of a semi-stable emulsion; the extraction must be performed without excessively vigorous shaking. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (≤1 torr.). Purification (FCC; 100% CH_2Cl_2; R_f = 0.3) affords 13.69 g of *tert*-butyl (*S*)-(2-hydroxy-2,4-dimethylpentan-3-yl)carbamate (78% yield) of the product as a pale yellow oil. All spectra are consistent with those previously reported.[144]

tert-Butyl (*S*)-(2-hydroxy-2,4-dimethylpentan-3-yl)carbamate (2.5 g, 10.8 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. An ethereal solution of hydrochloric acid (20 mL (2 M in Et_2O)) was added. The mixture was then stirred for 48 h at room temperature (23 °C). All volatiles were removed *in vacuo* (≤1 torr.) affording 1.44 g (80% yield) of

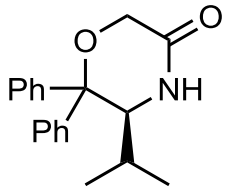
the product as a white solid. All spectra are consistent with those previously reported.[144]

Method 2:

Methyl (*tert*-butoxycarbonyl)-*L*-valinate (26.02 g, 112.5 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous tetrahydrofuran (280 mL (0.4 M)) was added. The mixture was cooled to 0 °C. Methylmagnesium bromide (150 mL of 3.0 M solution in Et_2O, 450 mmol, 4.00 equiv.) was added dropwise while stirring. The mixture was then stirred for 96 h at room temperature (23 °C). The reaction was then cooled to 0 °C and quenched by addition of aqueous $NH_4Cl_{(sat)}$ until all visible solid dissolves. The aqueous layer was extracted three times using dichloromethane. Care must be used to avoid formation of a semi-stable emulsion; the extraction must be performed without excessively vigorous shaking. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (≤1 torr.). The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. An ethereal solution of hydrochloric acid (200 mL (2 M in Et_2O)) was added. The mixture was then stirred for 16 h at room temperature (23 °C). The suspension was then filtered. All volatiles were removed *in vacuo* (≤1 torr.) and the resulting oil was suspended in an ethereal solution of hydrochloric acid (50 mL (2 M in Et_2O)). The mixture was then stirred for 16 h at room temperature (23 °C). The suspension was then filtered and the solids combined with those of the previous filtration. Affords 18.43 g (98% yield) of the product as a white solid. All spectra are consistent with those previously reported.[144]

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.94 (br. s, 3H), 5.47 (br. s, 1H), 3.30-3.23 (m, 1H), 2.02-1.96 (m, 1H), 1.40 (s, 3H), 1.37 (s, 3H), 1.25 (d, *J* = 18.6 Hz, 3H), 1.23 (d, *J* = 2.4 Hz, 3H).

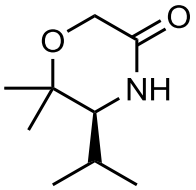
Synthesis of (*S*)-5-isopropyl-6,6-diphenylmorpholin-3-one (235):[143]



(*S*)-2-amino-3-methyl-1,1-diphenylbutan-1-ol (1.606 g, 6.30 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous dichloromethane (31.5 mL (0.2 M)) was added. Triethylamine (1.05 mL, 7.56 mmol, 1.20 equiv.) was added. The mixture was cooled to 0 °C. Chloroacetyl chloride (0.5 mL, 6.30 mmol, 1.00 equiv.) was added dropwise while stirring. The mixture was then stirred for 4 h at room temperature (23 °C). The reaction was then quenched by addition of aqueous $NH_4Cl_{(sat)}$. The aqueous layer was extracted three times using dichloromethane. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (ca. 50 torr.). The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous tetrahydrofuran (31.5 mL (0.2 M)) was added. The mixture was cooled to 0 °C. Sodium hydride (378 mg of a 60% suspension in oil, 9.45 mmol, 1.50 equiv.) was added portionwise while stirring. The mixture was then stirred for 1 h at room temperature (23 °C). The reaction was then quenched by addition of aqueous $NH_4Cl_{(sat)}$. The aqueous layer was extracted three times using ethyl acetate. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (≤1 torr.). Affords 1.25 g (67% yield) of the product as a white solid.

White solid (1.25 g, 67% yield). **$[\alpha]_D^{23}$** = -440 (*c* = 0.099, MeOH); **m.p.**: >260 °C (instrument limit); **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3196, 3060, 2960, 2877, 1679, 1448, 1337, 1103, 770, 752, 703, 650; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 8.47 (d, *J* = 5.0 Hz, 1H), 7.10-7.50 (m, 10H), 4.35 (d, *J* = 4.8 Hz, 1H), 4.18 (d, *J* = 17.0 Hz, 1H), 3.60 (d, *J* = 17.0 Hz, 1H), 1.35-1.50 (m, 1H), 0.83 (d, *J* = 7.0 Hz, 3H), 0.81 (d, *J* = 6.6 Hz, 3H); **^{13}C NMR** (125 MHz, $CDCl_3$) δ 170.2, 143.6, 141.8, 129.0, 128.4, 127.8, 127.6, 127.0, 125.4, 80.6, 63.7, 59.1, 29.5, 21.9, 15.9; **HRMS** (EI^+) *m*/*z* calculated for $C_{19}H_{21}NO_2$ $[M]^+$: 295.1572; found: 295.1578.

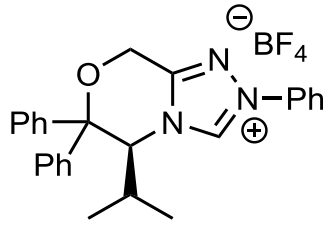
Synthesis of (*S*)-5-isopropyl-6,6-dimethylmorpholin-3-one (236):[143]



(*S*)-2-hydroxy-2,4-dimethylpentan-3-aminium chloride (8.01 g, 47.8 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous dichloromethane (240 mL (0.2 M)) was added. Triethylamine (17 mL, 143 mmol, 3.00 equiv.) was added. The mixture was cooled to 0 °C. Chloroacetyl chloride (3.8 mL, 47.8 mmol, 1.00 equiv.) was added dropwise while stirring. The mixture was then stirred for 4 h at room temperature (23 °C). The reaction was then quenched by addition of aqueous $NH_4Cl_{(sat)}$. The aqueous layer was extracted three times using dichloromethane. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (ca. 50 torr.). The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous tetrahydrofuran (240 mL (0.2 M)) was added. The mixture was cooled to 0 °C. Sodium hydride (2.67 g of a 60% suspension in oil, 66.9 mmol, 1.40 equiv.) was added portionwise while stirring. The mixture was then stirred for 1 h at room temperature (23 °C). The reaction was then quenched by addition of aqueous $NH_4Cl_{(sat)}$. The aqueous layer was extracted three times using ethyl acetate. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (≤1 torr.). The mixture was suspended in dichloromethane and passed through a short silica plug. All volatiles were removed *in vacuo* (≤1 torr.) affording 5.05 g (62% yield) of the product as a white solid.

White solid (5.05 g, 62% yield). **$[\alpha]_D^{23}$** = -85 (*c* = 0.93, MeOH); **m.p.**: 78.3-78.9 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3189, 3059, 1664, 1428, 1171, 1107, 816, 453; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 6.26 (br. s, 1H), 4.12 (dd, *J* = 22.5, 17.5 Hz, 2H), 3.01 (app. t, *J* = 2.3 Hz, 1H), 2.04 (dtt, *J* = 13.6, 6.8, 2.3 Hz, 1H), 1.35 (s, 3H), 1.27 (s, 3H), 0.96 (app. t, *J* = 6.7 Hz, 6H); **^{13}C NMR** (125 MHz, $CDCl_3$) δ 170.1, 72.5, 63.4, 63.0, 29.2, 25.3, 24.2, 21.7, 15.8; **HRMS** ($Cl^{+/}NH_3$) *m*/*z* calculated for $C_9H_{18}NO_2$ $[M+1]^+$: 172.1332; found: 172.1333.

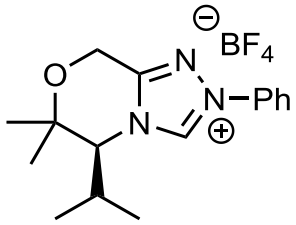
Synthesis of (*S*)-5-isopropyl-2,6,6-triphenyl-5,6-dihydro-8*H*-[1,2,4]triazolo[3,4-c][1,4]oxazin-2-ium tetrafluoroborate (243):



Following the *Modified Standard Procedure*, using (*S*)-5-isopropyl-6,6-diphenylmorpholin-3-one as the lactam. 3 h stirring with trimethyloxonium tetrafluoroborate. 6 h stirring with phenyl hydrazine. 1 h stirring with trimethyl orthoformate at 120 °C. Chlorobenzene was used. Reaction carried out on 1.00 equiv. = 0.68 mmol scale.

Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 10.61 (s, 1H).

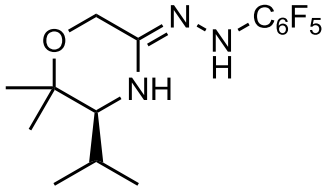
Synthesis of (*S*)-5-isopropyl-6,6-dimethyl-2-phenyl-5,6-dihydro-8H-[1,2,4]triazolo[3,4-c][1,4]oxazin-2-ium tetrafluoroborate (245):



Following the *Modified Standard Procedure*, using (*S*)-5-isopropyl-6,6-dimethylmorpholin-3-one as the lactam. 3 h stirring with trimethyloxonium tetrafluoroborate. 6 h stirring with phenyl hydrazine. 70 h stirring with trimethyl orthoformate at 120 °C. Chlorobenzene was used. Reaction carried out on 1.00 equiv. = 0.29 mmol scale.

Characteristic ^{1}H NMR (500 MHz, $CDCl_3$) signal at δ 10.30 (s, 1H).

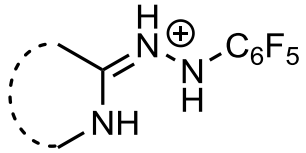
Synthesis of (*S*,*Z*)-3-isopropyl-2,2-dimethyl-5-(2-phenylhydrazineylidene)-morpholine (247):



(*S*)-5-isopropyl-6,6-dimethylmorpholin-3-one (5.05 g, 29.5 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous dichloromethane (148 mL (0.2 M)) was added. Trimethyloxonium tetrafluoroborate (4.37 g, 52.6 mmol, 1.00 equiv.) from a freshly-opened bottle was added while a mild positive pressure of argon gas flows. The mixture was then stirred for 3 h at room temperature (23 °C). Pentafluorophenyl hydrazine (5.84 g, 52.6 mmol, 1.00 equiv.) was added in one portion and stirring continued for 16 h. The organic layer was washed three times using $NaHCO_{3(sat.)}$. The organic layer was dried over Na_2SO_4 and all volatiles are removed *in vacuo* (ca. 50 torr.). The mixture was suspended in dichloromethane and passed through a short silica plug. After rinsing the plug with additional dichloromethane the silica plug was washed with acetonitrile, which was collected in a separate vessel. The acetonitrile fraction was dried over Na_2SO_4 and all volatiles were removed *in vacuo* (≤1 torr.), affording 5.40 g (52% yield) of the product as a very viscous brown oil which solidifies on standing.

Dark brown semi-solid (5.40 g, 52% yield). $\mathbf{[\alpha]_D^{23}}$ = *not determined, light could not pass through* (*c* = 0.11, MeOH); **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3322, 2969, 1654, 1517, 1427, 989, 716, 478; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 8.03 (s, 1H), 5.85 (s, 1H), 3.90 (dd, *J* = 25.4, 17.2 Hz, 2H), 2.91 (dd, *J* = 4.2, 1.9 Hz, 1H), 2.02-1.95 (m, 1H), 1.26 (s, 3H), 1.19 (s, 3H), 0.90 (d, *J* = 7.0 Hz, 3H), 0.85 (d, *J* = 6.7 Hz, 3H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 168.5, 72.4, 62.8, 62.2, 58.4, 29.0, 25.1, 25.0, 21.9, 16.2; **HRMS** (EI^+) *m*/*z* calculated for $C_{15}H_{18}N_3OF_5$ $[M]^+$: 351.1370; found: 351.1379.

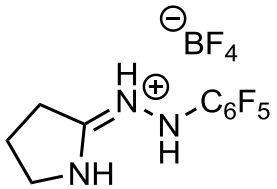
Optimized Procedure for Synthesis of N-pentafluorophenyl amidrazonium tetrafluoroborates:



The lactam (1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous dichloromethane (CH_2Cl_2 (0.2 M)) was

added. Trimethyloxonium tetrafluoroborate (1.00 equiv.) was added while a mild positive pressure of argon gas flows. The mixture was then stirred for 24 h at room temperature (23 °C) under the argon atmosphere. Pentafluorophenyl hydrazine (1.00 equiv.) was added in one portion and stirring continued for 24 h. The solvent was evaporated *in vacuo* (ca. 50 torr.) thoroughly. Trituration of the resulting oil or solid with diethyl ether resulted in formation of a solid which was then filtered.

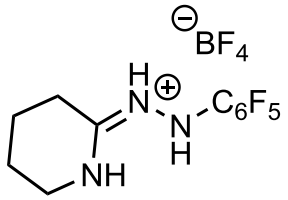
Synthesis of (*Z*)-2-(perfluorophenyl)-1-(pyrrolidin-2-ylidene)hydrazin-1-ium tetrafluoroborate (251):



Following the *Optimized Procedure*, using pyrrolidinone as the lactam. Reaction carried out on 1.00 equiv. = 37.88 mmol scale. Affords 9.923 g (74% yield over two steps) of the product as a white solid.

White solid (9.923 g, 74% yield). **m.p.**: 139.2-145.6 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3316, 1700, 1518, 1315, 1096, 1047, 931, 829, 611; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 11.43 (s, 1H), 10.42 (s, 1H), 8.90 (s, 1H), 3.66 (t, *J* = 7.1 Hz, 2H), 2.90 (t, *J* = 8.0 Hz, 2H), 2.19 (dt, *J* = 7.7, 7.4 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 170.3, 47.4, 28.7, 20.6; **HRMS** (ESI) *m*/*z* calculated for $C_{10}H_9N_3F_5$ $[M]^+$: 266.0717; found: 266.0700.

Synthesis of (*Z*)-2-(perfluorophenyl)-1-(piperidin-2-ylidene)hydrazin-1-ium tetrafluoroborate (254):

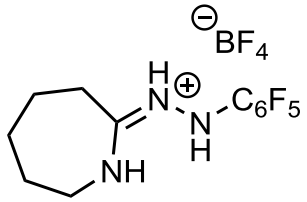


Following the *Optimized Procedure*, using 2-piperidinone as the lactam. Reaction carried out on 1.00 equiv. = 1.484 mmol scale. Affords 0.397 g (74% yield

over two steps) of the product as a red semi-solid contaminated with ca. 0.4-0.5 equiv. 2-piperidinone. Corrected mass = 0.358 g (67% yield over two steps).

Red semi-solid (0.358 g, 67% yield). **^{1}H NMR** (600 MHz, d_6-DMSO) δ 11.10 (br. s, 1H), 10.07 (br. s, 1H), 8.68 (br. s, 1H), 2.59 (t, *J* = 6.0 Hz, 2H), 2.15-2.08 (m, 2H), 1.89-1.71 (m, 2H).

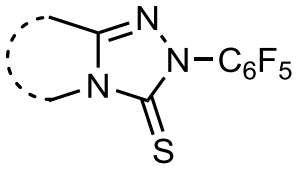
Synthesis of (*Z*)-1-(azepan-2-ylidene)-2-(perfluorophenyl)hydrazin-1-ium tetrafluoroborate (264):



Following the *Optimized Procedure*, using caprolactam as the lactam. Reaction carried out on 1.00 equiv. = 1.484 mmol scale. Affords 0.557 g (99% yield over two steps) of the product as a white solid.

White solid (0.557 g, 99% yield). **m.p.**: 215.4-216.8 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3291, 1675, 1520, 1455, 1012, 972, 821, 644; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 11.29 (s, 1H), 9.95 (s, 1H), 8.71 (s, 1H), 3.56-3.51 (m, 2H), 2.75-2.69 (m, 2H), 1.82-1.76 (m, 2H), 1.70-1.63 (m, 2H), 1.62-1.56 (m, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 170.5, 43.3, 28.8, 28.6, 27.4, 22.9; **HRMS** (ESI) *m/z* calculated for $C_{12}H_{13}N_3F_5$ $[M]^+$: 294.1030; found: 294.1019.

***Optimized Procedures for Synthesis of N-pentafluorophenyl 1,2,4-triazole-3-thiones*:**



Method 1:

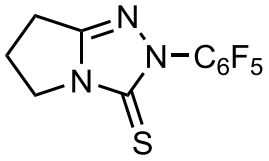
The lactam (1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous dichloromethane (CH_2Cl_2 (0.2 M) was added. Trimethyloxonium tetrafluoroborate (1.00 equiv.) was added while a mild

positive pressure of argon gas flows. The mixture was then stirred for 24 h at room temperature (23 °C) under the argon atmosphere. Pentafluorophenyl hydrazine (1.00 equiv.) was added in one portion and stirring continued for 24 h. The solvent was evaporated *in vacuo* (ca. 50 torr.) thoroughly. The resulting oil or semi-solid was suspended in pyridine (0.2 M) open to air. Thiocarbonyldiimidazole (if 90% assay, 1.1 equiv.; if 95% assay, 1.05 equiv) was added in one portion while stirring. The mixture was then stirred for 2-24 h at room temperature (23 °C). All volatiles were very thoroughly removed *in vacuo* (ca. 50 torr.). Co-evaporation using first ethyl acetate (4-8 times) and then dichloromethane (4-8 times) was required. For successful purification it was essential that all pyridine was removed. The mixture was suspended in dichloromethane and passed through a short silica plug. The plug was rinsed very thoroughly using dichloromethane. The dichloromethane fractions were combined, dried over $MgSO_4$, and all volatiles were removed *in vacuo* (≤1 torr.).

Method 2:

The isolated amidrazonium (1.00 equiv.) was added to a round bottom flask open to air. Pyridine (0.2 M) was added. Thiocarbonyldiimidazole (if 90% assay, 1.1 equiv.; if 95% assay, 1.05 equiv) was added in one portion while stirring. The mixture was then stirred for 2-24 h at room temperature (23 °C). All volatiles were very thoroughly removed *in vacuo* (ca. 50 torr.). Co-evaporation using first ethyl acetate (4-8 times) and then dichloromethane (4-8 times) was required. For successful purification it was essential that all pyridine was removed. The mixture was suspended in dichloromethane and passed through a short silica plug. The plug was rinsed very thoroughly using dichloromethane. The dichloromethane fractions were combined, dried over $MgSO_4$, and all volatiles were removed *in vacuo* (≤1 torr.).

Synthesis of 2-(perfluorophenyl)-2,5,6,7-tetrahydro-3*H*-pyrrolo[2,1-*c*][1,2,4]triazole-3-thione (253):



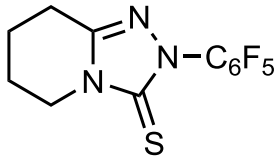
Following the *Optimized Procedure;*

Method 1, using pyrrolidinone as the lactam. Reaction carried out on 1.00 equiv. = 13.16 mmol scale. Affords 2.675 g (67% yield over three steps) of the product as an off-white solid.

Method 2, using (*Z*)-2-(perfluorophenyl)-1-(pyrrolidin-2-ylidene)hydrazin-1-ium tetrafluoroborate as the amidrazonium. Reaction carried out on 1.00 equiv. = 10.2 mmol scale. Affords 2.297 g (73% yield over one step) of the product as an off-white solid.

Off-white solid (2.675 g, 67% yield). **m.p.**: 132.5-133.5 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 1605, 1514, 1389, 991, 918, 752, 502; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 3.93 (t, *J* = 7.0 Hz, 2H), 3.04 (t, *J* = 7.5 Hz, 2H), 2.61 (dt, *J* = 7.5, 7.4 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 166.0, 160.3, 44.4, 25.7, 22.5; **HRMS** (EI^+) *m*/*z* calculated for $C_{11}H_6N_3SF_5$ $[M]^+$: 307.0202; found: 307.0210.

Synthesis of 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridine-3(2*H*)-thione (255):



Following the *Optimized Procedure;*

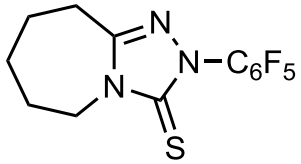
Method 1, using piperidinone as the lactam. Reaction carried out on 1.00 equiv. = 1.484 mmol scale. Affords 0.155 g (32% yield over three steps) of the product as an off-white solid. Additional compound contaminated with pentafluorophenyl hydrazine could be obtained by washing the silica plug using 1% *v*/*v* MeOH in dichloromethane as the eluent.

Method 2, using (*Z*)-2-(perfluorophenyl)-1-(piperidin-2-ylidene)hydrazin-1-ium tetrafluoroborate as the amidrazonium. Reaction carried out on 1.00 equiv. = 1.484 mmol scale. Affords 0.110 g (23% yield over one step) of the product as an off-white solid.

Off-white solid (0.110 g, 23% yield). **m.p.**: 114.6-115.6 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 2955, 1569, 1509, 1484, 1375, 1084, 993, 888, 717, 493; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 3.80 (t, *J* = 6.0 Hz, 2H), 2.86 (t, *J* = 6.0 Hz, 2H), 2.00 (app. t, *J* =

5.5 Hz, 2H), 1.88 (dd, *J* = 12.0, 6.0 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 168.2, 151.5, 44.0, 21.5, 20.9, 18.2; **HRMS** (EI^+) *m/z* calculated for $C_{12}H_8N_3SF_5$ $[M]^+$: 321.0359; found: 321.0367.

Synthesis of 2-(perfluorophenyl)-2,5,6,7,8,9-hexahydro-3H-[1,2,4]triazolo[4,3-a]azepine-3-thione (265):

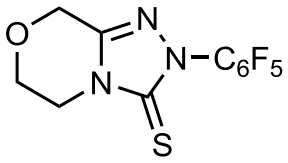


Following the *Optimized Procedure;*

Method 2, using (*Z*)-1-(azepan-2-ylidene)-2-(perfluorophenyl)hydrazin-1-ium tetrafluoroborate as the amidrazonium. Reaction carried out on 1.00 equiv. = 1.484 mmol scale. Affords 0.347 g (70% yield over one step) of the product as an off-white solid.

Off-white solid (0.347 g, 70% yield). **m.p.**: 86.9-96.6 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 2936, 1732, 1514, 1374, 1098, 992, 892, 964, 493; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 4.26 (m, 2H), 2.94 (m, 2H), 1.84 (m, 2H), 1.72 (m, 4H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 169.2, 156.7, 46.3, 29.6, 27.0, 26.0, 24.8; **HRMS** (EI^+) *m/z* calculated for $C_{13}H_{10}N_3SF_5$ $[M]^+$: 335.0515; found: 335.0509.

Synthesis of 2-(perfluorophenyl)-2,5,6,8-tetrahydro-3H-[1,2,4]triazolo[3,4-c][1,4]oxazine-3-thione (258):



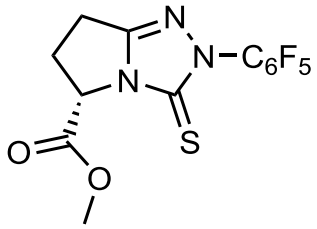
Following the *Optimized Procedure;*

Method 1, using 2-morpholinone as the lactam. Reaction carried out on 1.00 equiv. = 1.484 mmol scale. Affords 0.330 g (69% yield over three steps) of the product as an off-white solid.

Off-white solid (0.330 g, 69% yield). **m.p.**: 133.6-136.3 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 1581, 1514, 1363, 1077, 995, 895, 489; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 4.90 (s, 2H), 4.14 (t, *J* = 5.5 Hz, 2H), 3.87 (t, *J* = 5.5 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-

DMSO) δ 168.3, 148.6, 63.0, 61.4, 42.8; **HRMS** (EI^+) *m/z* calculated for $C_{11}H_6N_3OSF_5$ $[M]^+$: 323.0152; found: 323.0152.

Synthesis of methyl (*S*)-2-(perfluorophenyl)-3-thioxo-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-5-carboxylate (263):

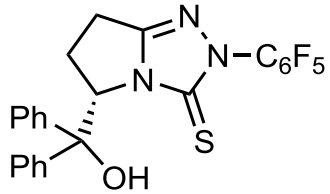


Following the *Optimized Procedure;*

Method 1, using (*S*)-methyl pyroglutamate as the lactam. Reaction carried out on 1.00 equiv. = 4.283 mmol scale. Affords 1.083 g (69% yield over three steps) of the product as a pale yellow oil.

Yellow oil (1.083 g, 69% yield). **$[\alpha]_D^{23}$** = -130 (*c* = 1.1, MeOH); **m.p.**: 123.9-125.1 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 2923, 1745, 1600, 1514, 1394, 1216, 988, 767; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 4.89-4.84 (m, 1H), 3.84 (s, 3H), 3.18-3.09 (m, 1H), 3.09-3.00 (m, 2H), 2.76-2.69 (m, 1H); **^{13}C NMR** (125 MHz, $CDCl_3$) δ 168.5, 167.5, 158.6, 57.0, 53.5, 32.0, 22.4; **HRMS** (EI^+) *m/z* calculated for $C_{13}H_8N_3O_2SF_5$ $[M]^+$: 365.0257; found: 365.0264.

Synthesis of (*S*)-5-(hydroxydiphenylmethyl)-2-(perfluorophenyl)-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-3-thione (275):[145]

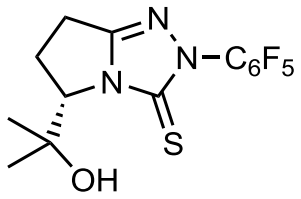


Methyl (*S*)-2-(perfluorophenyl)-3-thioxo-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-5-carboxylate (182 mg, 0.5 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous tetrahydrofuran (5.12 mL (~0.1 M)) was added. The mixture was cooled to 0 °C. Phenylmagnesium bromide (2.56 mL of 0.43 M solution in Et_2O, 1.1 mmol, 2.2

equiv.) was added dropwise while stirring. The mixture was then stirred for 24 h at 66 °C. The reaction was then quenched by addition of $NaHCO_{3(sat.)}$. The aqueous layer was extracted three times using dichloromethane. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (ca. 50 torr.). Affords 0.178 g (73% yield) of the product as a yellow oil which could not be purified.

Impure yellow oil (0.178 g, 73% yield). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.49-7.20 (m, 10H), 5.47 (app. d, *J* = 8.9 Hz, 1H), 2.98 (ddd, *J* = 19.4, 14.0, 9.7 Hz, 1H), 2.73-2.64 (m, 1H), 2.57 (app. dd, *J* = 17.3, 10.0 Hz, 1H), 1.86 (app. dt, *J* = 17.2, 9.5 Hz, 1H).

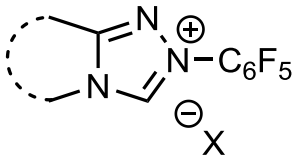
Synthesis of (*S*)-5-(2-hydroxypropan-2-yl)-2-(perfluorophenyl)-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-3-thione (276):[145]



Methyl (*S*)-2-(perfluorophenyl)-3-thioxo-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-5-carboxylate (182 mg, 0.5 mmol, 1.00 equiv.) was added to a round bottom flask. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Anhydrous tetrahydrofuran (5.1 mL (~0.1 M)) was added. The mixture was cooled to 0 °C. Methylmagnesium bromide (0.37 mL of 3.0 M solution in Et_2O, 1.1 mmol, 2.2 equiv.) was added dropwise while stirring. The mixture was then stirred for 24 h at 66 °C. The reaction was then quenched by addition of $NaHCO_{3(sat.)}$. The aqueous layer was extracted three times using dichloromethane. The organic layers were combined, dried over Na_2SO_4, and all volatiles were removed *in vacuo* (ca. 50 torr.). Affords 0.183 g (88% yield) of the product as a yellow oil which could not be purified.

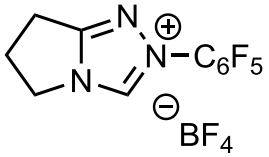
Impure yellow oil (0.183 g, 88% yield). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 5.46 (br. s, 1H), 4.50 (app. t, *J* = 7.4 Hz, 1H), 3.11-3.01 (m, 1H), 3.00-2.91 (m, 1H), 2.85-2.75 (m, 1H), 2.45-2.34 (m, 1H).

***Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones*:**



The 1,2,4-triazole-3-thione (1.00 equiv.) was added to a round bottom flask. Reagent grade diethyl ether (0.05 M) was added. Hydrogen peroxide (3.00 equiv., 30% w/w solution in water) was added. The acid (HX, 1.00 equiv.) was added dropwise. The reaction mixture was stirred for the desired amount of time, typically 2 h, open to air. Typically a suspension was formed and the mixture was filtered. The resulting solid was dried *in vacuo* (≤1 torr.). Trituration of the solid with diethyl ether may be used to increase compound purity, or to induce crystallization if a suspension was not formed.

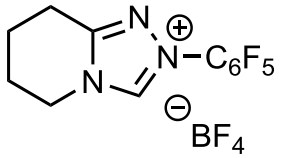
Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (5):



Following the *Optimized Procedure*, using 2-(perfluorophenyl)-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-3-thione as the substrate. 5 min. stirring with tetrafluoroboric acid (50% w/w solution in water). No trituration required. Reaction carried out on 1.00 equiv. = 1.654 mmol scale. Affords 0.345 g (79% yield) of the product as a white solid. All spectra and physical properties are consistent with those previously reported.[7]

White solid (0.345 g, 79% yield). **m.p.**: 244.1-244.9 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3144, 1601, 1517, 1498, 1026, 993, 874, 523; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 10.55 (s, 1H), 4.47 (t, *J* = 7.0 Hz, 2H), 3.24 (t, *J* = 8.0 Hz, 2H), 2.75 (dt, *J* = 15.0, 7.5 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 164.4, 144.0, 48.2, 26.6, 21.6; **HRMS** (ESI) *m*/*z* calculated for $C_{11}H_7N_3F_5$ $[M]^+$: 276.0555; found: 276.0558.

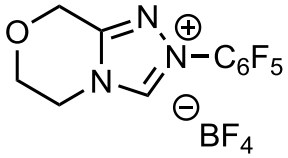
Synthesis of 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (156):



Following the *Optimized Procedure*, using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridine-3(2H)-thione as the substrate. 3 h stirring with tetrafluoroboric acid (50% w/w solution in water). No trituration required. Reaction carried out on 1.00 equiv. = 0.311 mmol scale. Affords 0.074 g (63% yield) of the product as a white solid. All spectra and physical properties are consistent with those previously reported.[146]

White solid (0.074 g, 63% yield). **m.p.**: 176.6-179.5 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3135, 1593, 1517, 1071, 991, 845, 520; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 10.62 (s, 1H), 4.39 (t, *J* = 5.5 Hz, 2H), 3.11 (t, *J* = 6.5 Hz, 2H), 2.05 (app. d, *J* = 4.5 Hz, 2H), 1.98 (app. d, *J* = 5.5 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 154.6, 146.1, 46.4, 20.7, 20.3, 18.0; **HRMS** (ESI) *m/z* calculated for $C_{12}H_9N_3F_5$ $[M]^+$: 290.0711; found: 290.0723.

Synthesis of 2-(perfluorophenyl)-5,6-dihydro-8H-[1,2,4]triazolo[3,4-c][1,4]oxazin-2-ium tetrafluoroborate (155):

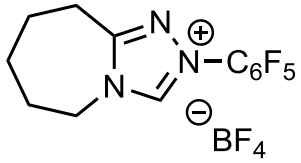


Following the *Optimized Procedure*, using 2-(perfluorophenyl)-2,5,6,8-tetrahydro-3H-[1,2,4]triazolo[3,4-c][1,4]oxazine-3-thione as the substrate. 3 h stirring with tetrafluoroboric acid (50% w/w solution in water). Trituration of the mother liquor is required. Reaction carried out on 1.00 equiv. = 0.311 mmol scale. Affords 0.061 g (52% yield) of the product as a white solid. All spectra and physical properties are consistent with those previously reported.[146]

White solid (0.061 g, 52% yield). **m.p.**: 155.6-156.8 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 1593, 1517, 1072, 978, 850, 575; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 10.75 (s, 1H), 5.19 (s, 2H), 4.50 (t, *J* = 5.2 Hz, 2H), 4.19 (t, *J* = 5.3 Hz, 2H); **^{13}C NMR** (125

MHz, d_6-DMSO) δ 151.1, 146.7, 62.2, 61.2, 45.5; **HRMS** (ESI) *m/z* calculated for $C_{11}H_7N_3OF_5$ $[M]^+$: 292.0509; found: 292.0500.

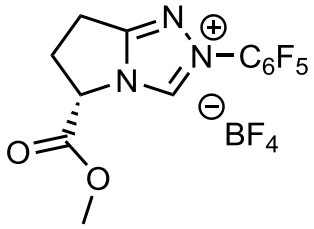
Synthesis of 2-(perfluorophenyl)-6,7,8,9-tetrahydro-5H-[1,2,4]triazolo[4,3-a]azepin-2-ium tetrafluoroborate (157):



Following the *Optimized Procedure*, using 2-(perfluorophenyl)-2,5,6,7,8,9-hexahydro-3H-[1,2,4]triazolo[4,3-a]azepine-3-thione as the substrate. 30 s stirring with tetrafluoroboric acid (50% w/w solution in water). No trituration required. Reaction carried out on 1.00 equiv. = 0.311 mmol scale. Affords 0.085 g (70% yield) of the product as a white solid. All spectra and physical properties are consistent with those previously reported.[146]

White solid (0.085 g, 70% yield). **m.p.**: 138.9-149.3 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3134, 2939, 1598, 1518, 1068, 990, 849, 576; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 10.60 (s, 1H), 4.49 (t, *J* = 3.5 Hz, 2H), 3.18 (t, *J* = 5.5 Hz, 2H), 2.00-1.85 (m, 4H), 1.84-1.71 (m, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 159.5, 147.2, 49.5, 28.9, 26.1, 25.1, 23.6; **HRMS** (ESI) *m/z* calculated for $C_{13}H_{11}N_3F_5$ $[M]^+$: 304.0868; found: 304.0876.

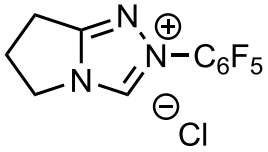
Synthesis of (*S*)-5-(methoxycarbonyl)-2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (277):



Following the *Optimized Procedure*, using methyl (S)-2-(perfluorophenyl)-3-thioxo-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-5-carboxylate as the substrate. 3 h stirring with tetrafluoroboric acid (50% w/w solution in water). No trituration required. Reaction carried out on 1.00 equiv. = 0.662 mmol scale. Affords 0.118 g (42% yield) of the product as a white solid.

White solid (0.118 g, 42% yield). **$[\alpha]_D^{23}$** = -72 (*c* = 0.98, MeOH); **m.p.**: 140.5-141.4 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 1754, 1604, 1525, 1064, 1001, 868, 523; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 10.78 (s, 1H), 5.72 (dd, *J* = 9.2, 6.6 Hz, 1H), 3.85 (s, 3H), 3.40-3.06 (m, 3H) 3.02-2.94 (m, 1H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 167.4, 164.0, 145.0, 61.0, 53.5, 30.4, 21.4; **HRMS** (ESI) *m/z* calculated for $C_{13}H_9N_3O_2F_5$ $[M]^+$: 334.0609; found: 334.0618.

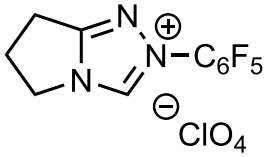
Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride (266):



Following the *Optimized Procedure*, using 2-(perfluorophenyl)-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-3-thione as the substrate. 3 h stirring with hydrochloric acid (12.1 M solution in water). Trituration of the mother liquor is required. Reaction carried out on 1.00 equiv. = 0.331 mmol scale. Affords 0.097 g (94% yield) of the product as a white solid.

White solid (0.097 g, 94% yield). **m.p.**: 135.6-137 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 2964, 1604, 1526, 1233, 1164, 1062, 999, 870, 578; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 10.55 (s, 1H), 4.47 (t, *J* = 7.5 Hz, 2H), 3.23 (t, *J* = 7.6 Hz, 2H), 2.74 (dt, *J* = 7.6, 7.5 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 164.4, 144.0, 48.2, 26.6, 21.5; **HRMS** (ESI) *m/z* calculated for $C_{11}H_7N_3F_5$ $[M]^+$: 276.0560; found: 276.0553.

Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium perchlorate (268):

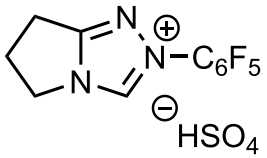


Following the *Optimized Procedure*, using 2-(perfluorophenyl)-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-3-thione as the substrate. 3 h stirring with perchloric acid (70% w/w solution in water). No trituration required.

Reaction carried out on 1.00 equiv. = 0.331 mmol scale. Affords 0.105 g (85% yield) of the product as a white solid.

White solid (0.105 g, 85% yield). **m.p.**: >260 °C (instrument limit); **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3131, 1659, 1524, 1068, 995, 622; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 10.54 (s, 1H), 4.47 (t, *J* = 7.5 Hz, 2H), 3.24 (t, *J* = 7.5 Hz, 2H), 2.75 (dt, *J* = 7.5, 7.5 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 164.4, 144.0, 48.2, 26.6, 21.6; **HRMS** (ESI) *m*/*z* calculated for $C_{11}H_7N_3F_5$ $[M]^+$: 276.0560; found: 276.0557.

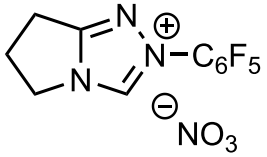
Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium bisulfate (270):



Following the *Optimized Procedure*, using 2-(perfluorophenyl)-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-3-thione as the substrate. 3 h stirring with sulfuric acid (18.8 M solution in water). Trituration of the mother liquor is required. Reaction carried out on 1.00 equiv. = 0.331 mmol scale. Affords 0.076 g (61% yield) of the product as a white solid.

White solid (0.076 g, 61% yield). **m.p.**: 136.0-136.4 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 3077, 2964, 1604, 1526, 1232, 1164, 1061, 999, 846, 578; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 10.55 (s, 1H), 4.47 (t, *J* = 7.5 Hz, 2H), 3.24 (t, *J* = 7.5 Hz, 2H), 2.75 (dt, *J* = 7.5, 7.6 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 164.4, 144.0, 48.2, 26.6, 21.6; **HRMS** (ESI) *m*/*z* calculated for $C_{11}H_7N_3F_5$ $[M]^+$: 275.0560; found: 276.0559.

Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium nitrate (269):



Following the *Optimized Procedure*, using 2-(perfluorophenyl)-2,5,6,7-tetrahydro-3H-pyrrolo[2,1-c][1,2,4]triazole-3-thione as the substrate. 3 h stirring with nitric acid (15.7 M solution in water). Trituration of the mother liquor is

required. Reaction carried out on 1.00 equiv. = 0.331 mmol scale. Affords 0.099 g (88% yield) of the product as a white solid.

White solid (0.099 g, 88% yield). **m.p.**: 135.7-139.6 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 2961, 1603, 1525, 1237, 1156, 1062, 999, 836, 578, 431; **^{1}H NMR** (500 MHz, d_6-DMSO) δ 10.55 (s, 1H), 4.48 (t, *J* = 7.5 Hz, 2H), 3.23 (t, *J* = 7.5 Hz, 2H), 2.75 (dt, *J* = 7.5, 7.5 Hz, 2H); **^{13}C NMR** (125 MHz, d_6-DMSO) δ 164.4, 144.0, 48.2, 26.6, 21.6; **HRMS** (ESI) *m*/*z* calculated for $C_{11}H_7N_3F_5$ $[M]^+$: 276.0560; found: 276.0557.

5.2.3. General Procedure for ^{1}H-NMR Monitoring Experiments

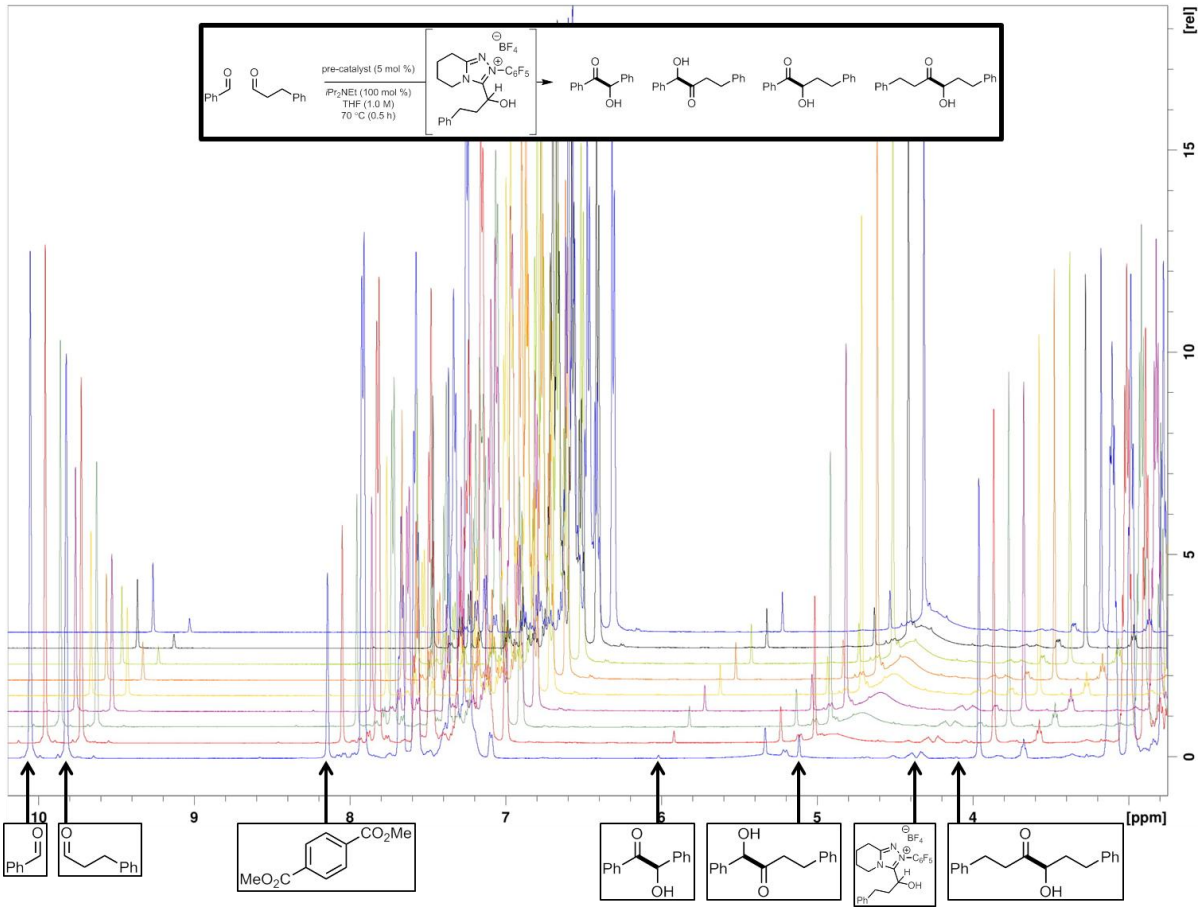
General Procedure:

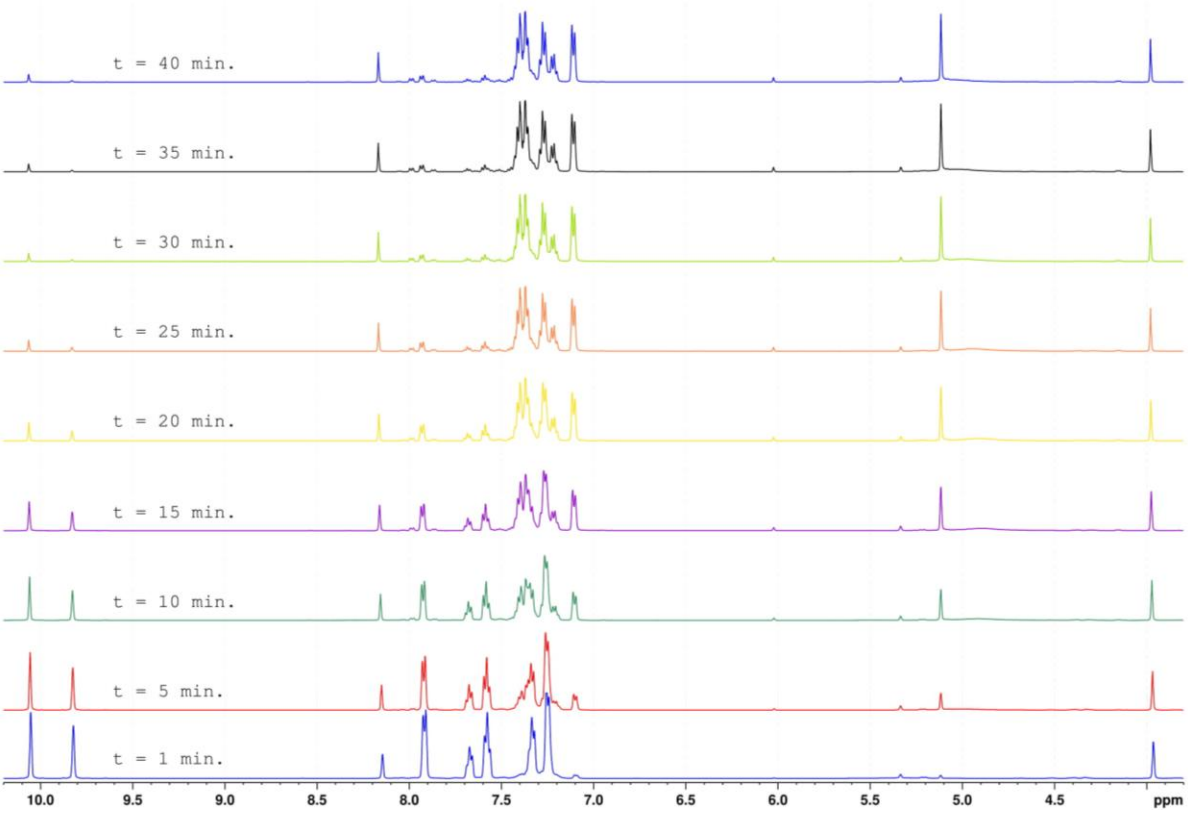
An NMR tube was placed inside a bottle with a Schlenk take-off. The bottle was capped, purged under vacuum (≤1 torr.) five times, and placed under inert (argon) atmosphere. The bottle was opened while a mild positive pressure of argon gas flows. The azolium salt was added to the NMR tube. Typically a solid internal standard such as dimethylterephthalate or bibenzyl was added. If one or more of the aldehydes is also a solid then they were also added at this stage. The bottle was again capped, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. The bottle was opened while a mild positive pressure of argon gas flows. Liquid aldehyde(s) and the solvent were then added. The NMR tube was capped and sealed with paraffin film. A vortex mixer may be used to ensure complete dissolution of the internal standard and any solid aldehyde(s). The NMR instrument with the sample inside was brought to the desired temperature. Locking and shimming must be performed at the desired temperature. A spectrum was acquired to confirm that the compounds were visible with an appropriate degree of resolution. As quickly as possible, the sample was removed from the spectrometer, the cap minimally removed, and the base was added in one portion. The exact time of addition, to the nearest second, was recorded. The tube was resealed with paraffin film, inverted once for mixing, and returned to the instrument. The total time from ejection and re-injection of the sample should not exceed 30 s. Spectra were acquired either manually or using a pre-programmed sequence with regular intervals. Time points were

determined using the experimentally recorded time in the audita.txt file, to the nearest second, relative to the time of base addition.

Monitoring species concentration (Scheme 3.15):

Following the *General Procedure*, using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (iPr$_2$NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 50 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.





Comparison of reaction rates:

Following the *General Procedure*, four separate experiments were carried out:

Experiment 1: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (the pyrrolidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 50 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

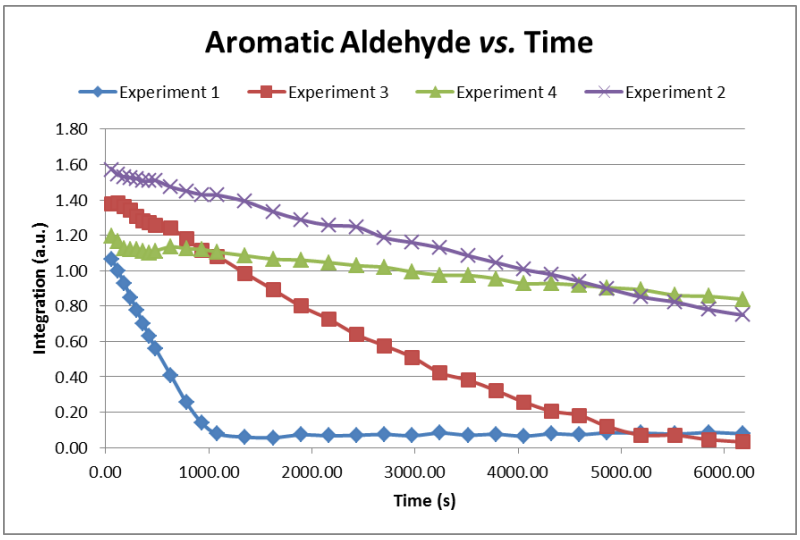
Experiment 2: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (the pyrrolidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). *p*-Anisaldehyde (*p*-OMe benzaldehyde; 1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in

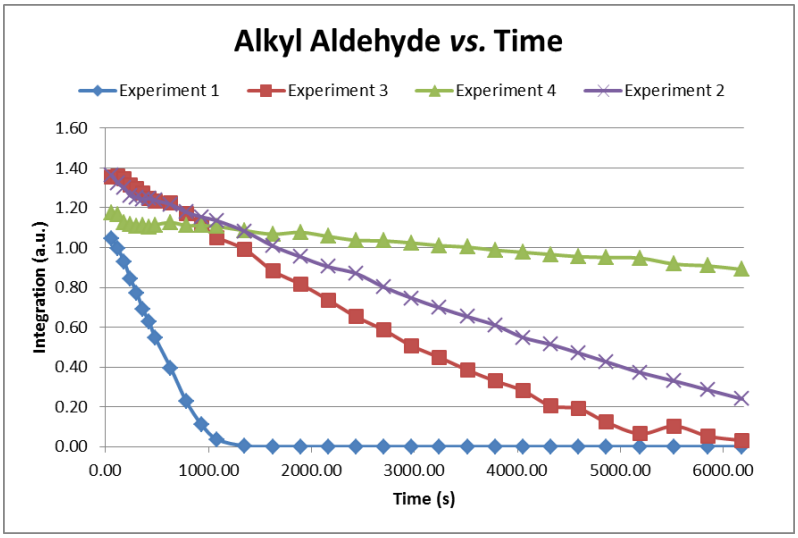
deuterated dichloromethane (1.0 M) at 50 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

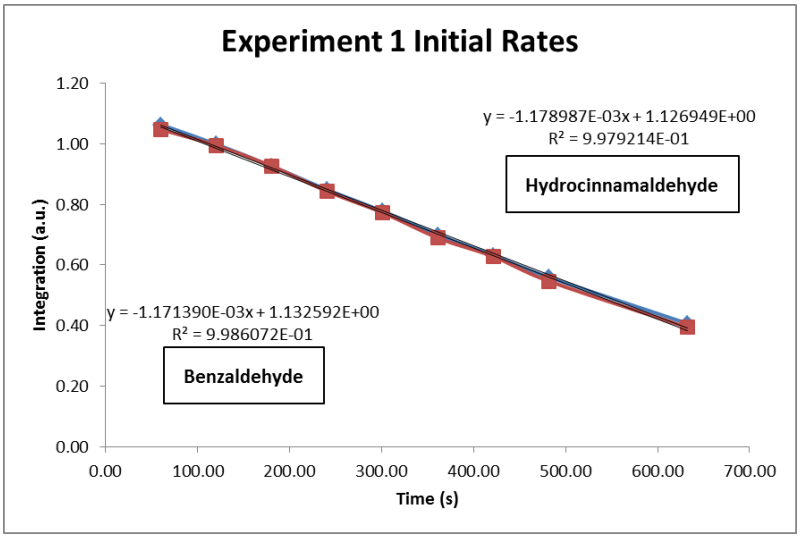
Experiment 3: using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (iPr$_2$NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 50 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

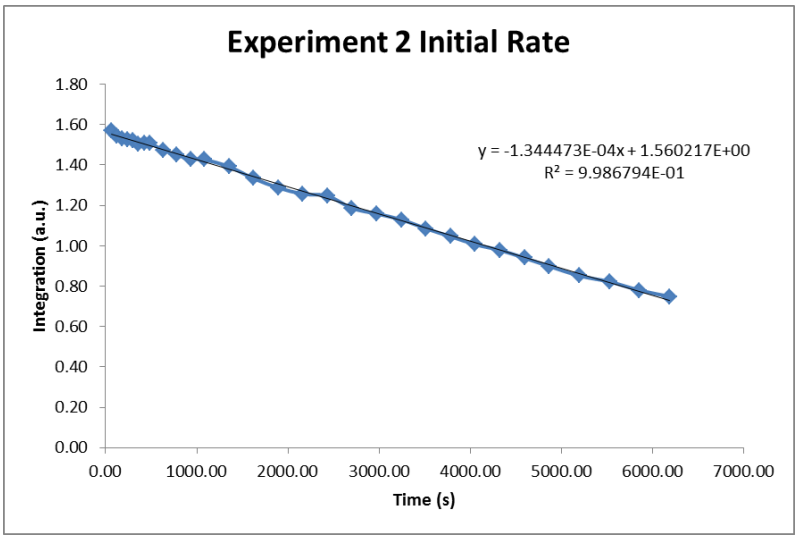
Experiment 4: using 2-(perfluorophenyl)-6,7,8,9-tetrahydro-5H-[1,2,4]triazolo[4,3-a]azepin-2-ium tetrafluoroborate (the caprolactam-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (iPr$_2$NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 50 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

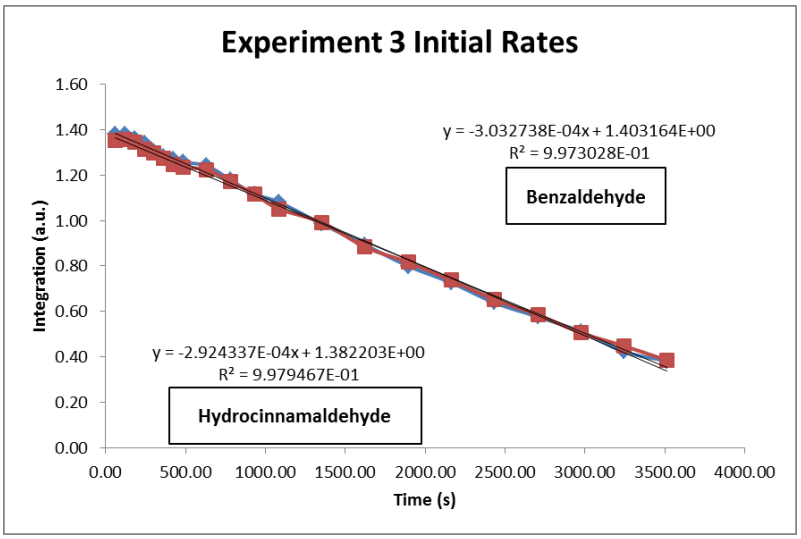
The initial rates were compared. In experiments 1, 3, and 4 the initial rate is determined by averaging the initial rates of consumption of benzaldehyde and hydrocinnamaldehyde. This is done to mitigate the effects of having multiple benzoin products being formed. In experiment 2 only the initial rate of consumption of *p*-anisaldehyde is used as the sole product formed on this timescale is the relevant cross-benzoin product. To account for differences in the integral values all slopes are adjusted (normalized) to a starting integration of 1.00 a.u. and then compared.

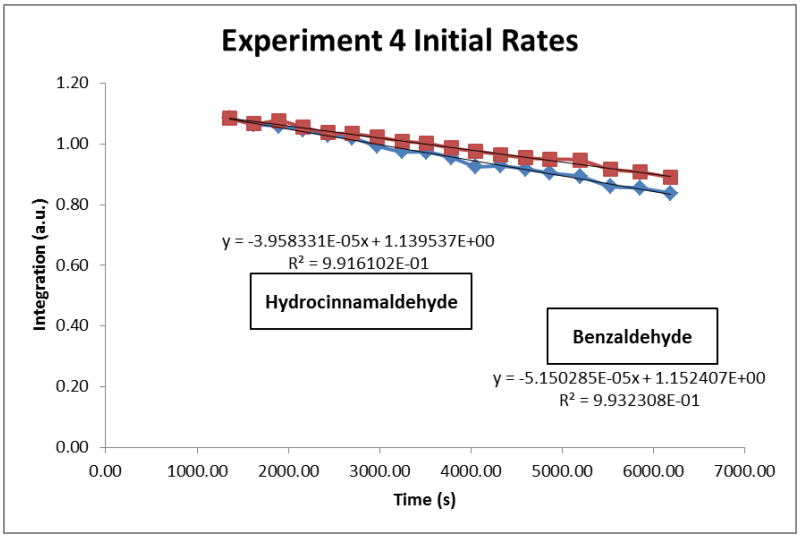

Aromatic Aldehyde vs. Time
Experiment 1
Experiment 3
Experiment 4
Experiment 2
Integration (a.u.)
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
1000.00
2000.00
3000.00
4000.00
5000.00
6000.00
Time (s)


Alkyl Aldehyde vs. Time
Experiment 1
Experiment 3
Experiment 4
Experiment 2
Integration (a.u.)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
1000.00
2000.00
3000.00
4000.00
5000.00
6000.00
Time (s)


Experiment 1 Initial Rates
y = -1.178987E-03x + 1.126949E+00
R² = 9.979214E-01
Hydrocinnamaldehyde
y = -1.171390E-03x + 1.132592E+00
R² = 9.986072E-01
Benzaldehyde
Integration (a.u.)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700.00
Time (s)


Experiment 2 Initial Rate
y = -1.344473E-04x + 1.560217E+00
R² = 9.986794E-01
Integration (a.u.)
Time (s)
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
1000.00
2000.00
3000.00
4000.00
5000.00
6000.00
7000.00


Experiment 3 Initial Rates
y = -3.032738E-04x + 1.403164E+00
R² = 9.973028E-01
Benzaldehyde
y = -2.924337E-04x + 1.382203E+00
R² = 9.979467E-01
Hydrocinnamaldehyde
Integration (a.u.)
Time (s)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
500.00
1000.00
1500.00
2000.00
2500.00
3000.00
3500.00
4000.00


Experiment 4 Initial Rates
y = -3.958331E-05x + 1.139537E+00
R² = 9.916102E-01
Hydrocinnamaldehyde
Benzaldehyde
y = -5.150285E-05x + 1.152407E+00
R² = 9.932308E-01
Integration (a.u.)
Time (s)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
1000.00
2000.00
3000.00
4000.00
5000.00
6000.00
7000.00

Experiment 1		Experiment 3		Experiment 4		Experiment 2	
Benz Trendline	**Hydro Trendline**	**Benz Trendline**	**Hydro Trendline**	**Benz Trendline**	**Hydro Trendline**	**Anis Trendline**	**Hydro Trendline**
x Intercept	**x Intercept**	**x Intercept**	**x Intercept**	**x Intercept**	**x Intercept**	**x Intercept**	**x Intercept**
966.8786655	955.8621087	4626.723443	4726.551694	22375.59669	28788.32013	11604.67336	n/a
Slope (m)	**Slope (m)**	**Slope (m)**	**Slope (m)**	**Slope (m)**	**Slope (m)**	**Slope (m)**	**Slope (m)**
-0.00117139	-0.001178987	-0.000303274	-0.000292434	-5.15029E-05	-3.95833E-05	-0.000134447	n/a
y Intercept	**y Intercept**	**y Intercept**	**y Intercept**	**y Intercept**	**y Intercept**	**y Intercept**	**y Intercept**
1.132592	1.126949	1.403164	1.382203	1.152407	1.139537	1.560217	n/a
			Assign all starting concentrations as an integral value of 1.				
Normalized m	**Normalized m**	**Normalized m**	**Normalized m**	**Normalized m**	**Normalized m**	**Normalized m**	**Normalized m**
-0.001034256	-0.001046176	-0.000216136	-0.000211571	-4.46915E-05	-3.47363E-05	-8.61722E-05	n/a
Averaged Normalized Slope (m)		**Averaged Normalized Slope (m)**		**Averaged Normalized Slope (m)**		**Averaged Normalized Slope (m)**	
-0.001040216		-0.000213853		-3.97139E-05		n/a	
Relative Rate		**Relative Rate**		**Relative Rate**		**Relative Rate**	
1		0.205585388		0.038178541		0.083318042	

Effect of temperature on the cross-benzoin reaction:

Following the *General Procedure*, two separate experiments were carried out:

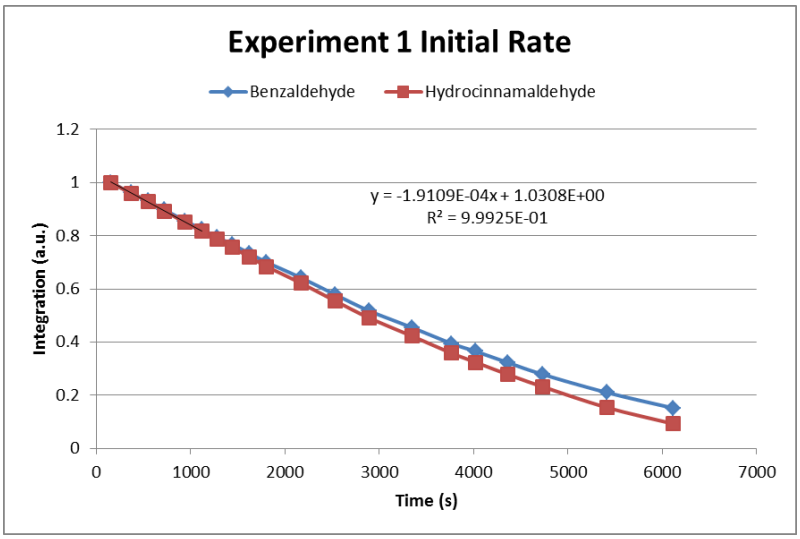
Experiment 1: using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (iPr$_2$NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 40 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

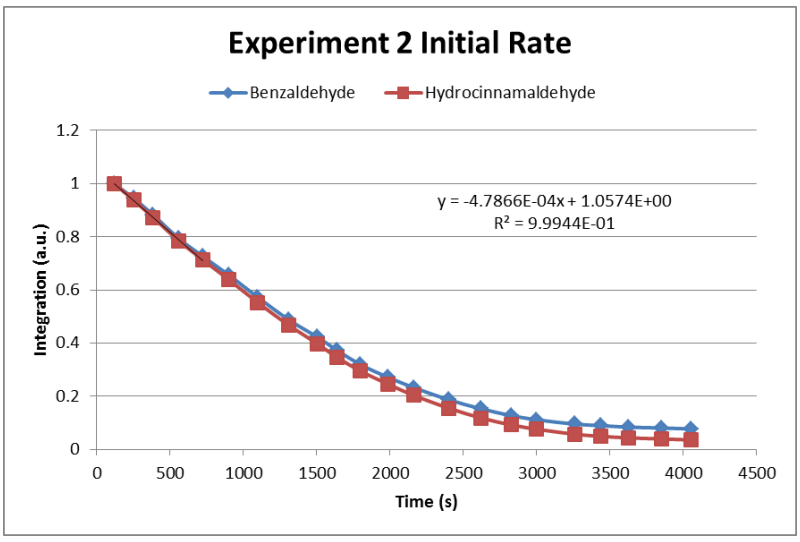
Experiment 2: using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (iPr$_2$NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 50 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

The initial rates were compared. To account for differences in the integral values all integrations are adjusted (normalized) to a starting integration of 1.00 a.u. and then compared. The initial rate is determined using the initial rate of consumption of hydrocinnamaldehyde. Using either or the average of the rates of

consumption of both hydrocinnamaldehyde and benzaldehyde affords, within error, the same value.

At 40 °C the initial rate is ca. 40% as much as at 50 °C (-1.91/-4.79 = 0.399). Therefore, each increase of 10 °C increases the reaction rate ca. 2.5-fold.





5.2.3.1. Determination of Reaction Order Using ^{1}H-NMR Monitoring Experiments

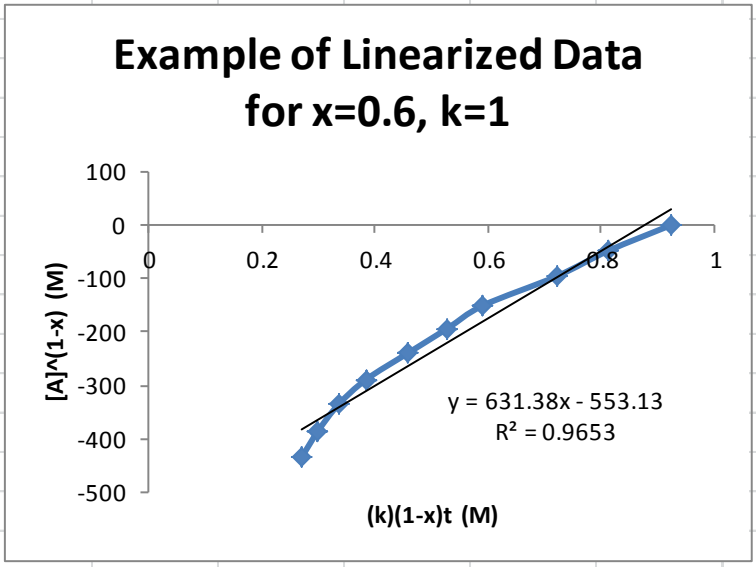
Order with respect to hydrocinnamaldehyde in the cross-benzoin reaction:

Following the *General Procedure*, using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in anhydrous toluene (1.0 M) at 70 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

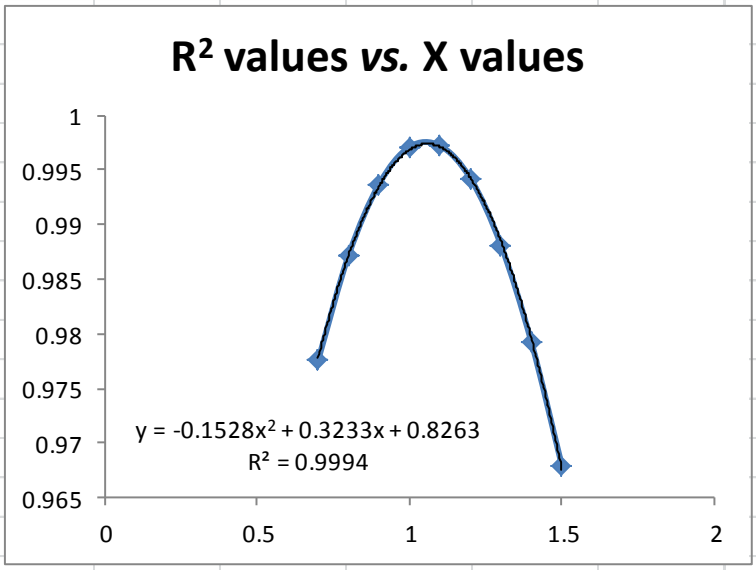
Using the steady state approximation, values of x (the order with respect to hydrocinnamaldehyde) were varied. A measure of how linear (R^2) the resulting plot of $[A]^{1-x}=(-k_{app})(1-x)t$ is was recorded. The maximum of the parabola describing the relationship between x and R^2 (*viz*. the most linear plot of the data with a given order with respect to hydrocinnamaldehyde) was determined and used to determine to the exponent. Based on this data, the reaction is first order with respect to hydrocinnamaldehyde, within error.

A+B => C
r = -dA/dt = k*[A]^(x)*[B]^(y)
if dB/dt = 0 (steady state), then
dA/dt = -k(app)*[A]^(x)
integrating gives
[A]^(1-x) = -k(app)*t*(1-x)

Raw Data	
t	[A]
1	0.8178
120	0.5954
240	0.4411
376	0.2686
484	0.2024
600	0.1416
723	0.0914
840	0.0651
961	0.0493
1080	0.0385



x	R^2
0.6	0.9653
0.7	0.9776
0.8	0.9872
0.9	0.9937
1.0001	0.9971
1.1	0.9972
1.2	0.9942
1.3	0.9881
1.4	0.9792
1.5	0.9679



The maximum of y = ax^2 + bx + c is c-(b^2/(4a)), so maximum is **.9973**

This means **x = 1.06**

Order with respect to benzaldehyde in the cross-benzoin reaction:

Following the *General Procedure*, eight separate experiments were carried out:

Experiment 1: using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) was used as internal standard. The reaction was carried out in anhydrous toluene (1.0 M) at 60 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

Experiment 2: as *Experiment 1* (replica data point).

Experiment 3: as *Experiment 1* using 0.50 equiv. benzaldehyde instead.

Experiment 4: as *Experiment 1* using 1.25 equiv. benzaldehyde instead.

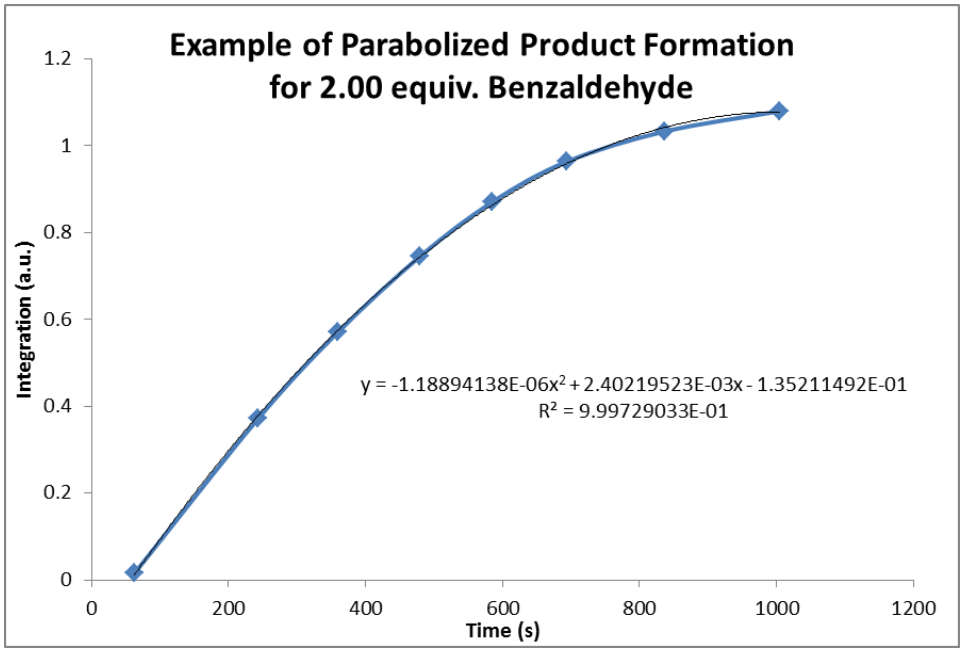
Experiment 5: as *Experiment 1* using 1.50 equiv. benzaldehyde instead.

Experiment 6: as *Experiment 1* using 2.00 equiv. benzaldehyde instead.

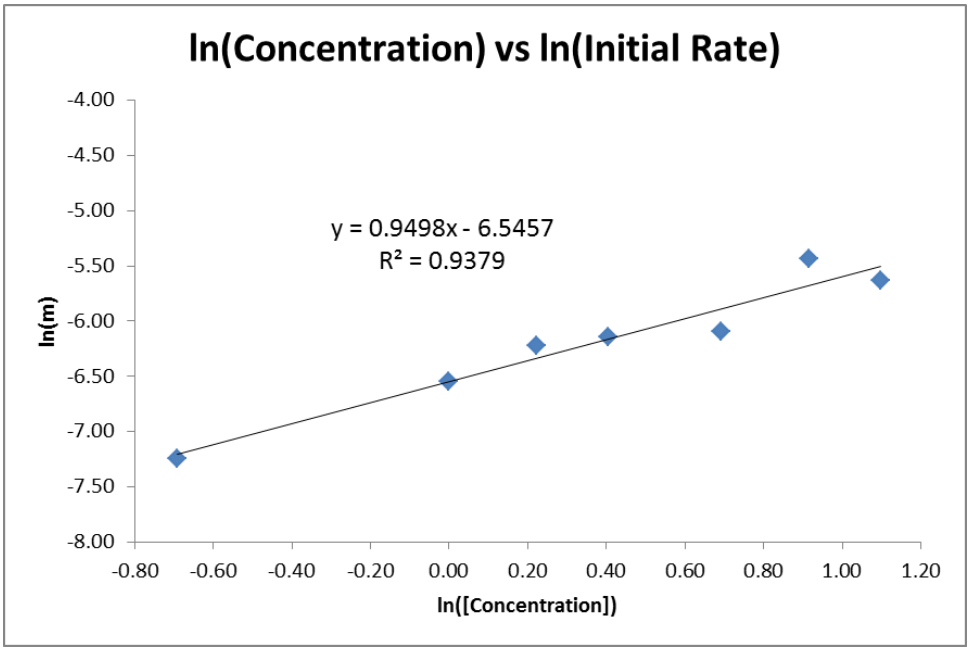
Experiment 7: as *Experiment 1* using 2.50 equiv. benzaldehyde instead.

Experiment 8: as *Experiment 1* using 3.00 equiv. benzaldehyde instead.

The initial rates were compared. The initial rate was determined by plotting the formation of the pertinent cross-benzoin product over time. This was done to mitigate the effects of having multiple benzoin products being formed in varying amounts as a result of the different stoichiometries. A parabola was fitted to the data and the slope of the tangent at the beginning of the reaction was determined. A plot of the natural logarithms of the concentrations and initial rates was used to determine the exponent from the slope of the line. Based on this data, the reaction is first order with respect to benzaldehyde, within error.



Equiv.	a	b	c	R^2	root	m at root	ln([])	ln(slope)
1.00	-7.3607E-08	4.8417E-04	-3.9656E-02	9.9366E-01	8.2951E+01	4.7196E-04	0.0000	-7.6586
2.00	-1.1889E-06	2.4022E-03	-1.3521E-01	9.9973E-01	5.7949E+01	2.2644E-03	0.6931	-6.0904
0.50	-1.6959E-07	7.5125E-04	-8.0640E-02	9.8779E-01	1.1008E+02	7.1391E-04	-0.6931	-7.2448
1.50	-1.1055E-06	2.3716E-03	-2.2876E-01	9.9347E-01	1.0124E+02	2.1478E-03	0.4055	-6.1433
3.00	-3.0398E-06	4.1731E-03	-3.7848E-01	9.9813E-01	9.7639E+01	3.5795E-03	1.0986	-5.6325
1.00	-4.8592E-07	1.4524E-03	-2.8370E-02	9.8473E-01	1.9662E+01	1.4333E-03	0.0000	-6.5478
1.25	-9.4181E-07	2.1116E-03	-1.2943E-01	9.9786E-01	6.3068E+01	1.9928E-03	0.2231	-6.2182
2.50	-4.2001E-06	5.1574E-03	-4.4446E-01	9.9351E-01	9.3263E+01	4.3739E-03	0.9163	-5.4321



5.2.3.2. Procedure for Catalyst Adduct Formation Using ^{1}H-NMR Monitoring Experiments

Adduct formation and exchange with hydrocinnamaldehyde (210) and octanal (212):

Following the *General Procedure*, two experiments were performed:

Experiment 1: using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.95 equiv.). Hydrocinnamaldehyde (1.00 equiv.) was used. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. The reaction was carried out in deuterated dichloromethane (0.05 M) at 50 °C. Reaction carried out on 1.00 equiv. = 0.05 mmol scale. Long term (>8 h) stability in solution was confirmed.

Experiment 2: using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.95 equiv.). Hydrocinnamaldehyde (1.00 equiv.) was initially used. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. The reaction was carried out in deuterated dichloromethane (0.1 M) at 23 °C. Reaction carried out on 1.00 equiv. = 0.05 mmol scale. After 3 min. octanal (1.00 equiv.) was added. Monitoring continued to confirm exchange and equilibration rather than homo- or cross-benzoin product formation.

Adduct formation with benzaldehyde (216):

Following the *General Procedure*, using 2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (the piperidinone-derived triazolium salt) as the pre-catalyst (0.95 equiv.). Benzaldehyde (1.00 equiv.) was used. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. The reaction was carried out in deuterated dichloromethane (0.1 M) at 23 °C. Reaction carried out on 1.00 equiv. = 0.05 mmol scale.

5.2.3.3. Determination of Counterion Effects Using ^{1}H-NMR Monitoring Experiments

Comparison of Counterion Effects in the Stetter Reaction:

Following the *General Procedure*, four separate experiments were carried out:

Experiment 1: Control reaction using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure For Synthesis of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate* (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). 2-Furfuraldehyde (1.00 equiv.) and *trans*-chalcone (1.00 equiv.) were used as the substrates. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 25 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

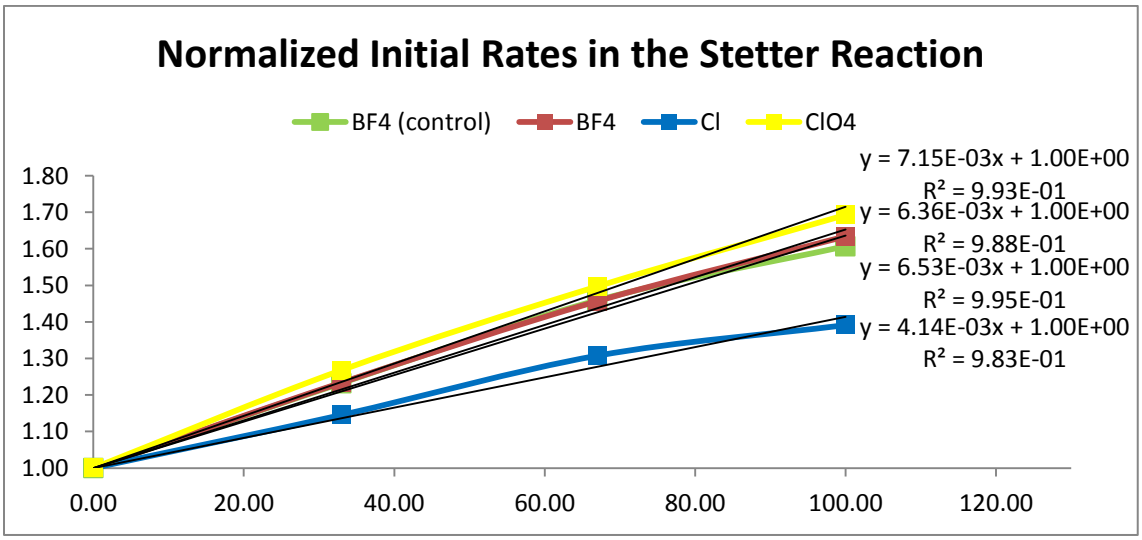
Experiment 2: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). 2-Furfuraldehyde (1.00 equiv.) and *trans*-chalcone (1.00 equiv.) were used as the substrates. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 25 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

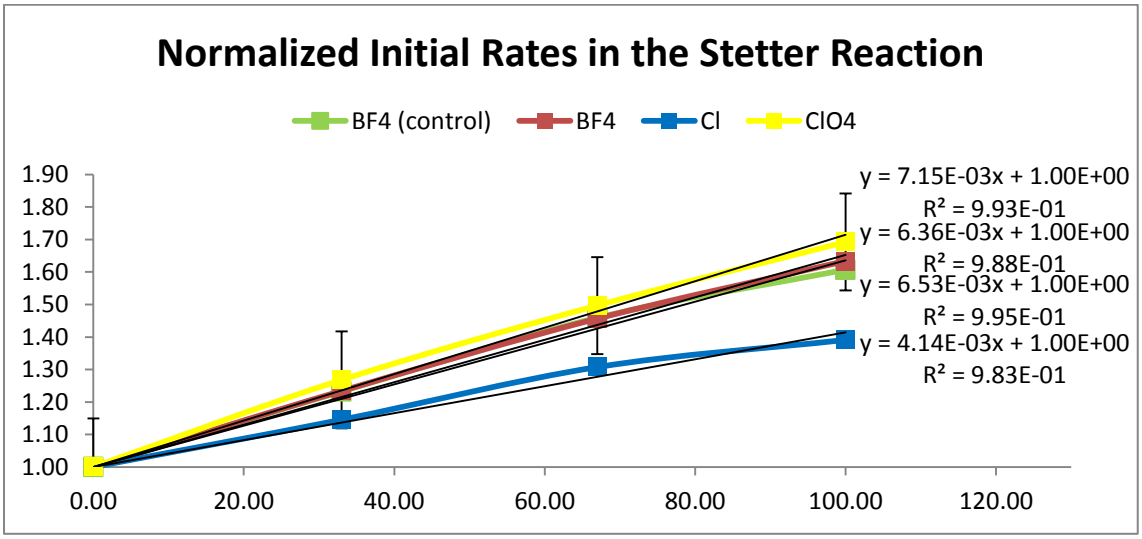
Experiment 3: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). 2-Furfuraldehyde (1.00 equiv.) and *trans*-chalcone (1.00 equiv.) were used as the substrates. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 25 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

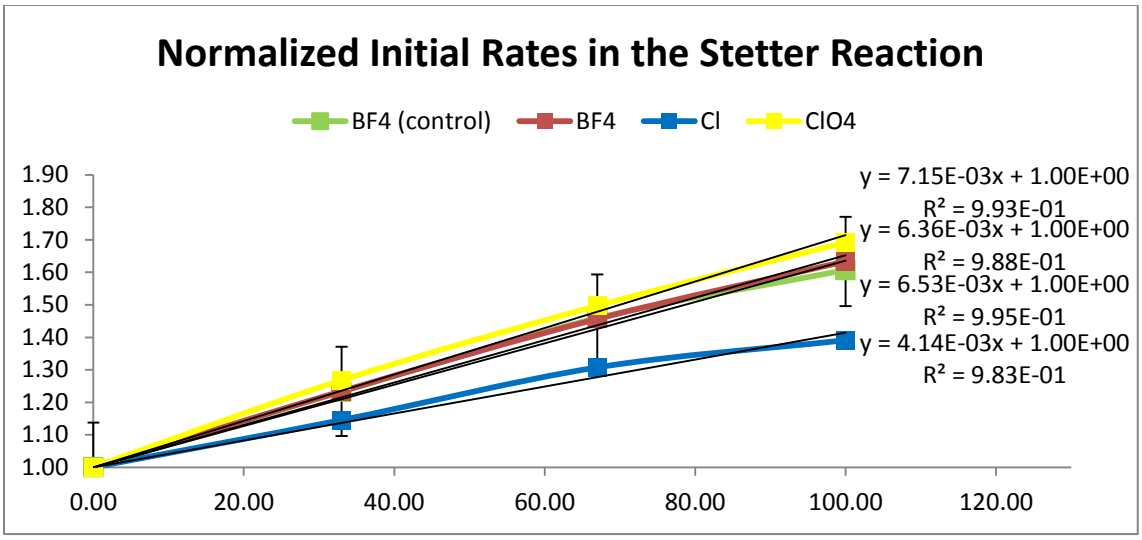
Experiment 4: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium perchlorate (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl*

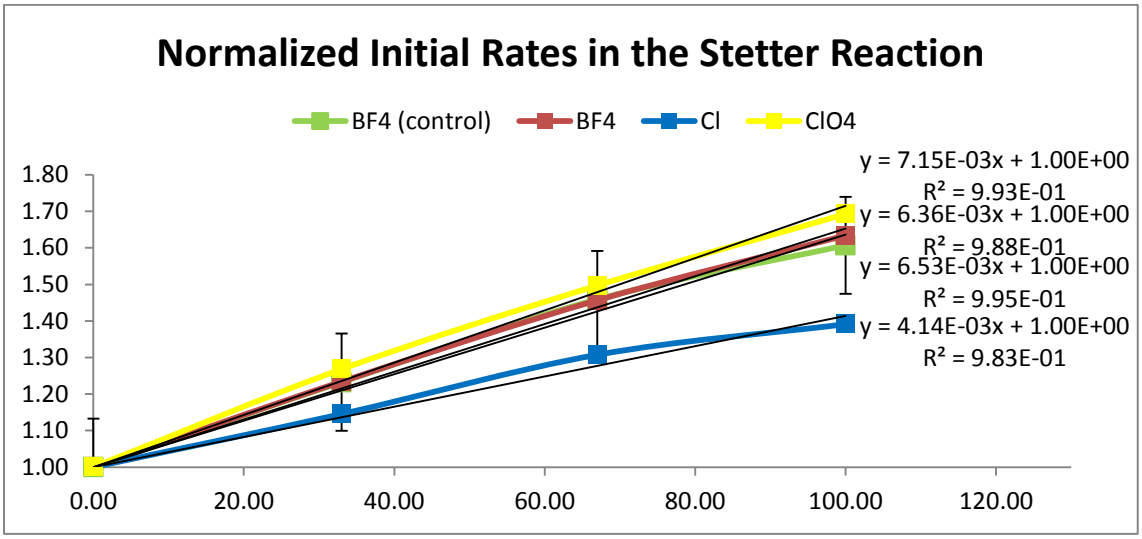
triazolium salts from 1,2,4-triazole-3-thiones (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). 2-Furfuraldehyde (1.00 equiv.) and *trans*-chalcone (1.00 equiv.) were used as the substrates. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (1.00 equiv.) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 25 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

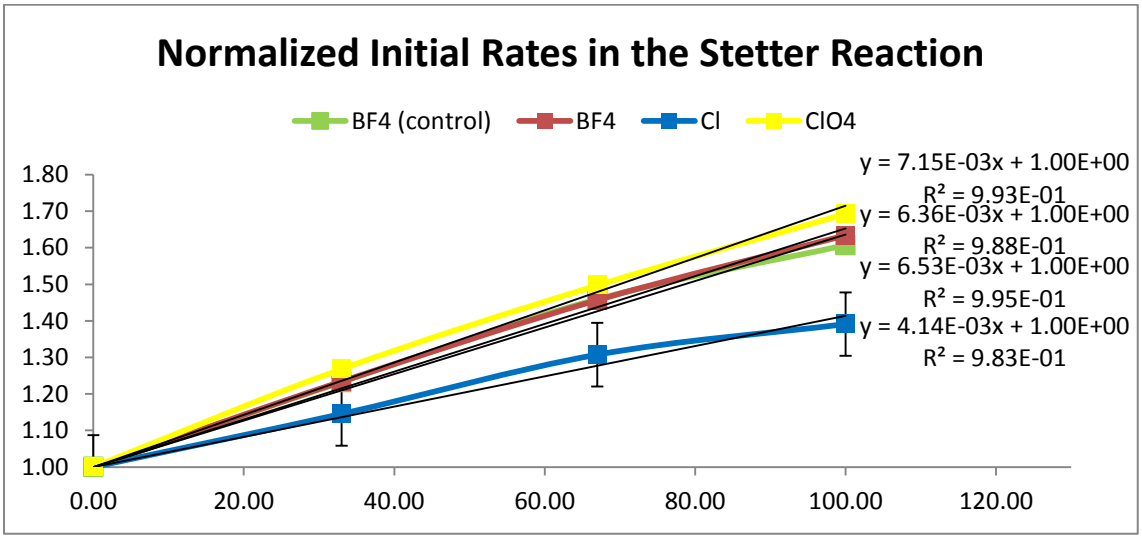
The initial rates were compared. The initial rate was determined by plotting the formation of the Stetter product over time. This was done to mitigate the effects of having a competitive benzoin product being formed. Standard error of the mean was used to determine whether two reactions are statistically different with respect to their rates.






Normalized Initial Rates in the Stetter Reaction
BF4 (control)
BF4
Cl
ClO4
y = 7.15E-03x + 1.00E+00
R² = 9.93E-01
y = 6.36E-03x + 1.00E+00
R² = 9.88E-01
y = 6.53E-03x + 1.00E+00
R² = 9.95E-01
y = 4.14E-03x + 1.00E+00
R² = 9.83E-01
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00


Normalized Initial Rates in the Stetter Reaction
BF4 (control)
BF4
Cl
ClO4
y = 7.15E-03x + 1.00E+00
R² = 9.93E-01
y = 6.36E-03x + 1.00E+00
R² = 9.88E-01
y = 6.53E-03x + 1.00E+00
R² = 9.95E-01
y = 4.14E-03x + 1.00E+00
R² = 9.83E-01
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00


Normalized Initial Rates in the Stetter Reaction
BF4 (control)
BF4
Cl
ClO4
y = 7.15E-03x + 1.00E+00
R² = 9.93E-01
y = 6.36E-03x + 1.00E+00
R² = 9.88E-01
y = 6.53E-03x + 1.00E+00
R² = 9.95E-01
y = 4.14E-03x + 1.00E+00
R² = 9.83E-01
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00

Comparison of Counterion Effects in a Cross-Benzoin Reaction:

Following the *General Procedure*, five separate experiments were carried out:

Experiment 1: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 35 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

Experiment 2: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 35 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

Experiment 3: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium perchlorate (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 35 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

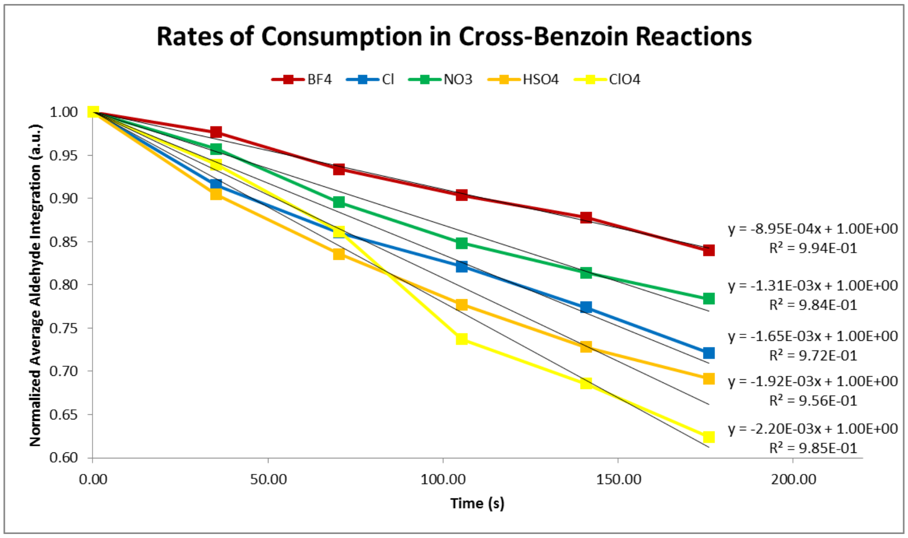
Experiment 4: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium nitrate (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) as the pre-

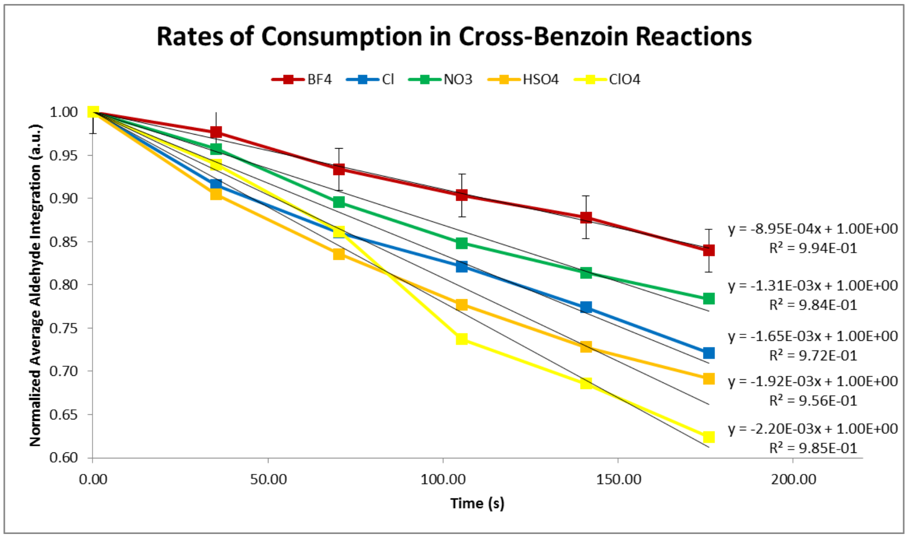
catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 35 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

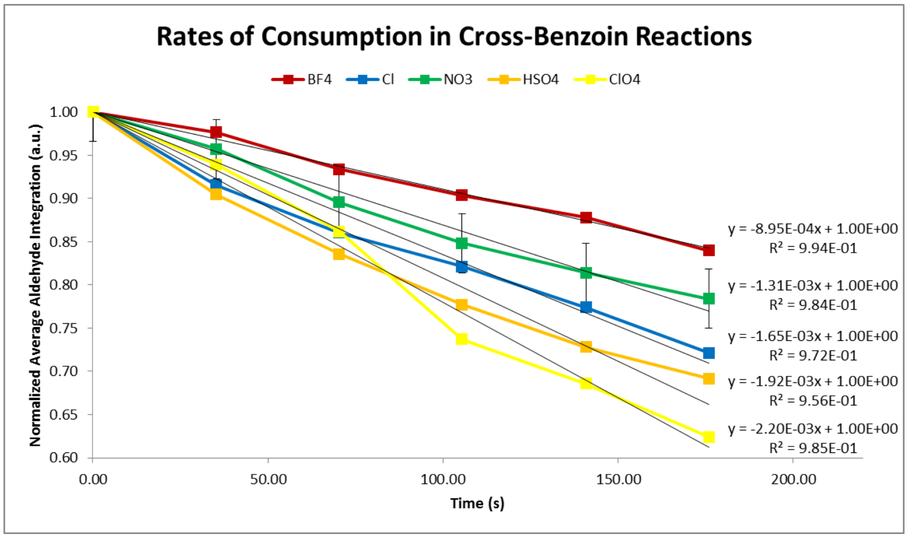
Experiment 5: using 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium bisulfate (the pyrrolidinone-derived triazolium salt) synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) as the pre-catalyst (0.05 equiv.). Benzaldehyde (1.00 equiv.) and hydrocinnamaldehyde (1.00 equiv.) were used as the aldehydes. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 1.00 equiv.) was used as the base. Dimethyl terephthalate (10 mg) used as internal standard. The reaction was carried out in deuterated dichloromethane (1.0 M) at 35 °C. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

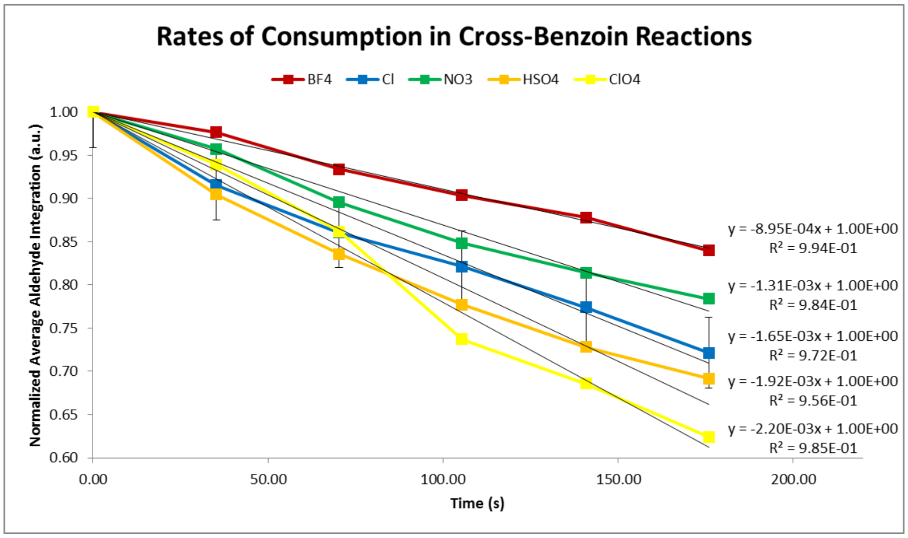
The initial rates were compared. The initial rate was determined by plotting the average initial rates of consumption of benzaldehyde and hydrocinnamaldehyde over time. This was done to mitigate the effects of having multiple benzoin products being formed. Standard error of the mean was used to determine whether two reactions are statistically different with respect to their rates.

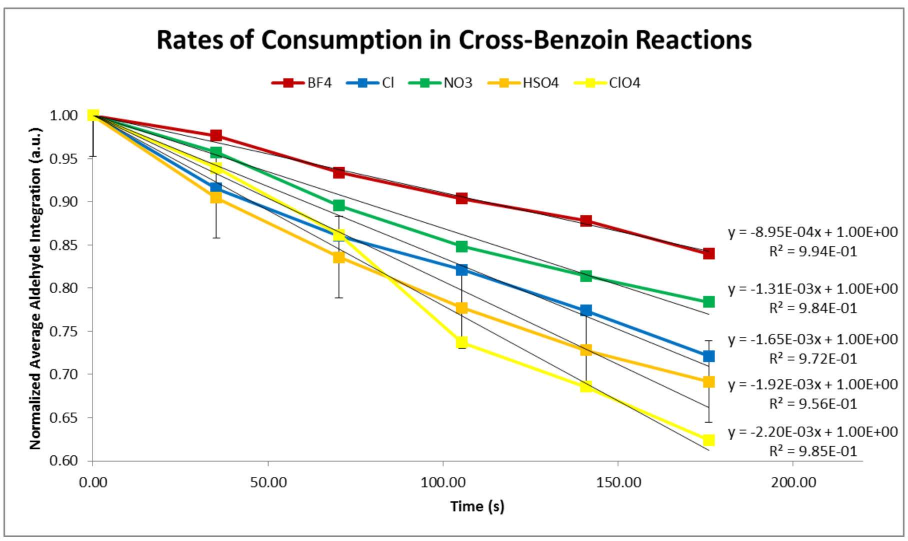
Experiments 1, 2, and 3 were repeated. The relative rates of experiments 2 and 3 remained consistent, within error. However, experiment 1 proved variable; across four replica experiments the tetrafluoroborate salt provided the fastest, slowest, slowest, and fastest results. In all cases use of tetrafluoroborate pre-catalyst synthesized *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) and *via* the *Optimized Procedure for Synthesis of N-pentafluorophenyl triazolium salts from 1,2,4-triazole-3-thiones* (see Section 5.2.2) affords, within error, the same relative rates.

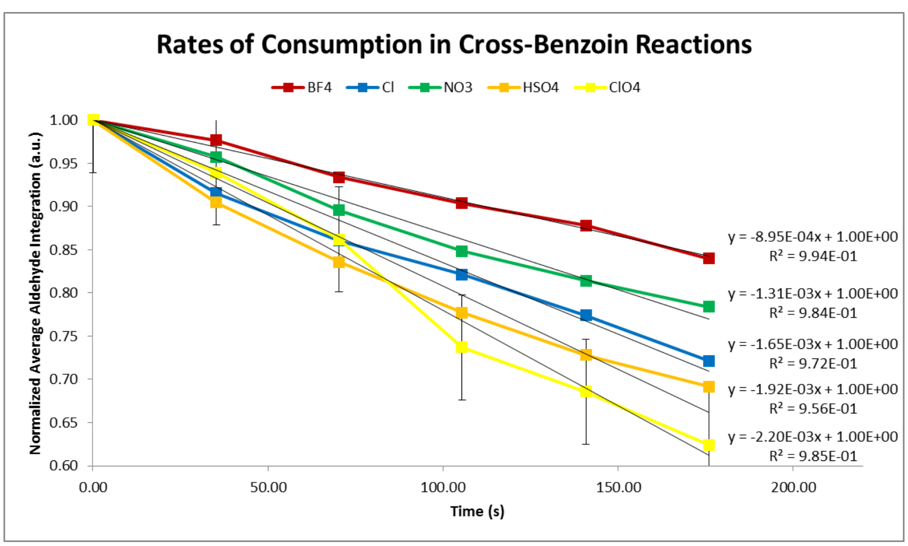

Rates of Consumption in Cross-Benzoin Reactions
BF4
Cl
NO3
HSO4
ClO4
Normalized Average Aldehyde Integration (a.u.)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.00
50.00
100.00
150.00
200.00
Time (s)
y = -8.95E-04x + 1.00E+00
R² = 9.94E-01
y = -1.31E-03x + 1.00E+00
R² = 9.84E-01
y = -1.65E-03x + 1.00E+00
R² = 9.72E-01
y = -1.92E-03x + 1.00E+00
R² = 9.56E-01
y = -2.20E-03x + 1.00E+00
R² = 9.85E-01


Rates of Consumption in Cross-Benzoin Reactions
BF4
Cl
NO3
HSO4
ClO4
Normalized Average Aldehyde Integration (a.u.)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.00
50.00
100.00
150.00
200.00
Time (s)
y = -8.95E-04x + 1.00E+00
R² = 9.94E-01
y = -1.31E-03x + 1.00E+00
R² = 9.84E-01
y = -1.65E-03x + 1.00E+00
R² = 9.72E-01
y = -1.92E-03x + 1.00E+00
R² = 9.56E-01
y = -2.20E-03x + 1.00E+00
R² = 9.85E-01


Rates of Consumption in Cross-Benzoin Reactions
BF4
Cl
NO3
HSO4
ClO4
Normalized Average Aldehyde Integration (a.u.)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.00
50.00
100.00
150.00
200.00
Time (s)
y = -8.95E-04x + 1.00E+00
R² = 9.94E-01
y = -1.31E-03x + 1.00E+00
R² = 9.84E-01
y = -1.65E-03x + 1.00E+00
R² = 9.72E-01
y = -1.92E-03x + 1.00E+00
R² = 9.56E-01
y = -2.20E-03x + 1.00E+00
R² = 9.85E-01


Rates of Consumption in Cross-Benzoin Reactions
BF4
Cl
NO3
HSO4
ClO4
Normalized Average Aldehyde Integration (a.u.)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.00
50.00
100.00
150.00
200.00
Time (s)
y = -8.95E-04x + 1.00E+00
R² = 9.94E-01
y = -1.31E-03x + 1.00E+00
R² = 9.84E-01
y = -1.65E-03x + 1.00E+00
R² = 9.72E-01
y = -1.92E-03x + 1.00E+00
R² = 9.56E-01
y = -2.20E-03x + 1.00E+00
R² = 9.85E-01


Rates of Consumption in Cross-Benzoin Reactions
BF4
Cl
NO3
HSO4
ClO4
Normalized Average Aldehyde Integration (a.u.)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.00
50.00
100.00
150.00
200.00
Time (s)
y = -8.95E-04x + 1.00E+00
R² = 9.94E-01
y = -1.31E-03x + 1.00E+00
R² = 9.84E-01
y = -1.65E-03x + 1.00E+00
R² = 9.72E-01
y = -1.92E-03x + 1.00E+00
R² = 9.56E-01
y = -2.20E-03x + 1.00E+00
R² = 9.85E-01


Rates of Consumption in Cross-Benzoin Reactions
BF4
Cl
NO3
HSO4
ClO4
Normalized Average Aldehyde Integration (a.u.)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.00
50.00
100.00
150.00
200.00
Time (s)
y = -8.95E-04x + 1.00E+00
R² = 9.94E-01
y = -1.31E-03x + 1.00E+00
R² = 9.84E-01
y = -1.65E-03x + 1.00E+00
R² = 9.72E-01
y = -1.92E-03x + 1.00E+00
R² = 9.56E-01
y = -2.20E-03x + 1.00E+00
R² = 9.85E-01

5.2.4. General Procedure for Crossover Benzoin Reactions

General Procedure:

The piperidinone-derived triazolium salt (0.05 equiv.) was added to a test tube with a Schlenk take-off. If one or more of the substrates is also a solid then they were added with the azolium salt. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Liquid substrate(s) were then added. The substrates were rinsed to the bottom of the vessel as the anhydrous solvent (CH_2Cl_2 (1.0 M)) was added. Lastly *i*Pr_2NEt (1.00 equiv.) was added and the septum quickly exchanged for a cold finger while a mild positive pressure of argon gas flowed. The flask was then sealed and brought to 70 °C. The reaction mixture was stirred for the desired amount of time, typically 30 min. and was then quenched by washing with 2 M HCl. The organic component was dried over Na_2SO_4. Volatiles were then removed *in vacuo* (ca. 50 torr.).

Crossover experiment between 4-hydroxy-1,6-diphenylhexan-3-one and octanal:

Following the *General Procedure* using 4-hydroxy-1,6-diphenylhexan-3-one (the homo-benzoin product of hydrocinnamaldehyde; 1.00 equiv.) and octanal (1.00 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.36 mmol scale.

Crossover experiment between 4-hydroxy-1,6-diphenylhexan-3-one and benzaldehyde:

Following the *General Procedure* using 4-hydroxy-1,6-diphenylhexan-3-one (the homo-benzoin product of hydrocinnamaldehyde; 1.00 equiv.) and benzaldehyde (0.75 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

Crossover experiment between 2-hydroxy-1,2-diphenylethan-1-one and hydrocinnamaldehyde:

Following the *General Procedure* using 2-hydroxy-1,2-diphenylethan-1-one (the homo-benzoin product of benzaldehyde; 0.50 equiv.) and hydrocinnamaldehyde (1.50 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.25 mmol scale.

Crossover experiment between 2-hydroxy-1,2-diphenylethan-1-one and *p*-anisaldehyde:

Following the *General Procedure* using 2-hydroxy-1,2-diphenylethan-1-one (the homo-benzoin product of benzaldehyde; 1.00 equiv.) and *p*-anisaldehyde (*p*-OMe benzaldehyde; 1.00 equiv.). Reaction time = 2 h. Reaction carried out on 1.00 equiv. = 0.5 mmol scale.

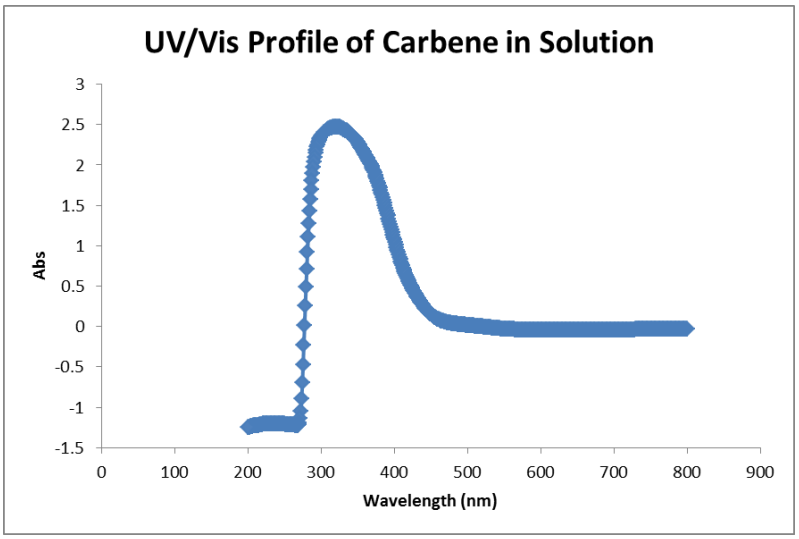
5.2.5. Procedure for Monitoring Catalyst Solubility

Three cuvettes were placed inside a bottle with a Schlenk take-off. The bottle was capped, purged under vacuum (≤1 torr.) five times, and placed under inert (argon) atmosphere. The bottle was opened while a mild positive pressure of argon gas flowed. 2-(Perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetra-fluoroborate (the pyrrolidinone-derived triazolium salt; 0.006 g, ca. 0.015 mmol, 1.00 equiv.) was added to two of the cuvettes. The bottle was again capped, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. The bottle was opened while a mild positive pressure of argon gas flows. Anhydrous dichloromethane (1.5 mL, 1.0 M) was added to each cuvette.

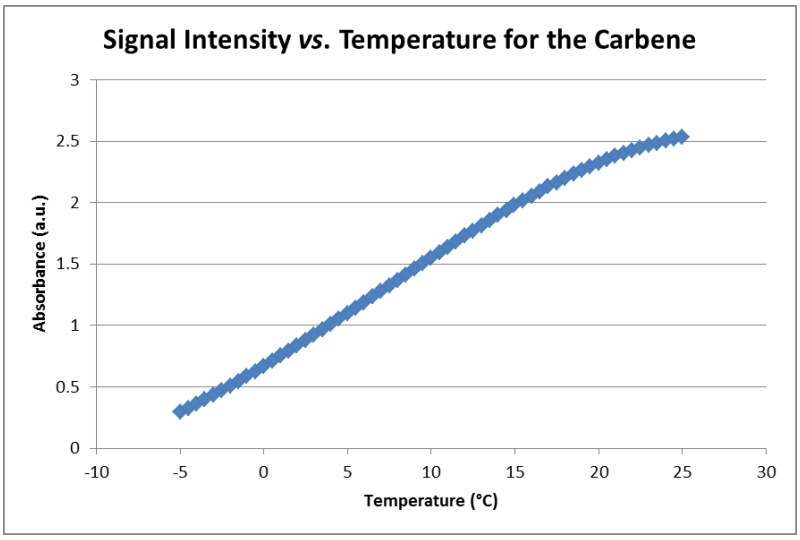
The cuvette without 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate was capped and sealed with paraffin film. A blank UV/Vis spectrum was acquired at room temperature on a Cary 6000i UV Spectrometer. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 10 µL, 1.00 equiv.) was added through the paraffin film using a syringe. Additional paraffin film was used to re-seal the vessel. The cuvette was inverted once for mixing and an additional UV/Vis spectrum was acquired.

The first cuvette with 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate was capped and sealed with paraffin film.

A UV/Vis spectrum was acquired at room temperature on a Cary 6000i UV Spectrometer. *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 6 µL, 0.35 mmol, 23 equiv.) was added through the paraffin film using a syringe. Additional paraffin film is used to re-seal the vessel. The cuvette was inverted once for mixing and an additional UV/Vis spectrum was acquired. A new maximum was observed, confirming the formation of free carbene.



The second cuvette with 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate was capped and sealed with paraffin film. The UV/Vis instrument with the sample inside was brought to the desired temperature starting temperature (-5 °C) using a Varian 18 Cell Holder Transporter Water Thermo with ethanol as the solvent. As quickly as possible, the sample was removed from the spectrometer and *N*,*N*-diisopropylethylamine (*i*Pr_2NEt; 6 µL, 0.35 mmol, 23 equiv.) was added through the paraffin film using a syringe. Additional paraffin film was used to re-seal the vessel. The cuvette was inverted once for mixing and re-placed into the spectrometer. The temperature was raised by 0.25 °C/min. A UV/Vis measurement at 320 nm (determined using the UV/Vis profile of the carbene in solution above) was acquired at half degree intervals.



5.2.6. General Computational Methods

All reported calculations were performed with the Gaussian 09 software package.[116] The M06-2X exchange-correlation functional with the polarized diffuse split-valence 6-31+G(d,p) basis set was used for all geometry optimizations (including those with constraints), transition state calculations, infrared frequency calculations, and IRC calculations. This level of theory was chosen as it is both commonly utilized and accounts for non-covalent interactions (London dispersion forces, π interactions, etc.) which may have a pronounced effect on the calculated energy.[117] Subsequent single-point energies were determined using the same functional with the corresponding triple-ζ 6-311+G(d,p) basis set. Solvent effects were added using the integral equation formalism model (IEFPCM)[118] with radii and nonelectrostatic terms for Truhlar and co-workers' SMD solvation model (CH_2Cl_2).[119]

For each species a broad conformational search was performed using the MMFF94 force field in Spartan '08.[147] Additional conformers were generated by hand as needed. The lowest energy structures (typically 20−30) were carried forward for full optimization. The conformer with the lowest energy had its vibrational frequencies computed using the same level of theory to confirm that it was an energy minimum and to evaluate its zero-point vibrational energy (ZPVE) and thermal corrections at 298.15 K.

Transition states were found using a similar conformer search, but with a single constrained interatomic distance. The lowest energy conformers found with this process were optimized without the constraint and confirmed to be first-order saddle points by harmonic vibrational frequency analysis (*viz*. they contain only one imaginary frequency). The imaginary frequency was inspected to ensure it represented the desired reaction coordinate/transition. For key transition states the intrinsic reaction coordinate (IRC) was followed to ensure it connects the reactants and products.

Non-covalent interactions (NCIs) were plotted using NCIPLOT version 1.0 with the coordinates from the corresponding structure/transition state.[120] Other three-dimensional representations were generated using CYLview.[121]

The reaction pathways reported represent the Minimum Energy Pathway (MEP), or a representative member thereof, for the transformation. Each of the four possible pathways was explored to the same extent. Energies for the various steps on the reaction coordinate were calculated using the summed Gibbs Free Energy values for materials at that stage. The sum of the energies of the starting materials was then subtracted from each of the totals to relativize them. A generic example of how the summed values were determined (for a cross-benzoin path) is shown below:

(I) Starting Materials

(NHC Salt) + (trimethylamine) + 2(aromatic aldehyde) + 2(aliphatic aldehyde)

(II) Free Carbene

(Carbene) + ($HNMe_3BF_4$) + 2(aromatic aldehyde) + 2(aliphatic aldehyde)

(IV) Adduct

(catalyst adduct) + (trimethylamine) + 2(aromatic aldehyde) + (aliphatic aldehyde)

(V) Breslow Intermediate

(Breslow intermediate) + ($HNMe_3BF_4$) + 2(aromatic aldehyde) + (aliphatic aldehyde)

[V-VI] Carbon-Carbon Bond Formation TS

(C-C bond formation) + ($HNMe_3BF_4$) + (aromatic aldehyde) + (aliphatic aldehyde)

(VI) Tetrahedral Intermediate

(tetrahedral intermediate) + ($HNMe_3BF_4$) + (aromatic aldehyde) + (aliphatic aldehyde)

[VI-I] Ejection TS

(ejection of product) + ($HNMe_3BF_4$) + (aromatic aldehyde) + (aliphatic aldehyde)

(VII) Product

(product) + (NHC Salt) + (trimethylamine) + (aromatic aldehyde) + (aliphatic aldehyde)

All tabular values reported in hartrees. Values may be converted to kcal/mol using the conversion factor:

1 hartree = 627.509469 kcal/mol

Single Point SCF, G_{298}, and G_{298} (Single Point) values reported with all calculated significant figures. All other values truncated for brevity.

Piperidinone-Derived Catalyst System Thermochemical Parameters:

Structure/Filename	SCF	Single Point SCF	ZPE	Hcorr	Gcorr	SCFZPE	H298	G298	G289 (Single Point)
Benzaldehyde (**19**)	-345.45	-345.5295397	0.110612	0.117934	0.07985	-345.342	-345.335	-345.3730048890	-345.4496897170
Piperidinone-Based_Triazolium_Salt (**156**)	-1550.12	-1550.522098	0.223972	0.247223	0.170636	-1549.89	-1549.87	-1549.9465700200	-1550.3514617700
Propionaldehyde (**320**)	-193.07	-193.1176958	0.084801	0.09073	0.057536	-192.985	-192.979	-193.0122908560	-193.0601598400
Trimethylamine (**321**)	-174.40	-174.4350713	0.12102	0.127335	0.093784	-174.275	-174.269	-174.3026034630	-174.3412873450
Piperidinone-Based_Free_Carbene (**322**)	-1125.12	-1125.405034	0.19461	0.211757	0.149016	-1124.93	-1124.91	-1124.9740571800	-1125.2560184400
$HNMe_3BF_4$ (**323**)	-599.39	-599.5472774	0.152299	0.164941	0.112793	-599.235	-599.222	-599.2740444970	-599.4344843930
Benzaldehyde_Adduct (**216**)	-1895.59	-1896.073188	0.339238	0.369399	0.278141	-1895.25	-1895.22	-1895.3129807200	-1895.7950465700
Propionaldehyde_Adduct (**324**)	-1743.22	-1743.669948	0.314172	0.342624	0.255371	-1742.9	-1742.87	-1742.9620551000	-1743.4145767700
(E)-Benzaldehyde_BI_((***E***)-**325**)	-1470.59	-1470.953847	0.308846	0.332178	0.258261	-1470.28	-1470.26	-1470.3355169900	-1470.6955860500
(E)-Propionaldehyde_BI_((***E***)-**326**)	-1318.21	-1318.53625	0.28393	0.306405	0.233661	-1317.92	-1317.9	-1317.9719590900	-1318.3025888000
(Z)-Benzaldehyde_BI_((***Z***)-**325**)	-1470.59	-1470.950308	0.308398	0.332794	0.254489	-1470.28	-1470.26	-1470.3368806500	-1470.6958193900
(Z)-Propionaldehyde_BI_((***Z***)-**326**)	-1318.20	-1318.534864	0.28363	0.306282	0.232749	-1317.92	-1317.9	-1317.9715770900	-1318.3021148600
TS ([V-VI](E)B-(re)B)	-1816.05	-1816.482956	0.421507	0.45173	0.361565	-1815.63	-1815.6	-1815.6891010100	-1816.1213910900
TS ([V-VI](E)B-(re)P)	-1663.66	-1664.065492	0.397362	0.425877	0.340693	-1663.27	-1663.24	-1663.3230697100	-1663.7247989800
TS ([V-VI](E)B-(si)B)	-1816.05	-1816.486534	0.422544	0.452336	0.364071	-1815.63	-1815.6	-1815.6838994300	-1816.1224632100
TS ([V-VI](E)B-(si)P)	-1663.66	-1664.070261	0.39734	0.425721	0.340288	-1663.26	-1663.23	-1663.3190296500	-1663.7299734200
TS ([V-VI](E)P-(re)B)	-1663.66	-1664.065329	0.396849	0.425381	0.339216	-1663.27	-1663.24	-1663.3243544800	-1663.7261125500
TS ([V-VI](E)P-(re)P)	-1511.28	-1511.651278	0.371682	0.398919	0.314258	-1510.9	-1510.88	-1510.9623013500	-1511.3370203200
TS ([V-VI](E)P-(si)B)	-1663.66	-1664.069718	0.396305	0.425177	0.336953	-1663.26	-1663.23	-1663.3221281200	-1663.7327651000
TS ([V-VI](E)P-(si)P)	-1511.27	-1511.654075	0.371269	0.398719	0.314016	-1510.9	-1510.88	-1510.9600350200	-1511.3400589500
TS ([V-VI](Z)B-(re)B)	-1816.04	-1816.477699	0.422126	0.452371	0.361424	-1815.62	-1815.59	-1815.6819216100	-1816.1162749700
TS ([V-VI](Z)B-(re)P)	-1663.66	-1664.064021	0.396702	0.42546	0.337865	-1663.26	-1663.23	-1663.3204154700	-1663.7261557200
TS ([V-VI](Z)B-(si)B)	-1816.04	-1816.479502	0.421729	0.451951	0.361622	-1815.62	-1815.59	-1815.6831052100	-1816.1178795600
TS ([V-VI](Z)B-(si)P)	-1663.66	-1664.065362	0.396266	0.42515	0.33705	-1663.26	-1663.23	-1663.3222311400	-1663.7283116700
TS ([V-VI](Z)P-(re)B)	-1663.66	-1664.071303	0.397536	0.426134	0.339978	-1663.27	-1663.24	-1663.3248844800	-1663.7313254900
TS ([V-VI](Z)P-(re)P)	-1511.28	-1511.654121	0.371638	0.398759	0.315244	-1510.91	-1510.88	-1510.9616577500	-1511.3388767800
TS ([V-VI](Z)P-(si)B)	-1663.67	-1664.074191	0.396686	0.425208	0.339163	-1663.27	-1663.24	-1663.3283825300	-1663.7350280700
TS ([V-VI](Z)P-(si)P)	-1511.28	-1511.655526	0.371549	0.398631	0.315849	-1510.91	-1510.88	-1510.9625068900	-1511.3396772900

Int. VI(E)B-(re)B)	-1816.06	-1816.489638	0.424366	0.454131	0.366397	-1815.64	-1815.61	-1815.6946058400	-1816.1232409100
Int. VI(E)B-(re)P)	-1663.68	-1664.079861	0.399035	0.42744	0.342273	-1663.28	-1663.25	-1663.3363232600	-1663.7375878400
Int. VI(E)B-(si)B)	-1816.05	-1816.495457	0.424113	0.454777	0.363153	-1815.63	-1815.6	-1815.6917066800	-1816.1323042300
Int. VI(E)B-(si)P)	-1663.67	-1664.083757	0.39886	0.427826	0.340044	-1663.28	-1663.25	-1663.3343980900	-1663.7437129800
Int. VI(E)P-(re)B)	-1663.68	-1664.080476	0.399271	0.427716	0.342172	-1663.28	-1663.25	-1663.3337891200	-1663.7383043800
Int. VI(E)P-(re)P)	-1511.29	-1511.669896	0.373889	0.400807	0.318442	-1510.92	-1510.89	-1510.9756995600	-1511.3514542700
Int. VI(E)P-(si)B)	-1663.68	-1664.080983	0.399796	0.428156	0.34228	-1663.28	-1663.25	-1663.3334690600	-1663.7387027300
Int. VI(E)P-(si)P)	-1511.29	-1511.669808	0.373583	0.400827	0.316441	-1510.92	-1510.89	-1510.9776455400	-1511.3533665400
Int. VI(Z)B-(re)B)	-1816.06	-1816.490472	0.424535	0.455066	0.363173	-1815.63	-1815.6	-1815.6929805200	-1816.1272992000
Int. VI(Z)B-(re)P)	-1663.68	-1664.08563	0.399956	0.428566	0.342757	-1663.28	-1663.25	-1663.3376710100	-1663.7428726900
Int. VI(Z)B-(si)B)	-1816.06	-1816.49548	0.423916	0.454251	0.363868	-1815.64	-1815.61	-1815.6972288500	-1816.1316115500
Int. VI(Z)B-(si)P)	-1663.68	-1664.082532	0.398835	0.427628	0.340049	-1663.28	-1663.25	-1663.3375150900	-1663.7424826300
Int. VI(Z)P-(re)B)	-1663.68	-1664.08623	0.399727	0.428139	0.342225	-1663.28	-1663.25	-1663.3392748300	-1663.7440052400
Int. VI(Z)P-(re)P)	-1511.30	-1511.674938	0.374226	0.401079	0.319078	-1510.92	-1510.9	-1510.9798593500	-1511.3558595000
Int. VI(Z)P-(si)B)	-1663.68	-1664.086827	0.399258	0.427516	0.342253	-1663.28	-1663.25	-1663.3398934400	-1663.7445739900
Int. VI(Z)P-(si)P)	-1511.30	-1511.673079	0.374205	0.401093	0.318704	-1510.92	-1510.9	-1510.9784192000	-1511.3543746800
TS ([VI-I](E)B-(re)B)	-1816.05	-1816.477495	0.422719	0.453058	0.362737	-1815.62	-1815.59	-1815.6824456400	-1816.1147584900
TS ([VI-I](E)B-(re)B)_Non-Hydrogon_bonding	-1816.04	-1816.47989	0.422188	0.452782	0.361241	-1815.62	-1815.59	-1815.6829274500	-1816.1186491200
TS ([VI-I](E)B-(re)B)_No_Rotation	-1816.04	-1816.476327	0.422724	0.452873	0.363621	-1815.62	-1815.59	-1815.6776328700	-1816.1127055500
TS ([VI-I](E)B-(re)P)	-1663.67	-1664.075368	0.398134	0.426773	0.340126	-1663.27	-1663.24	-1663.3264830800	-1663.7352421200
TS ([VI-I](E)B-(si)B)	-1816.04	-1816.481024	0.422829	0.453342	0.361641	-1815.62	-1815.59	-1815.6785925900	-1816.1193826600
TS ([VI-I](E)B-(si)P)	-1663.67	-1664.073081	0.397871	0.426605	0.339869	-1663.27	-1663.24	-1663.3287970500	-1663.7332116300
TS ([VI-I](E)P-(re)B)	-1663.67	-1664.073495	0.398135	0.426701	0.34029	-1663.27	-1663.24	-1663.3249568500	-1663.7332047200
TS ([VI-I](E)P-(re)P)	-1511.28	-1511.661962	0.372263	0.399478	0.315209	-1510.91	-1510.88	-1510.9675720500	-1511.3467525200
TS ([VI-I](E)P-(si)B)	-1663.67	-1664.071796	0.397334	0.425399	0.339367	-1663.27	-1663.24	-1663.3280591400	-1663.7324293400
TS ([VI-I](E)P-(si)P)	-1511.29	-1511.659426	0.372414	0.399541	0.315829	-1510.91	-1510.89	-1510.9698244900	-1511.3435970300
TS ([VI-I](Z)B-(re)B)	-1816.05	-1816.485654	0.42263	0.4533	0.3606	-1815.6	-1815.6	-1815.6895841700	-1816.1250558500
TS ([VI-I](Z)B-(si)B)	-1816.05	-1816.482432	0.422538	0.453022	0.361255	-1815.62	-1815.59	-1815.6854030000	-1816.1211765200
TS ([VI-I](Z)B-(re)P)	-1663.67	-1664.075855	0.398141	0.426924	0.339194	-1663.27	-1663.24	-1663.3307417100	-1663.7366606200
TS ([VI-I](Z)B-(si)P)	-1663.66	-1664.068602	0.397209	0.426406	0.337722	-1663.27	-1663.24	-1663.3248699400	-1663.7308802300
TS ([VI-I](Z)P-(re)B)	-1663.67	-1664.074835	0.397283	0.426246	0.337361	-1663.27	-1663.24	-1663.3311156300	-1663.7374739100

TS ([VI-I](Z)P-(re)P)	-1511.29	-1511.664041	0.372023	0.399296	0.314828	-1510.92	-1510.89	-1510.9722221800	-1511.3492125100
TS ([VI-I](Z)P-(si)B)	-1663.67	-1664.079591	0.397326	0.426118	0.338211	-1663.28	-1663.25	-1663.3347285300	-1663.7413804100
TS ([VI-I](Z)P-(si)P)	-1511.29	-1511.663716	0.372551	0.399644	0.316077	-1510.91	-1510.89	-1510.9708486900	-1511.3476388000
Prod. (VIIP-B) (171)	-538.55	-538.676321	0.200517	0.213022	0.161802	-538.352	-538.339	-538.3907098320	-538.5145190140
Prod. (VIIP-P) (327)	-386.17	-386.2683772	0.175777	0.186432	0.140765	-385.998	-385.987	-386.0327440260	-386.1276121630
Prod. (VIIB-B) (20)	-690.93	-691.0840827	0.226334	0.240358	0.185187	-690.705	-690.691	-690.7463504570	-690.8988957370
Prod. (VIIB-P) (328)	-538.55	-538.6763233	0.20112	0.213456	0.163318	-538.352	-538.339	-538.3894100890	-538.5130052590

Pyrrolidinone-Derived Catalyst System Thermochemical Parameters:

Structure/Filename	SCF	Single Point SCF	ZPE	Hcorr	Gcorr	SCFZPE	H298	G298	G289 (Single Point)
Pyrrolidinone-Based_Triazolium_Salt_(**5**)	-1510.806	-1511.202718	0.194172	0.216483	0.141757	-1510.61	-1510.59	-1510.664626	-1511.0609608800
Pyrrolidinone-Based_Free_Carbene_(**329)**	-1085.814	-1086.087751	0.165544	0.181532	0.122553	-1085.65	-1085.63	-1085.691574	-1085.9651976700
Benzaldehyde_Adduct_(**330**)	-1856.28	-1856.753518	0.308881	0.338334	0.247326	-1855.97	-1855.94	-1856.032518	-1856.5061920800
Propionaldehyde_Adduct_(**331**)	-1703.908	-1704.351854	0.285169	0.312425	0.22796	-1703.62	-1703.6	-1703.679673	-1704.1238943900
(E)-Benzaldehyde_BI_(**(E)-332**)	-1431.286	-1431.638062	0.278883	0.301443	0.228706	-1431.01	-1430.98	-1431.057349	-1431.4093563800
(E)-Propionaldehyde_BI_(**(E)-333**)	-1278.898	-1279.220635	0.254023	0.275709	0.204268	-1278.64	-1278.62	-1278.69369	-1279.0163670900
(Z)-Benzaldehyde_BI_(**(Z)-332**)	-1431.284	-1431.635344	0.27896	0.302389	0.226768	-1431.01	-1430.98	-1431.057687	-1431.4085755100
(Z)-Propionaldehyde_BI_(**(Z)-333**)	-1278.898	-1279.220301	0.253708	0.275613	0.203618	-1278.64	-1278.62	-1278.69423	-1279.0166834700
TS ([V-VI](pyr)(E)B-(re)B)	-1776.743	-1777.166636	0.392536	0.421668	0.334035	-1776.35	-1776.32	-1776.408967	-1776.8326009700
TS ([V-VI](pyr)(E)B-(re)P)	-1624.356	-1624.74932	0.367754	0.395247	0.312137	-1623.99	-1623.96	-1624.044074	-1624.4371830800
TS ([V-VI](pyr)(E)B-(si)B)	-1776.74	-1777.17031	0.392607	0.4216	0.334463	-1776.35	-1776.32	-1776.405519	-1776.8358471500
TS ([V-VI](pyr)(E)B-(si)P)	-1624.352	-1624.754459	0.367116	0.394836	0.309852	-1623.98	-1623.96	-1624.041795	-1624.4446068500
TS ([V-VI](pyr)(E)P-(re)B)	-1624.357	-1624.752216	0.367267	0.394934	0.31074	-1623.99	-1623.96	-1624.045793	-1624.4414761200
TS ([V-VI](pyr)(E)P-(re)P)	-1471.97	-1472.337296	0.342249	0.368461	0.286904	-1471.63	-1471.6	-1471.683075	-1472.0503918500
TS ([V-VI](pyr)(E)P-(si)B)	-1624.354	-1624.754468	0.366691	0.394674	0.308606	-1623.99	-1623.96	-1624.045186	-1624.4458621900
TS ([V-VI](pyr)(E)P-(si)P)	-1471.968	-1472.339057	0.341513	0.368049	0.285201	-1471.63	-1471.6	-1471.682778	-1472.0538556500
TS ([V-VI](pyr)(Z)B-(re)B)	-1776.736	-1777.162191	0.392142	0.421463	0.331482	-1776.34	-1776.31	-1776.404209	-1776.8307087600
TS ([V-VI](pyr)(Z)B-(re)P)	-1624.351	-1624.748035	0.366896	0.394718	0.308895	-1623.98	-1623.96	-1624.042024	-1624.4391395300
TS ([V-VI](pyr)(Z)B-(si)B)	-1776.739	-1777.165325	0.392341	0.421508	0.333819	-1776.35	-1776.32	-1776.404867	-1776.8315056900
TS ([V-VI](pyr)(Z)B-(si)P)	-1624.354	-1624.751376	0.366972	0.394735	0.309562	-1623.99	-1623.96	-1624.044021	-1624.4418136900

TS ([V-VI](pyr)(Z)P-(re)B)	-1624.358	-1624.756533	0.367216	0.395113	0.309526	-1623.99	-1623.96	-1624.048829	-1624.4470065800
TS ([V-VI](pyr)(Z)P-(re)P)	-1471.97	-1472.339191	0.342037	0.36821	0.286874	-1471.63	-1471.6	-1471.683304	-1472.0523174900
TS ([V-VI](pyr)(Z)P-(si)B)	-1624.36	-1624.758443	0.367123	0.394778	0.310193	-1623.99	-1623.97	-1624.049944	-1624.4482502400
TS ([V-VI](pyr)(Z)P-(si)P)	-1471.971	-1472.340122	0.341723	0.368071	0.286263	-1471.63	-1471.6	-1471.684936	-1472.0538590600
Int. (VI(pyr)(E)B-(re)B)	-1776.751	-1777.177087	0.394896	0.423762	0.337227	-1776.36	-1776.33	-1776.413292	-1776.8398601800
Int. (VI(pyr)(E)B-(re)P)	-1624.371	-1624.766583	0.369471	0.396945	0.313579	-1624	-1623.97	-1624.057385	-1624.4530035600
Int. (VI(pyr)(E)B-(si)B)	-1776.75	-1777.176721	0.395209	0.424782	0.335044	-1776.35	-1776.33	-1776.415144	-1776.8416767300
Int. (VI(pyr)(E)B-(si)P)	-1624.369	-1624.768337	0.369475	0.397408	0.311825	-1624	-1623.97	-1624.057345	-1624.4565116600
Int. (VI(pyr)(E)P-(re)B)	-1624.37	-1624.768394	0.370505	0.397889	0.314625	-1624	-1623.97	-1624.055681	-1624.4537686900
Int. (VI(pyr)(E)P-(re)P)	-1471.988	-1472.35576	0.345028	0.370832	0.29146	-1471.64	-1471.62	-1471.696459	-1472.0642997600
Int. (VI(pyr)(E)P-(si)B)	-1624.372	-1624.767501	0.369534	0.396995	0.313176	-1624	-1623.97	-1624.058467	-1624.4543249900
Int. (VI(pyr)(E)P-(si)P)	-1471.988	-1472.355582	0.344059	0.370279	0.2886	-1471.64	-1471.62	-1471.699532	-1472.0669822000
Int. (VI(pyr)(Z)B-(re)B)	-1776.75	-1777.175881	0.394662	0.424331	0.333731	-1776.36	-1776.33	-1776.415952	-1776.8421501900
Int. (VI(pyr)(Z)B-(re)P)	-1624.37	-1624.766553	0.369967	0.397915	0.312011	-1624	-1623.97	-1624.057612	-1624.4545416700
Int. (VI(pyr)(Z)B-(si)B)	-1776.753	-1777.179405	0.395509	0.424679	0.337045	-1776.36	-1776.33	-1776.416083	-1776.8423596300
Int. (VI(pyr)(Z)B-(si)P)	-1624.371	-1624.767754	0.370108	0.397731	0.313385	-1624	-1623.97	-1624.057433	-1624.4543694400
Int. (VI(pyr)(Z)P-(re)B)	-1624.373	-1624.77015	0.368996	0.396862	0.310775	-1624	-1623.98	-1624.062335	-1624.4593749700
Int. (VI(pyr)(Z)P-(re)P)	-1471.991	-1472.358728	0.344908	0.370883	0.290343	-1471.65	-1471.62	-1471.70038	-1472.0683850200
Int. (VI(pyr)(Z)P-(si)B)	-1624.374	-1624.770478	0.369312	0.396678	0.31265	-1624	-1623.98	-1624.061041	-1624.4578283300
Int. (VI(pyr)(Z)P-(si)P)	-1471.992	-1472.359529	0.345401	0.371078	0.292063	-1471.65	-1471.62	-1471.69981	-1472.0674658300
TS ([VI-I](pyr)(E)B-(re)B)	-1776.737	-1777.160534	0.392856	0.422354	0.332856	-1776.34	-1776.31	-1776.403753	-1776.8276783200
TS ([VI-I](pyr)(E)B-(re)P)	-1624.358	-1624.759754	0.36848	0.396226	0.31136	-1623.99	-1623.96	-1624.04696	-1624.4483935900
TS ([VI-I]'(E)B-(si)B)	-1776.733	-1777.16451	0.392613	0.421392	0.334299	-1776.34	-1776.31	-1776.398272	-1776.8302111000
TS ([VI-I](pyr)(E)B-(si)P)	-1624.361	-1624.756783	0.368343	0.396139	0.31127	-1623.99	-1623.96	-1624.049865	-1624.4455128100
TS ([VI-I](pyr)(E)P-(re)B)	-1624.36	-1624.75711	0.368693	0.396183	0.312129	-1623.99	-1623.96	-1624.047548	-1624.4449812900
TS ([VI-I](pyr)(E)P-(re)P)	-1471.975	-1472.34646	0.342439	0.369004	0.281576	-1471.63	-1471.61	-1471.693071	-1472.0648836000
TS ([VI-I](pyr)(E)P-(si)B)	-1624.359	-1624.758507	0.367613	0.395636	0.307668	-1623.99	-1623.96	-1624.051461	-1624.4508385000
TS ([VI-I](pyr)(E)P-(si)P)	-1471.978	-1472.34331	0.342835	0.369198	0.285175	-1471.64	-1471.61	-1471.692668	-1472.0581353700
TS ([VI-I](pyr)(Z)B-(re)B)	-1776.741	-1777.168462	0.393003	0.422777	0.331599	-1776.35	-1776.32	-1776.409412	-1776.8368626400
TS ([VI-I](pyr)(Z)B-(re)P)	-1624.361	-1624.758913	0.368253	0.396253	0.309957	-1623.99	-1623.96	-1624.051127	-1624.4489564300
TS ([VI-I](pyr)(Z)B-(si)B)	-1776.737	-1777.164728	0.392659	0.422224	0.332239	-1776.34	-1776.31	-1776.404753	-1776.8324888000

TS ([VI-I](pyr)(Z)B-(si)P)	-1624.353	-1624.751241	0.368222	0.396221	0.310683	-1623.99	-1623.96	-1624.042701	-1624.4405576800
TS ([VI-I](pyr)(Z)P-(re)B)	-1624.359	-1624.757344	0.368162	0.396028	0.30951	-1623.99	-1623.96	-1624.0496	-1624.4478338300
TS ([VI-I](pyr)(Z)P-(re)P)	-1471.978	-1472.346574	0.343147	0.369266	0.287714	-1471.63	-1471.61	-1471.690246	-1472.0588600300
TS ([VI-I](pyr)(Z)P-(si)B)	-1624.364	-1624.762167	0.36774	0.395564	0.310102	-1624	-1623.97	-1624.053562	-1624.4520650500
TS ([VI-I](pyr)(Z)P-(si)P)	-1471.978	-1472.346571	0.343039	0.369182	0.287227	-1471.63	-1471.61	-1471.690732	-1472.0593440700

Caprolactam-Derived Catalyst System Thermochemical Parameters:

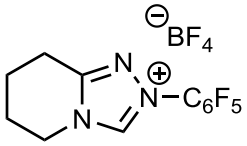
Structure/Filename	SCF	Single Point SCF	ZPE	Hcorr	Gcorr	SCFZPE	H298	G298	G289 (Single Point)
Caprolactam-Based_Triazolium_Salt_(**157**)	-1589.415	-1589.828087	0.252868	0.277098	0.199227	-1589.16	-1589.14	-1589.2157	-1589.6288602300
TS ([V-VI](cap)(Z)P-(si)B)	-1702.96	-1703.37462	0.42526	0.454971	0.366577	-1702.53	-1702.51	-1702.59364	-1703.0080425200

p-Anisaldehyde System Thermochemical Parameters:

Structure/Filename	SCF	Single Point SCF	ZPE	Hcorr	Gcorr	SCFZPE	H298	G298	G289 (Single Point)
Anisaldehyde_(**39**)	-459.9398	-460.0464985	0.143241	0.153262	0.107696	-459.797	-459.786	-459.8320604	-459.9388024880
TS ([VI-I](E)A-(re)A)	-2045.016	-2045.515886	0.48907	0.524293	0.423668	-2044.53	-2044.49	-2044.592132	-2045.0922181400
TS ([VI-I](E)A-(re)P)	-1778.152	-1778.58494	0.430901	0.46198	0.370351	-1777.72	-1777.69	-1777.782108	-1778.2145893400
TS ([VI-I](Z)P-(si)A)	-1778.157	-1778.589014	0.430653	0.461798	0.368953	-1777.73	-1777.7	-1777.788265	-1778.2200607900
TS ([V-VI](E)A-(re)A)	-2045.02	-2045.512522	0.487936	0.523115	0.421651	-2044.53	-2044.5	-2044.598461	-2045.0908705200
TS ([V-VI](E)A-(re)P)	-1778.148	-1778.589668	0.429481	0.46081	0.368407	-1777.72	-1777.69	-1777.779432	-1778.2212605300
TS ([V-VI](Z)P-(si)A)	-1778.153	-1778.594016	0.429364	0.460451	0.367788	-1777.72	-1777.69	-1777.784928	-1778.2262278800

Piperidinone-Derived Catalyst System Structures:

Starting Materials



156



321

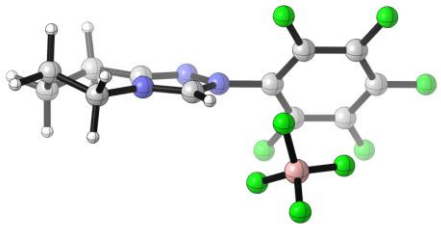


320



19

2-(Perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (*Piperidinone-Based Triazolium Salt*) (**156**)

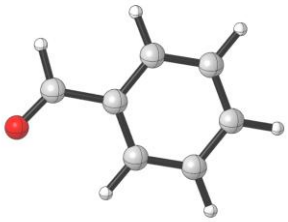


XYZ Coordinates

34

H	4.1390470	-2.4037050	-1.2269630
C	4.2546790	-1.7584050	-0.3532060
C	5.3330720	0.3103800	0.5847390
N	2.9009270	0.2483310	0.3223360
C	4.0652570	1.1480470	0.4859380
C	2.9602810	-1.0618060	-0.1001540
C	5.3854150	-0.7385640	-0.5277860
H	5.3781950	-0.1803690	1.5640970
H	4.0877580	1.7991670	-0.3913590
H	5.2991700	-0.2468830	-1.5037310
H	4.4623450	-2.4020340	0.5091540
H	6.1835460	0.9931020	0.5172710
H	3.8896600	1.7485380	1.3790690
H	6.3419920	-1.2651550	-0.5081600
C	1.6162160	0.5545990	0.4745660
H	1.1839440	1.5012730	0.7754240
N	0.9335990	-0.5404150	0.1657550
C	-0.4705800	-0.7184700	0.1841500
C	-3.2183750	-1.1068470	0.2119590
C	-1.1393500	-1.0777410	-0.9815820
C	-1.1909730	-0.5450430	1.3593030
C	-2.5634740	-0.7350690	1.3771390
C	-2.5087840	-1.2816510	-0.9684050
N	1.7578920	-1.5626780	-0.1972590
F	-0.4660290	-1.2190020	-2.1174390
F	-3.1490980	-1.6182330	-2.0850490
F	-4.5328510	-1.2918690	0.2240590
F	-3.2497030	-0.5702190	2.5053440
F	-0.5629580	-0.2057040	2.4819460
B	-1.1713000	2.4387690	-0.5617570
F	-0.7158600	2.3831780	0.7790580
F	-2.4067130	1.7872320	-0.6549930
F	-0.2266050	1.7754360	-1.3736500
F	-1.2897830	3.7712910	-0.9616980

Benzaldhyde (**19**)

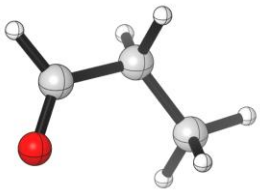


XYZ Coordinates

14

C	-1.9879350	0.4703790	-0.0007590
H	-2.2752050	1.5388690	0.0007160
O	-2.8397850	-0.3969720	0.0006660
C	-0.5315400	0.2063330	-0.0003600
C	2.2130830	-0.2429120	0.0002550
C	-0.0422110	-1.1056000	-0.0002090
C	0.3516650	1.2896450	-0.0001830
C	1.7272370	1.0646100	0.0001130
C	1.3299790	-1.3278600	0.0000930
H	-0.7449210	-1.9338660	-0.0003470
H	-0.0417120	2.3036920	-0.0003060
H	2.4169830	1.9027700	0.0002350
H	1.7170300	-2.3421300	0.0002000
H	3.2844420	-0.4211270	0.0004910

Propionaldehyde (**320**)

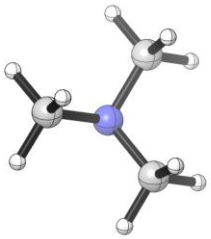


XYZ Coordinates

10

C	0.5445390	0.7316070	0.0000170
H	0.7330600	1.3718970	0.8729760
H	0.7330780	1.3719380	-0.8729080
C	1.4318680	-0.5036010	-0.0000040
H	1.2438460	-1.1199250	0.8835510
H	2.4865850	-0.2168850	0.0000060
H	1.2438520	-1.1198890	-0.8835860
C	-0.9243380	0.4277740	-0.0000090
H	-1.5969340	1.3076680	0.0000110
O	-1.3944870	-0.6911850	-0.0000100

Trimethylamine (321)

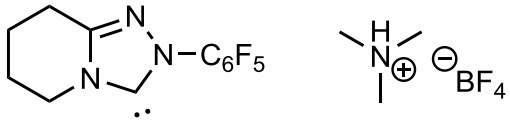


XYZ Coordinates

13

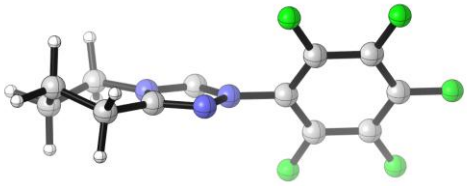
N	-0.0005760	0.0000000	-0.3983940
C	-1.3803830	-0.0000910	0.0641840
H	-1.8978360	-0.8877690	-0.3119810
H	-1.8979540	0.8875160	-0.3119820
H	-1.4482680	-0.0000970	1.1687770
C	0.6903270	-1.1943450	0.0640470
H	0.1823160	-2.0872850	-0.3122640
H	0.7236430	-1.2527520	1.1686580
H	1.7180540	-1.1969000	-0.3112500
C	0.6901680	1.1944370	0.0640470
H	1.7178950	1.1971280	-0.3112500
H	0.7234770	1.2528480	1.1686580
H	0.1820390	2.0873090	-0.3122640

Free Carbene



322 **323**

Carbene (**322**)



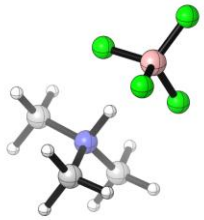
XYZ Coordinates

28

N	-1.3394940	0.5397210	0.9120560
N	-0.6449420	-0.1251740	-0.0776220
C	-2.5799560	0.3332820	0.5801440
N	-2.6438220	-0.4260300	-0.5681780
C	-1.3981020	-0.7314790	-1.0223000
C	-3.7927180	0.8060490	1.3159140
H	-3.6112110	1.8182220	1.6861510
H	-3.9381540	0.1591220	2.1888690
C	-5.0771790	-0.6206480	-0.2971740
H	-5.9989350	-0.7257250	-0.8756430
H	-5.0609130	-1.4256930	0.4482270
C	-3.8983230	-0.7776600	-1.2497020
H	-4.0099230	-0.1106570	-2.1103400
H	-3.8031530	-1.8017660	-1.6131620
C	0.7644420	-0.0727720	-0.0516860
C	3.5531060	0.0720810	0.0167150
C	1.4211130	1.1463380	-0.2002220
C	1.5321010	-1.2183380	0.1353330
C	2.9178090	-1.1524290	0.1609690
C	2.8040990	1.2268270	-0.1622170
F	0.9475890	-2.4018370	0.3067980
F	3.6397260	-2.2581710	0.3410440
F	4.8810640	0.1389120	0.0490600
F	3.4155590	2.4013380	-0.3112290
F	0.7172930	2.2603220	-0.3945940
C	-5.0260110	0.7346610	0.4103970
H	-5.9252340	0.8892770	1.0121480

H -4.9880250 1.5370510 -0.336772

Trimethylammonium tetrafluoroborate (**323**)

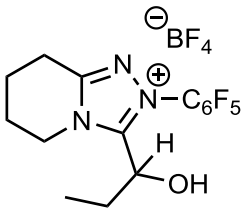


XYZ Coordinates

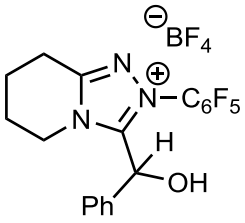
19

H -0.7366380 0.0022880 -0.4417140
N -1.6899720 0.0006680 -0.0564500
C -1.5514260 -0.1033940 1.4214450
H -0.9818550 0.7542940 1.7790480
H -1.0270180 -1.0294690 1.6564640
H -2.5512850 -0.1078650 1.8584300
C -2.3993340 -1.1773240 -0.6222280
H -2.4260720 -1.0784590 -1.7072550
H -3.4121190 -1.1963470 -0.2165640
H -1.8569330 -2.0788340 -0.3377040
C -2.3375810 1.2777130 -0.4569020
H -2.3586660 1.3302920 -1.5453620
H -1.7570750 2.1054620 -0.0498970
H -3.3521200 1.2893180 -0.0553080
B 1.7313990 0.0010920 -0.0585550
F 0.9259690 -1.1263580 -0.3619260
F 2.8582850 0.0140790 -0.8773050
F 2.0955720 -0.0351320 1.2890480
F 0.9382450 1.1493240 -0.3060520

Adducts

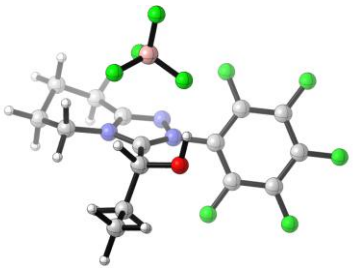


324



216

3-(1-hydroxypropyl)-2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (*Propionaldehyde Adduct*) (**324**)



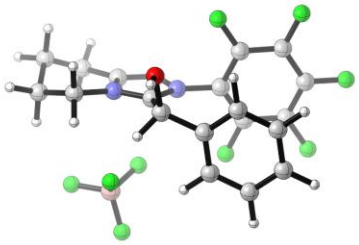
XYZ Coordinates

44

H 3.1080870 -0.3284690 -3.5532410
C 3.0408280 -0.9236170 -2.6352340
C 4.5808510 0.5252450 -1.2885360
N 2.1888680 0.4995090 -0.7441820
C 3.5337020 0.8377350 -0.2275960
C 1.9483660 -0.3618330 -1.7902200
C 4.3709370 -0.8696090 -1.8770910
H 5.5607540 0.6056030 -0.8115890
H 3.5418000 1.8933470 0.0458700
H 5.1830080 -1.1193260 -2.5635350
H 2.7639470 -1.9419500 -2.9169870
H 4.5362710 1.2774870 -2.0854220
H 3.6774520 0.2289450 0.6706500
H 4.3727120 -1.6157480 -1.0739250
C 1.0122430 0.7865510 -0.1753260
N 0.1010420 0.1120480 -0.8822670
C 0.8184220 1.6774910 1.0343510
H 1.6111570 1.3889270 1.7392330
C -1.2965380 -0.0149880 -0.6801830
C -4.0400560 -0.3062430 -0.3257640
C -1.8443610 -1.2725670 -0.4417630
C -2.1390690 1.0874880 -0.7559630
C -3.5037830 0.9511850 -0.5691230
C -3.2130570 -1.4183890 -0.2658480
N 0.6732050 -0.6053690 -1.8936250
O -0.4506160 1.4840690 1.5993370
H -0.4609400 0.6153160 2.0347900
F -1.0720610 -2.3472020 -0.3844430
F -3.7332640 -2.6218490 -0.0378520
F -5.3495820 -0.4443710 -0.1563390
F -4.3019960 2.0148700 -0.6335900
F -1.6345330 2.2924900 -1.0029640
C 0.9720300 3.1602280 0.6777080
H 1.8949420 3.3046860 0.1074240

H	0.1373910	3.4471780	0.0317000
C	0.9933390	4.0177320	1.9391030
H	1.8356310	3.7453190	2.5837160
H	0.0692010	3.8943780	2.5091690
H	1.0941200	5.0744360	1.6772960
B	1.4083090	-1.7152020	1.8990520
F	0.0908550	-1.1786170	1.8812040
F	1.4338180	-2.8581950	2.6939950
F	1.7880500	-2.0168420	0.5836160
F	2.2779270	-0.7367770	2.4168530

3-(hydroxy(phenyl)methyl)-2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-2-ium tetrafluoroborate (*Benzaldehyde Adduct*) (**216**)

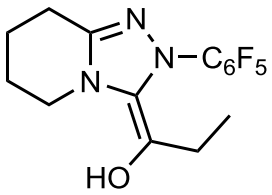


XYZ Coordinates

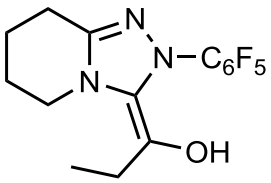
48

H	3.8856940	-1.4184220	-2.1121300
C	3.4766710	-2.1681020	-1.4244930
C	4.6777380	-1.2853120	0.5897450
N	2.2445140	-1.0065530	0.4272430
C	3.3964200	-0.9776260	1.3553340
C	2.2448970	-1.5927870	-0.8150200
C	4.5026400	-2.4909850	-0.3338930
H	5.4610360	-1.4689330	1.3292980
H	3.4293100	0.0148450	1.8069380
H	5.4538420	-2.7460690	-0.8063890
H	3.1985790	-3.0449590	-2.0134310
H	4.9678860	-0.4074610	0.0032100
H	3.1978210	-1.7278100	2.1252210
H	4.1756460	-3.3638500	0.2440380
C	1.0068280	-0.5636080	0.6637580
N	0.2938120	-0.8955130	-0.4147970
C	0.5779020	0.1065960	1.9465520
H	1.3934640	0.7980300	2.1908820
C	-1.1063700	-0.7855350	-0.6274800
C	-3.8491280	-0.6262020	-1.0234570
C	-1.9417110	-1.8047520	-0.1833450
C	-1.6519990	0.3043510	-1.2967900
C	-3.0241030	0.3922150	-1.4816560
C	-3.3115350	-1.7296110	-0.3741150
C	-0.6998440	0.9143580	1.8144940
C	-3.0288740	2.4198600	1.5080700
C	-0.6467290	2.1646740	1.1925640
C	-1.9130330	0.4254640	2.3019790
C	-3.0761860	1.1801060	2.1478430
C	-1.8123010	2.9120320	1.0327200
H	0.3038800	2.5412070	0.8213320
H	-1.9476920	-0.5450140	2.7894110
H	-4.0201860	0.7973330	2.5248640
H	-1.7680800	3.8782540	0.5392040
H	-3.9374270	3.0018010	1.3834190
N	1.0523870	-1.5392290	-1.3437660
O	0.5058480	-0.9467250	2.8874410
H	0.5403370	-0.5652540	3.7782520
F	-1.4264200	-2.8513070	0.4551820
F	-4.1095240	-2.6999970	0.0650870
F	-5.1614040	-0.5380980	-1.1986880
F	-3.5520740	1.4477140	-2.0946480
F	-0.8715460	1.2758000	-1.7436690
B	2.9205690	2.0889690	-0.7324200
F	2.6676900	1.9463880	0.6523380
F	2.0090230	1.2910140	-1.4422550
F	4.2299380	1.6637420	-1.0070580
F	2.7647120	3.4318020	-1.0950840

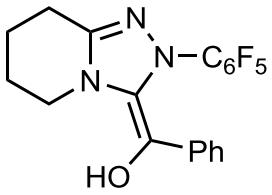
Breslow Intermediates



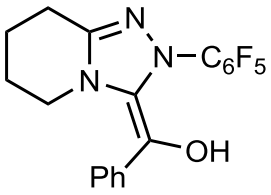
(*E*)-326



(*Z*)-326

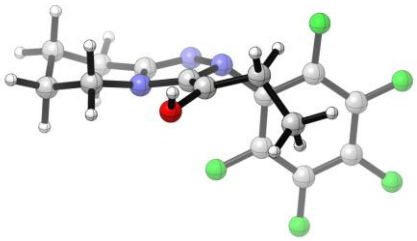


(*E*)-325



(*Z*)-325

(*E*)-1-(2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-3(2H)-ylidene)propan-1-ol (*(E)-Propionaldehyde BI*) (**(*E*)-326**)

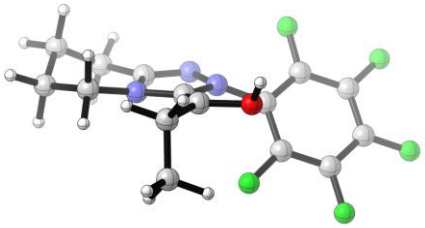


XYZ Coordinates

38

C 1.9558820 -3.1559570 1.1225790
H 3.0195980 -3.1824980 0.8769560
H 1.8669730 -3.0470010 2.2104560
C -0.2842210 -4.2335150 0.8943310
C -0.8306290 -3.0935210 0.0428500
C 1.3501260 -1.9467300 0.4848380
N 0.0026970 -1.8957720 0.1964730
N 2.0019870 -0.8787220 0.1704760
C -0.2156260 -0.6916920 -0.4918310
N 1.0458020 -0.0177090 -0.4600350
C -1.3258210 -0.2221990 -1.0877710
C 1.0747210 1.2978230 0.0677740
C 1.1114570 3.9107990 1.0833670
C 0.6083470 1.5855480 1.3512700
C 1.5722890 2.3559230 -0.6868560
C 1.5894150 3.6537970 -0.1921950
C 0.6150150 2.8729710 1.8611650
F 0.1251290 0.5988970 2.1078470
F 0.1584110 3.1223200 3.0892480
F 1.1283490 5.1516300 1.5648230
F 2.0649110 4.6526570 -0.9374310
F 2.0289100 2.1461610 -1.9216150
C 1.2158300 -4.4206260 0.6780000
H -1.8506730 -2.8418060 0.3304820
C -1.3816090 1.0228000 -1.9219780
H -1.9368510 0.7833320 -2.8411730
H -0.3704570 1.2934150 -2.2426970
C -2.0647420 2.2080000 -1.2298730
H -1.5070110 2.5229950 -0.3411320
H -3.0765970 1.9386310 -0.9113520
H -2.1399490 3.0630380 -1.9089320
O -2.5304620 -0.8699890 -0.8548480
H -3.0215030 -0.9260200 -1.6885240
H -0.8387540 -3.3783680 -1.0190440
H -0.8349620 -5.1418210 0.6331950
H -0.4775980 -4.0243390 1.9538070
H 1.4162940 -4.6171360 -0.3827310
H 1.5848260 -5.2781600 1.2470830

(*Z*)-1-(2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-3(2H)-ylidene)propan-1-ol (*(Z)-Propionaldehyde BI*) (**(*Z*)-326**)



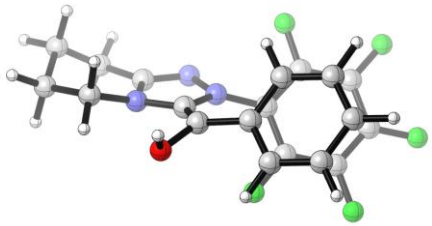
XYZ Coordinates

38

C 3.2618840 -1.1539270 -1.4148820
H 3.6276930 -2.1423960 -1.1291200
H 3.0717250 -1.1669680 -2.4949130
C 3.6021350 1.3092410 -1.3895510
C 2.3919490 1.5574870 -0.4936620
C 1.9672900 -0.9058980 -0.7103140
N 1.5376550 0.3734520 -0.4291280
N 1.1452440 -1.8229190 -0.3262060
C 0.3581450 0.2630040 0.3263470
N 0.0952850 -1.1221640 0.2988770
C -0.3614420 1.1869510 0.9999440
C -1.1435570 -1.7535820 0.3597540
C -3.6117880 -3.0970560 0.5318620
C -2.3019700 -1.2278540 -0.2183820
C -1.2619430 -2.9859260 1.0082690
C -2.4711700 -3.6573970 1.0873040
C -3.5235020 -1.8740460 -0.1151380
F -2.2510060 -0.0826180 -0.9023080
F -4.6132330 -1.3377270 -0.6729300
F -4.7824830 -3.7327250 0.6132070
F -2.5464800 -4.8316560 1.7197890
F -0.1948080 -3.5297620 1.6009180
C 4.2556930 -0.0372140 -1.0896830
H 1.8044390 2.3910840 -0.8863680
C -0.2566670 2.6838420 0.9731350
H 0.7671510 3.0127460 0.7918370
H -0.5157700 3.0502510 1.9763250
C -1.2049430 3.3174460 -0.0529420

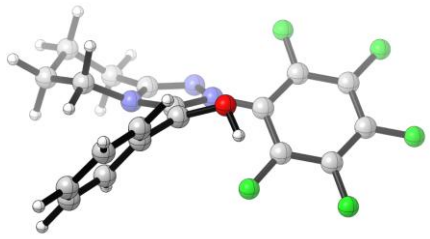
H -1.1863890 4.4100940 0.0158650
H -2.2334310 2.9822560 0.1135650
H -0.9184260 3.0329980 -1.0709180
O -1.5060390 0.6927780 1.6294890
H -1.5362550 1.0438650 2.5314060
H 2.7151140 1.8108800 0.5257580
H 4.3043760 2.1331980 -1.2359840
H 3.2907900 1.3334680 -2.4409650
H 4.5438890 -0.0870270 -0.0320670
H 5.1628660 -0.1669570 -1.6857310

(*E*)-(2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-3(2H)-ylidene)(phenyl)methanol (*(E)-Benzaldehyde BI*) (**(*E*)-325**)



XYZ Coordinates
42
C 3.5082460 -2.5957490 -1.0128960
H 4.0667310 -2.8378260 -0.1062070
H 3.1647380 -3.5377970 -1.4575690
C 3.4519930 -1.3988430 -3.1985700
C 2.3555190 -0.4417330 -2.7441280
C 2.3106370 -1.7899710 -0.6319560
N 1.6879690 -0.9555150 -1.5403220
N 1.7477040 -1.7915290 0.5305380
C 0.6821050 -0.2749750 -0.8507690
N 0.6856890 -0.8895490 0.4041210
C -0.1180970 0.7362210 -1.2911560
C -0.3295230 -0.8910590 1.3552560
C -2.3604630 -0.6786860 3.2840210
C -1.6711680 -1.0845000 1.0191300
C -0.0368060 -0.6169240 2.6929750
C -1.0316380 -0.5244340 3.6521880
C -2.6791850 -0.9523300 1.9617980
F -2.0109710 -1.3880820 -0.2339740
F -3.9535820 -1.1265430 1.6083940
F -3.3245460 -0.5807050 4.1984240
F -0.7189450 -0.2532460 4.9209170
F 1.2249700 -0.3808240 3.0569990
C 4.3469990 -1.8278910 -2.0383380
H 1.6062120 -0.3072960 -3.5220450
O -0.2551220 0.8773790 -2.6696570
H -0.1277720 1.8081270 -2.9072270
H 2.7769030 0.5442220 -2.5016590
H 4.0315090 -0.8935610 -3.9763810
H 2.9961790 -2.2870410 -3.6532410
C -1.0059950 1.5334730 -0.4369030
C -2.7587650 3.0083880 1.2074190
C -2.3046820 1.8511520 -0.8705510
C -0.5892760 2.0112850 0.8197610
C -1.4609170 2.7228330 1.6385020
C -3.1693720 2.5809490 -0.0564670
H -2.6389710 1.4981310 -1.8421600
H 0.4284350 1.8200410 1.1538470
H -1.1198070 3.0709740 2.6097880
H -4.1736450 2.8048630 -0.4053900
H -3.4368010 3.5681950 1.8445890
H 4.7981580 -0.9451800 -1.5679630
H 5.1612040 -2.4644470 -2.3944990

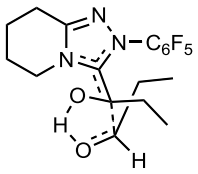
(*Z*)-(2-(perfluorophenyl)-5,6,7,8-tetrahydro-[1,2,4]triazolo[4,3-a]pyridin-3(2H)-ylidene)(phenyl)methanol (*(Z)-Benzaldehyde BI*) (**(*Z*)-325**)



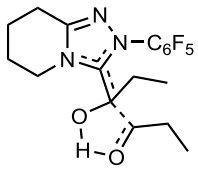
XYZ Coordinates
42
C 2.6238760 -2.9891040 -0.0659810
H 2.9810420 -3.5229950 0.8170780
H 2.1439010 -3.7172800 -0.7314830
C 3.1484240 -1.4194110 -1.9342050
C 2.2145130 -0.3483850 -1.3831280
C 1.5936500 -1.9988010 0.3628830
N 1.2346380 -0.9392480 -0.4572060
N 0.9521810 -2.0205190 1.4803350
C 0.2929090 -0.1798330 0.2496550
N 0.1220250 -0.8965310 1.4361190
C -0.2672090 1.0221610 -0.0635520
C -0.8801260 -0.7754810 2.3948640

C	-2.8691100	-0.5460670	4.3681320
C	-2.2242380	-0.6108070	2.0571460
C	-0.5659130	-0.8391020	3.7546620
C	-1.5439550	-0.7371480	4.7312380
C	-3.2064440	-0.4729150	3.0252640
F	-2.5904030	-0.5802870	0.7727120
F	-4.4808530	-0.3019200	2.6672640
F	-3.8123670	-0.4364190	5.3035130
F	-1.2113820	-0.8002480	6.0218730
F	0.7043110	-0.9721670	4.1401040
C	3.7493300	-2.2776920	-0.8238930
H	1.6893630	0.1401440	-2.2023600
O	-0.8341900	1.7202510	0.9990710
H	-1.7528090	1.9459600	0.7801450
H	2.7750320	0.4212260	-0.8344620
H	3.9325520	-0.9130970	-2.5044400
H	2.5941170	-2.0589230	-2.6324770
C	-0.3843560	1.6242060	-1.3921840
C	-0.7268240	2.8311980	-3.9191240
C	-0.4504580	3.0239270	-1.5217840
C	-0.5319520	0.8430860	-2.5534940
C	-0.6872290	1.4406530	-3.8012500
C	-0.6166770	3.6172130	-2.7706120
H	-0.3585360	3.6432660	-0.6340480
H	-0.5438190	-0.2414030	-2.4708490
H	-0.7965370	0.8162850	-4.6836630
H	-0.6547230	4.7002250	-2.8476340
H	-0.8546620	3.2959200	-4.8920040
H	4.3231370	-1.6463160	-0.1347020
H	4.4360040	-3.0199850	-1.2392360

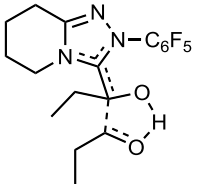
Carbon-Carbon Bond Formation Transition States



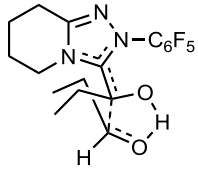
TS [V-VI]$_{(E)P\text{-}(re)P}$



TS [V-VI]$_{(E)P\text{-}(si)P}$

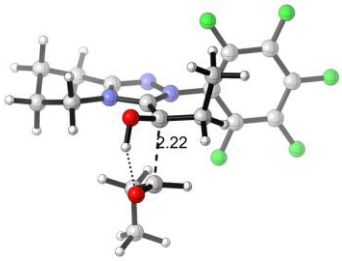


TS [V-VI]$_{(Z)P\text{-}(re)P}$



TS [V-VI]$_{(Z)P\text{-}(si)P}$

(*E*)-Propionaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]$_{(E)P\text{-}(re)P}$**)



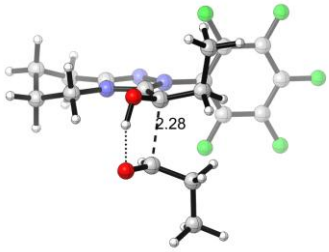
XYZ Coordinates

48

C	1.6060880	-3.6371230	-0.4691620
H	2.4150260	-3.9133600	0.2175920
H	0.8989790	-4.4694240	-0.4961920
C	2.9821710	-2.0145540	-1.7587710
H	3.7459320	-2.1017320	-0.9753070
H	3.4992610	-1.8019230	-2.6984870
C	2.0724400	-0.8300810	-1.4597130
H	2.6511100	0.0488600	-1.1816150
H	1.4614880	-0.5752350	-2.3302300
C	0.9103640	-2.4400830	0.0941040
N	1.1629730	-1.1584240	-0.3443620
N	0.0326160	-2.4640400	1.0447880
C	0.3652480	-0.2941560	0.3740610
N	-0.3009870	-1.1303600	1.2403630
C	0.3558890	1.1019220	0.3193880
O	0.8975880	1.6554010	-0.8277900
C	2.0826550	1.5635040	1.6323120
O	2.6146440	2.4275610	0.8870390
H	1.6751570	2.1828370	-0.5024440
C	-1.3462310	-0.8521560	2.1396730
C	-3.4320580	-0.3759420	3.9318210
C	-2.6719680	-1.0519930	1.7618470
C	-1.0860330	-0.4344410	3.4429150
C	-2.1170740	-0.1849340	4.3346090
C	-3.7139600	-0.8124700	2.6449980
F	-2.9522690	-1.4728070	0.5310000
F	-4.9774680	-0.9990480	2.2684080
F	-4.4246170	-0.1387870	4.7823610
F	-1.8563530	0.2329820	5.5720730
F	0.1692920	-0.2349570	3.8379480
C	-0.7185070	1.9622180	0.9403870
H	-0.9657390	1.6371070	1.9544810
H	-0.2737890	2.9604980	1.0480000
C	-1.9868190	2.0657670	0.0884670
H	-2.6989010	2.7731950	0.5259150

H -2.4865370 1.0951740 -0.0047460
H -1.7390220 2.4112780 -0.9197280
C 2.1930050 -3.3184010 -1.8445500
H 1.3741150 1.8892820 2.4165840
C 2.8128610 0.2744520 1.9413450
H 3.2900480 -0.0971960 1.0270240
H 2.1156480 -0.4871810 2.3064300
C 3.8765600 0.5500400 3.0111050
H 4.4163060 -0.3660860 3.2681990
H 3.4174090 0.9388150 3.9267520
H 4.6015770 1.2876800 2.6547320
H 2.8376040 -4.1417390 -2.1619980
H 1.3912570 -3.2207470 -2.5868180

(*E*)-Propionaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]**$_{(E)P\text{-}(si)P}$)

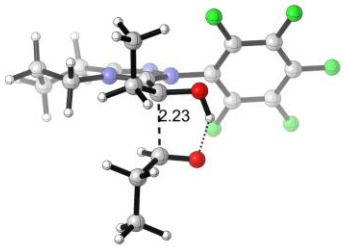


XYZ Coordinates

48

C 4.2602150 -0.3227320 -0.1156750
H 4.8131830 0.3059750 -0.8175370
C 4.7561670 -0.1799570 1.3235030
C 3.7998150 -0.9285030 2.2478790
H 3.7185410 -1.9715510 1.9172780
H 4.1686200 -0.9390720 3.2771200
C 2.4172940 -0.2866610 2.2685500
H 1.6869890 -0.9593850 2.7147970
H 2.4299720 0.6476190 2.8357940
C 2.8110940 0.0328260 -0.2022880
N 1.9743180 0.0211250 0.8924490
N 2.1902850 0.3708680 -1.2859140
C 0.7162110 0.4067850 0.4771760
N 0.8842700 0.5990950 -0.8744820
C -0.0602030 0.9449680 -1.8552780
C -1.9121350 1.6224570 -3.8266910
C -0.2417160 2.2723140 -2.2346610
C -0.7912730 -0.0408860 -2.5151310
C -1.7251900 0.2893250 -3.4844880
C -1.1707670 2.6174210 -3.2042850
F -0.6079340 -1.3218830 -2.2019590
F -2.4326910 -0.6583170 -4.0970730
F -2.8011560 1.9472640 -4.7584900
F -1.3440610 3.8905640 -3.5535950
F 0.4801200 3.2316370 -1.6613800
C -0.4591950 0.4449260 1.2371260
O -0.2768150 0.4863530 2.6097840
C -1.7166520 1.1503590 0.7893240
H -2.5374120 0.7343470 1.3860630
H -1.9613210 0.9316210 -0.2537030
C -1.6629880 2.6660280 1.0105610
H -0.8750030 3.1291630 0.4076130
H -1.4545900 2.8893880 2.0611790
H -2.6155300 3.1362740 0.7441020
C -0.7826090 -1.8156320 1.1801630
O -0.6131960 -2.0285490 2.4067310
H 4.3771470 -1.3632660 -0.4403700
H -0.4663630 -0.4337870 2.9316530
H 0.0540270 -2.0059960 0.4818330
C -2.1584580 -1.9173810 0.5649650
H -2.8933280 -1.5349250 1.2810300
H -2.2162760 -1.3179410 -0.3481700
C -2.4517010 -3.3868170 0.2358990
H -3.4389680 -3.4899340 -0.2239460
H -2.4307180 -3.9997370 1.1419860
H -1.7110640 -3.7877390 -0.4648000
H 5.7681710 -0.5847720 1.4016680
H 4.7987950 0.8793940 1.6056830

(*Z*)-Propionaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]**$_{(Z)P\text{-}(re)P}$)



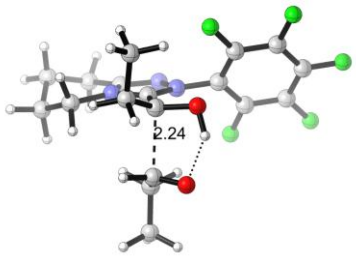
XYZ Coordinates

48

C 1.2908250 -3.6392480 -0.8541410
H 2.0324670 -4.1091650 -0.1973030
H 0.4859290 -4.3599310 -1.0138990
C 2.9519430 -2.0815650 -1.8550360
H 3.6689190 -2.4233000 -1.0988340
H 3.5209460 -1.8022900 -2.7456350
C 2.2423550 -0.8285490 -1.3522070

H	2.9604710	-0.1450560	-0.8974730
H	1.7346060	-0.3115830	-2.1748510
C	0.7284790	-2.4475990	-0.1515700
N	1.2290070	-1.1761700	-0.3458490
N	-0.2421260	-2.4586540	0.7035080
C	0.4842330	-0.3053220	0.4161650
N	-0.3899040	-1.1308050	1.0763140
C	0.4246790	1.0982010	0.3829380
O	-0.3745400	1.6612650	1.3600580
C	-1.2021590	1.0470970	-1.1451730
H	-1.0582880	-0.0011540	-1.4710120
O	-2.1600450	1.3074500	-0.3676070
H	-1.2819410	1.7283020	0.9433260
C	-1.3153590	-0.8285560	2.0891650
C	-3.1636590	-0.2787670	4.1037490
C	-2.6662390	-1.1118940	1.9100630
C	-0.9047020	-0.2800190	3.3009990
C	-1.8197530	0.0104760	4.2987100
C	-3.5884360	-0.8464310	2.9115380
F	-3.0922940	-1.6350900	0.7633560
F	-4.8809250	-1.1231400	2.7311460
F	-4.0460160	-0.0130660	5.0647860
F	-1.4179780	0.5506430	5.4505640
F	0.3845280	-0.0235680	3.5082900
C	-0.7069790	2.0857620	-2.1268490
H	-0.5961880	3.0457020	-1.6104720
H	0.2697530	1.7912540	-2.5253450
C	-1.7186810	2.2220910	-3.2719870
H	-1.8663380	1.2640260	-3.7825910
H	-1.3687480	2.9483680	-4.0116230
H	-2.6877880	2.5576900	-2.8921250
C	1.5881980	1.9760290	-0.0074950
H	2.0027330	1.7033160	-0.9804270
H	1.1791060	2.9858800	-0.1210150
C	2.6934800	1.9953120	1.0534940
H	3.4855830	2.7029870	0.7869050
H	3.1482930	1.0042150	1.1669330
H	2.2861650	2.2895780	2.0259230
C	1.9653770	-3.2072080	-2.1569940
H	1.2123190	-2.8649990	-2.8775090
H	2.4823330	-4.0616540	-2.6003930

(*Z*)-Propionaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]$_{(Z)P\text{-}(si)P}$**)

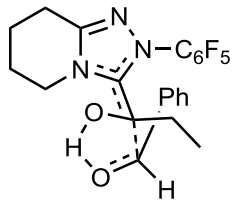


XYZ Coordinates

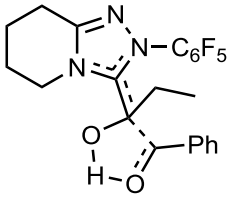
48

C	-0.9633010	1.7631520	3.2467670
H	-0.9682480	0.9259960	3.9543340
C	0.3127180	2.5861390	3.4312810
C	1.5069840	1.7791570	2.9270250
H	2.4500750	2.2886730	3.1411200
H	1.5324110	0.8083390	3.4376740
C	1.4303030	1.5630180	1.4192200
H	1.6919660	2.4808390	0.8827740
H	2.1098950	0.7642680	1.1094950
C	-1.0258610	1.1999690	1.8633400
N	0.0707060	1.1680920	1.0294840
N	-2.0722730	0.6833600	1.3039270
C	-0.3083770	0.5802580	-0.1562090
N	-1.6348150	0.2904670	0.0472180
C	-2.5967220	-0.1836180	-0.8595420
C	-4.5744520	-1.1086450	-2.6011430
C	-3.3428420	-1.3177700	-0.5545050
C	-2.8718970	0.4885150	-2.0482130
C	-3.8398170	0.0257860	-2.9225070
C	-4.3298510	-1.7793910	-1.4131630
F	-2.1969580	1.5935860	-2.3539420
F	-4.0854290	0.6723390	-4.0633790
F	-5.5175090	-1.5467800	-3.4326410
F	-5.0328790	-2.8704030	-1.1057780
F	-3.1049870	-1.9911280	0.5711510
C	0.4732380	0.2035040	-1.2541660
O	-0.2514830	-0.3684010	-2.2861490
C	1.3556390	-1.7262760	-0.5413460
O	1.1012000	-2.3967480	-1.5735400
H	-1.8683230	2.3491080	3.4255830
H	0.0869970	-1.3018880	-2.3427160
H	2.3436170	-1.2389490	-0.4476760
C	1.6858840	0.9655290	-1.7355740
H	2.2692750	0.2623610	-2.3449340
H	2.3345970	1.2683490	-0.9115280

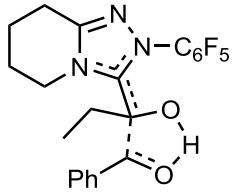
C 1.3188120 2.1864680 -2.5851460
H 2.2163620 2.6565100 -3.0009380
H 0.7885140 2.9371700 -1.9884210
H 0.6706860 1.8957700 -3.4170300
C 0.6671660 -2.0600760 0.7635270
H -0.4132870 -2.1377120 0.5880020
H 0.8434780 -1.2668840 1.4992510
C 1.2050310 -3.3913330 1.3016590
H 2.2865890 -3.3394150 1.4686000
H 1.0090910 -4.2001940 0.5921990
H 0.7281550 -3.6450150 2.2528880
H 0.2398770 3.5302330 2.8775360
H 0.4337630 2.8334660 4.4885640



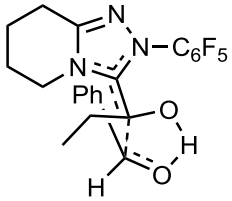
TS [V-VI]$_{(E)P\text{-}(re)B}$



TS [V-VI]$_{(E)P\text{-}(si)B}$

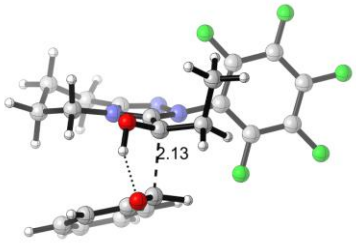


TS [V-VI]$_{(Z)P\text{-}(re)B}$



TS [V-VI]$_{(Z)P\text{-}(si)B}$

(E)-Propionaldehyde BI Attacking re Face of Benzaldehyde (**TS [V-VI]$_{(E)P\text{-}(re)B}$**)



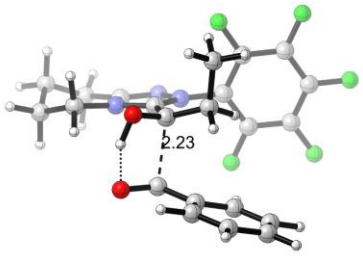
XYZ Coordinates

52

C 1.6099180 -3.6367220 -0.3066210
C 2.8736720 -2.0644030 -1.7611840
C 2.0329540 -0.8546430 -1.3741800
H 2.6561280 0.0120880 -1.1716170
H 1.3294840 -0.5958640 -2.1710320
C 0.9625650 -2.4255290 0.2787440
N 1.2379520 -1.1478770 -0.1608270
N 0.1022120 -2.4284420 1.2454570
C 0.4827430 -0.2753240 0.5783050
N -0.1904110 -1.0883450 1.4574430
C 0.5357920 1.1345360 0.5548600
O 1.0420390 1.6799730 -0.6082070
C 2.2151560 1.6066910 1.7692970
O 2.6023460 2.6213410 1.1100850
H 1.7754870 2.2775730 -0.2723120
C -1.3588460 -0.8328960 2.2101230
C -3.7000640 -0.4861740 3.6978070
C -2.6038040 -1.1683850 1.6793620
C -1.3130380 -0.3406670 3.5109700
C -2.4713350 -0.1510180 4.2487660
C -3.7693960 -0.9964400 2.4090990
F -2.6858440 -1.6525340 0.4426010
F -4.9498440 -1.3142950 1.8817230
F -4.8119430 -0.3147150 4.4029220
F -2.4081410 0.3430210 5.4837270
F -0.1480110 -0.0036870 4.0589480
C -0.5252720 2.0026960 1.1928300
H -0.7629420 1.6737440 2.2071440
H -0.0586030 2.9900980 1.3030370
C -1.7969120 2.1390770 0.3526060
H -2.4893060 2.8565420 0.8046320
H -2.3204020 1.1819390 0.2511610
H -1.5496840 2.4923290 -0.6528480
C 2.0577710 -3.3547080 -1.7414590
C 3.0848640 0.3886890 1.8225620
C 4.7478740 -1.8671590 1.9135320
C 4.2065960 0.3017180 0.9912590
C 2.8075720 -0.6611820 2.7058380
C 3.6318120 -1.7852020 2.7489250
C 5.0345260 -0.8189040 1.0365680
H 4.4255020 1.1300360 0.3229420
H 1.9457960 -0.5950010 3.3637280
H 3.4061260 -2.5947380 3.4375070
H 5.9061470 -0.8736480 0.3901650
H 5.3928460 -2.7404360 1.9495180
H 1.5752260 1.7399140 2.6581630
H 2.4845990 -3.8852550 0.3070740
H 0.9069700 -4.4699890 -0.2373010
H 3.2825300 -1.8705040 -2.7568310
H 3.7200020 -2.1591110 -1.0693950

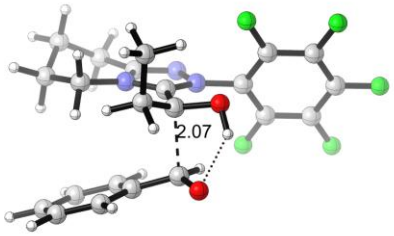
H 2.6543740 -4.1944610 -2.1063490
H 1.1838890 -3.2579900 -2.3974220

(*E*)-Propionaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]**$_{(E)P\text{-}(si)B}$)



XYZ Coordinates
52
C 1.8709960 -3.2909230 -0.5588330
H 2.7740200 -3.4598110 0.0402630
H 1.2730020 -4.2042920 -0.5227940
C 2.9212670 -1.5195090 -1.9430710
H 3.7760800 -1.5384680 -1.2557430
H 3.2996330 -1.2321440 -2.9279790
C 1.9411400 -0.4373610 -1.5074100
H 2.4736330 0.4758730 -1.2625450
H 1.2121180 -0.2327750 -2.2963200
C 1.0887890 -2.1920950 0.0825050
N 1.1905040 -0.8717890 -0.3045010
N 0.2584140 -2.3458370 1.0635120
C 0.3468460 -0.1290990 0.4908070
N -0.2082280 -1.0693140 1.3204140
C 0.2406880 1.2826760 0.5443090
O 0.7104380 1.9420760 -0.5730190
C 2.1340150 1.5791390 1.6826130
H 2.1774920 0.5665600 2.1174860
O 2.8651630 1.8720600 0.6911500
H 1.6642180 2.1667750 -0.3561910
C -1.1973330 -0.9281330 2.3109690
C -3.1410660 -0.6542720 4.2896480
C -2.5511200 -0.9552600 1.9849420
C -0.8382830 -0.8334750 3.6525660
C -1.7974720 -0.6769350 4.6407620
C -3.5223050 -0.7973840 2.9622530
F -2.9286760 -1.1359370 0.7219190
F -4.8140490 -0.8070010 2.6408850
F -4.0667180 -0.5115850 5.2313820
F -1.4429690 -0.5603030 5.9186570
F 0.4464150 -0.8915190 3.9952200
C -0.9156710 1.9892910 1.2070720
H -1.1459330 1.5530240 2.1838300
H -0.5782990 3.0120570 1.4104830
C -2.1699030 2.0532410 0.3285610
H -2.9739310 2.5962070 0.8364920
H -2.5401520 1.0561820 0.0734320
H -1.9474380 2.5746600 -0.6073620
C 1.6863280 2.6425210 2.6238420
C 0.8149030 4.6522420 4.3674260
C 1.8085000 3.9899140 2.2646520
C 1.1374260 2.3109230 3.8667180
C 0.7016800 3.3099650 4.7352670
C 1.3725450 4.9893570 3.1319470
H 2.2488060 4.2394060 1.3031990
H 1.0617630 1.2661240 4.1549380
H 0.2815470 3.0429140 5.7010200
H 1.4682840 6.0331720 2.8468440
H 0.4763830 5.4321210 5.0433420
C 2.2698100 -2.8980330 -1.9809510
H 2.9607520 -3.6425100 -2.3838160
H 1.3857760 -2.8788700 -2.6298580

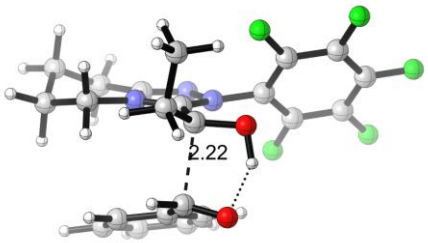
(*Z*)-Propionaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]**$_{(Z)P\text{-}(re)B}$)



XYZ Coordinates
52
C 1.2437200 -3.0394110 -1.6843180
H 1.1981750 -4.0074740 -1.1804870
H 0.6077750 -3.0983780 -2.5756560
C 2.6642610 -2.6496800 -2.0958610
C 2.6420710 -1.2236490 -2.6378010
H 3.6201360 -0.9283680 -3.0267420
H 1.9284050 -1.1668460 -3.4683810
C 2.2551800 -0.2037450 -1.5698730
H 3.0998450 0.0120830 -0.9079150
H 1.9250700 0.7203560 -2.0478060
C 0.6828360 -2.0059470 -0.7638380
N 1.1506260 -0.7091550 -0.7335960
N -0.2581700 -2.1968610 0.1055780
C 0.4673470 -0.0377030 0.2472540

N	-0.4038010	-0.9733100	0.7315480
C	0.4732770	1.3367230	0.5688290
O	-0.1658930	1.6238460	1.7740640
C	-1.0886350	2.0394710	-0.5989300
H	-1.7326630	1.1799300	-0.3203160
O	-1.3010860	3.1560910	-0.0434890
H	-0.7406410	2.3964310	1.5630700
C	-1.3171310	-0.8889610	1.8007200
C	-3.1483940	-0.8110880	3.9005220
C	-2.6801990	-1.0215030	1.5594570
C	-0.8834520	-0.7379240	3.1150040
C	-1.7894470	-0.6829260	4.1598120
C	-3.5970180	-0.9856750	2.6002030
F	-3.1226250	-1.1727280	0.3117560
F	-4.9010310	-1.1133280	2.3551880
F	-4.0200290	-0.7728870	4.9045700
F	-1.3675700	-0.5231080	5.4144040
F	0.4160040	-0.6382480	3.3779110
C	1.6551660	2.2471000	0.3348670
H	2.0664690	2.1464550	-0.6696390
H	1.2440610	3.2642390	0.3977120
C	2.7596380	2.0712790	1.3810830
H	3.5291180	2.8419560	1.2695490
H	3.2448440	1.0935580	1.2827660
H	2.3474010	2.1448720	2.3917010
C	-0.5637540	1.9269390	-1.9914860
C	0.4631930	1.6336380	-4.5768470
C	0.1417550	2.9769340	-2.5896730
C	-0.7778570	0.7432470	-2.7067500
C	-0.2704270	0.5972200	-3.9970870
C	0.6629550	2.8251210	-3.8728830
H	0.2770730	3.9028780	-2.0372070
H	-1.3520030	-0.0611130	-2.2471280
H	-0.4478880	-0.3215050	-4.5495220
H	1.2180730	3.6381390	-4.3323400
H	0.8653880	1.5212990	-5.5795500
H	3.3420130	-2.7207670	-1.2364810
H	3.0252040	-3.3428520	-2.8594300

(*Z*)-Propionaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$_{(Z)P\text{-}(si)B}$**)



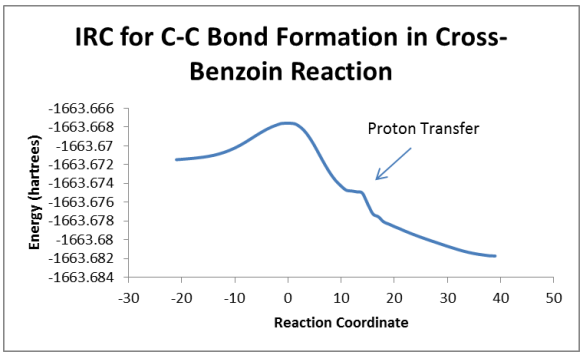
XYZ Coordinates

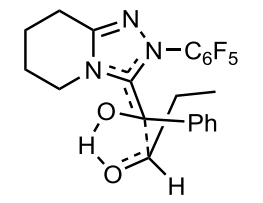
52

C	-0.9570310	1.6179920	3.2586440
H	-0.7940810	0.7801970	3.9480750
C	0.2048070	2.6068590	3.3710700
C	1.4753630	1.9483240	2.8381930
H	2.3453340	2.5956760	2.9769740
H	1.6606710	1.0213040	3.3941100
C	1.3711830	1.6336570	1.3493720
H	1.4961300	2.5410940	0.7483600
H	2.1360010	0.9114560	1.0591700
C	-1.0299530	1.0658160	1.8738190
N	0.0579870	1.0577820	1.0293220
N	-2.0737010	0.5367910	1.3182690
C	-0.3214960	0.4680380	-0.1474830
N	-1.6409330	0.1595900	0.0581480
C	-2.6207020	-0.2195410	-0.8780210
C	-4.6239430	-0.9405700	-2.6963210
C	-3.5018790	-1.2606200	-0.5981890
C	-2.7919980	0.4779940	-2.0731840
C	-3.7663570	0.1122160	-2.9854100
C	-4.4970300	-1.6205910	-1.4961490
F	-2.0173310	1.5237350	-2.3498750
F	-3.9013940	0.7827740	-4.1306760
F	-5.5717630	-1.2862590	-3.5644750
F	-5.3277500	-2.6231720	-1.2063260
F	-3.4057210	-1.9432690	0.5413080
C	0.4718810	0.0729310	-1.2451120
O	-0.2449720	-0.5348940	-2.2501710
C	1.3882670	-1.8152830	-0.5260470
O	1.0110250	-2.5274400	-1.5024920
H	-1.9209990	2.0690670	3.5054060
H	0.1003350	-1.4844370	-2.2477160
H	2.3933310	-1.3588870	-0.5393970
C	0.8318940	-2.0295940	0.8369820
C	-0.2283390	-2.3923990	3.4020660
C	1.5658650	-1.6482970	1.9655610

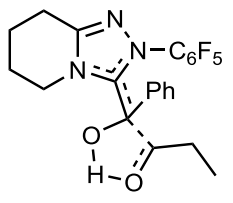
C	-0.4326560	-2.6077200	1.0022290
C	-0.9636570	-2.7782990	2.2781880
C	1.0423530	-1.8357980	3.2443950
H	2.5574190	-1.2170840	1.8385330
H	-0.9883210	-2.9136940	0.1196670
H	-1.9506070	-3.2145980	2.4009460
H	1.6243120	-1.5519090	4.1168740
H	-0.6425080	-2.5315060	4.3965150
C	1.6615800	0.8593980	-1.7488470
H	2.2256920	0.1727640	-2.3930750
H	2.3368080	1.1461410	-0.9408920
C	1.2595990	2.0951700	-2.5591850
H	2.1417330	2.5830990	-2.9869670
H	0.7387340	2.8263390	-1.9308260
H	0.5924860	1.8164210	-3.3799350
H	-0.0168180	3.5181630	2.8024610
H	0.3353470	2.8948860	4.4170290

IRC for (*Z*)-Propionaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$_{(Z)P\text{-}(si)B}$**)

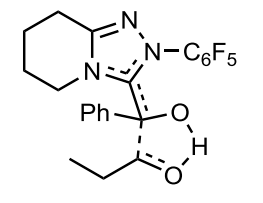




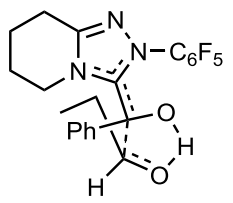
TS [V-VI]$_{(E)B\text{-}(re)P}$



TS [V-VI]$_{(E)B\text{-}(si)P}$

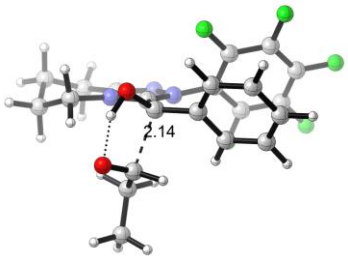


TS [V-VI]$_{(Z)B\text{-}(re)P}$



TS [V-VI]$_{(Z)B\text{-}(si)P}$

(*E*)-Benzaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]$_{(E)B\text{-}(re)P}$**)



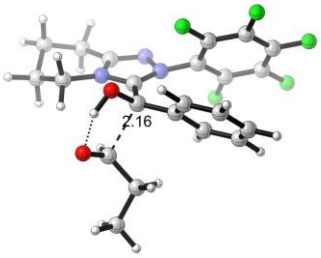
XYZ Coordinates

52

C	-4.7789890	-0.9946550	1.2413050
H	-5.3640520	-0.3856540	1.9346220
C	-4.5387160	-1.8585060	-1.0878750
H	-4.1038580	-2.7748090	-0.6681210
H	-5.0537240	-2.1328970	-2.0123120
C	-3.4300420	-0.8814990	-1.4557370
H	-2.6281170	-1.3710000	-2.0076800
H	-3.8203270	-0.0558840	-2.0566620
C	-3.4675800	-0.3180260	1.0044120
N	-2.8487820	-0.3011040	-0.2253580
N	-2.7566130	0.2873930	1.9047340
C	-1.6601970	0.3573820	-0.0931190
N	-1.6352660	0.7186780	1.2210140
C	-0.8101100	1.6667370	1.8554610
C	0.8617000	3.5139320	3.1020050
C	-0.7051030	2.9675370	1.3712190
C	-0.0863890	1.3148650	2.9895930
C	0.7428930	2.2303430	3.6172780
C	0.1409910	3.8843510	1.9741430
F	-0.1518750	0.0690940	3.4560100
F	1.4398770	1.8795840	4.6970780
F	1.6642930	4.3929170	3.6928300
F	0.2486810	5.1214180	1.4935680
F	-1.4083790	3.3363820	0.3033830
C	-0.6618280	0.5058940	-1.1049310
O	-1.2034450	0.7075550	-2.3617250
C	0.0432410	-1.4862320	-1.4698030
O	-0.3939730	-1.6520980	-2.6488870
H	-4.5780850	-1.9529600	1.7342030
H	-0.9553940	-0.1192620	-2.8686610
C	0.5884090	1.2584960	-0.8129790
C	2.9519360	2.6924470	-0.2748330
C	1.4795800	0.8322270	0.1859060
C	0.9245410	2.3917930	-1.5655510
C	2.0931660	3.1043060	-1.2943390

C 2.6428440 1.5461820 0.4612780
H 1.2545010 -0.0673790 0.7572340
H 0.2534290 2.7161340 -2.3550300
H 2.3303390 3.9886840 -1.8790700
H 3.3125540 1.2021990 1.2449560
H 3.8589820 3.2505980 -0.0624560
C -0.4377450 -2.3758540 -0.3403580
H -0.2416160 -1.8974250 0.6276600
H -1.5176750 -2.5389570 -0.4306500
C 0.2923390 -3.7218990 -0.4101960
H 1.3767790 -3.5824830 -0.3424510
H 0.0751400 -4.2326280 -1.3530830
H -0.0148560 -4.3746700 0.4123100
H 1.0878790 -1.1508800 -1.3445590
C -5.5068830 -1.2402190 -0.0815560
H -6.3576870 -1.9024010 0.0959350
H -5.8992520 -0.2958810 -0.4776160

(*E*)-Benzaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]**$_{(E)\text{B-}(si)\text{P}}$)

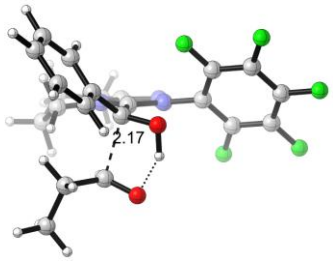


XYZ Coordinates

52

C -4.7234120 -1.0622920 1.1340160
H -5.2896530 -0.4733610 1.8595070
C -5.4448870 -1.1911340 -0.2093250
C -4.4915800 -1.7808820 -1.2466920
H -4.1033660 -2.7433570 -0.8903550
H -5.0053440 -1.9628330 -2.1943670
C -3.3350620 -0.8326370 -1.5300450
H -2.5648460 -1.3017870 -2.1410570
H -3.6842100 0.0662010 -2.0458860
C -3.3793890 -0.4332400 0.9575950
N -2.7259860 -0.3955950 -0.2538620
N -2.6656550 0.1011900 1.9002680
C -1.5106320 0.1914430 -0.0594280
N -1.5076730 0.5046330 1.2648350
C -0.6843330 1.4299750 1.9369030
C 0.9838030 3.2338790 3.2493710
C -0.5059810 2.7190830 1.4426400
C -0.0341760 1.0673940 3.1114510
C 0.7932100 1.9613780 3.7715420
C 0.3381140 3.6137670 2.0805910
F -0.1659070 -0.1697380 3.5860690
F 1.4181880 1.6013600 4.8911660
F 1.7818640 4.0930460 3.8737810
F 0.5162380 4.8391110 1.5919200
F -1.1325680 3.0974110 0.3317360
C -0.4896910 0.3472730 -1.0593130
O -1.0267220 0.7666460 -2.2607880
C -0.1465230 -1.6811390 -1.7209470
O -0.4424290 -1.5111510 -2.9476260
H -4.5698420 -2.0579890 1.5661650
H -0.8601030 -0.0130490 -2.8832180
H -0.9079950 -2.1353570 -1.0565010
C 0.8208460 0.9569460 -0.7090200
C 3.3127540 2.1576250 -0.1367530
C 1.6002380 0.5280380 0.3805980
C 1.3347990 1.9779090 -1.5213630
C 2.5649940 2.5715900 -1.2378780
C 2.8225790 1.1269190 0.6700990
H 1.2492760 -0.2857700 1.0106710
H 0.7496320 2.3093930 -2.3722370
H 2.9348280 3.3663080 -1.8797720
H 3.3996980 0.7809010 1.5236930
H 4.2678330 2.6235430 0.0868800
C 1.2692220 -2.0558530 -1.3510880
H 1.9699810 -1.3377740 -1.7913510
H 1.3925580 -2.0330080 -0.2648540
C 1.5623910 -3.4673260 -1.8734250
H 2.5718340 -3.7823280 -1.5921980
H 1.4820590 -3.4974720 -2.9636000
H 0.8545180 -4.1949420 -1.4605030
H -6.3238080 -1.8280250 -0.0837690
H -5.7952240 -0.2082910 -0.5467430

(*Z*)-Benzaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]**$_{(Z)\text{B-}(re)\text{P}}$)

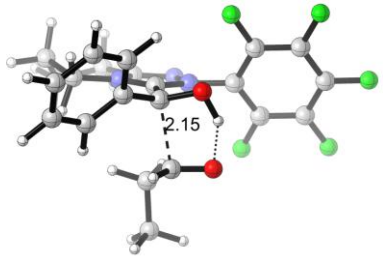


XYZ Coordinates

52

C	1.8993370	-3.2673380	2.4057300
H	2.0048890	-3.3903880	3.4867110
H	1.5213410	-4.2147680	2.0064950
C	3.2290770	-2.9125300	1.7346480
C	2.9815280	-2.3817260	0.3228000
H	3.9247820	-2.2089770	-0.2017070
H	2.4019810	-3.1087880	-0.2597230
C	2.2379510	-1.0550220	0.3878970
H	2.8804260	-0.2867090	0.8257990
H	1.9098980	-0.7106490	-0.5941050
C	0.8586320	-2.2271470	2.1370220
N	1.0383830	-1.2057840	1.2282640
N	-0.3311120	-2.1953790	2.6526580
C	-0.1231610	-0.4932230	1.1607770
N	-0.9384340	-1.1166420	2.0484520
C	-0.5111240	0.5179400	0.2164530
O	-1.8650910	0.7814110	0.2388090
C	-0.6214840	-0.7713820	-1.5256830
H	-0.0887410	-1.6288740	-1.0719400
O	-1.8865060	-0.8396950	-1.6188090
H	-2.2373400	0.1955190	-0.4956180
C	-2.2241320	-0.7399560	2.4844770
C	-4.7643430	-0.0182160	3.3743550
C	-3.2738350	-1.6510880	2.4429120
C	-2.4653470	0.5363330	2.9817420
C	-3.7271740	0.9040720	3.4162360
C	-4.5383800	-1.2981120	2.8906950
F	-3.0826810	-2.8733330	1.9506930
F	-5.5361130	-2.1806250	2.8474130
F	-5.9757980	0.3264330	3.8021210
F	-3.9496620	2.1326860	3.8818710
F	-1.4759160	1.4243550	3.0301830
C	0.3289590	1.7188770	-0.0042070
C	1.8073670	4.0715930	-0.5072620
C	-0.0967430	2.6521530	-0.9661210
C	1.4823390	2.0199340	0.7366620
C	2.2195880	3.1765810	0.4778920
C	0.6330910	3.8082720	-1.2174800
H	-1.0176010	2.4625310	-1.5092650
H	1.7892180	1.3767500	1.5566670
H	3.1064540	3.3884760	1.0687210
H	0.2815590	4.5103150	-1.9684210
H	2.3772700	4.9747110	-0.7037270
C	0.1668330	-0.0715220	-2.6149000
H	1.1254190	0.3031100	-2.2412880
H	-0.4110300	0.7883520	-2.9666930
C	0.4044440	-1.0544390	-3.7677470
H	0.9620880	-0.5741980	-4.5773960
H	-0.5453960	-1.4149280	-4.1740550
H	0.9813990	-1.9233890	-3.4311280
H	3.7564410	-2.1500260	2.3202190
H	3.8628230	-3.8018110	1.7095730

(*Z*)-Benzaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]$_{(Z)B\text{-}(si)P}$**)

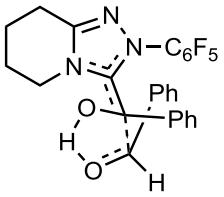


XYZ Coordinates

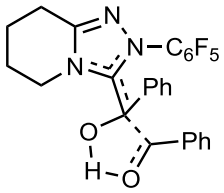
52

C	-1.1749030	1.7627880	3.1200050
H	-1.7183130	1.0804250	3.7782120
C	0.2523400	2.0281920	3.6007680
C	1.0199860	2.7695920	2.5089460
H	0.4798460	3.6835440	2.2344640
H	2.0143220	3.0655280	2.8535010
C	1.2076100	1.8895970	1.2793970
H	1.5505950	2.4717080	0.4235120
H	1.9394670	1.1021420	1.4847060
C	-1.1655340	1.1830430	1.7423460
N	-0.0640230	1.2446310	0.9134800
N	-2.1644420	0.5981860	1.1622280
C	-0.3850930	0.6296960	-0.2660140
N	-1.6910220	0.2635220	-0.0921130
C	-2.6110660	-0.2926150	-1.0047750
C	-4.4975930	-1.3646570	-2.7513880
C	-3.1512340	-1.5534830	-0.7744780
C	-3.0484900	0.4328240	-2.1082720
C	-3.9731710	-0.1015820	-2.9904250
C	-4.0919700	-2.0903660	-1.6406610
F	-2.5779320	1.6578070	-2.3267750
F	-4.3767800	0.5959530	-4.0536580
F	-5.4010650	-1.8768500	-3.5840030
F	-4.6031270	-3.3014880	-1.4150590
F	-2.7713380	-2.2612260	0.2842530
C	0.4256500	0.2235710	-1.3584230
O	-0.3097310	-0.0718490	-2.4957650

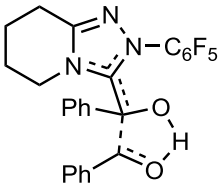
C	0.6719490	-1.8267670	-0.7654520
O	-0.2639000	-2.3417490	-1.4442430
H	-1.7347530	2.7043700	3.0864950
H	-0.4402470	-1.0648250	-2.4516010
C	1.7618970	0.8281320	-1.6489330
C	4.2431070	1.9756850	-2.3235250
C	2.9229870	0.4982630	-0.9374650
C	1.8731400	1.7185540	-2.7278790
C	3.0990000	2.2896970	-3.0603120
C	4.1503170	1.0757040	-1.2630740
H	2.8736710	-0.2122430	-0.1173190
H	0.9841540	1.9593820	-3.3036110
H	3.1615920	2.9833950	-3.8939660
H	5.0364460	0.8098290	-0.6938610
H	5.1995400	2.4212720	-2.5809650
H	1.6898430	-1.8123160	-1.1987500
C	0.6359870	-1.9047210	0.7465620
H	-0.3753470	-1.6638790	1.0944720
H	1.3365240	-1.1831240	1.1834620
C	1.0030990	-3.3252010	1.1895790
H	1.9989320	-3.6059930	0.8293490
H	0.2825340	-4.0469300	0.7939520
H	1.0037980	-3.4044770	2.2806500
H	0.2209940	2.6170530	4.5204410
H	0.7568220	1.0815870	3.8313370



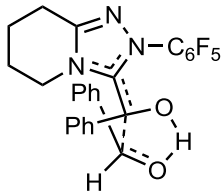
TS [V-VI]$_{(E)B\text{-}(re)B}$



TS [V-VI]$_{(E)B\text{-}(si)B}$

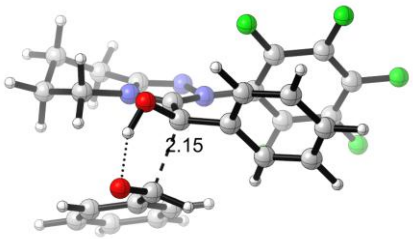


TS [V-VI]$_{(Z)B\text{-}(re)B}$



TS [V-VI]$_{(Z)B\text{-}(si)B}$

(*E*)-Benzaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]$_{(E)B\text{-}(re)B}$**)



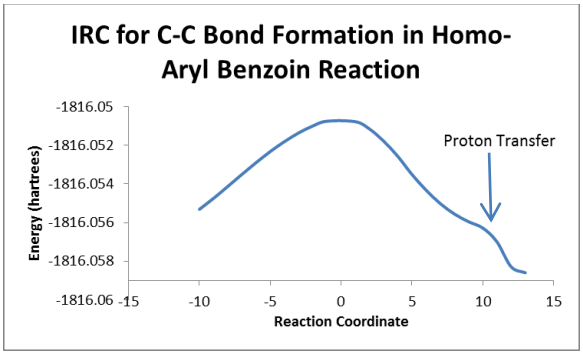
XYZ Coordinates

56

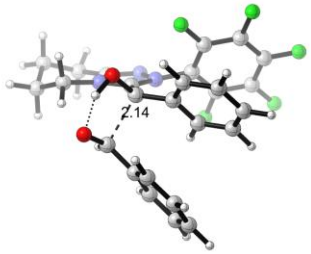
C	-4.7100880	-0.9283420	1.3367160
H	-5.2556240	-0.3227960	2.0643930
C	-4.5534120	-1.7610260	-1.0062850
H	-4.1889830	-2.7145630	-0.6052110
H	-5.0905170	-1.9752390	-1.9343700
C	-3.3703300	-0.8715030	-1.3631850
H	-2.6034740	-1.4227790	-1.9053300
H	-3.6863320	-0.0223580	-1.9738170
C	-3.3809620	-0.2918650	1.0936760
N	-2.7554610	-0.3234480	-0.1331520
N	-2.6648450	0.3309750	1.9783760
C	-1.5640940	0.3287410	-0.0144540
N	-1.5340470	0.7202320	1.2878650
C	-0.6821230	1.6595350	1.9013700
C	1.0392340	3.4976100	3.0917990
C	-0.5972710	2.9646530	1.4234400
C	0.0824510	1.3005950	3.0061340
C	0.9396120	2.2112960	3.6036420
C	0.2719410	3.8775940	1.9982220
F	0.0200750	0.0590920	3.4823010
F	1.6769840	1.8534450	4.6537470
F	1.8668200	4.3712840	3.6546930
F	0.3626220	5.1177510	1.5225110
F	-1.3451270	3.3410260	0.3889210
C	-0.5591500	0.4325150	-1.0285910
O	-1.0927460	0.5015200	-2.2958740
C	0.1861790	-1.5698890	-1.2355470
O	-0.0697930	-1.7247220	-2.4734010
H	-4.5351780	-1.9125260	1.7874520
H	-0.7458310	-0.3430090	-2.7380530
C	0.6508080	1.2887830	-0.8229630
C	2.8925990	2.9712320	-0.5265910
C	1.6418250	1.0074810	0.1302290
C	0.8238460	2.4098480	-1.6466390
C	1.9286400	3.2457140	-1.4976570

C	2.7460460	1.8446180	0.2839040
H	1.5527570	0.1284850	0.7630120
H	0.0717430	2.6223990	-2.3995990
H	2.0339160	4.1155650	-2.1398770
H	3.4978660	1.6095220	1.0326110
H	3.7539230	3.6222500	-0.4090630
H	1.1926900	-1.2438020	-0.9331620
C	-5.4692520	-1.0965510	0.0192490
C	-0.4902160	-2.4366530	-0.2164360
C	-1.7296000	-4.0883190	1.6827090
C	-1.3847090	-3.4320070	-0.6199870
C	-0.2105500	-2.2876240	1.1481150
C	-0.8324930	-3.0985830	2.0937170
C	-1.9974900	-4.2568470	0.3237990
H	-1.5831630	-3.5580820	-1.6810340
H	0.4984310	-1.5298390	1.4723030
H	-0.6142220	-2.9635810	3.1493630
H	-2.6837360	-5.0333360	-0.0032240
H	-2.2097650	-4.7276850	2.4178380
H	-6.3595150	-1.7059910	0.1933280
H	-5.8046220	-0.1205610	-0.3520750

IRC for (*E*)-Benzaldehyde BI Attacking *re* Face of Benzaldehyde (TS [V-VI]$_{(E)B\text{-}(re)B}$)



(*E*)- Benzaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$_{(E)B\text{-}(si)B}$**)



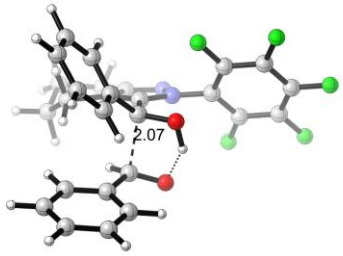
XYZ Coordinates

56

C	-4.7215350	-1.1120980	1.1875770
H	-5.3089720	-0.4757880	1.8535590
C	-5.4268100	-1.3767400	-0.1445790
C	-4.4518510	-2.0304280	-1.1219490
H	-4.0461330	-2.9520780	-0.6861160
H	-4.9544360	-2.3007470	-2.0543980
C	-3.3150640	-1.0825900	-1.4770550
H	-2.5298280	-1.5788670	-2.0455090
H	-3.6812210	-0.2361020	-2.0644910
C	-3.3926050	-0.4669630	0.9648590
N	-2.7256140	-0.5262590	-0.2379230
N	-2.7023220	0.1779650	1.8559700
C	-1.5346990	0.1142540	-0.0908370
N	-1.5537260	0.5501690	1.1939610
C	-0.7234140	1.5081030	1.8118240
C	0.9592390	3.3690950	3.0171190
C	-0.5428550	2.7671880	1.2473290
C	-0.0679750	1.2031300	2.9995150
C	0.7663060	2.1270290	3.6074810
C	0.3080830	3.6904420	1.8335970
F	-0.2019250	-0.0068700	3.5380720
F	1.3977890	1.8230670	4.7397890
F	1.7638310	4.2561720	3.5915720
F	0.4912530	4.8860380	1.2782470
F	-1.1710820	3.0851740	0.1190000
C	-0.5135910	0.2294810	-1.1113930
O	-1.0638150	0.5695500	-2.3244910
C	-0.1086850	-1.7919850	-1.6699350
O	-0.4316100	-1.6850750	-2.9059990
H	-4.5473770	-2.0616000	1.7070260
H	-0.8795160	-0.2589520	-2.9017620
H	-0.8240000	-2.2674780	-0.9740930
C	0.7803580	0.8867790	-0.7892480
C	3.2743160	2.1017030	-0.2857330
C	1.5599300	0.5068960	0.3173300
C	1.2867640	1.8686550	-1.6496310
C	2.5207280	2.4716720	-1.3984410
C	2.7858090	1.1112810	0.5724220
H	1.2075910	-0.2813270	0.9779370
H	0.6995180	2.1585770	-2.5145890
H	2.8907100	3.2357580	-2.0763920
H	3.3691360	0.7988700	1.4348210
H	4.2341150	2.5712250	-0.0913470
C	1.3087240	-2.0430320	-1.2916810
C	3.9690470	-2.4873800	-0.5451930

C	1.6064860	-2.6880800	-0.0888380
C	2.3530110	-1.6354450	-2.1299030
C	3.6762600	-1.8490550	-1.7540550
C	2.9313360	-2.9136530	0.2844620
H	0.7931550	-3.0087080	0.5605220
H	2.1141970	-1.1428500	-3.0687470
H	4.4834170	-1.5202010	-2.4025610
H	3.1531540	-3.4207300	1.2192180
H	5.0022480	-2.6565500	-0.2556780
H	-6.2906840	-2.0220920	0.0315590
H	-5.7979100	-0.4355780	-0.5676950

(*Z*)-Benzaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]**$_{(Z)B\text{-}(re)B}$)

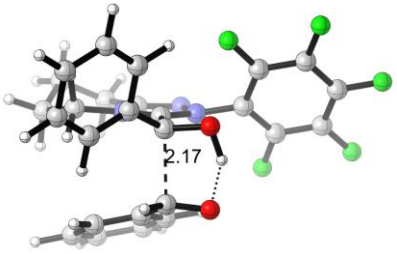


XYZ Coordinates

56

C	1.8430440	-3.2881250	2.5923530
H	1.8110930	-3.4477810	3.6730070
H	1.5135300	-4.2180050	2.1157740
C	3.2489020	-2.9237290	2.1050300
C	3.1869720	-2.3517300	0.6889670
H	4.1907260	-2.1634760	0.2994870
H	2.6937410	-3.0614620	0.0131460
C	2.4368150	-1.0283300	0.6947160
H	3.0032020	-0.2740350	1.2480830
H	2.2487940	-0.6442590	-0.3089860
C	0.8485370	-2.2314930	2.2303940
N	1.1330770	-1.2075610	1.3545140
N	-0.3884550	-2.1808690	2.6224950
C	-0.0029830	-0.4798900	1.1747180
N	-0.9133220	-1.0939850	1.9622800
C	-0.2800710	0.5158250	0.1515290
O	-1.6092180	0.8764120	0.0965290
C	-0.4342800	-0.8794290	-1.3755770
H	0.3505840	-1.5835920	-1.0518900
O	-1.6641900	-1.2029140	-1.2027090
H	-2.0235350	0.1215590	-0.4451220
C	-2.2341040	-0.7023380	2.2637670
C	-4.8394000	0.0484790	2.8973460
C	-3.2797400	-1.6110750	2.1394470
C	-2.5100540	0.5834800	2.7172320
C	-3.8046350	0.9657150	3.0238560
C	-4.5780480	-1.2416640	2.4603680
F	-3.0516670	-2.8438500	1.6960120
F	-5.5746970	-2.1181340	2.3395910
F	-6.0834730	0.4086260	3.1983890
F	-4.0601580	2.2024010	3.4491180
F	-1.5213460	1.4618270	2.8583710
C	0.6547690	1.6704350	0.0312150
C	2.3627130	3.9065420	-0.1877200
C	0.5279700	2.5728890	-1.0378560
C	1.6123960	1.9518010	1.0169360
C	2.4673420	3.0472860	0.9037840
C	1.3759030	3.6713220	-1.1480780
H	-0.2453820	2.4146790	-1.7819240
H	1.6708550	1.3339790	1.9090160
H	3.1991870	3.2375850	1.6835590
H	1.2630610	4.3501590	-1.9887150
H	3.0240350	4.7631260	-0.2773700
C	-0.0621980	-0.1070660	-2.6028660
C	0.5972950	1.3809970	-4.8835620
C	-1.0657950	0.4986580	-3.3663110
C	1.2707410	0.0179500	-3.0054760
C	1.6011920	0.7582390	-4.1393380
C	-0.7379320	1.2433220	-4.4977510
H	-2.1004930	0.3773050	-3.0588740
H	2.0565400	-0.4695630	-2.4322500
H	2.6401760	0.8497310	-4.4427470
H	-1.5233940	1.7152140	-5.0813710
H	0.8536320	1.9612520	-5.7651250
H	3.7002300	-2.1831420	2.7758170
H	3.8768940	-3.8168550	2.1339660

(*Z*)- Benzaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]**$_{(Z)B\text{-}(si)B}$)



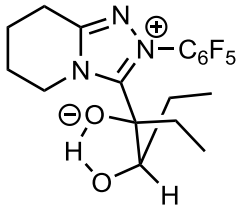
XYZ Coordinates

56

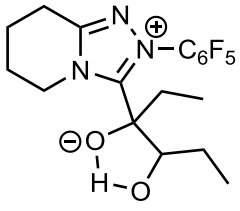
C	-1.1477050	1.7255470	3.0787320

H -1.0230630 0.9200380 3.8128200
C 0.0108330 2.7172980 3.2038170
C 1.3051030 2.0303270 2.7743260
H 2.1688500 2.6834050 2.9253070
H 1.4579590 1.1330490 3.3867590
C 1.2830450 1.6386770 1.3006240
H 1.4321840 2.5119540 0.6567650
H 2.0638960 0.9092160 1.0858340
C -1.1510780 1.1163370 1.7169390
N -0.0124420 1.0350240 0.9437810
N -2.1761990 0.6063400 1.1109680
C -0.3468110 0.4380840 -0.2367680
N -1.6776780 0.1674230 -0.1027120
C -2.6209480 -0.1870850 -1.0916740
C -4.5569140 -0.8307750 -2.9973820
C -3.4915820 -1.2521460 -0.8888020
C -2.7592230 0.5689570 -2.2529310
C -3.7044520 0.2443360 -3.2099140
C -4.4556810 -1.5759860 -1.8330650
F -1.9802320 1.6287890 -2.4506400
F -3.8145320 0.9695110 -4.3233640
F -5.4757840 -1.1396180 -3.9080600
F -5.2804690 -2.6026320 -1.6258790
F -3.4113500 -1.9879940 0.2185340
C 0.4919680 -0.0196440 -1.2962920
O -0.2235590 -0.4883800 -2.3790880
C 0.9435660 -2.0123130 -0.5606530
O 0.0844390 -2.6424560 -1.2530770
H -2.1219200 2.1882440 3.2520590
H -0.2562830 -1.4925210 -2.2270590
C 1.7023300 0.7799500 -1.6997030
C 3.8656610 2.3417880 -2.5971850
C 3.0001770 0.5327280 -1.2444100
C 1.5098410 1.8098210 -2.6344700
C 2.5774180 2.5866620 -3.0769090
C 4.0731410 1.3114790 -1.6825490
H 3.1851130 -0.2665640 -0.5346780
H 0.5078260 1.9970700 -3.0109770
H 2.4049160 3.3832820 -3.7948510
H 5.0729310 1.1047890 -1.3115690
H 4.7009880 2.9463660 -2.9381730
H 1.9764650 -1.9328210 -0.9373180
C 0.8285710 -1.9763790 0.9277340
C 0.6029900 -1.9244750 3.7207820
C -0.3946850 -2.2617530 1.5438380
C 1.9417950 -1.6846840 1.7230580
C 1.8322170 -1.6622130 3.1129750
C -0.5101380 -2.2256380 2.9320110
H -1.2464750 -2.5167450 0.9221660
H 2.9029910 -1.4879300 1.2527400
H 2.7053650 -1.4409980 3.7204270
H -1.4671060 -2.4391300 3.4003540
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H 0.0855490 3.0576660 4.2394060

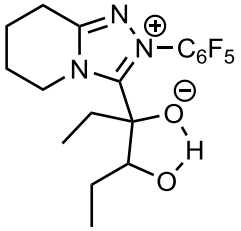
Tetrahedral Intermediates



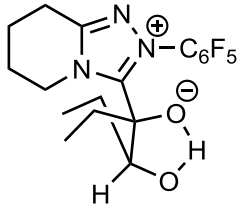
Int. VI$_{(E)P\text{-}(re)P}$



Int. VI$_{(E)P\text{-}(si)P}$



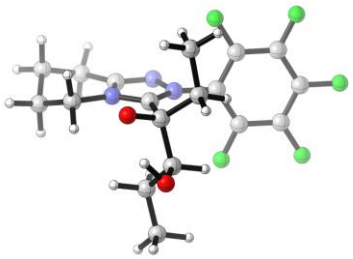
Int. VI$_{(Z)P\text{-}(re)P}$



Int. VI$_{(Z)P\text{-}(si)P}$

(*E*)-Propionaldehyde BI + *re* Face of Propionaldehyde

(Int. VI$_{(E)P\text{-}(re)P}$)



XYZ Coordinates

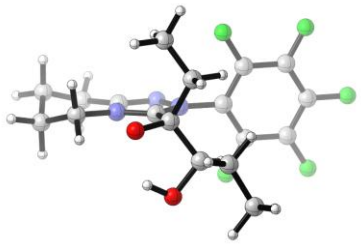
48

C 1.6439260 3.3128620 -2.1580380
H 1.5740650 3.2016380 -3.2461400
H 1.1304270 4.2392320 -1.8898250
C 3.1123770 3.3082200 -1.7308450
C 3.6731640 1.8942280 -1.8617030
H 3.5414690 1.5343010 -2.8900230

H	4.7443960	1.8756750	-1.6433600
C	3.0035640	0.9360600	-0.8879650
H	3.2518870	-0.1044830	-1.0715490
H	3.2664250	1.1661630	0.1464020
C	0.9067540	2.1703530	-1.5398490
N	1.5247230	1.0671680	-0.9914060
N	-0.3879240	2.0560840	-1.4697680
C	0.5683120	0.2269280	-0.5547120
N	-0.5850990	0.8470280	-0.8632030
C	-1.9222730	0.4540070	-0.6060420
C	-4.5514990	-0.2792920	-0.0656640
C	-2.6203350	1.0456320	0.4437000
C	-2.5746270	-0.4719570	-1.4124260
C	-3.8793060	-0.8533110	-1.1357680
C	-3.9250790	0.6749040	0.7256160
F	-1.9565490	-1.0059700	-2.4610020
F	-4.4953580	-1.7463460	-1.9049480
F	-5.8024190	-0.6359810	0.1946250
F	-4.5793350	1.2296030	1.7419060
F	-2.0298700	1.9666350	1.1984490
C	0.5735550	-2.2656810	-1.0176340
C	0.8088620	-1.1524540	0.0964010
O	2.0845080	-1.2383770	0.5284130
O	1.2996170	-3.3748920	-0.5357320
H	1.9867900	-2.9040570	0.0104050
H	3.6699380	4.0079910	-2.3577020
H	3.2049170	3.6477540	-0.6924540
H	-0.4917110	-2.5368190	-1.0627850
C	-0.2010560	-1.3880290	1.2503410
H	-1.2394990	-1.3867290	0.9001040
H	0.0090860	-2.4103700	1.5845270
C	-0.0098900	-0.4174610	2.4096030
H	-0.7104480	-0.6282880	3.2239190
H	-0.1673040	0.6232530	2.1007650
H	1.0086380	-0.4983850	2.7976790
C	1.0654750	-1.8784290	-2.4128750
H	0.5326190	-0.9875860	-2.7702310
H	2.1301630	-1.6167770	-2.3389080
C	0.8755830	-3.0106100	-3.4186350
H	1.2569500	-2.7334680	-4.4064470
H	-0.1866610	-3.2593450	-3.5270410
H	1.4008190	-3.9113040	-3.0887600

(*E*)-Propionaldehyde BI + *si* Face of Propionaldehyde

(Int. VI$_{(E)P\text{-}(si)P}$)



XYZ Coordinates

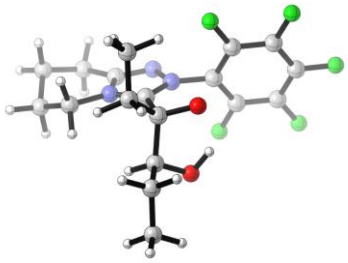
48

C	1.6958020	3.3334130	-2.0141000
H	1.7896130	3.2422750	-3.1024670
H	1.0596480	4.1977310	-1.8088280
C	3.0832810	3.4617970	-1.3838880
C	3.8034310	2.1193060	-1.4752540
H	3.8541420	1.7965800	-2.5225670
H	4.8301260	2.1982190	-1.1074830
C	3.1125420	1.0523560	-0.6386310
H	3.4827400	0.0497370	-0.8250610
H	3.2158250	1.2602150	0.4297240
C	1.0007570	2.1096290	-1.5141490
N	1.6520580	1.0431880	-0.9295910
N	-0.2785990	1.8859220	-1.5837950
C	0.7331570	0.1095300	-0.6217320
N	-0.4319940	0.6441780	-1.0307770
C	-1.7546280	0.1361970	-0.9514150
C	-4.3983650	-0.7284810	-0.8659170
C	-2.5407150	0.3778050	0.1703830
C	-2.3236920	-0.5076420	-2.0466970
C	-3.6353970	-0.9528870	-2.0043830
C	-3.8534220	-0.0653560	0.2249240
F	-1.5994810	-0.7165810	-3.1405770
F	-4.1680260	-1.5817350	-3.0482550
F	-5.6555640	-1.1496050	-0.8211420
F	-4.5938880	0.1560210	1.3075980
F	-2.0353090	1.0326580	1.2101550
C	0.4310840	-2.3846110	-0.8309860
C	1.0009020	-1.2560880	0.1132150
O	2.3247420	-1.4386700	0.2436540
O	1.4093100	-2.5352860	-1.8417430
H	2.2214380	-2.2778990	-1.3356270
H	3.6430770	4.2412500	-1.9059580
H	2.9952060	3.7655510	-0.3337780
C	0.2605030	-1.1721280	1.4688980
H	-0.8287590	-1.1608850	1.3324480

H -0.5075160 -2.0919150 -1.3166600
H 0.5016710 -2.1032070 1.9916890
C 0.7190510 0.0116590 2.3158310
H 1.7963380 -0.0523160 2.4937510
H 0.2096250 0.0209130 3.2841990
H 0.5105210 0.9731820 1.8302380
C 0.1914220 -3.7033860 -0.0982170
H 1.1045830 -3.9708010 0.4484230
H -0.6058010 -3.5667780 0.6423110
C -0.1972910 -4.8217340 -1.0618130
H 0.5916620 -4.9914270 -1.7993610
H -1.1150850 -4.5683120 -1.6063450
H -0.3741060 -5.7602870 -0.5272750

(*Z*)-Propionaldehyde BI + *re* Face of Propionaldehyde

(**Int. VI$_{(Z)P\text{-}(re)P}$**)



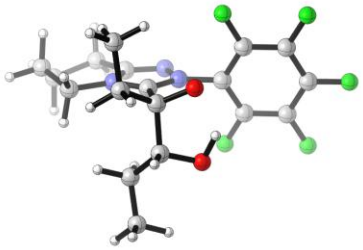
XYZ Coordinates

48

C 1.7154420 3.2734030 -2.0281740
H 1.2584540 3.5350200 -2.9855650
H 1.5648650 4.1189750 -1.3473410
C 3.2095710 2.9677870 -2.1556110
C 3.7183580 2.3461960 -0.8558680
H 4.8011530 2.2008270 -0.8860000
H 3.4954590 3.0108290 -0.0127540
C 3.0842020 0.9826300 -0.6159110
H 3.4541060 0.2481770 -1.3376580
H 3.2810870 0.6228750 0.3944470
C 0.9895000 2.0980680 -1.4628010
N 1.6181650 1.0718460 -0.7920560
N -0.2950760 1.8920540 -1.5047160
C 0.6777670 0.1860720 -0.4065790
N -0.4716600 0.7066550 -0.8472460
C -1.8017440 0.2317660 -0.7032070
C -4.4475380 -0.5798590 -0.4845900
C -2.6600510 0.8722780 0.1776650
C -2.2858550 -0.7970440 -1.5016480
C -3.6000560 -1.2123960 -1.3870850
C -3.9822150 0.4654760 0.2967590
F -1.4884230 -1.3920680 -2.3803990
F -4.0628980 -2.2095550 -2.1419030
F -5.7145520 -0.9724230 -0.3798210
F -4.8034400 1.0823810 1.1464710
F -2.2197150 1.8828520 0.9239330
C 1.0481990 -0.6530710 1.9006050
C 0.7851330 -1.1327340 0.4100690
O -0.4080410 -1.7578050 0.3625520
O -0.2289590 -0.2803820 2.3786880
H -0.7968300 -0.8757700 1.8180100
H 3.3824440 2.2762380 -2.9891550
H 3.7480120 3.8920400 -2.3765140
H 1.6973470 0.2353260 1.9319010
C 1.9425490 -1.9826120 -0.1582580
H 2.9205840 -1.5375760 0.0585900
H 1.8946040 -2.9256750 0.3948340
C 1.7987400 -2.2681690 -1.6501090
H 2.5713910 -2.9639620 -1.9911050
H 1.8913430 -1.3567840 -2.2551900
H 0.8212810 -2.7135320 -1.8546970
C 1.6636900 -1.7418750 2.7775190
H 2.6634390 -1.9916790 2.4028890
H 1.0479880 -2.6468410 2.6962370
C 1.7612310 -1.3016930 4.2362220
H 2.3782450 -0.4001730 4.3318820
H 2.2121020 -2.0833900 4.8556420
H 0.7708830 -1.0738530 4.6394240

(*Z*)-Propionaldehyde BI + *si* Face of Propionaldehyde

(**Int. VI$_{(Z)P\text{-}(si)P}$**)

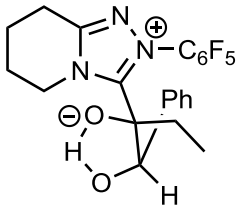


XYZ Coordinates

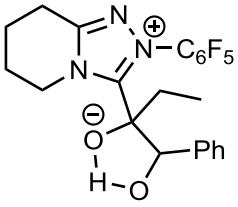
48

C 1.6374040 3.3113510 -2.2058540
H 1.6239000 3.1645630 -3.2917680
H 1.0425650 4.2010660 -1.9860470
C 3.0809400 3.4373650 -1.7178190
C 3.7578530 2.0720460 -1.7915060
H 3.6906510 1.6769730 -2.8125730
H 4.8176480 2.1403190 -1.5324260

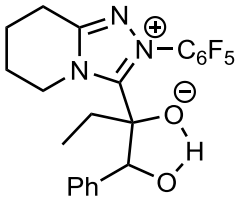
C	3.1211880	1.0879700	-0.8193880
H	3.4820060	0.0795840	-1.0016720
H	3.3382930	1.3689880	0.2138560
C	0.9681940	2.1328520	-1.5778910
N	1.6473290	1.0919910	-0.9786330
N	-0.3145220	1.9214490	-1.5377280
C	0.7355000	0.1928180	-0.5440420
N	-0.4422700	0.7190060	-0.9060570
C	-1.7616690	0.2342140	-0.7018580
C	-4.3851110	-0.6002220	-0.3542370
C	-2.5379770	0.7738200	0.3131270
C	-2.3189920	-0.6984790	-1.5690550
C	-3.6224890	-1.1253740	-1.3912770
C	-3.8479060	0.3516180	0.4975300
F	-1.6051120	-1.1886070	-2.5751020
F	-4.1569490	-2.0322770	-2.2105210
F	-5.6431350	-1.0016940	-0.1912900
F	-4.5918850	0.8675480	1.4763250
F	-2.0370810	1.7085250	1.1155660
C	0.7922190	-0.8027340	1.7882210
C	0.8374490	-1.1515940	0.2414300
O	-0.2643070	-1.8763670	-0.0516820
O	-0.5754350	-0.6978990	2.1111290
H	-0.9499200	-1.2920500	1.4011340
H	3.6085900	4.1649850	-2.3385380
H	3.0999810	3.8059060	-0.6852380
H	1.2238730	-1.6921430	2.2830580
C	2.1445720	-1.8984160	-0.0877140
H	3.0246570	-1.3723130	0.3016140
H	2.0647450	-2.8295070	0.4837260
C	2.2937960	-2.2417380	-1.5664620
H	3.1641130	-2.8828980	-1.7360890
H	2.4129990	-1.3536450	-2.2004370
H	1.4014940	-2.7734740	-1.9089420
C	1.5422650	0.4263170	2.2737550
H	2.5999110	0.3248580	2.0006800
H	1.1510880	1.3225020	1.7717510
C	1.4244030	0.6052290	3.7863990
H	1.9900820	1.4781840	4.1264080
H	1.8112880	-0.2745930	4.3126600
H	0.3792030	0.7400640	4.0780030



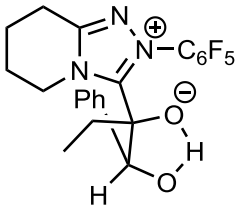
Int. VI$_{(E)P\text{-}(re)B}$



Int. VI$_{(E)P\text{-}(si)B}$



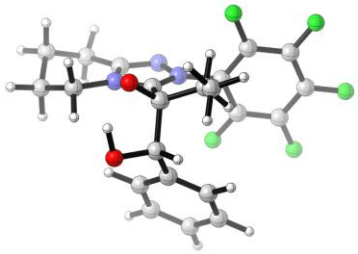
Int. VI$_{(Z)P\text{-}(re)B}$



Int. VI$_{(Z)P\text{-}(si)B}$

(*E*)-Propionaldehyde BI + *re* Face of Benzaldehyde

(Int. VI$_{(E)P\text{-}(re)B}$)



XYZ Coordinates

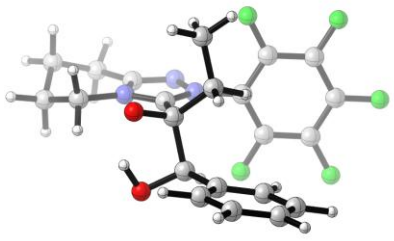
52

C	1.7831580	3.6122760	-1.5259050
H	1.7591190	3.6877430	-2.6190750
H	1.2267330	4.4630110	-1.1254350
C	3.2332000	3.5761210	-1.0420240
C	3.8522700	2.2339530	-1.4216930
H	3.7669620	2.0811880	-2.5049430
H	4.9161860	2.2053610	-1.1713130
C	3.1901260	1.0823290	-0.6772000
H	3.4666930	0.1192040	-1.1010030
H	3.4399640	1.0835320	0.3841560
C	1.0697940	2.3587630	-1.1373730
N	1.7119790	1.1992600	-0.7673130
N	-0.2211320	2.1994690	-1.1048180
C	0.7768290	0.2701590	-0.4845000
N	-0.3907370	0.9046230	-0.6978990
C	-1.7196680	0.4078300	-0.7093630
C	-4.3395530	-0.5128470	-0.8347390
C	-2.5141930	0.3943910	0.4319590

C	-2.2782310	0.0317830	-1.9262210
C	-3.5767390	-0.4496520	-1.9927790
C	-3.8128180	-0.0865310	0.3779300
F	-1.5723170	0.1669810	-3.0386410
F	-4.1003850	-0.8192120	-3.1588330
F	-5.5859830	-0.9664490	-0.8876070
F	-4.5613030	-0.1280250	1.4777270
F	-2.0341560	0.8292690	1.5928030
C	1.4951220	-2.1559940	-1.0815270
C	1.0950000	-1.1417430	0.1030130
O	2.1707970	-0.9967520	0.9007940
O	2.8942050	-2.1078760	-1.1401010
H	3.0617650	-1.7182920	-0.2173200
H	3.7844680	4.4020210	-1.4974440
H	3.2718850	3.7096710	0.0456470
H	1.1681240	-3.1457450	-0.7315390
C	0.8621980	-1.9354330	-2.4321050
C	-0.2606360	-1.6697030	-4.9946160
C	1.4260830	-1.0614710	-3.3690290
C	-0.2792490	-2.6620970	-2.7916450
C	-0.8384630	-2.5321730	-4.0633260
C	0.8687950	-0.9293110	-4.6406610
H	2.3301980	-0.5159270	-3.1085540
H	-0.7084790	-3.3640190	-2.0790930
H	-1.7159820	-3.1146970	-4.3301440
H	1.3250330	-0.2575870	-5.3626100
H	-0.6865190	-1.5744250	-5.9891730
C	-0.1497240	-1.6982800	0.8343430
H	-0.9216350	-1.9901150	0.1083180
H	-0.5619910	-0.9107320	1.4724140
C	0.1990580	-2.8800570	1.7357780
H	0.9422430	-2.5781860	2.4766400
H	0.6064620	-3.7287390	1.1780210
H	-0.6975300	-3.2263440	2.2592710

(*E*)-Propionaldehyde BI + *si* Face of Benzaldehyde

(Int. VI$_{(E)P\text{-}(si)B}$)



XYZ Coordinates

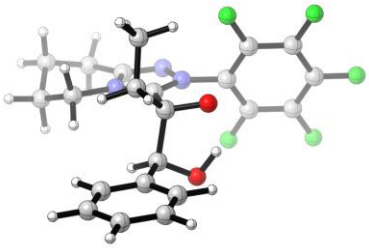
52

C	1.7642450	3.2746350	-2.0705280
H	1.7678210	3.1808470	-3.1624740
H	1.2074530	4.1806500	-1.8198110
C	3.2003130	3.2999600	-1.5470780
C	3.8074410	1.9085350	-1.6991280
H	3.7405150	1.5897860	-2.7467800
H	4.8656620	1.9071100	-1.4240160
C	3.1166430	0.8892530	-0.8036980
H	3.3894520	-0.1287380	-1.0623070
H	3.3484940	1.0513380	0.2498150
C	1.0254880	2.1028600	-1.5129190
N	1.6386710	1.0061710	-0.9436910
N	-0.2679940	1.9642940	-1.5013740
C	0.6788890	0.1484070	-0.5481870
N	-0.4703120	0.7483090	-0.9117210
C	-1.8134430	0.3097400	-0.7821540
C	-4.4698100	-0.4929500	-0.5553980
C	-2.6159390	0.8010820	0.2448690
C	-2.3786130	-0.5386470	-1.7285080
C	-3.6948280	-0.9602770	-1.6067160
C	-3.9338390	0.3936290	0.3703490
F	-1.6633100	-0.9569930	-2.7682030
F	-4.2203350	-1.7900760	-2.5035000
F	-5.7318290	-0.8842130	-0.4378180
F	-4.6899100	0.8528130	1.3632700
F	-2.1193640	1.6635500	1.1251590
C	0.7441320	-2.3417010	-0.9698590
C	0.9106590	-1.2190400	0.1823630
O	2.1802660	-1.2706420	0.6193130
O	2.0388020	-2.4575350	-1.4959780
H	2.5532740	-2.0832490	-0.7040150
H	3.7751890	4.0395520	-2.1091970
H	3.2131160	3.6009760	-0.4926290
C	-0.1149480	-1.3637940	1.3232960
H	-1.1448550	-1.4027900	0.9478520
H	0.0560430	-1.9987340	-1.7496670
C	0.2232410	-3.6536650	-0.4277580
C	-0.7834010	-6.0389490	0.6600380
C	-1.1292690	-3.9816430	-0.5572160
C	1.0720730	-4.5426860	0.2395500
C	0.5719850	-5.7258020	0.7820980
C	-1.6342160	-5.1643610	-0.0160540
H	-1.7941890	-3.3102720	-1.0988360
H	2.1270260	-4.2999180	0.3302670
H	1.2415790	-6.4070140	1.3000050
H	-2.6870850	-5.4066470	-0.1310020

H -1.1708460 -6.9631410 1.0788500
H 0.0835440 -2.3452000 1.7651580
C 0.0502720 -0.2893480 2.3949180
H 1.0377860 -0.3745300 2.8551130
H -0.7069650 -0.3975140 3.1776730
H -0.0415430 0.7234150 1.9865050

(*Z*)-Propionaldehyde BI + *re* Face of Benzaldehyde

(Int. VI$_{(Z)P\text{-}(re)B}$)



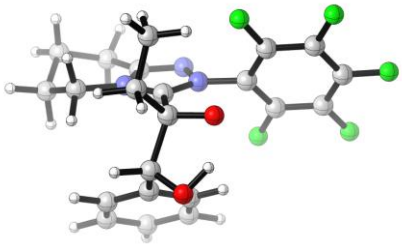
XYZ Coordinates

52

C -3.2095680 -2.2047800 1.8715280
H -4.0400380 -2.6933500 1.3568140
H -2.7402210 -2.9510050 2.5228990
C -3.6641700 -1.0006930 2.7009120
H -4.3265800 -0.3617150 2.1049790
H -4.2354500 -1.3538440 3.5621990
C -2.4477130 -0.1975010 3.1577680
H -2.7431840 0.6201720 3.8200430
H -1.7612020 -0.8450160 3.7161130
C -1.7215890 0.4203020 1.9707990
H -2.3183260 1.2180530 1.5181660
H -0.7492210 0.8208260 2.2606390
C -2.1969360 -1.7904020 0.8554460
N -1.4990560 -0.6051330 0.9291880
N -1.8223870 -2.4724100 -0.1882240
C -0.6555730 -0.5512020 -0.1192430
N -0.8666130 -1.6936650 -0.7803020
C -0.2310850 -2.2035770 -1.9430580
C 0.9491360 -3.3086320 -4.1995020
C 0.6808700 -3.2414980 -1.8192730
C -0.5720910 -1.7413210 -3.2079800
C 0.0210790 -2.2822630 -4.3347330
C 1.2795840 -3.7925630 -2.9437700
F -1.4673050 -0.7696840 -3.3436650
F -0.2932210 -1.8298590 -5.5487180
F 1.5144990 -3.8352010 -5.2822380
F 2.1588390 -4.7865830 -2.8212050
F 0.9954380 -3.7152380 -0.6157050
C 0.3976200 0.5110020 -0.5097620
O 0.8905570 0.2056710 -1.7247270
C -0.2393870 1.9118130 -0.4421460
H 0.5330140 2.5899590 -0.8189580
H -0.4437980 2.2168150 0.5895680
C -1.4929610 2.0306740 -1.3034470
H -1.8583330 3.0617580 -1.3205250
H -2.3107570 1.3997220 -0.9306130
H -1.2735220 1.7265760 -2.3304100
C 1.5823090 0.2897910 0.5703780
H 1.1719580 -0.0752340 1.5222670
C 2.3499590 1.5634340 0.8461650
C 3.7017940 3.9748640 1.3367810
C 3.3650230 1.9938150 -0.0132650
C 2.0299270 2.3473120 1.9591470
C 2.6968410 3.5468660 2.2050660
C 4.0354220 3.1930490 0.2293120
H 3.6297200 1.3811560 -0.8700840
H 1.2524370 2.0101690 2.6427550
H 2.4388990 4.1417810 3.0766930
H 4.8219180 3.5179010 -0.4462320
H 4.2270200 4.9065310 1.5262030
O 2.3749930 -0.7049220 -0.0152820
H 2.0812440 -0.5927850 -0.9785460

(*Z*)-Propionaldehyde BI + *si* Face of Benzaldehyde

(Int. VI$_{(Z)P\text{-}(si)B}$)

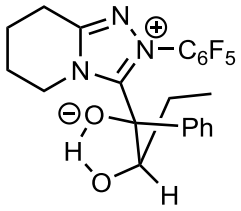


XYZ Coordinates

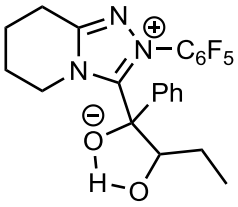
52

C -0.6153240 2.1008940 2.7622710
H -0.7501570 1.3335390 3.5330920
C 0.7236180 2.8132910 2.9690850
C 1.8712100 1.8805590 2.5846840
H 2.8395990 2.3390690 2.8010060
H 1.8057890 0.9487680 3.1601810
C 1.8402490 1.5632520 1.0964430
H 2.0783350 2.4520960 0.5044080
H 2.5389100 0.7668790 0.8419990
C -0.6498920 1.4188510 1.4349280

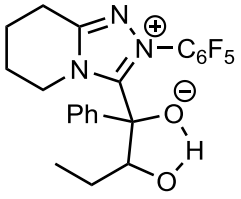
N	0.4817380	1.1289150	0.7058560
N	-1.7113740	0.9963260	0.8118240
C	0.1037990	0.4740570	-0.4079370
N	-1.2328300	0.4164330	-0.3300000
C	-2.1919610	-0.0939190	-1.2445850
C	-4.1877500	-1.0046230	-2.9611650
C	-3.0257560	-1.1374420	-0.8670580
C	-2.4031840	0.5227200	-2.4732750
C	-3.3816970	0.0636730	-3.3358950
C	-4.0146560	-1.6025130	-1.7239040
F	-1.6745210	1.5747620	-2.8233520
F	-3.5701150	0.6530350	-4.5170250
F	-5.1389330	-1.4370020	-3.7842070
F	-4.8045380	-2.6092620	-1.3496300
F	-2.8938050	-1.7117330	0.3264590
C	0.9520870	-0.1665150	-1.5054190
O	0.1340690	-0.6769870	-2.4501940
C	1.8023970	-1.4149010	-0.8674720
O	1.7325230	-2.3771740	-1.8754240
H	-1.4660370	2.7835540	2.8232310
H	0.9720690	-1.9685980	-2.4292310
H	2.8395630	-1.0820820	-0.7194620
C	1.2687380	-1.9383060	0.4480680
C	0.2254110	-2.8545620	2.8904710
C	1.9872350	-1.7762680	1.6364120
C	0.0265990	-2.5819950	0.4949900
C	-0.4926750	-3.0351900	1.7062520
C	1.4704220	-2.2277110	2.8525070
H	2.9699890	-1.3089110	1.6079750
H	-0.5238200	-2.7308710	-0.4318030
H	-1.4583690	-3.5321610	1.7281500
H	2.0447840	-2.1003670	3.7661450
H	-0.1778450	-3.2128870	3.8331100
C	1.9735610	0.8470310	-2.0762470
H	2.5270930	0.2744730	-2.8304670
H	2.7024000	1.1471350	-1.3161040
C	1.3403270	2.0740680	-2.7191360
H	2.1071570	2.7162120	-3.1635300
H	0.7902830	2.6772160	-1.9850250
H	0.6411370	1.7765240	-3.5033570
H	0.7647740	3.7217670	2.3565390
H	0.8093710	3.1168790	4.0148190



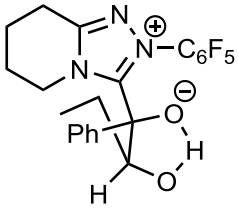
Int. VI$_{(E)B-(re)P}$



Int. VI$_{(E)B-(si)P}$



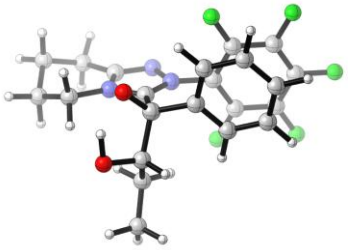
Int. VI$_{(Z)B-(re)P}$



Int. VI$_{(Z)B-(si)P}$

(*E*)-Benzaldehyde BI + *re* Face of Propionaldehyde

(**Int. VI$_{(E)B-(re)P}$**)



XYZ Coordinates

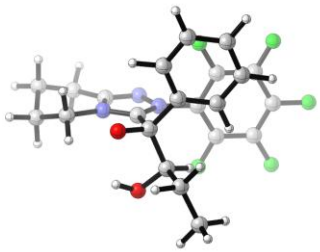
52

C	1.6459490	3.2199600	-2.3968260
H	1.5403620	3.0395920	-3.4728190
H	1.1791660	4.1831210	-2.1777550
C	3.1243540	3.1786570	-2.0071040
C	3.6307840	1.7398280	-2.0873830
H	3.4608830	1.3410550	-3.0952740
H	4.7056700	1.6913750	-1.8940750
C	2.9506650	0.8515970	-1.0549040
H	3.1427780	-0.2053760	-1.2340580
H	3.2629490	1.0923520	-0.0374180
C	0.8864020	2.1545930	-1.6776660
N	1.4814720	1.0573060	-1.1022530
N	-0.4045280	2.1154470	-1.5134120
C	0.5170010	0.2921680	-0.5554310
N	-0.6211780	0.9550300	-0.8209960
C	-1.9663220	0.6540350	-0.4861120
C	-4.6155920	0.1145220	0.1439960
C	-2.4843900	1.0337200	0.7464980

C	-2.7978570	0.0416330	-1.4150840
C	-4.1200840	-0.2339980	-1.1045470
C	-3.8003710	0.7472840	1.0731120
F	-2.3184200	-0.3121450	-2.6046440
F	-4.9085460	-0.8414710	-1.9885750
F	-5.8750150	-0.1673610	0.4572910
F	-4.2865770	1.0776270	2.2663000
F	-1.7147620	1.6674100	1.6239590
C	1.2427340	-2.1860340	-0.7486210
C	0.8085810	-0.9996690	0.2604230
O	1.8581370	-0.7147130	1.0613360
O	2.6282830	-2.3203080	-0.5779760
H	2.7365280	-1.7313530	0.2467990
H	3.6912190	3.8272580	-2.6790420
H	3.2556970	3.5613360	-0.9880610
H	0.7430870	-3.0970570	-0.3848570
C	0.8827840	-1.9933840	-2.2172010
H	-0.1840180	-1.7458390	-2.3032750
H	1.4428470	-1.1374310	-2.6174740
C	1.1945790	-3.2379870	-3.0446070
H	0.9436830	-3.0883680	-4.0992120
H	0.6242910	-4.0999920	-2.6804880
H	2.2580950	-3.4862550	-2.9790590
C	-0.4535570	-1.4118000	1.0422390
C	-2.7131090	-2.0935670	2.5683770
C	-1.4774860	-2.1929180	0.4914730
C	-0.5671620	-0.9969360	2.3698730
C	-1.6906690	-1.3293310	3.1291860
C	-2.6016140	-2.5274710	1.2455350
H	-1.4136580	-2.5368340	-0.5390710
H	0.2426970	-0.4123560	2.7950920
H	-1.7654070	-0.9918350	4.1592250
H	-3.3887150	-3.1306000	0.8005860
H	-3.5891780	-2.3535070	3.1558870

(*E*)-Benzaldehyde BI + *si* Face of Propionaldehyde

(Int. VI$_{(E)B\text{-}(si)P}$)



XYZ Coordinates

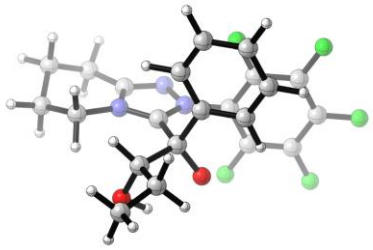
52

C	1.7160410	3.2979130	-2.0055120
H	1.8111450	3.2138160	-3.0941760
H	1.1092510	4.1821730	-1.7958200
C	3.1043730	3.3755190	-1.3694540
C	3.7666260	2.0033720	-1.4464530
H	3.7986980	1.6649290	-2.4896920
H	4.7970450	2.0417300	-1.0826270
C	3.0319490	0.9804520	-0.5926680
H	3.3733970	-0.0349730	-0.7622590
H	3.1416710	1.1999120	0.4714500
C	0.9752750	2.0937870	-1.5211960
N	1.5744370	1.0197990	-0.8957840
N	-0.3049670	1.8993880	-1.6472660
C	0.6164720	0.1159130	-0.6133050
N	-0.5112830	0.6701690	-1.0866400
C	-1.8405920	0.1803920	-1.0593190
C	-4.4718250	-0.7087450	-1.0261800
C	-2.6936460	0.5452080	-0.0233120
C	-2.3280010	-0.6074720	-2.0958410
C	-3.6367040	-1.0659280	-2.0769120
C	-4.0042520	0.0984790	0.0024060
F	-1.5382710	-0.9337250	-3.1140190
F	-4.1003700	-1.8244540	-3.0668020
F	-5.7261020	-1.1425350	-1.0056540
F	-4.8091200	0.4242150	1.0104260
F	-2.2393070	1.2907860	0.9761950
C	0.5580420	-2.3659890	-0.9418110
C	0.8336410	-1.2657480	0.1375170
O	2.1031440	-1.3322520	0.5402860
O	1.5099470	-2.1456340	-1.9749210
H	2.3387040	-1.9995220	-1.4808030
H	3.6979790	4.1269840	-1.8952510
H	3.0245700	3.6907180	-0.3221450
H	-0.4300310	-2.2613590	-1.4064070
C	0.7154910	-3.7754620	-0.3733050
H	1.7551770	-3.8782310	-0.0433110
H	0.0887800	-3.8977750	0.5161710
C	0.3678440	-4.8439020	-1.4067400
H	0.9685200	-4.7191360	-2.3127670
H	-0.6890370	-4.7854280	-1.6935230
H	0.5501000	-5.8487160	-1.0132570
C	-0.1921460	-1.2769720	1.2981050
C	-1.9314910	-1.2124810	3.5083290
C	-1.4415820	-1.9027290	1.2420040
C	0.1768500	-0.6289060	2.4815460
C	-0.6849710	-0.5866420	3.5755110

C -2.3039090 -1.8763870 2.3405180
H -1.7619600 -2.4173330 0.3381050
H 1.1618690 -0.1728250 2.5314240
H -0.3832940 -0.0718530 4.4834050
H -3.2680690 -2.3744540 2.2790640
H -2.6034920 -1.1885050 4.3611790

(*Z*)-Benzaldehyde BI + *re* Face of Propionaldehyde

(Int. VI$_{(Z)B\text{-}(re)P}$)



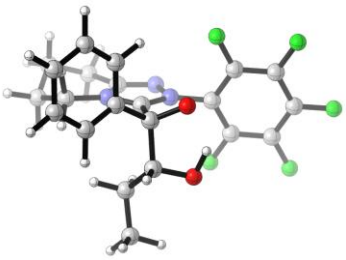
XYZ Coordinates

52

C 1.9849650 3.9325600 -1.4483310
H 1.6481250 4.1238750 -2.4700140
H 1.6700110 4.7814990 -0.8309580
C 3.5016340 3.7600320 -1.3523220
C 3.8601860 3.2478760 0.0399850
H 4.9435390 3.1960100 0.1765140
H 3.4657820 3.9351700 0.7978160
C 3.3116090 1.8478210 0.2861450
H 3.8619200 1.1046140 -0.2982840
H 3.3505390 1.5952250 1.3445460
C 1.2879590 2.7103360 -0.9478090
N 1.8914240 1.7684090 -0.1351230
N 0.0536400 2.3799620 -1.1929430
C 0.9835150 0.8086690 0.1275350
N -0.1199710 1.2088910 -0.5179950
C -1.3728830 0.5487820 -0.5786500
C -3.8036870 -0.7864440 -0.6937860
C -2.3456860 0.7842720 0.3872190
C -1.6391160 -0.3377220 -1.6129640
C -2.8493820 -1.0130530 -1.6733270
C -3.5567770 0.1155410 0.3349810
F -0.7192170 -0.5696120 -2.5452470
F -3.0927870 -1.8779560 -2.6578560
F -4.9687720 -1.4244900 -0.7437410
F -4.4922550 0.3362970 1.2587210
F -2.1331640 1.6639220 1.3553040
C 2.2484570 -0.6372170 1.8457530
C 2.3346060 -2.0043160 2.5242260
H 2.4543120 -2.7785080 1.7577960
H 1.3836030 -2.1950960 3.0358510
C 3.4968030 -2.0760700 3.5111540
H 4.4539000 -1.9004110 3.0055100
H 3.5477900 -3.0608490 3.9857280
H 3.3894500 -1.3235390 4.2969650
C 0.9485070 -0.5031230 0.9890670
O -0.1126170 -0.3866430 1.8028200
C 0.8844520 -1.6557300 -0.0313110
C 0.7476830 -3.8071160 -1.8174530
C -0.1393330 -2.5944880 0.0787930
C 1.8405880 -1.7969320 -1.0420250
C 1.7761320 -2.8690330 -1.9310660
C -0.2095650 -3.6673050 -0.8115810
H -0.8740410 -2.4567530 0.8678520
H 2.6399280 -1.0621210 -1.1402020
H 2.5222630 -2.9712780 -2.7138710
H -1.0126040 -4.3939170 -0.7218870
H 0.6922150 -4.6405080 -2.5117080
H 3.1557780 -0.4905790 1.2462700
O 2.1775060 0.4034000 2.8065850
H 1.2138240 0.4413050 2.9910570
H 3.8529370 3.0535050 -2.1138260
H 3.9856570 4.7202220 -1.5451550

(*Z*)-Benzaldehyde BI + *si* Face of Propionaldehyde

(Int. VI$_{(Z)B\text{-}(si)P}$)

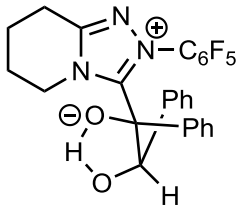


XYZ Coordinates

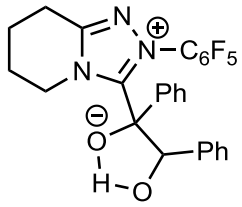
52

C 1.6963810 3.2481050 -2.2369500
H 1.1687490 3.4887900 -3.1626470
H 1.6048840 4.1134110 -1.5704340
C 3.1736490 2.9282770 -2.4689970
C 3.7736870 2.3560860 -1.1874820
H 4.8505250 2.1995960 -1.2912230
H 3.6193680 3.0581160 -0.3590620
C 3.1569630 1.0067810 -0.8442260
H 3.4728740 0.2389210 -1.5563850
H 3.4298430 0.6876480 0.1591120

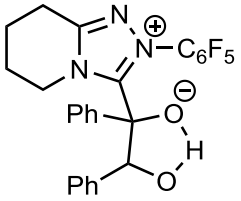
C	1.0086230	2.0930160	-1.5865710
N	1.6770920	1.0892430	-0.9171250
N	-0.2761820	1.8879790	-1.5489130
C	0.7582270	0.2182420	-0.4506260
N	-0.4151140	0.7268260	-0.8444410
C	-1.7326650	0.2453230	-0.6250130
C	-4.3454330	-0.6050120	-0.2444770
C	-2.5032170	0.7896980	0.3917890
C	-2.2888700	-0.7040820	-1.4739650
C	-3.5882220	-1.1380250	-1.2811830
C	-3.8078980	0.3603030	0.5924590
F	-1.5774260	-1.2027010	-2.4774470
F	-4.1223160	-2.0578700	-2.0854090
F	-5.5990930	-1.0122540	-0.0669020
F	-4.5471190	0.8809370	1.5719280
F	-2.0006820	1.7355900	1.1789190
C	0.7664610	-0.7220850	1.9065490
C	0.8767600	-1.1045930	0.3666500
O	-0.1843640	-1.8787950	0.0521160
O	-0.6149600	-0.7246240	2.1829980
H	-0.9206980	-1.3442040	1.4579220
H	3.2797140	2.2031330	-3.2845070
H	3.6970050	3.8396750	-2.7662220
H	1.2480850	-1.5516560	2.4502620
C	1.3746570	0.5974970	2.3609900
H	2.4324060	0.6362160	2.0748060
H	0.8634810	1.4221860	1.8461220
C	1.2473230	0.7875300	3.8711840
H	1.7587830	-0.0189550	4.4087380
H	0.1958940	0.7795290	4.1711030
H	1.6873980	1.7373360	4.1899520
C	2.2116120	-1.7693250	-0.0076980
C	4.5713180	-3.0338410	-0.8640140
C	2.3011290	-2.3270740	-1.2890210
C	3.3124520	-1.8705390	0.8455470
C	4.4856350	-2.4996450	0.4198460
C	3.4702240	-2.9482490	-1.7199280
H	1.4322140	-2.2759310	-1.9408600
H	3.2784520	-1.4544210	1.8482430
H	5.3314920	-2.5713940	1.0976390
H	3.5230030	-3.3713950	-2.7191290
H	5.4843190	-3.5211490	-1.1937660



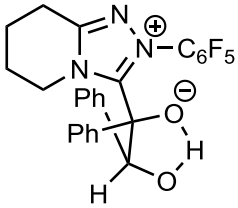
Int. VI$_{(E)B\text{-}(re)B}$



Int. VI$_{(E)B\text{-}(si)B}$



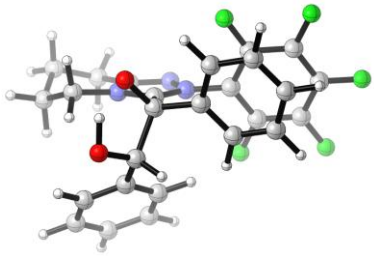
Int. VI$_{(Z)B\text{-}(re)B}$



Int. VI$_{(E)B\text{-}(si)B}$

(*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde

(**Int. VI$_{(E)B\text{-}(re)B}$**)



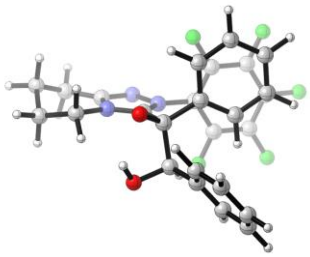
XYZ Coordinates

56

C	-3.0441520	-1.8107470	2.5627470
H	-2.6341120	-2.3279430	3.4333630
C	-4.4463330	0.0923960	1.7412350
H	-4.7332280	-0.5187600	0.8758320
H	-5.2794810	0.7649100	1.9625630
C	-3.2472630	0.9564370	1.3842470
H	-3.3873140	1.4970000	0.4509930
H	-3.0211300	1.6823000	2.1680720
C	-1.9244450	-1.1348350	1.8413000
N	-2.0472790	0.0974120	1.2456430
N	-0.7285370	-1.6168900	1.6566490
C	-0.8815220	0.3892350	0.6409750
N	-0.0893880	-0.6610240	0.9132210
C	1.2842570	-0.8713940	0.6306120
C	3.9798050	-1.2823680	0.0947010
C	2.2580120	-0.1879160	1.3522860
C	1.6771760	-1.8054930	-0.3202490
C	3.0204290	-2.0094970	-0.5956120

C	3.6020850	-0.3693830	1.0702950
F	0.7645660	-2.4995060	-0.9960000
F	3.3925910	-2.8903690	-1.5215430
F	5.2663750	-1.4566720	-0.1823990
F	4.5290080	0.3115630	1.7384760
F	1.9013580	0.6539630	2.3159130
C	-0.6489370	1.7014820	-0.1255600
O	-1.1202930	2.6907100	0.6639740
C	-1.5683950	1.7056990	-1.5096200
O	-2.3797200	2.8207590	-1.3494560
H	-3.4567610	-2.5711120	1.8897310
H	-2.0525830	3.1202900	-0.4118830
C	0.8350890	1.8875560	-0.4963890
C	3.5593630	2.3056090	-1.0517260
C	1.4546000	1.2333490	-1.5683040
C	1.5921400	2.7707770	0.2756440
C	2.9459640	2.9770340	0.0050620
C	2.8072940	1.4325490	-1.8405140
H	0.8885210	0.5536210	-2.2000800
H	1.0976590	3.2875590	1.0913860
H	3.5209780	3.6636090	0.6201330
H	3.2722510	0.9116820	-2.6732280
H	4.6127510	2.4641850	-1.2649190
H	-0.8679910	1.8567860	-2.3411070
C	-4.1367540	-0.8059600	2.9377790
C	-2.3668470	0.4462870	-1.8051750
C	-3.8349550	-1.8914380	-2.3601090
C	-3.7599660	0.4869520	-1.9098700
C	-1.7192800	-0.7789910	-2.0077290
C	-2.4419630	-1.9402810	-2.2737810
C	-4.4885790	-0.6722450	-2.1852090
H	-4.2663380	1.4375750	-1.7737400
H	-0.6350790	-0.8320160	-1.9509480
H	-1.9173790	-2.8810360	-2.4170210
H	-5.5712150	-0.6198680	-2.2631590
H	-4.4018800	-2.7935320	-2.5706450
H	-5.0284850	-1.3522920	3.2535160
H	-3.8086590	-0.1909020	3.7841730

(*E*)- Benzaldehyde BI + *si* Face of Benzaldehyde (**Int. VI$_{(E)B\text{-}(si)B}$**)



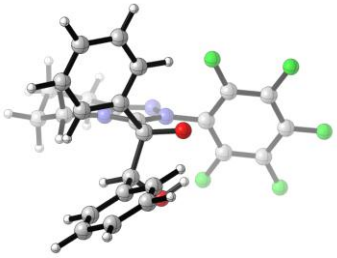
XYZ Coordinates

56

C	1.7709320	3.2076080	-2.1508620
H	1.8225830	3.0770430	-3.2379000
H	1.2048630	4.1212110	-1.9537860
C	3.1826840	3.2512910	-1.5662380
C	3.7925060	1.8554560	-1.6428500
H	3.7725760	1.5010020	-2.6809140
H	4.8367760	1.8615050	-1.3187840
C	3.0570100	0.8693260	-0.7463620
H	3.3544520	-0.1515670	-0.9546800
H	3.2283090	1.0718180	0.3113590
C	1.0062800	2.0556420	-1.5869840
N	1.5898580	0.9693090	-0.9706350
N	-0.2890150	1.9313470	-1.6103140
C	0.6069460	0.1296130	-0.5879610
N	-0.5207670	0.7330260	-0.9975520
C	-1.8739850	0.3506280	-0.8236320
C	-4.5432550	-0.3341160	-0.4874960
C	-2.6236190	0.9258300	0.1983690
C	-2.4837520	-0.5416510	-1.6957500
C	-3.8138670	-0.8944020	-1.5265730
C	-3.9525400	0.5793350	0.3766730
F	-1.7879800	-1.0868540	-2.6905580
F	-4.3929190	-1.7623570	-2.3528910
F	-5.8151690	-0.6743070	-0.3168340
F	-4.6641750	1.1089720	1.3676150
F	-2.0592750	1.8073680	1.0164850
C	0.8628380	-2.3577450	-0.8622560
C	0.8070670	-1.2107350	0.2269900
O	1.9839590	-1.1239950	0.8590290
O	2.1284550	-2.2074800	-1.4846060
H	2.6929940	-1.9758560	-0.7146490
H	3.7832730	3.9708530	-2.1275120
H	3.1489880	3.5876390	-0.5230600
H	0.0985840	-2.2154300	-1.6355020
C	-0.4012950	-1.3379440	1.1819350

C	-2.5382880	-1.4310270	3.0077760
C	-1.5273810	-2.1277310	0.9245030
C	-0.3553440	-0.6079980	2.3725280
C	-1.4172270	-0.6449690	3.2762870
C	-2.5864090	-2.1787190	1.8304120
H	-1.5980170	-2.7054080	0.0078090
H	0.5312550	-0.0167900	2.5836790
H	-1.3685110	-0.0630420	4.1924030
H	-3.4506430	-2.8003750	1.6116350
H	-3.3648040	-1.4656200	3.7118000
C	0.7306160	-3.7626120	-0.2975290
C	0.5201630	-6.3960710	0.6541570
C	-0.0501710	-4.7045740	-0.9729140
C	1.4155410	-4.1555610	0.8592610
C	1.3073570	-5.4626510	1.3314770
C	-0.1584050	-6.0143090	-0.5025600
H	-0.5859480	-4.4080730	-1.8730810
H	2.0167570	-3.4197580	1.3857170
H	1.8385470	-5.7530980	2.2336510
H	-0.7717160	-6.7332750	-1.0384920
H	0.4375860	-7.4133410	1.0258340

(*Z*)- Benzaldehyde BI + *re* Face of Benzaldehyde (**Int. VI$_{(Z)B\text{-}(re)B}$**)

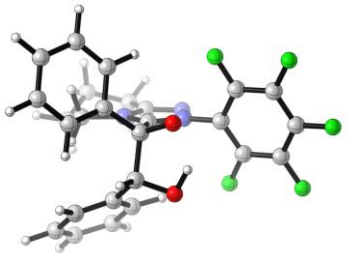


XYZ Coordinates

56

C	1.6846740	3.3196390	-2.0141740
H	1.2759490	3.5126240	-3.0088030
H	1.4166290	4.1701600	-1.3769850
C	3.2046040	3.1415070	-2.0309630
C	3.6721260	2.5819460	-0.6891870
H	4.7626070	2.5192170	-0.6478120
H	3.3464920	3.2410930	0.1245060
C	3.1297800	1.1772850	-0.4599110
H	3.5872850	0.4596770	-1.1465730
H	3.3040610	0.8490960	0.5637140
C	1.0152930	2.1071490	-1.4557380
N	1.6715890	1.1531880	-0.7092800
N	-0.2453200	1.8048220	-1.5702460
C	0.7728880	0.2161860	-0.3460530
N	-0.3810270	0.6347370	-0.8789290
C	-1.6908930	0.0908590	-0.7868760
C	-4.3064270	-0.8400140	-0.6858180
C	-2.6258890	0.7126380	0.0268790
C	-2.0848390	-0.9792010	-1.5808590
C	-3.3820310	-1.4545400	-1.5231080
C	-3.9316460	0.2444850	0.0905610
F	-1.2113890	-1.5653060	-2.3921800
F	-3.7567410	-2.4916940	-2.2727050
F	-5.5570630	-1.2914340	-0.6384380
F	-4.8235640	0.8430110	0.8794310
F	-2.2742550	1.7609410	0.7690200
C	1.0921120	-0.5691820	2.0066780
C	0.8912980	-1.0891610	0.5186140
O	-0.2855480	-1.7278610	0.4403010
O	-0.1900370	-0.1039710	2.3850510
H	-0.7735400	-0.7194290	1.8777900
C	2.0689790	-1.9109470	-0.0461390
C	4.0801760	-3.5056120	-1.1939680
C	3.3751270	-1.8761070	0.4497510
C	1.7821110	-2.7621520	-1.1183980
C	2.7784080	-3.5475210	-1.6954120
C	4.3736430	-2.6707290	-0.1165670
H	3.6306200	-1.2382200	1.2901380
H	0.7583020	-2.8079550	-1.4762590
H	2.5361790	-4.1991170	-2.5302880
H	5.3801570	-2.6387730	0.2909290
H	4.8572050	-4.1241940	-1.6337460
H	3.4969720	2.4597960	-2.8381550
H	3.6758590	4.1068350	-2.2288750
H	1.7795230	0.2840970	2.0527450
C	1.5898280	-1.6318420	2.9681420
C	2.5168110	-3.5419220	4.8050270
C	0.9959950	-2.8985670	3.0333360
C	2.6412830	-1.3331510	3.8384430
C	3.1063410	-2.2798900	4.7526150
C	1.4600720	-3.8465480	3.9440630
H	0.1802060	-3.1321820	2.3550790
H	3.1066930	-0.3498310	3.7958230
H	3.9264740	-2.0307550	5.4200760
H	0.9965560	-4.8285230	3.9818440
H	2.8764910	-4.2833140	5.5126930

(*Z*)- Benzaldehyde BI + *si* Face of Benzaldehyde (**Int. VI$_{(Z)B\text{-}(si)B}$**)

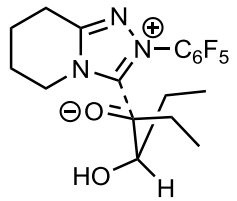


XYZ Coordinates

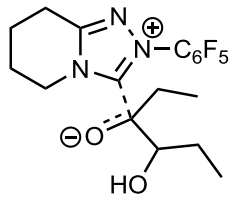
56

C	1.5553790	3.2204260	-2.2590450
H	1.0883710	3.3946480	-3.2312000
H	1.3639040	4.1035350	-1.6383250
C	3.0620020	2.9775510	-2.3668690
C	3.5944560	2.4848890	-1.0229870
H	4.6837970	2.3961220	-1.0367580
H	3.3286240	3.1981010	-0.2331940
C	3.0335270	1.1103900	-0.6815310
H	3.4511010	0.3402340	-1.3366390
H	3.2295390	0.8420940	0.3569420
C	0.8858460	2.0536670	-1.6111410
N	1.5650370	1.1050330	-0.8799850
N	-0.3903920	1.7895020	-1.6253900
C	0.6671310	0.2112460	-0.4248070
N	-0.5094860	0.6449280	-0.8894840
C	-1.8060220	0.0848690	-0.7414880
C	-4.3757090	-0.9374240	-0.5127230
C	-2.7083430	0.6537840	0.1449210
C	-2.2082340	-0.9806090	-1.5383160
C	-3.4844690	-1.5003300	-1.4197070
C	-3.9924080	0.1404060	0.2697390
F	-1.3660940	-1.5100500	-2.4175290
F	-3.8710960	-2.5285710	-2.1748420
F	-5.6069760	-1.4286140	-0.4063920
F	-4.8578190	0.6888820	1.1217350
F	-2.3497480	1.6985020	0.8867700
C	0.8156710	-0.5593200	1.9948160
C	0.8400400	-1.0537400	0.4622980
O	-0.2398490	-1.8430310	0.2931540
O	-0.5565960	-0.4502080	2.2811580
H	-0.9088560	-1.1242520	1.6248570
H	3.2682400	2.2325340	-3.1447300
H	3.5552330	3.9069470	-2.6600430
H	1.2595300	-1.3851820	2.5701680
C	2.1332930	-1.7469360	0.0094120
C	4.3894440	-3.0833900	-1.0097210
C	2.1942110	-2.1343640	-1.3366260
C	3.2084730	-2.0598060	0.8409470
C	4.3305610	-2.7225340	0.3335590
C	3.3093160	-2.7906220	-1.8470700
H	1.3480190	-1.9183440	-1.9858710
H	3.1936300	-1.7981980	1.8922320
H	5.1582260	-2.9572570	0.9968340
H	3.3366620	-3.0773140	-2.8944750
H	5.2634410	-3.5949890	-1.4020550
C	1.5188980	0.7308190	2.3487650
C	2.8305460	3.1485670	2.9437080
C	2.7647220	0.7315070	2.9838230
C	0.9189940	1.9630250	2.0559030
C	1.5700950	3.1610620	2.3426230
C	3.4212480	1.9293430	3.2722730
H	3.2266700	-0.2098700	3.2685310
H	-0.0751810	1.9760390	1.6161940
H	1.0874830	4.1056270	2.1064590
H	4.3884290	1.9068910	3.7662080
H	3.3391890	4.0813660	3.1691950

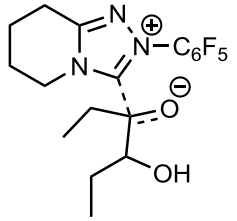
Ejection Transition States



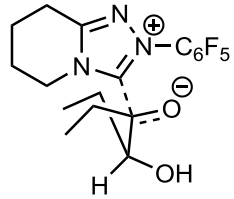
TS [VI-I]$_{(E)P\text{-}(re)P}$



TS [VI-I]$_{(E)P\text{-}(si)P}$

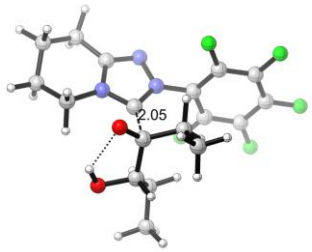


TS [VI-I]$_{(Z)P\text{-}(re)P}$



TS [VI-I]$_{(Z)P\text{-}(si)P}$

(*E*)-Propionaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]$_{(E)P\text{-}(re)P}$**)

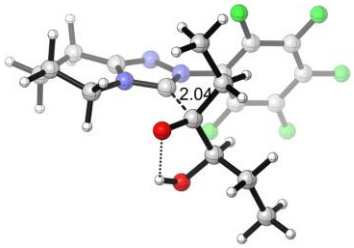


XYZ Coordinates

48

N	-0.9570310	-0.4749230	-1.1559670
C	-0.4242410	0.5427760	-0.4526270
N	-0.8059210	1.6164470	-1.1833920
C	-1.5480960	1.2037140	-2.2685040
N	-1.6594910	-0.0930050	-2.2760650
C	-0.8438690	-1.8555760	-0.8766890
C	-0.6296630	-4.5739650	-0.3087830
C	-1.9154420	-2.5511340	-0.3251710
C	0.3258230	-2.5486080	-1.1686260
C	0.4434340	-3.8992120	-0.8731820
C	-1.8141500	-3.9024280	-0.0352390
F	1.3499720	-1.9241450	-1.7433890
F	1.5710930	-4.5530210	-1.1459410
F	-0.5248450	-5.8692400	-0.0334100
F	-2.8407330	-4.5572440	0.5029930
F	-3.0491900	-1.9119320	-0.0483110
C	-0.5165130	3.0303480	-0.8768690
H	0.5151130	3.0817270	-0.5277100
H	-1.1746010	3.3274110	-0.0566720
C	-2.1011180	2.1446070	-3.2895970
H	-3.1028070	1.8093030	-3.5700220
H	-1.4709540	2.0795500	-4.1841520
C	-2.0965310	3.5798940	-2.7565100
C	-0.7442110	3.8884720	-2.1149370
H	-0.6874980	4.9363140	-1.8078710
H	0.0577130	3.7147050	-2.8432980
C	0.0266180	0.7810250	1.5289400
O	-0.5756540	1.8453150	1.8406540
C	1.5701420	0.8841300	1.5234810
O	1.9284340	2.2342620	1.2959610
H	1.1494460	2.7360710	1.6029270
C	-0.5395630	-0.5406190	2.0542980
H	0.0248050	-1.3910220	1.6557100
H	-1.5750950	-0.6274960	1.7093100
C	-0.5236660	-0.5690810	3.5853080
H	0.4953480	-0.5283500	3.9822000
H	-0.9874710	-1.4897640	3.9516640
H	-1.0816110	0.2800870	3.9891240
H	1.8559630	0.6071150	2.5555330
C	2.3403530	-0.0093120	0.5687740
H	2.1417630	0.3231990	-0.4559090
H	1.9617540	-1.0350610	0.6569350
C	3.8431650	0.0105310	0.8414580
H	4.3775390	-0.6356960	0.1382020
H	4.0639320	-0.3404970	1.8556220
H	4.2440470	1.0235190	0.7408380
H	-2.3002270	4.2692170	-3.5797010
H	-2.8936660	3.7081270	-2.0143980

(*E*)-Propionaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]$_{(E)P\text{-}(si)P}$**)



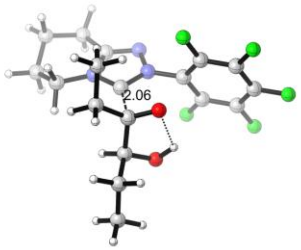
XYZ Coordinates

48

N	-1.4512370	0.0412020	-0.4980030
C	-0.2239930	0.5640740	-0.6665790
N	-0.3342530	1.1648700	-1.8721840
C	-1.6026370	0.9642980	-2.3769160
N	-2.3184630	0.2678770	-1.5426970
C	-1.9037460	-0.7212330	0.6023870
C	-2.7965670	-2.2470310	2.7536920
C	-2.2402810	-0.1143850	1.8073560
C	-2.0377580	-2.1018770	0.4851730
C	-2.4802570	-2.8674280	1.5521370
C	-2.6742060	-0.8710710	2.8862330
F	-1.7157370	-2.7014480	-0.6569510
F	-2.5995550	-4.1876290	1.4341730
F	-3.2212430	-2.9747080	3.7805400
F	-2.9860780	-0.2841460	4.0398640
F	-2.1414380	1.2055350	1.9415370
C	0.7357280	1.8822520	-2.5957940
H	1.4180290	1.1301590	-3.0012660
H	1.2841150	2.4775450	-1.8677120
C	-2.0575710	1.5185950	-3.6877390
H	-2.6678360	2.4067110	-3.4852940

H	-2.7001560	0.7830560	-4.1775670
C	-0.8518800	1.9056490	-4.5480460
C	0.1339740	2.7235620	-3.7141540
H	-0.3759170	3.5983060	-3.2910660
H	0.9578490	3.0914930	-4.3316490
C	1.5461100	0.4350450	0.3352330
O	2.4100070	0.9558120	-0.4221600
C	1.6043340	-1.1061410	0.4130620
H	0.6348220	-1.5218310	0.7145470
O	1.9014300	-1.5901340	-0.8833380
H	2.4271790	-0.8720850	-1.2832960
C	1.1591850	1.1546710	1.6217540
H	2.0330610	1.0775940	2.2826140
H	0.3387270	0.6200030	2.1160310
C	0.8194020	2.6239940	1.4116130
H	1.6478490	3.1378390	0.9156090
H	0.6285220	3.1221950	2.3666900
H	-0.0750080	2.7384320	0.7889550
C	2.6617380	-1.5614450	1.4240220
H	2.3960910	-1.1777210	2.4163870
H	3.6259800	-1.1157270	1.1478040
C	2.7752210	-3.0825060	1.4756450
H	3.5324240	-3.3977540	2.2000120
H	3.0501440	-3.4849140	0.4968520
H	1.8207690	-3.5348070	1.7703010
H	-0.3558960	1.0026730	-4.9250220
H	-1.1950960	2.4780660	-5.4131290

(*Z*)-Propionaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]**$_{(Z)P\text{-}(re)P}$)

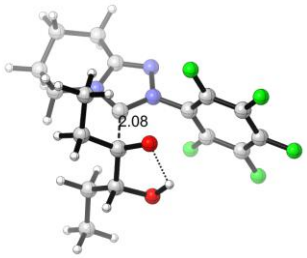


XYZ Coordinates

48

N	-1.1657810	-0.9259920	-0.7833230
C	-0.1794970	-0.0190270	-0.7386330
N	-0.3418670	0.6337530	-1.9135380
C	-1.4043840	0.0916720	-2.6062570
N	-1.9376890	-0.8784870	-1.9219350
C	-1.5306220	-1.8328630	0.2395180
C	-2.2680550	-3.5763780	2.2751550
C	-2.5834330	-1.5188290	1.0903880
C	-0.8607470	-3.0381250	0.4080350
C	-1.2205490	-3.9068840	1.4257110
C	-2.9549270	-2.3821640	2.1099920
F	0.1314120	-3.3725470	-0.4089530
F	-0.5721570	-5.0602950	1.5918120
F	-2.6215260	-4.4142040	3.2459050
F	-3.9651450	-2.0757360	2.9243920
F	-3.2483370	-0.3774350	0.9312210
C	0.5059060	1.7248980	-2.4214210
H	1.4441560	1.2815940	-2.7717460
H	0.7219480	2.3943380	-1.5866640
C	-1.8541790	0.6017470	-3.9369720
H	-2.7517020	1.2113710	-3.7795180
H	-2.1397600	-0.2463880	-4.5638840
C	-0.7544300	1.4529630	-4.5792020
C	-0.2033470	2.4495190	-3.5590580
H	-1.0227730	3.0578930	-3.1570190
H	0.5149760	3.1301440	-4.0233290
C	1.2105630	-0.0695480	0.7842340
O	1.0604010	-1.1876110	1.3433300
C	0.6627940	1.1357030	1.5764050
H	0.4072500	1.9601820	0.8988200
O	-0.5291170	0.7169740	2.2172460
H	-0.3803500	-0.2315540	2.3907910
C	2.4640240	0.1820230	-0.0451630
H	3.2864070	0.2525310	0.6794030
H	2.3945490	1.1566810	-0.5410090
C	2.7672630	-0.9323150	-1.0382360
H	1.9868760	-1.0111980	-1.8042960
H	2.8273820	-1.8939520	-0.5214120
H	3.7203700	-0.7549320	-1.5453520
C	1.6917890	1.6263100	2.6007680
H	2.5892770	1.9672410	2.0706460
H	1.9888170	0.7789270	3.2321900
C	1.1433470	2.7598240	3.4629400
H	1.8921630	3.1041190	4.1829170
H	0.2599410	2.4337930	4.0186230
H	0.8542480	3.6174580	2.8442800
H	0.0562600	0.8076660	-4.9392820
H	-1.1658280	1.9773140	-5.4450290

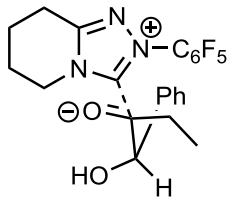
(*Z*)-Propionaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]$_{(Z)P\text{-}(si)P}$**)



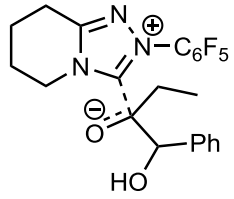
XYZ Coordinates

48

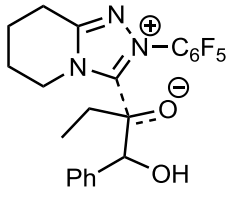
N	-0.1569260	-0.8079380	-1.2812550
C	0.0801740	0.2440740	-0.4829570
N	-0.1950230	1.2865320	-1.3054070
C	-0.5702990	0.8171550	-2.5463330
N	-0.5579230	-0.4843890	-2.5567900
C	-0.0675670	-2.1752760	-0.9280370
C	0.1157490	-4.8474710	-0.1877560
C	-1.1795470	-2.8458790	-0.4355200
C	1.1327910	-2.8617960	-1.0638580
C	1.2314700	-4.1921510	-0.6924540
C	-1.0934250	-4.1789440	-0.0599960
F	2.2031600	-2.2403570	-1.5455750
F	2.3868890	-4.8466830	-0.8147670
F	0.2056010	-6.1266970	0.1651030
F	-2.1617030	-4.8194200	0.4155840
F	-2.3429840	-2.2127170	-0.3156770
C	-0.0706920	2.7143970	-0.9692990
H	0.9953520	2.9649810	-0.9684800
H	-0.4675140	2.8533890	0.0373510
C	-0.9510700	1.7156970	-3.6784810
H	-2.0438220	1.7120170	-3.7641750
H	-0.5483770	1.3033680	-4.6068260
C	-0.4578930	3.1419360	-3.4155410
C	-0.8198630	3.5610040	-1.9910170
H	-1.9009740	3.4552650	-1.8383740
H	-0.5625750	4.6081910	-1.8117190
C	1.0729650	-0.0782070	1.3110700
O	1.6210350	-1.2029960	1.1650760
C	-0.1146000	-0.0711380	2.2987750
O	-0.7455180	-1.3363530	2.2353400
H	-0.0284890	-1.9410920	1.9669970
C	1.9544750	1.1656650	1.3099340
H	2.4325360	1.1833410	2.2997940
H	1.3467590	2.0719220	1.2383680
C	3.0265220	1.1282990	0.2287120
H	2.5809130	1.1091360	-0.7733480
H	3.6417580	0.2310330	0.3329120
H	3.6772040	2.0055270	0.2914640
H	0.3743150	0.0441150	3.2857150
C	-1.1629150	1.0199480	2.1704070
H	-1.6799680	0.9062850	1.2104660
H	-0.6593910	1.9938090	2.1643730
C	-2.1768810	0.9738040	3.3125870
H	-2.9216640	1.7688110	3.2097550
H	-1.6822480	1.0997270	4.2821470
H	-2.7035610	0.0153740	3.3248570
H	0.6296100	3.1933640	-3.5495620
H	-0.9102920	3.8197440	-4.1433610



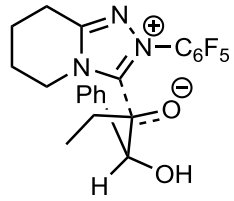
TS [VI-I]$_{(E)P\text{-}(re)B}$



TS [VI-I]$_{(E)P\text{-}(si)B}$

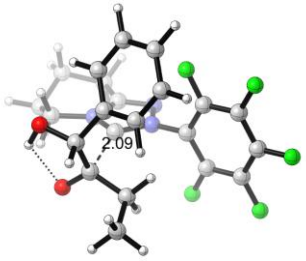


TS [VI-I]$_{(Z)P\text{-}(re)B}$



TS [VI-I]$_{(Z)P\text{-}(si)B}$

(*E*)-Propionaldehyde BI + *re* Face of Benzaldehyde Eject (**TS [VI-I]$_{(E)P\text{-}(re)B}$**)



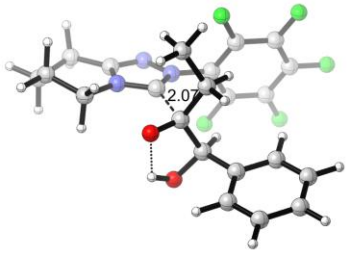
XYZ Coordinates

52

N	-1.5283690	-0.4367060	-0.2340600
C	-0.8432220	0.7116630	-0.0669360
N	-1.5929590	1.5855170	-0.7818130
C	-2.6629890	0.9299500	-1.3534520

N	-2.6461560	-0.3297040	-1.0291930
C	-1.1870960	-1.7171970	0.2606010
C	-0.4741800	-4.2300740	1.2214660
C	-1.6570330	-2.1617890	1.4921270
C	-0.3957970	-2.5677030	-0.5031550
C	-0.0239740	-3.8153260	-0.0243150
C	-1.2954800	-3.4067010	1.9816080
F	-0.0019400	-2.1892870	-1.7119460
F	0.7423520	-4.6218970	-0.7564240
F	-0.1288240	-5.4264220	1.6852150
F	-1.7356110	-3.8196400	3.1693450
F	-2.4481870	-1.3823540	2.2250060
C	-1.3038560	3.0166370	-0.9968390
H	-0.4798790	3.0797850	-1.7137710
H	-0.9737470	3.4233590	-0.0414930
C	-3.6858650	1.6109800	-2.2037530
H	-4.5852410	1.7663520	-1.5964380
H	-3.9564380	0.9447380	-3.0266980
C	-3.1580450	2.9609760	-2.6967290
C	-2.5413600	3.7280540	-1.5283450
H	-3.2816850	3.8352030	-0.7256900
H	-2.2406450	4.7337740	-1.8341840
C	0.5622100	1.3826690	1.3273780
O	0.1364170	2.5125450	1.6768810
C	1.8462730	1.4407880	0.4485690
O	1.7951890	2.6240900	-0.3145420
H	1.2463720	3.2258440	0.2214660
C	0.4680990	0.2350750	2.3245210
H	0.7008270	-0.7176700	1.8413110
H	-0.5652520	0.1979120	2.6826220
C	1.4092560	0.4637510	3.5112320
H	2.4605360	0.4439420	3.2062120
H	1.2666660	-0.3182090	4.2627770
H	1.2104540	1.4306830	3.9822440
H	2.6545010	1.5219970	1.1967430
C	2.1786460	0.2646620	-0.4372600
C	2.9702840	-1.8707590	-2.0851600
C	2.0395860	0.3477160	-1.8266770
C	2.7219200	-0.9013860	0.1159610
C	3.1021230	-1.9673940	-0.6992650
C	2.4398330	-0.7091330	-2.6448210
H	1.6420680	1.2594890	-2.2615010
H	2.8768440	-0.9656850	1.1913250
H	3.5231130	-2.8642070	-0.2527950
H	2.3357960	-0.6236430	-3.7229910
H	3.2791460	-2.6950270	-2.7215160
H	-2.4020490	2.8074550	-3.4763310
H	-3.9794960	3.5272210	-3.1425910

(*E*)-Propionaldehyde BI + *si* Face of Benzaldehyde Eject (**TS [VI-I]**$_{(E)\text{P-}(si)\text{B}}$)



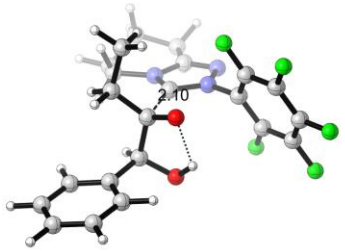
XYZ Coordinates

52

N	-1.5510140	0.1693470	-1.3317020
C	-0.4398700	0.8538220	-1.0082480
N	-0.3547660	1.7478800	-2.0168620
C	-1.3961480	1.5551250	-2.9009150
N	-2.1567760	0.5783610	-2.4982040
C	-2.1253890	-0.8962050	-0.6024570
C	-3.2358730	-3.0071840	0.8363320
C	-2.8387840	-0.6574630	0.5677120
C	-1.9944880	-2.2070960	-1.0525590
C	-2.5435910	-3.2618800	-0.3405000
C	-3.3834750	-1.7054400	1.2950450
F	-1.3132780	-2.4593760	-2.1660260
F	-2.4021340	-4.5138820	-0.7692650
F	-3.7555370	-4.0149950	1.5275190
F	-4.0540740	-1.4677180	2.4204090
F	-3.0018230	0.5881310	1.0067190
C	0.7047100	2.7595630	-2.1972980
H	1.5952990	2.2421890	-2.5649680
H	0.9335640	3.1748270	-1.2169980
C	-1.6025210	2.3999760	-4.1160840
H	-2.4170480	3.1021820	-3.9043910
H	-1.9282220	1.7591350	-4.9391560
C	-0.3256360	3.1752350	-4.4546460
C	0.2445680	3.8186900	-3.1906790
H	-0.5153030	4.4601220	-2.7266840
H	1.1058300	4.4487910	-3.4282520
C	1.0418340	0.6304920	0.4137320
O	1.9639600	1.4136650	0.0760680
C	1.3310070	-0.8710920	0.1182440
H	0.3957040	-1.4127230	-0.0554340
O	2.1142830	-0.9259200	-1.0511980
H	2.5326870	-0.0440230	-1.0994290

C	2.0242210	-1.5081420	1.3085590
C	3.2576510	-2.6287930	3.5633980
C	3.3820410	-1.2847850	1.5550430
C	1.2936320	-2.3003690	2.1974960
C	1.9031650	-2.8577590	3.3217700
C	3.9953640	-1.8426490	2.6759030
H	3.9580980	-0.6739830	0.8650300
H	0.2380670	-2.4860400	2.0039400
H	1.3234720	-3.4758040	4.0014290
H	5.0512300	-1.6638510	2.8582620
H	3.7376360	-3.0654820	4.4342810
C	0.2235930	0.9227180	1.6608750
H	0.8899460	0.7177770	2.5097140
H	-0.6063130	0.2097000	1.7329360
C	-0.2679090	2.3613990	1.7334420
H	0.5753390	3.0563370	1.6874390
H	-0.8094380	2.5404890	2.6667880
H	-0.9446680	2.5905140	0.9025460
H	0.4190430	2.4984480	-4.8910080
H	-0.5562320	3.9359050	-5.2044470

(*Z*)-Propionaldehyde BI + *re* Face of Benzaldehyde Eject (**TS [VI-I]**$_{(Z)\text{P-}(re)\text{B}}$)

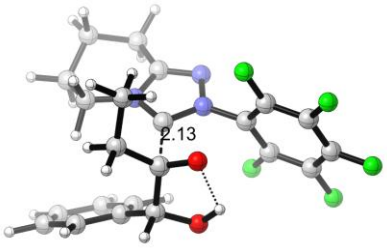


XYZ Coordinates

52

N	-1.2985250	-0.9971450	-1.5494470
C	-0.1969280	-0.3122210	-1.2081740
N	0.1404320	0.2777180	-2.3782260
C	-0.7613900	-0.0766560	-3.3597410
N	-1.6681550	-0.8714450	-2.8694710
C	-2.1044440	-1.7761690	-0.6875610
C	-3.6801690	-3.2705090	1.0501650
C	-3.3569910	-1.3155280	-0.2980530
C	-1.6576520	-3.0021340	-0.2094610
C	-2.4351100	-3.7461060	0.6631870
C	-4.1469050	-2.0548490	0.5696110
F	-0.4732550	-3.4732260	-0.5825260
F	-1.9983320	-4.9159740	1.1301070
F	-4.4314430	-3.9836520	1.8843460
F	-5.3472830	-1.6090300	0.9402070
F	-3.8060320	-0.1463820	-0.7489620
C	1.3192620	1.1292390	-2.6026300
H	2.1993530	0.4785510	-2.6330280
H	1.4094800	1.8025990	-1.7478650
C	-0.6715780	0.4253650	-4.7641660
H	-1.4113470	1.2248380	-4.8868790
H	-0.9459410	-0.3827670	-5.4466550
C	0.7325620	0.9697250	-5.0443890
C	1.1684810	1.8980800	-3.9099790
H	0.4276570	2.6970210	-3.7837060
H	2.1282750	2.3704250	-4.1353970
C	0.5082160	-0.3067200	0.7687470
O	-0.0872520	-1.2461240	1.3456180
C	-0.0348220	1.1125370	1.0991940
H	0.1402400	1.7885950	0.2552140
O	-1.4246020	0.9933260	1.3053350
H	-1.5492940	0.0639620	1.5790330
C	0.6862980	1.6581780	2.3188210
C	2.1062380	2.5914940	4.5495170
C	0.3779170	1.1905030	3.5999940
C	1.7062680	2.6010490	2.1674160
C	2.4161280	3.0655990	3.2752010
C	1.0829830	1.6545610	4.7090590
H	-0.4147870	0.4580460	3.7260430
H	1.9450060	2.9762520	1.1741320
H	3.2037320	3.8019420	3.1438010
H	0.8352230	1.2844200	5.6998910
H	2.6546180	2.9523720	5.4148220
C	1.9989350	-0.4063110	0.4900840
H	2.4844390	-0.3054340	1.4706020
H	2.3230580	0.4511220	-0.1105680
C	2.4140340	-1.7245790	-0.1476390
H	2.0784920	-2.5671850	0.4627160
H	3.5021650	-1.7821260	-0.2441750
H	1.9788820	-1.8381870	-1.1470170
H	1.4447990	0.1405430	-5.1366700
H	0.7272600	1.5050770	-5.9969030

(*Z*)-Propionaldehyde BI + *si* Face of Benzaldehyde Eject (**TS [VI-I]$_{(Z)P\text{-}(si)B}$**)

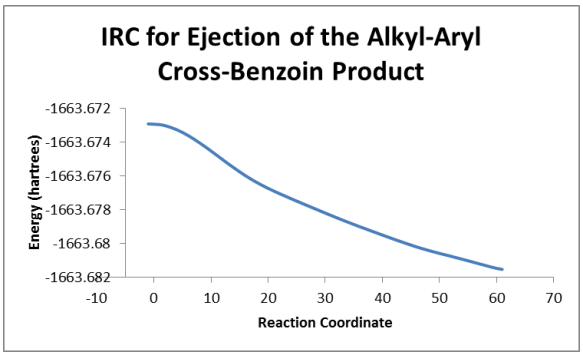


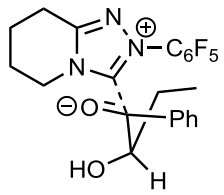
XYZ Coordinates

52

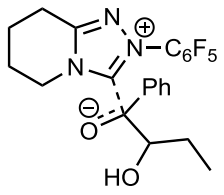
N	-0.6545030	-1.3586950	-0.9187390
C	0.0337230	-0.2592970	-0.5734020
N	-0.5478270	0.6864530	-1.3515870
C	-1.5458720	0.1196500	-2.1137310
N	-1.6361500	-1.1545940	-1.8622950
C	-0.4980060	-2.6562380	-0.3784080
C	-0.1865140	-5.1882150	0.7249330
C	-1.3458330	-3.0938490	0.6316010
C	0.4981250	-3.5066820	-0.8416470
C	0.6623360	-4.7671410	-0.2899300
C	-1.1951440	-4.3551640	1.1885490
F	1.3095050	-3.1146670	-1.8171880
F	1.6268110	-5.5777870	-0.7264950
F	-0.0368660	-6.4006260	1.2511070
F	-2.0112080	-4.7728320	2.1565060
F	-2.3125120	-2.2952840	1.0777930
C	-0.1610340	2.1039840	-1.4226180
H	0.7610990	2.1685190	-2.0106390
H	0.0432840	2.4424030	-0.4048180
C	-2.4019990	0.9080390	-3.0519960
H	-3.3714430	1.0703840	-2.5666620
H	-2.5822750	0.3158500	-3.9525750
C	-1.7504300	2.2582700	-3.3663380
C	-1.2728540	2.9180480	-2.0725360
H	-2.1138420	3.0130170	-1.3739190
H	-0.8871590	3.9235450	-2.2616740
C	1.7437090	-0.4537690	0.6865560
O	2.0441490	-1.6672060	0.6291380
C	1.0875440	-0.0291350	2.0325000
O	0.3278460	-1.1203030	2.5004940
H	0.7739790	-1.9004440	2.1200380
C	2.6233890	0.5708030	-0.0097160
H	3.5050310	0.6907870	0.6367860
H	2.1207270	1.5410770	-0.0442830
C	3.0619870	0.1212450	-1.3973300
H	3.5776140	-0.8411020	-1.3448270
H	3.7386560	0.8532980	-1.8475620
H	2.1979290	0.0008260	-2.0614870
H	1.9547270	0.1398440	2.6960290
C	0.2564950	1.2281700	2.0289520
C	-1.2599280	3.5895290	1.9466760
C	-1.1303530	1.1744190	1.8524790
C	0.8699580	2.4740130	2.1946020
C	0.1197390	3.6498320	2.1457940
C	-1.8830680	2.3474190	1.8079890
H	-1.6132460	0.2064680	1.7536210
H	1.9435210	2.5237920	2.3644340
H	0.6113420	4.6099600	2.2735380
H	-2.9591810	2.2916970	1.6681150
H	-1.8473960	4.5025120	1.9136900
H	-0.8995720	2.1158810	-4.0439320
H	-2.4745360	2.8960950	-3.8792150

IRC for (*Z*)-Propionaldehyde BI + *si* Face of Benzaldehyde Eject (**TS [VI-I]$_{(Z)P\text{-}(si)B}$**)

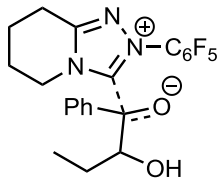




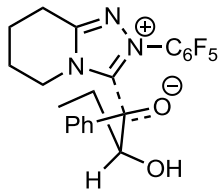
TS [VI-I]$_{(E)B\text{-}(re)P}$



TS [VI-I]$_{(E)B\text{-}(si)P}$

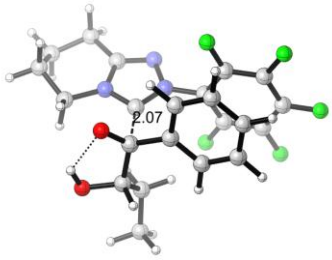


TS [VI-I]$_{(Z)B\text{-}(re)P}$



TS [VI-I]$_{(Z)B\text{-}(si)P}$

(*E*)-Benzaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]$_{(E)B\text{-}(re)P}$**)

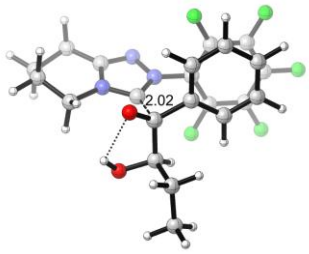


XYZ Coordinates

52

N	-1.3067630	0.0267340	-0.7859070
C	-0.0389210	0.4432840	-0.9575910
N	-0.0844190	0.9802960	-2.1985300
C	-1.3580110	0.8619190	-2.7127300
N	-2.1391780	0.2743410	-1.8536910
C	-1.8574760	-0.5975480	0.3574080
C	-2.9546760	-1.7970320	2.6171980
C	-2.5541470	0.1603520	1.2931260
C	-1.7563580	-1.9711630	0.5474440
C	-2.2890450	-2.5720150	1.6783120
C	-3.0928080	-0.4292660	2.4257350
F	-1.1500390	-2.7318460	-0.3618390
F	-2.1765000	-3.8870460	1.8603030
F	-3.4601760	-2.3662200	3.7069650
F	-3.7341620	0.3071240	3.3306270
F	-2.7105400	1.4668020	1.1027570
C	1.0579470	1.5316840	-2.9526630
H	1.6566750	0.6843500	-3.2998590
H	1.6519760	2.1170880	-2.2518230
C	-1.7476740	1.3839080	-4.0576580
H	-2.2713990	2.3356920	-3.9103600
H	-2.4548260	0.6881680	-4.5154810
C	-0.5059460	1.6087020	-4.9252740
C	0.5549890	2.3641410	-4.1250250
H	0.1348730	3.3074350	-3.7542870
H	1.4160660	2.6120860	-4.7514950
C	1.5637480	0.7925160	0.3015610
O	1.9761990	1.9363250	-0.0302280
C	2.5090440	-0.3781270	-0.0784100
C	0.8276160	0.6891960	1.6313400
C	-0.4883450	0.6927000	4.1137950
C	0.8287280	-0.4557930	2.4375380
C	0.1719730	1.8355630	2.0908420
C	-0.4860530	1.8399860	3.3182980
C	0.1726600	-0.4524270	3.6701660
H	1.3523120	-1.3553120	2.1288680
H	0.1877710	2.7260070	1.4692750
H	-0.9978770	2.7375190	3.6542080
H	0.1847040	-1.3475070	4.2860250
H	-1.0009500	0.6913630	5.0716380
C	1.8837540	-1.6952000	-0.5119100
H	1.4704370	-1.5536740	-1.5174130
H	1.0419400	-1.9404890	0.1413460
C	2.8933490	-2.8403430	-0.5184130
H	3.7376330	-2.6123880	-1.1763080
H	2.4316950	-3.7681170	-0.8697780
H	3.2893210	-3.0216260	0.4872640
H	3.1039110	-0.5491610	0.8377800
O	3.3683970	0.0683080	-1.1088460
H	3.3376300	1.0414260	-1.0444850
H	-0.1007010	0.6456710	-5.2590740
H	-0.7893580	2.1723290	-5.8174110

(*E*)-Benzaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]$_{(E)B\text{-}(si)P}$**)



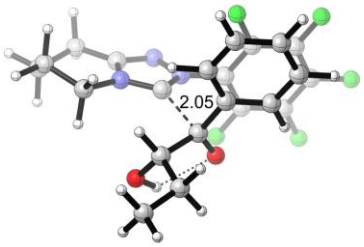
XYZ Coordinates

52

N	-1.4564160	-0.3747790	-0.8536410
C	-0.1410020	-0.6134600	-0.9999080
N	-0.0828110	-1.1229970	-2.2524020
C	-1.3509670	-1.1742150	-2.7922080
N	-2.2233890	-0.7134040	-1.9440460
C	-2.1122520	0.1770350	0.2695530
C	-3.4520530	1.2760900	2.4471470
C	-2.6357710	1.4642810	0.2016940
C	-2.2775790	-0.5551180	1.4391680
C	-2.9381900	-0.0102270	2.5295150
C	-3.3026030	2.0169610	1.2833090
F	-1.7857340	-1.7892700	1.5318440
F	-3.0803630	-0.7129000	3.6526470
F	-4.0718240	1.8087620	3.4957920
F	-3.7805960	3.2580750	1.2203280
F	-2.4932170	2.1810600	-0.9095550
C	1.1168420	-1.6359700	-2.9435750

H	1.3402880	-2.6166870	-2.5142490
H	1.9341160	-0.9512160	-2.7173700
C	-1.6373430	-1.6716690	-4.1723490
H	-1.7973920	-0.8016450	-4.8196730
H	-2.5692590	-2.2419360	-4.1537600
C	-0.4609640	-2.4968360	-4.7003720
C	0.8480030	-1.7529320	-4.4378910
H	0.8027480	-0.7532720	-4.8879850
H	1.6946200	-2.2780730	-4.8882580
C	1.4923240	0.1020730	-0.0461590
O	2.3208560	0.3480380	-0.9656360
C	1.8216290	-1.1287320	0.8214110
H	0.9401040	-1.4649830	1.3778200
O	2.1834260	-2.1901820	-0.0447150
H	2.7430560	-1.7761370	-0.7240620
C	0.8310000	1.2845980	0.6511130
C	-0.3367910	3.5360560	1.8538290
C	0.3722910	1.2269230	1.9724170
C	0.6962360	2.4798990	-0.0594570
C	0.1081120	3.5969360	0.5321080
C	-0.1991890	2.3486160	2.5732510
H	0.4549110	0.3083760	2.5477000
H	1.0590730	2.5209730	-1.0827980
H	-0.0005920	4.5165380	-0.0359640
H	-0.5419320	2.2915370	3.6031300
H	-0.7900600	4.4068450	2.3191050
C	2.9759400	-0.8174080	1.7817670
H	2.7429220	0.0731170	2.3753340
H	3.8572020	-0.5720310	1.1760680
C	3.2775880	-1.9941960	2.7051550
H	4.1242170	-1.7716760	3.3617360
H	3.5218220	-2.8896280	2.1265130
H	2.4136580	-2.2266340	3.3385670
H	-0.4344770	-3.4740460	-4.2027220
H	-0.5989820	-2.6756130	-5.7695260

(*Z*)-Benzaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]**$_{(Z)\text{B-}(re)\text{P}}$)



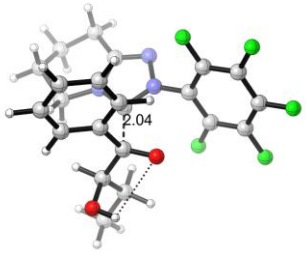
XYZ Coordinates

52

N	-1.4520020	-0.8118910	-1.0142020
C	-0.7388910	0.2843440	-0.7151230
N	-1.2068440	1.1828030	-1.6119000
C	-2.1889220	0.5973950	-2.3842960
N	-2.3580270	-0.6451720	-2.0342020
C	-1.3319800	-2.0806060	-0.4009580
C	-1.0669180	-4.5612560	0.8288340
C	-2.2257310	-2.4756480	0.5887230
C	-0.3091840	-2.9448860	-0.7689700
C	-0.1693550	-4.1824620	-0.1574130
C	-2.0986700	-3.7095120	1.2049140
F	0.5660110	-2.5862830	-1.7052100
F	0.8216090	-5.0020460	-0.5089530
F	-0.9423150	-5.7465710	1.4188970
F	-2.9546640	-4.0845240	2.1556310
F	-3.2114060	-1.6645200	0.9543280
C	-0.7801940	2.5874540	-1.7390730
H	0.3099050	2.6067660	-1.6875080
H	-1.1860420	3.1278070	-0.8796460
C	-2.9209800	1.3286830	-3.4623070
H	-3.9696070	1.0217340	-3.4443630
H	-2.5049530	1.0235690	-4.4294980
C	-2.7546070	2.8401320	-3.2804690
C	-1.2796830	3.1718380	-3.0556250
H	-1.1200510	4.2528140	-3.0226330
H	-0.6847380	2.7758480	-3.8880170
C	0.1567810	0.2604920	1.1282490
O	-0.7063970	-0.2790630	1.8667640
C	0.3209750	1.7794850	1.3227210
H	0.8065090	2.2438920	0.4580540
O	-0.9726850	2.3423910	1.4412010
H	-1.5020410	1.6528980	1.8812450
C	1.4152400	-0.5151950	0.7805240
C	3.7289840	-1.9891790	0.2219070
C	2.3329460	-0.0561300	-0.1700830
C	1.6675080	-1.7106170	1.4533450
C	2.8188510	-2.4497750	1.1717790
C	3.4851140	-0.7862330	-0.4471620
H	2.1339350	0.8658230	-0.7126660
H	0.9455100	-2.0555290	2.1891410
H	3.0027460	-3.3848100	1.6938560
H	4.1894290	-0.4244620	-1.1905630
H	4.6238970	-2.5630260	-0.0002610
C	1.1600190	2.0525200	2.5752350
H	2.1435370	1.5817020	2.4561330

H	0.6703940	1.5704780	3.4304840
C	1.3263580	3.5472320	2.8325640
H	1.9166250	3.7271480	3.7361160
H	0.3528960	4.0290700	2.9601890
H	1.8384040	4.0351870	1.9951940
H	-3.1341880	3.3538140	-4.1671040
H	-3.3453060	3.1806340	-2.4214000

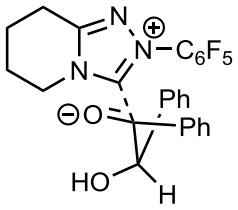
(*Z*)-Benzaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]$_{(Z)B\text{-}(si)P}$**)



XYZ Coordinates

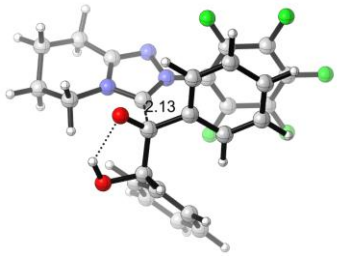
52

N	-1.5505480	-0.6775140	-0.4688470
C	-0.5531310	0.2153480	-0.3760230
N	-0.5788570	0.8026800	-1.5932430
C	-1.5830320	0.2473130	-2.3576070
N	-2.2034600	-0.6756300	-1.6814940
C	-1.9539480	-1.6160200	0.5092040
C	-2.7202840	-3.4918340	2.4181430
C	-2.5108110	-1.2079320	1.7150750
C	-1.7980020	-2.9765120	0.2676170
C	-2.1785380	-3.9157480	1.2132690
C	-2.8851990	-2.1372690	2.6717210
F	-1.2548350	-3.3925670	-0.8756410
F	-2.0216260	-5.2178810	0.9741020
F	-3.0868930	-4.3870000	3.3308350
F	-3.4133940	-1.7386630	3.8289860
F	-2.6967770	0.0834440	1.9643460
C	0.2899420	1.9046140	-2.0370340
H	1.3024340	1.6828930	-1.6945340
H	-0.0600470	2.8209170	-1.5502510
C	-1.8608700	0.6714690	-3.7632800
H	-2.9417310	0.6806320	-3.9231980
H	-1.4351840	-0.0818730	-4.4360640
C	-1.2204930	2.0344870	-4.0440610
C	0.2277370	2.0395470	-3.5533530
H	0.7330980	2.9688390	-3.8287140
H	0.7774480	1.2127500	-4.0196490
C	0.7442580	0.1195730	1.1983190
O	0.2041390	-0.5692430	2.0983540
C	0.9018590	1.6281790	1.4663710
C	1.8615910	-0.5427330	0.3923460
C	3.8497910	-1.8891380	-1.0615010
C	2.9247090	0.1651600	-0.1760710
C	1.8190780	-1.9334310	0.2450800
C	2.7982340	-2.6039030	-0.4828890
C	3.9139770	-0.5062870	-0.8983180
H	3.0080570	1.2386100	-0.0377300
H	1.0090700	-2.4790150	0.7220490
H	2.7468090	-3.6833140	-0.5945260
H	4.7404430	0.0539660	-1.3265080
H	4.6200710	-2.4087780	-1.6238120
C	-0.3666720	2.2688240	2.0128970
H	-0.6544200	1.7387170	2.9283190
H	-1.1772710	2.1098500	1.2919180
C	-0.1893250	3.7601970	2.2824790
H	-1.1126240	4.2011030	2.6703580
H	0.0785710	4.2975320	1.3649610
H	0.6034830	3.9362060	3.0152620
H	1.2120990	2.1542290	0.5574770
O	1.9907760	1.7750880	2.3769800
H	1.7771420	1.2584180	3.1690560
H	-1.2631090	2.2372580	-5.1168160
H	-1.7850150	2.8261640	-3.5363430



TS [VI-I]$_{(E)B\text{-}(re)B}$

(*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde Eject (**TS [VI-I]$_{(E)B\text{-}(re)B}$**)

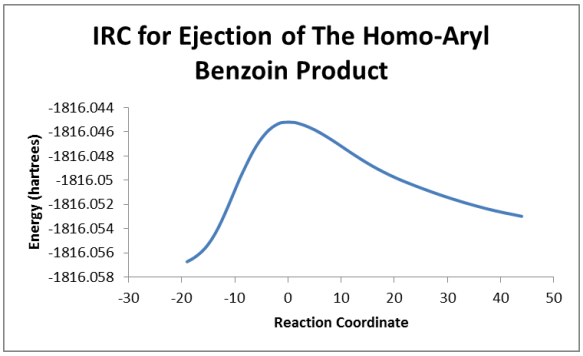


XYZ Coordinates

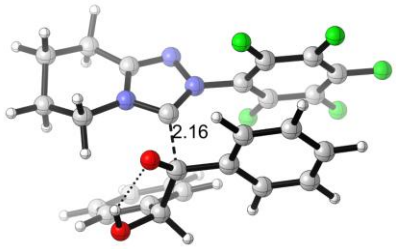
56

N	-0.6935400	0.3110340	-1.3819490
C	0.3620970	0.7951280	-0.7024850
N	1.0071560	1.5046670	-1.6602720
C	0.3218800	1.4138600	-2.8527000
N	-0.7442690	0.6826590	-2.7074000
C	-1.7546710	-0.4729610	-0.8742630
C	-3.8831380	-1.9845700	0.0947030
C	-2.9986790	0.1116430	-0.6569540
C	-1.5970920	-1.8295530	-0.6161680
C	-2.6523640	-2.5853750	-0.1270540
C	-4.0609040	-0.6344070	-0.1727470
F	-0.4274720	-2.4213800	-0.8355380
F	-2.4898820	-3.8830210	0.1306620
F	-4.8921680	-2.7009170	0.5815490
F	-5.2396760	-0.0596290	0.0603760
F	-3.1761900	1.4042980	-0.9165150
C	2.2196090	2.3229190	-1.4761750
H	2.8826640	1.7864960	-0.7962540
H	1.9155930	3.2552750	-0.9921770
C	0.7993440	2.0430420	-4.1217700
H	-0.0619410	2.4426550	-4.6629720
H	1.2386690	1.2527040	-4.7416190
C	1.8520210	3.1173020	-3.8319290
C	2.8744550	2.5895010	-2.8249150
H	3.6780490	3.3142550	-2.6695980
H	3.3299190	1.6671290	-3.2070710
C	0.7121190	1.2515590	1.3445000
O	1.0555450	2.4544650	1.2927980
C	1.8818860	0.2812350	1.7512520
O	3.0863040	0.9811870	1.5202460
H	2.8121810	1.9197320	1.4836490
C	-0.6920430	0.9487530	1.8333460
C	-3.3003370	0.5626000	2.7954140
C	-1.0853940	-0.2957230	2.3347900
C	-1.6194690	1.9955510	1.8164540
C	-2.9164780	1.8049220	2.2884350
C	-2.3813670	-0.4863880	2.8156740
H	-0.3918260	-1.1277790	2.3517960
H	-1.3067630	2.9611390	1.4311040
H	-3.6275710	2.6256880	2.2612470
H	-2.6716170	-1.4582270	3.2058730
H	-4.3098390	0.4117170	3.1675550
H	1.7305890	0.1513030	2.8370760
C	2.0186470	-1.0975790	1.1383700
C	2.4252380	-3.6645290	0.0605000
C	2.5317410	-1.2585480	-0.1546530
C	1.7535380	-2.2425650	1.8945940
C	1.9426420	-3.5180210	1.3593120
C	2.7291290	-2.5281210	-0.6915540
H	2.8029630	-0.3831850	-0.7357440
H	1.4110290	-2.1389540	2.9218090
H	1.7254490	-4.3936170	1.9642290
H	3.1288110	-2.6313900	-1.6963730
H	2.5782390	-4.6547540	-0.3585430
H	2.3416130	3.4009900	-4.7668100
H	1.3707670	4.0156870	-3.4268910

IRC for (*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde Eject (**TS [VI-I]$_{(E)B\text{-}(re)B}$**)



(*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde Eject – No Rotation (**TS [VI-I]$_{(E)B\text{-}(re)B(2)}$**)



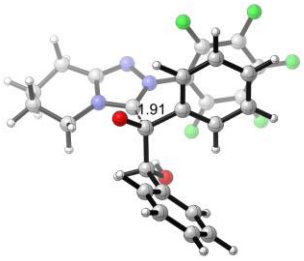
XYZ Coordinates

56

C	3.1142720	-2.4105340	-2.1206330
H	2.7372070	-3.1110510	-2.8697730
C	4.4881770	-0.3523130	-1.6994710
H	4.7663840	-0.7653720	-0.7208280
H	5.3212300	0.2644790	-2.0476960
C	3.2694510	0.5468360	-1.5444760
H	3.3866350	1.2623370	-0.7303530
H	3.0752060	1.1024330	-2.4667850
C	1.9723330	-1.6089470	-1.5863990

N	2.0790680	-0.2734960	-1.2620930
N	0.7755690	-2.0445420	-1.3181470
C	0.9120030	0.1694840	-0.7411330
N	0.1431730	-0.9327790	-0.8058140
C	-1.2290770	-1.0357110	-0.4792940
C	-3.9439180	-1.2736270	0.1146500
C	-2.1927520	-0.5012140	-1.3296550
C	-1.6507100	-1.7218720	0.6554050
C	-2.9984390	-1.8371270	0.9596240
C	-3.5430080	-0.6037660	-1.0320210
F	-0.7596570	-2.2868420	1.4665570
F	-3.3882570	-2.4873830	2.0553630
F	-5.2368570	-1.3697610	0.4079130
F	-4.4542230	-0.0650920	-1.8398720
F	-1.8271420	0.1071220	-2.4543820
C	0.7566710	2.2106940	-0.0543740
O	1.2258750	2.8880510	-0.9917000
C	1.6787030	2.1792660	1.2452790
O	2.7442350	3.0641770	0.9885420
H	3.5206320	-3.0015580	-1.2911340
H	2.5872190	3.3783580	0.0745880
C	-0.7487920	2.2258500	0.1426130
C	-3.5442690	2.3868880	0.3673720
C	-1.3846440	1.9023300	1.3454870
C	-1.5288700	2.6492940	-0.9392710
C	-2.9148740	2.7273830	-0.8316220
C	-2.7748170	1.9763970	1.4550610
H	-0.8138410	1.6062630	2.2192800
H	-1.0304310	2.9113510	-1.8672660
H	-3.5056980	3.0488960	-1.6846740
H	-3.2527670	1.7233160	2.3973290
H	-4.6259420	2.4437300	0.4533170
H	1.0594350	2.6083000	2.0457850
C	4.2022880	-1.4899280	-2.6815810
C	2.2304000	0.8495390	1.7492510
C	3.3021470	-1.5748360	2.7093190
C	3.6137360	0.6579900	1.8302880
C	1.3923450	-0.1882600	2.1768580
C	1.9203000	-1.3883650	2.6489920
C	4.1455100	-0.5445250	2.3005010
H	4.2749220	1.4595340	1.5203150
H	0.3136660	-0.0743790	2.1267690
H	1.2500030	-2.1807890	2.9677060
H	5.2237620	-0.6699210	2.3487810
H	3.7123340	-2.5105890	3.0774390
H	5.1065700	-2.0746120	-2.8680470
H	3.8781570	-1.0707830	-3.6419580

(*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde Eject – No Hydrogen Bond (**TS [VI-I]**$_{(E)B\text{-}(re)B(3)}$)

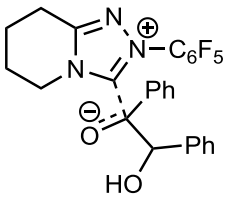


XYZ Coordinates

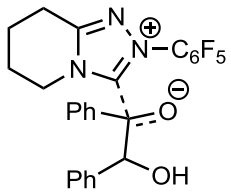
56

N	0.8017460	1.6939630	0.1479430
C	-0.5267450	1.4940540	0.1125220
N	-1.0143930	2.7527420	0.0613810
C	0.0307950	3.6481280	0.0622800
N	1.1689900	3.0168280	0.1179820
C	1.8168140	0.7202670	0.2947430
C	3.8269200	-1.1748090	0.5955330
C	2.6577420	0.4133880	-0.7691350
C	2.0061430	0.0802720	1.5139860
C	3.0025830	-0.8697360	1.6695070
C	3.6583060	-0.5351180	-0.6248470
F	1.2116840	0.3670640	2.5455680
F	3.1695040	-1.4936550	2.8341650
F	4.7727980	-2.0985630	0.7309100
F	4.4460570	-0.8474190	-1.6512980
F	2.5005600	1.0272300	-1.9375500
C	-2.4393050	3.1412220	0.0839540
H	-2.7935810	3.0096880	1.1112310
H	-2.9626190	2.4465750	-0.5743850
C	-0.1641160	5.1275780	-0.0058350
H	0.0313710	5.4469450	-1.0359000
H	0.5800320	5.6079980	0.6341510
C	-1.5774320	0.0418000	-0.5343640
O	-2.2900560	0.5510810	-1.4545980
C	-2.3705220	-0.3621050	0.7499800
O	-1.5894050	-0.4992290	1.9206610
H	-1.1177830	0.3307070	2.0735970
C	-0.4800820	-0.9278030	-0.9936530
C	1.4690510	-2.6805230	-2.0059860
C	0.0908460	-1.9070660	-0.1714180
C	-0.0644600	-0.8401590	-2.3247270
C	0.9092850	-1.7027660	-2.8282840
C	1.0542520	-2.7802490	-0.6770810

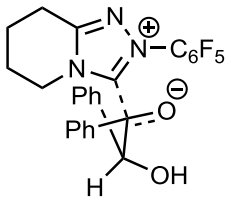
H	-0.2076180	-1.9834670	0.8686540
H	-0.5227690	-0.0880890	-2.9600320
H	1.2258550	-1.6153430	-3.8639450
H	1.4831990	-3.5388710	-0.0273000
H	2.2229200	-3.3588170	-2.3958880
H	-3.1086630	0.4422760	0.8770420
C	-3.1241140	-1.6613300	0.5206660
C	-4.5207010	-4.0536370	0.0530150
C	-2.8837570	-2.7898520	1.3093020
C	-4.0815650	-1.7389960	-0.4983040
C	-4.7730540	-2.9262910	-0.7307680
C	-3.5776540	-3.9785360	1.0761780
H	-2.1528530	-2.7369320	2.1092330
H	-4.2712460	-0.8645190	-1.1131930
H	-5.5110640	-2.9713100	-1.5268190
H	-3.3752710	-4.8472610	1.6964500
H	-5.0588530	-4.9792490	-0.1295970
C	-1.5976380	5.4944250	0.3892100
H	-1.7780420	6.5448570	0.1487410
H	-1.7290530	5.3765590	1.4719090
C	-2.5872920	4.5937140	-0.3498590
H	-3.6180880	4.8965260	-0.1478160
H	-2.4258300	4.6750430	-1.4316120



TS [VI-I]$_{(E)B\text{-}(si)B}$



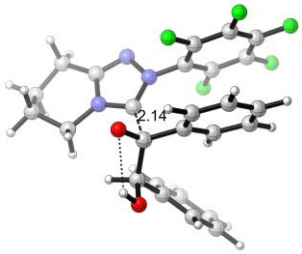
TS [VI-I]$_{(Z)B\text{-}(re)B}$



TS [VI-I]$_{(Z)B\text{-}(si)B}$

(*E*)- Benzaldehyde BI + *si* Face of Benzaldehyde Eject

(TS [VI-I]$_{(E)B\text{-}(si)B}$)



XYZ Coordinates

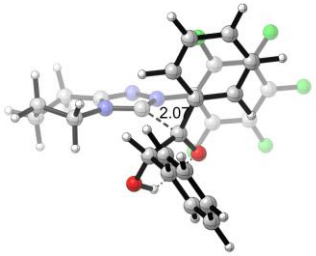
56

N	-1.4730110	-0.0461070	-1.0055340
C	-0.1664930	-0.3640900	-0.9467420
N	-0.0753480	-1.3163110	-1.9103970
C	-1.3131220	-1.5387040	-2.4739720
N	-2.2013710	-0.7592690	-1.9313670
C	-2.1499800	0.9637750	-0.2844050
C	-3.4913550	2.9487710	1.1254320
C	-2.0495160	2.2951230	-0.6738740
C	-2.9463300	0.6375280	0.8056360
C	-3.6177740	1.6222380	1.5133270
C	-2.7062050	3.2905230	0.0324440
F	-3.0529340	-0.6321480	1.1927890
F	-4.3666720	1.3061010	2.5692650
F	-4.1126060	3.8996450	1.8164430
F	-2.5853510	4.5674760	-0.3254370
F	-1.3076880	2.6253450	-1.7271630
C	1.1500910	-2.0247340	-2.3211770
H	1.3824610	-2.7677850	-1.5512230
H	1.9501490	-1.2836910	-2.3629040
C	-1.5503240	-2.5282130	-3.5691080
H	-1.6656690	-1.9750280	-4.5081770
H	-2.4928870	-3.0471400	-3.3776160
C	-0.3684550	-3.4947700	-3.6842160
C	0.9406320	-2.7071140	-3.6677230
H	0.9288080	-1.9550730	-4.4662510
H	1.7973250	-3.3624290	-3.8458130
C	1.5796670	0.7045230	-0.3173600
O	2.1122620	1.0135530	-1.4036370
C	2.3481820	-0.4324920	0.4395330
H	2.4762880	-1.2404660	-0.2880600
O	3.6141340	0.1373330	0.7453180
H	3.9243960	0.5703700	-0.0646820
C	1.7674470	-1.0119250	1.7032330
C	0.5931220	-2.0504410	4.0292460
C	2.1448510	-0.5319440	2.9605240

C	0.8241200	-2.0414080	1.6242030
C	0.2307340	-2.5516380	2.7781000
C	1.5594760	-1.0474420	4.1167010
H	2.8887810	0.2555200	3.0272630
H	0.5481170	-2.4436210	0.6517080
H	-0.5073420	-3.3447710	2.7003310
H	1.8579240	-0.6632360	5.0879770
H	0.1354350	-2.4484990	4.9301760
C	0.9443890	1.8050830	0.5191550
C	-0.0361760	3.9574760	2.0344870
C	0.1392350	1.5764760	1.6433220
C	1.2354860	3.1232030	0.1570720
C	0.7435260	4.1948640	0.9037420
C	-0.3384640	2.6436720	2.4003990
H	-0.1429770	0.5649980	1.9182310
H	1.8503230	3.2958780	-0.7209170
H	0.9751650	5.2131040	0.6047100
H	-0.9566690	2.4478290	3.2726300
H	-0.4153640	4.7888690	2.6224460
H	-0.3813950	-4.2088560	-2.8514270
H	-0.4622980	-4.0683130	-4.6094850

(*Z*)- Benzaldehyde BI + *re* Face of Benzaldehyde Eject

(TS [VI-I]$_{(Z)B\text{-}(re)B}$)



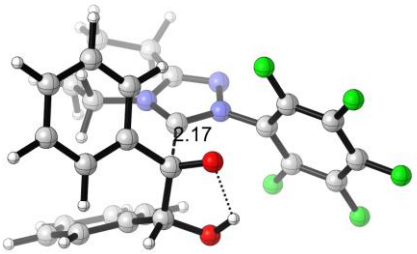
XYZ Coordinates

56

N	-1.7639520	0.5577210	-1.5443890
C	-1.2215790	-0.4246940	-0.8093720
N	-2.0282980	-1.4726740	-1.0941570
C	-2.9930980	-1.0818480	-2.0002930
N	-2.8513470	0.1782760	-2.2950580
C	-1.3032330	1.8919580	-1.6293450
C	-0.3380780	4.4955530	-1.7978470
C	-0.5723940	2.3043720	-2.7387330
C	-1.5456710	2.8002880	-0.6072080
C	-1.0617940	4.0991760	-0.6837040
C	-0.0927850	3.5993310	-2.8313710
F	-2.2355350	2.4325900	0.4697550
F	-1.2867690	4.9621110	0.3068730
F	0.1226100	5.7405430	-1.8805650
F	0.6103630	3.9892490	-3.8945270
F	-0.3148530	1.4426730	-3.7173970
C	-1.8812050	-2.8461140	-0.5818610
H	-1.6855790	-2.7807370	0.4900200
H	-1.0096550	-3.2856890	-1.0753460
C	-4.0336160	-2.0128940	-2.5319670
H	-4.2006600	-1.7859150	-3.5877350
H	-4.9729470	-1.8200800	-2.0007840
C	-3.6029940	-3.4655970	-2.3102410
C	-3.1447470	-3.6508360	-0.8637960
H	-2.9261160	-4.7006130	-0.6518060
H	-3.9454130	-3.3358990	-0.1830280
C	0.7061790	-0.0479050	-0.1591610
O	1.2320470	0.5304500	-1.1391560
C	1.1456990	-1.5189500	0.0468210
H	0.4126340	-2.0594700	0.6515170
O	1.2119200	-2.1237310	-1.2253860
H	1.4172560	-1.3970770	-1.8421580
C	2.4833160	-1.5384760	0.7677720
C	4.9428150	-1.5153060	2.1146060
C	2.5451860	-1.8143000	2.1360700
C	3.6655630	-1.2511380	0.0782630
C	4.8882230	-1.2411680	0.7465810
C	3.7678700	-1.8024710	2.8085420
H	1.6303860	-2.0434140	2.6786220
H	3.6283070	-1.0358510	-0.9860390
H	5.7999320	-1.0184120	0.1996720
H	3.8017630	-2.0232880	3.8715250
H	5.8961890	-1.5087570	2.6348690
C	0.3967010	0.7390400	1.0977690
C	-0.0935980	2.2417250	3.4054990
C	-0.4064810	0.2216500	2.1184960
C	0.9619980	2.0056110	1.2440510
C	0.7136980	2.7585350	2.3938560
C	-0.6503400	0.9664200	3.2681460
H	-0.8612700	-0.7602500	2.0019300
H	1.5926750	2.3909480	0.4473080
H	1.1507290	3.7477210	2.4974450
H	-1.2827650	0.5610900	4.0526100
H	-0.2923060	2.8270710	4.2985450
H	-4.4414270	-4.1286820	-2.5365200
H	-2.7839900	-3.7218520	-2.9932820

(*Z*)- Benzaldehyde BI + *si* Face of Benzaldehyde Eject

(TS [VI-I]$_{(Z)B\text{-}(si)B}$)

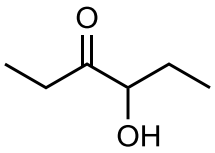


XYZ Coordinates

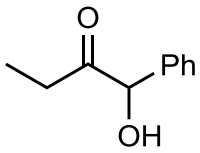
56

N	1.3824540	-1.4511500	-0.5149000
C	0.3168160	-0.6977540	-0.2027820
N	-0.2033300	-1.3724550	0.8491020
C	0.5679050	-2.4796090	1.1255460
N	1.5646100	-2.5549390	0.2893490
C	2.3131310	-1.1873110	-1.5466070
C	4.1110700	-0.5761520	-3.5784770
C	3.5472900	-0.6213740	-1.2497750
C	1.9967420	-1.4579890	-2.8723060
C	2.8862160	-1.1505530	-3.8894450
C	4.4485380	-0.3134840	-2.2576340
F	0.8266630	-2.0073910	-3.1784950
F	2.5718470	-1.3976890	-5.1608250
F	4.9697330	-0.2824110	-4.5503920
F	5.6306010	0.2293500	-1.9675120
F	3.8726200	-0.3603740	0.0138470
C	-1.4203460	-1.0021180	1.5874930
H	-2.2827420	-1.2892480	0.9769170
H	-1.4190070	0.0842880	1.7009790
C	0.2807590	-3.4044070	2.2643190
H	0.9879570	-3.1739120	3.0699640
H	0.4714350	-4.4324080	1.9459300
C	-1.1536160	-3.2085360	2.7661460
C	-1.4490870	-1.7169590	2.9330880
H	-0.7067350	-1.2670490	3.6043230
H	-2.4347870	-1.5590130	3.3791580
C	-0.2097680	1.0210710	-1.4155040
O	0.3780670	0.8228510	-2.4988830
C	0.4500790	2.1185140	-0.5176820
O	1.8310370	2.0979240	-0.8044940
H	1.8874580	1.7443380	-1.7122450
C	-1.7092460	0.8151780	-1.3895740
C	-4.4811760	0.4103620	-1.5554170
C	-2.5937370	1.8679430	-1.1476030
C	-2.2270430	-0.4326180	-1.7572070
C	-3.6001300	-0.6384730	-1.8343920
C	-3.9746640	1.6633730	-1.2226600
H	-2.2211950	2.8616690	-0.9248520
H	-1.5381620	-1.2442830	-1.9794230
H	-3.9847550	-1.6151640	-2.1135970
H	-4.6501430	2.4911270	-1.0276270
H	-5.5540040	0.2511780	-1.6105100
H	0.0087550	3.0627760	-0.8802130
C	0.2486460	2.0495920	0.9793210
C	-0.1397700	1.8729490	3.7578280
C	1.1461460	1.3336410	1.7812060
C	-0.8132290	2.7183810	1.5957420
C	-1.0148960	2.6227510	2.9738880
C	0.9506320	1.2393700	3.1571420
H	2.0001600	0.8521990	1.3143160
H	-1.4870740	3.3279550	1.0017520
H	-1.8499740	3.1432470	3.4335850
H	1.6522170	0.6718970	3.7626910
H	-0.2945310	1.7967000	4.8302990
H	-1.8639980	-3.6476720	2.0552030
H	-1.2755440	-3.7328990	3.7172700

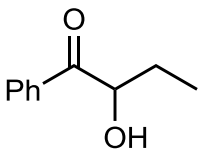
Products



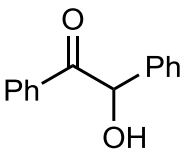
327



171

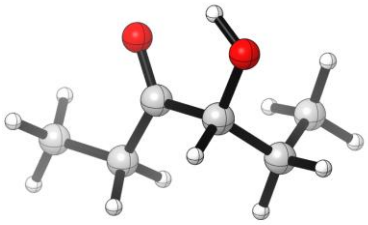


328



20

4-hydroxyhexan-3-one (**327**)

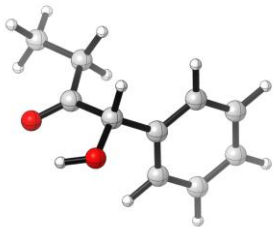


XYZ Coordinates

20

C 0.7249390 -1.0388000 -0.5715570
H 1.7923620 -1.1031980 -0.3093390
O 0.5101360 -1.6616650 -1.8174330
H 0.2268160 -0.9699310 -2.4383790
C 0.3934760 0.4472330 -0.6652000
O 0.0168000 0.9051170 -1.7307170
C -0.0950580 -1.7377950 0.5196130
H 0.2059020 -1.3465240 1.4978580
H 0.1864770 -2.7961160 0.5007980
C -1.5998180 -1.5907650 0.3147120
H -1.8947350 -1.9628700 -0.6709470
H -1.9175990 -0.5438200 0.3891620
H -2.1516930 -2.1574610 1.0698840
C 0.5500310 1.2889370 0.5740630
H -0.2392600 0.9740100 1.2709180
H 1.4970830 1.0145750 1.0546960
C 0.4647030 2.7842630 0.3032340
H -0.4964100 3.0457850 -0.1467410
H 1.2547150 3.1061620 -0.3811530
H 0.5711310 3.3426660 1.2367270

1-hydroxy-1-phenylbutan-2-one (**171**)

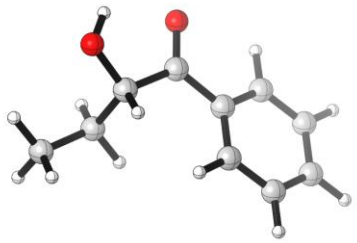


XYZ Coordinates

24

C -1.6350240 0.2659200 0.5461910
C -0.4985380 -0.2053280 1.4665390
H -0.2459860 0.6543170 2.1065930
C 0.7263420 -0.5768990 0.6521540
C 2.9372680 -1.2335420 -0.9316240
C 1.8030290 0.3045300 0.5470070
C 0.7628110 -1.7937420 -0.0347630
C 1.8646890 -2.1212110 -0.8225340
C 2.9055920 -0.0207680 -0.2446430
H 1.7821240 1.2456630 1.0918690
H -0.0706740 -2.4854160 0.0578230
H 1.8874330 -3.0692130 -1.3520250
H 3.7409150 0.6694740 -0.3165620
H 3.7964760 -1.4906950 -1.5438860
C -1.3544280 1.3887050 -0.4149670
H -0.6723610 0.9897050 -1.1774670
H -0.7811520 2.1561510 0.1200360
C -2.6119490 1.9616360 -1.0530140
H -3.1501990 1.1935650 -1.6139240
H -2.3500080 2.7696930 -1.7405190
H -3.2908800 2.3626290 -0.2950960
O -0.9395420 -1.2832240 2.2514820
H -1.8864030 -1.4022120 2.0636750
O -2.7195110 -0.2796250 0.6375540

2-hydroxy-1-phenylbutan-1-one (**328**)



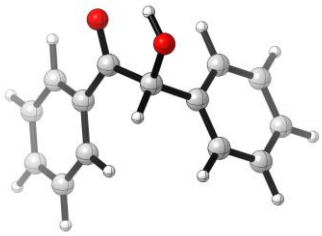
XYZ Coordinates

24

C -1.5635420 -0.5386610 0.5109200
C -0.1998850 -0.5883550 1.1928320
C 1.0491250 -0.4248960 0.3954640
C 3.4414460 -0.1206470 -1.0113510
C 2.2409270 -0.1564210 1.0810430
C 1.0629800 -0.5414680 -1.0003230
C 2.2590480 -0.3936340 -1.6992200
C 3.4316070 -0.0003190 0.3800950
H 2.2175800 -0.0682090 2.1628810
H 0.1506300 -0.7561600 -1.5484850
H 2.2673230 -0.4917900 -2.7802200
H 4.3515890 0.2142300 0.9151160
H 4.3718600 -0.0013610 -1.5587550
C -1.8581700 0.8977120 0.0486180
H -1.0598860 1.2385650 -0.6194090
H -1.8419700 1.5456090 0.9342780

C	-3.2081550	0.9923560	-0.6538250
H	-3.2196340	0.3789660	-1.5616930
H	-3.4238220	2.0253470	-0.9419910
H	-4.0116260	0.6461990	0.0018840
H	-1.5642910	-1.2094780	-0.3573580
O	-0.1634580	-0.7166690	2.4074460
O	-2.5538640	-0.9933680	1.4044950
H	-2.1756350	-0.9377590	2.2978480

2-hydroxy-1,2-diphenylethanone (**20**)



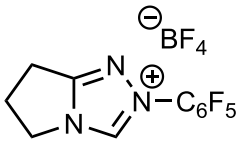
XYZ Coordinates

28

C	1.3361840	-1.4196790	-0.0750710
H	1.8058380	-1.2692890	0.9041840
C	-0.1544710	-1.6573350	0.1214700
C	-2.8883430	-2.1473750	0.4591170
C	-0.9948430	-1.7628820	-0.9915180
C	-0.6902190	-1.8032530	1.4015670
C	-2.0539350	-2.0469890	1.5713190
C	-2.3558810	-2.0071220	-0.8243940
H	-0.5837570	-1.6572090	-1.9936340
H	-0.0376980	-1.7299160	2.2685700
H	-2.4621750	-2.1619570	2.5710430
H	-3.0018050	-2.0846810	-1.6939040
H	-3.9496600	-2.3364580	0.5901350
O	1.9562510	-2.5191120	-0.6994900
H	2.1549240	-2.2527450	-1.6135460
C	1.5494260	-0.1649060	-0.9319750
O	1.9985450	-0.3105120	-2.0576820
C	1.1674710	1.1782480	-0.4156250
C	0.4672180	3.7369110	0.4515920
C	1.0711730	2.2316130	-1.3340840
C	0.9123370	1.4136710	0.9410770
C	0.5684140	2.6933010	1.3713160
C	0.7180240	3.5053690	-0.9027170
H	1.2707430	2.0354170	-2.3830150
H	0.9890180	0.6137040	1.6705930
H	0.3778860	2.8746180	2.4244120
H	0.6367790	4.3167780	-1.6193070
H	0.1925560	4.7317920	0.7894650

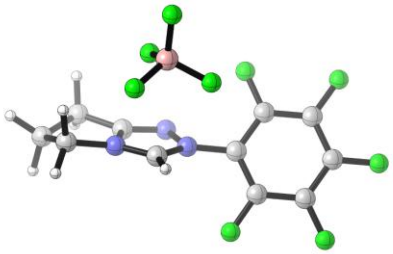
Pyrrolidinone-Derived Catalyst System Structures:

Starting Materials



5

2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (*Pyrrolidinone-Based Triazolium Salt*) (**5**)



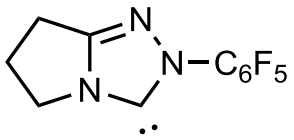
XYZ Coordinates

31

H	3.5679030	-2.1386300	2.5485760
C	3.5921280	-1.3944110	1.7523100
N	2.4185920	-1.1174910	-0.2667760
C	3.8250910	-1.1781980	-0.6966440
C	2.2667950	-1.2093750	1.0916470
C	4.4797170	-1.8065640	0.5507210
H	3.9194630	-1.7771340	-1.6012110
H	4.4761090	-2.8947000	0.4505140
H	3.9028580	-0.4333260	2.1749860
H	4.1536940	-0.1532220	-0.8826190
H	5.5092690	-1.4687760	0.6662400
C	1.2316210	-0.8633030	-0.7890590
H	0.9719990	-0.6898150	-1.8239090
N	0.3882040	-0.8327170	0.2445790
C	-1.0002820	-0.5667180	0.2000000
C	-3.7233660	-0.0194990	0.0975550
C	-1.8537000	-1.3730870	-0.5459590
C	-1.5245140	0.5171740	0.9007090
C	-2.8832280	0.7874660	0.8538010
C	-3.2114010	-1.1002800	-0.6057680
N	1.0220870	-1.0457430	1.4373980
F	-1.3716800	-2.4208190	-1.2111910

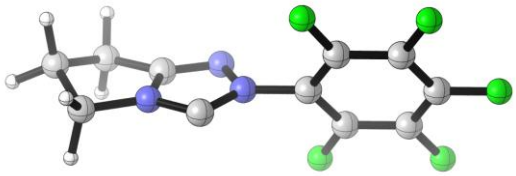
F	-4.0228090	-1.8760870	-1.3200500
F	-5.0232390	0.2433890	0.0477790
F	-3.3842230	1.8232880	1.5200650
F	-0.7332440	1.3012680	1.6169240
B	1.7156290	2.1628900	-0.8319390
F	0.3446960	1.8751630	-0.9916810
F	1.9266410	3.5416280	-0.8891810
F	2.4362030	1.5189010	-1.8606220
F	2.1526800	1.6547780	0.4062730

Free Carbene



329

Carbene (**329**)

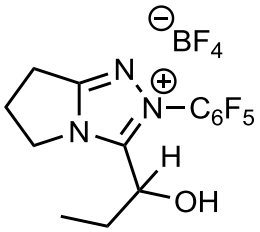


XYZ Coordinates

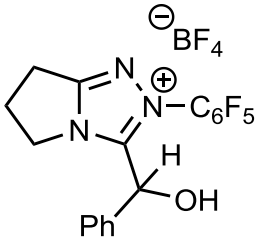
25

N	1.3286730	-0.3508490	0.9295750
N	0.6336050	0.1052500	-0.1843020
C	2.5586320	-0.2073610	0.5470500
N	2.6177360	0.3087340	-0.7215820
C	1.3855790	0.5202240	-1.2382340
C	3.9284990	-0.4501480	1.0919880
H	4.1658630	-1.5169380	1.0261880
H	4.0299330	-0.1387130	2.1322580
C	4.7930910	0.3906790	0.1171480
H	5.7834760	-0.0398050	-0.0336240
H	4.9119600	1.3995160	0.5212620
C	3.9934920	0.4638970	-1.2018370
H	4.2306410	-0.3614030	-1.8785990
H	4.1091330	1.4120070	-1.7269170
C	-0.7760240	0.0958640	-0.1320710
C	-3.5658680	0.0480100	-0.0046940
C	-1.4668170	-1.1099590	-0.0448620
C	-1.5102590	1.2782220	-0.1479660
C	-2.8964400	1.2595300	-0.0938970
C	-2.8507600	-1.1412800	0.0234530
F	-0.8910920	2.4552980	-0.2029210
F	-3.5852090	2.4003590	-0.1099890
F	-4.8943530	0.0260970	0.0545450
F	-3.4965040	-2.3042950	0.1024680
F	-0.7956970	-2.2602990	-0.0357460

Adducts

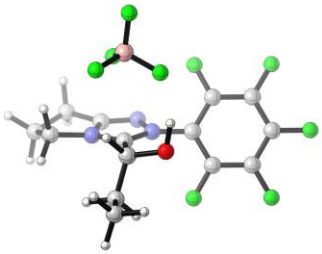


331



330

3-(1-hydroxypropyl)-2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (*Propionaldehyde Adduct*) (**331**)



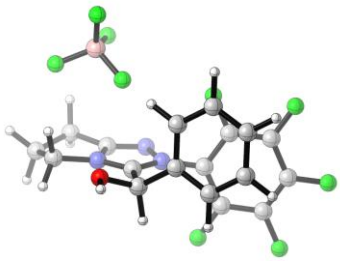
XYZ Coordinates

41

H	3.1832650	-0.5638260	-3.7605600
C	3.2729540	-0.6701820	-2.6792860
N	2.3318990	0.4851170	-0.8581510
C	3.7806680	0.6525680	-0.6519510
C	2.0306780	-0.2707040	-1.9574140
C	4.3178550	0.2870330	-2.0521970
H	4.0105060	1.6723950	-0.3456920
H	4.3913210	1.1941700	-2.6569560
H	3.4875620	-1.7174440	-2.4433500
H	4.0905260	-0.0550610	0.1215560
H	5.3050860	-0.1693230	-1.9855200
C	1.2048420	0.7289870	-0.1948640
N	0.2473630	0.1365540	-0.9261520

C	1.0971150	1.5093340	1.0949460
H	1.8866880	1.1043840	1.7445990
C	-1.1452040	0.0471990	-0.6795570
C	-3.8815280	-0.1556650	-0.2347040
C	-1.7390300	-1.2019600	-0.5220700
C	-1.9379700	1.1878990	-0.6293600
C	-3.2992810	1.0946120	-0.3967890
C	-3.1047480	-1.3036020	-0.3000650
N	0.7533200	-0.4950970	-2.0351500
O	-0.1683330	1.3551000	1.6770150
H	-0.2268920	0.4552380	2.0389520
F	-1.0140420	-2.3085030	-0.5896790
F	-3.6726840	-2.4982170	-0.1527820
F	-5.1884700	-0.2522660	-0.0213120
F	-4.0499080	2.1927000	-0.3362380
F	-1.3854190	2.3856750	-0.7960080
C	1.3624450	2.9972160	0.8486380
H	2.3232300	3.1018750	0.3331120
H	0.5851120	3.3868500	0.1842360
C	1.3839710	3.7703910	2.1632450
H	2.1552620	3.3793710	2.8352490
H	0.4197550	3.7008750	2.6722620
H	1.5978360	4.8261920	1.9775970
B	1.5348320	-1.9604640	1.6324260
F	0.2493760	-1.3551500	1.7106270
F	1.5077010	-3.1922680	2.2817240
F	1.8749160	-2.1236960	0.2815800
F	2.4650380	-1.1014920	2.2433080

3-(hydroxy(phenyl)methyl)-2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate (*Benzaldehyde Adduct*) (**330**)

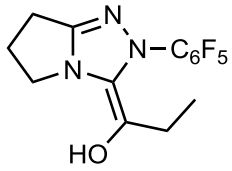


XYZ Coordinates

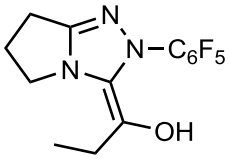
45

H	-3.7112930	-2.7657280	-1.8678170
C	-3.6364100	-1.9339910	-1.1668490
N	-2.0951080	-1.4081150	0.5400530
C	-3.3710830	-1.5391830	1.2735890
C	-2.2250620	-1.6186500	-0.8075070
H	-3.2191780	-2.1208280	2.1805510
H	-4.0817150	-1.0435330	-1.6201300
H	-3.7145880	-0.5341470	1.5183650
C	-0.8435210	-1.0377680	0.7751180
N	-0.2413790	-1.0632230	-0.4234070
C	-0.2206370	-0.6999240	2.1073470
H	0.3250820	-1.5958050	2.4401840
C	1.1175420	-0.7800310	-0.7115710
C	3.7859280	-0.1685650	-1.1700830
C	1.4716110	0.4611010	-1.2342880
C	2.1081970	-1.7164480	-0.4398460
C	3.4424900	-1.4145150	-0.6631570
C	2.8040610	0.7719890	-1.4570810
C	0.7508300	0.4602340	2.0097000
C	2.5508000	2.5762570	1.7857620
C	2.0996350	0.2628170	2.3102660
C	0.2962910	1.7200480	1.6100660
C	1.1986700	2.7755760	1.4973560
C	3.0010930	1.3211350	2.1966810
H	2.4452540	-0.7204970	2.6221700
H	-0.7529370	1.8644180	1.3635240
H	0.8479510	3.7506130	1.1735440
H	4.0510070	1.1645600	2.4262600
H	3.2531630	3.3989700	1.6902250
N	-1.0979180	-1.4244710	-1.4281870
O	-1.3241050	-0.4380290	2.9479740
H	-0.9888840	-0.2441000	3.8364460
F	0.5362210	1.3608070	-1.4970740
F	3.1466740	1.9627770	-1.9376480
F	5.0621340	0.1303850	-1.3729490
F	4.3913290	-2.3049880	-0.3853940
F	1.7849280	-2.8998200	0.0759160
B	-3.5391620	1.6510520	-0.8225980
F	-3.7282860	3.0056740	-0.5208270
F	-2.2752680	1.2354150	-0.3542830
F	-3.6094820	1.4505660	-2.2101600
F	-4.5360940	0.8793730	-0.1919170
C	-4.2550610	-2.2412450	0.2198850
H	-4.2414980	-3.3194120	0.3964180
H	-5.2845330	-1.8896080	0.2869600

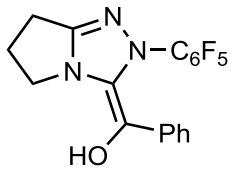
Breslow Intermediates



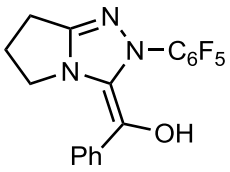
(*E*)-333



(*Z*)-333

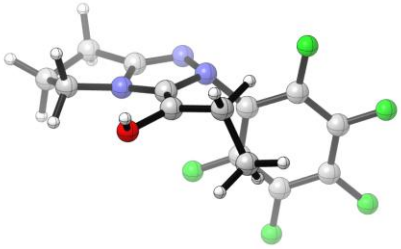


(*E*)-332



(*Z*)-332

(*E*)-1-(2-(perfluorophenyl)-6,7-dihydro-2H-pyrrolo[2,1-c][1,2,4]triazol-3(5H)-ylidene)propan-1-ol (*(E)-Propionaldehyde BI*) (**(*E*)-333**)

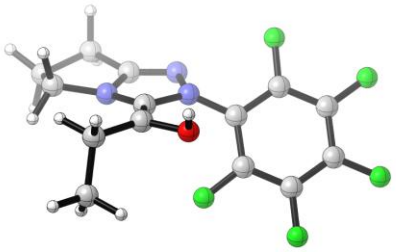


XYZ Coordinates

35

C	1.6074780	-3.2692610	0.9988110
H	2.1665070	-3.8211680	0.2362790
H	2.2115320	-3.2321760	1.9064140
C	0.1985810	-3.8709030	1.2168480
C	-0.7250650	-3.1197150	0.2349980
C	1.2848010	-1.9076290	0.4634590
N	-0.0415150	-1.8340180	0.1448780
N	1.9750530	-0.8577570	0.1762110
C	-0.2428720	-0.6536210	-0.5647590
N	1.0296260	0.0139500	-0.4878190
C	-1.3468570	-0.2091880	-1.1843840
C	1.0412370	1.3271270	0.0471650
C	1.0550870	3.9328980	1.0819500
C	0.5620800	1.6033750	1.3286360
C	1.5358490	2.3940350	-0.6970640
C	1.5414690	3.6884710	-0.1929130
C	0.5589830	2.8865860	1.8486780
F	0.0747620	0.6089270	2.0720500
F	0.0915630	3.1244840	3.0750210
F	1.0617700	5.1699950	1.5729370
F	2.0159140	4.6955680	-0.9276070
F	2.0019680	2.1965910	-1.9302600
H	-1.7405700	-2.9972330	0.6110190
C	-1.4398430	1.0531810	-1.9850610
H	-1.9847110	0.8270400	-2.9133980
H	-0.4348280	1.3632130	-2.2912590
C	-2.1535530	2.1966950	-1.2541240
H	-1.5950090	2.5006430	-0.3617830
H	-3.1533130	1.8873040	-0.9337010
H	-2.2607700	3.0693560	-1.9059680
O	-2.5167440	-0.9295460	-0.9819920
H	-2.9875850	-1.0044730	-1.8255710
H	-0.7630580	-3.5994610	-0.7511920
H	0.1767430	-4.9488410	1.0514030
H	-0.1299300	-3.6710560	2.2402480

(*Z*)-1-(2-(perfluorophenyl)-6,7-dihydro-2H-pyrrolo[2,1-c][1,2,4]triazol-3(5H)-ylidene)propan-1-ol (*(Z)-Propionaldehyde BI*) (**(*Z*)-333**)



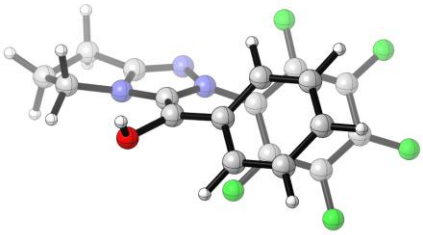
XYZ Coordinates

35

C	3.2797300	-0.7716790	-1.2827180
H	3.9902860	-1.0988100	-0.5165530
H	3.4054110	-1.4064800	-2.1608490
C	3.4266420	0.7368660	-1.5858200
C	2.4650140	1.4492850	-0.6114370
C	1.8983820	-0.8360830	-0.7107910
N	1.4469780	0.4228810	-0.4201020
N	1.0968120	-1.7832490	-0.3643610
C	0.2747880	0.3020290	0.3275980
N	0.0294240	-1.0921680	0.2670360
C	-0.4437910	1.2278600	0.9922100
C	-1.2008590	-1.7349470	0.3449800
C	-3.6581600	-3.0924290	0.5547620
C	-2.3710830	-1.2159980	-0.2160590
C	-1.3019330	-2.9683290	0.9951610
C	-2.5057110	-3.6470250	1.0916300

C	-3.5873690	-1.8687420	-0.0933090
F	-2.3346320	-0.0735660	-0.9050060
F	-4.6881430	-1.3396580	-0.6357800
F	-4.8235020	-3.7351150	0.6540420
F	-2.5647400	-4.8220040	1.7243000
F	-0.2230640	-3.5056890	1.5720500
H	2.0368480	2.3566840	-1.0415790
C	-0.2364970	2.7112020	0.9677680
H	0.7955110	2.9465690	0.6948020
H	-0.3767360	3.0956660	1.9881770
C	-1.2075480	3.4262410	0.0200520
H	-1.0964910	4.5132530	0.0894240
H	-2.2438070	3.1735450	0.2650320
H	-1.0232300	3.1276240	-1.0172980
O	-1.6095890	0.7763590	1.6071030
H	-1.6300720	1.1116110	2.5155490
H	2.9430770	1.6934130	0.3458090
H	4.4523950	1.0881920	-1.4690400
H	3.1070700	0.9370770	-2.6119350

(*E*)-(2-(perfluorophenyl)-6,7-dihydro-2H-pyrrolo[2,1-c][1,2,4]triazol-3(5H)-ylidene)(phenyl)methanol (*(E)-Benzaldehyde BI*) (**(*E*)-332**)

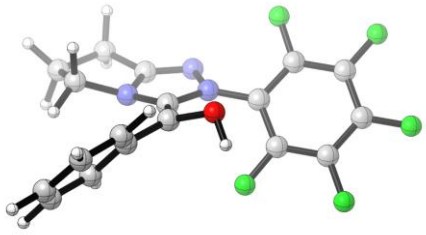


XYZ Coordinates

39

C	3.4866430	-2.3080610	-1.2918640
H	4.3760000	-1.8261810	-0.8728980
H	3.5694410	-3.3832260	-1.1270050
C	3.2770410	-1.9248230	-2.7764750
C	2.3778850	-0.6702190	-2.7603160
C	2.2727520	-1.7156210	-0.6477150
N	1.6292910	-0.8839490	-1.5246370
N	1.7585790	-1.7312850	0.5354170
C	0.6653100	-0.1785150	-0.8239480
N	0.6979860	-0.8008260	0.4365550
C	-0.1197850	0.8365530	-1.2706190
C	-0.3326960	-0.8469610	1.3715960
C	-2.3900260	-0.7380250	3.2822810
C	-1.6647210	-1.0727650	1.0173600
C	-0.0634700	-0.5902780	2.7179690
C	-1.0704760	-0.5472460	3.6677010
C	-2.6863730	-0.9926950	1.9516090
F	-1.9860010	-1.3576660	-0.2448580
F	-3.9509210	-1.1977950	1.5799440
F	-3.3657030	-0.6893240	4.1877560
F	-0.7804200	-0.2949340	4.9455870
F	1.1872850	-0.3275290	3.1006010
H	1.7076840	-0.6103070	-3.6165640
O	-0.1710630	0.9959460	-2.6536910
H	-0.0130680	1.9273430	-2.8691850
H	2.9566260	0.2587510	-2.6884390
H	4.2192270	-1.7398020	-3.2937480
H	2.7519900	-2.7330180	-3.2920500
C	-1.0367250	1.6277890	-0.4451030
C	-2.8410520	3.0995830	1.1443880
C	-2.3064260	1.9787640	-0.9348210
C	-0.6740780	2.0688470	0.8415510
C	-1.5719250	2.7796410	1.6322660
C	-3.1967550	2.7063970	-0.1471610
H	-2.5973390	1.6560140	-1.9306680
H	0.3240640	1.8561260	1.2183590
H	-1.2727970	3.1004610	2.6265090
H	-4.1782490	2.9572640	-0.5399420
H	-3.5398090	3.6583590	1.7596440

(*Z*)-(2-(perfluorophenyl)-6,7-dihydro-2H-pyrrolo[2,1-c][1,2,4]triazol-3(5H)-ylidene)(phenyl)methanol (*(Z)-Benzaldehyde BI*) (**(*Z*)-332**)



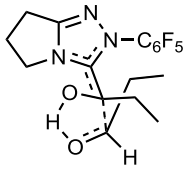
XYZ Coordinates

39

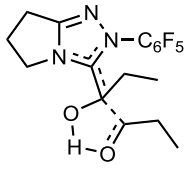
C	2.7349690	-2.5979390	-0.2359240
H	3.5968490	-2.3642710	0.3961900
H	2.6306130	-3.6830200	-0.2855830
C	2.8457480	-1.9309170	-1.6264390
C	2.0949610	-0.5905520	-1.5037260
C	1.5264450	-1.9251120	0.3362380
N	1.0860250	-0.9220030	-0.4960050
N	0.9143770	-1.9750780	1.4677100

C	0.1617200	-0.1609700	0.2123210
N	0.0127860	-0.8968370	1.3986580
C	-0.4029580	1.0389910	-0.0935380
C	-0.9525570	-0.7663180	2.3905290
C	-2.8832440	-0.5173280	4.4204530
C	-2.3084180	-0.6178480	2.0925230
C	-0.5961850	-0.7993690	3.7416790
C	-1.5456340	-0.6888180	4.7452890
C	-3.2619620	-0.4713790	3.0872380
F	-2.7126430	-0.6118790	0.8189630
F	-4.5482520	-0.3176440	2.7654000
F	-3.7982010	-0.3993910	5.3829160
F	-1.1721450	-0.7224180	6.0259390
F	0.6859930	-0.9091290	4.0932030
H	1.6425270	-0.2784030	-2.4440240
O	-0.9922840	1.7272920	0.9609670
H	-1.9096250	1.9442940	0.7291110
H	2.7312470	0.2209900	-1.1283520
H	3.8808780	-1.7841830	-1.9366100
H	2.3456170	-2.5513870	-2.3747240
C	-0.4245050	1.6714010	-1.4127080
C	-0.5490170	2.9410020	-3.9280830
C	-0.4355540	3.0753940	-1.5136470
C	-0.5203980	0.9196230	-2.5980120
C	-0.5667800	1.5483720	-3.8398160
C	-0.4942570	3.6993670	-2.7562860
H	-0.3858930	3.6714640	-0.6069590
H	-0.5900570	-0.1639050	-2.5410190
H	-0.6396180	0.9471040	-4.7418430
H	-0.4922930	4.7844260	-2.8110840
H	-0.5946710	3.4298650	-4.8965330

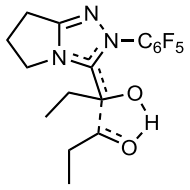
Carbon-Carbon Bond Formation Transition States



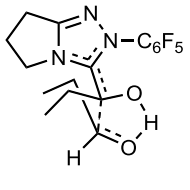
TS [V-VI]$^{(pyr)}_{(E)P\text{-}(re)P}$



TS [V-VI]$^{(pyr)}_{(E)P\text{-}(si)P}$

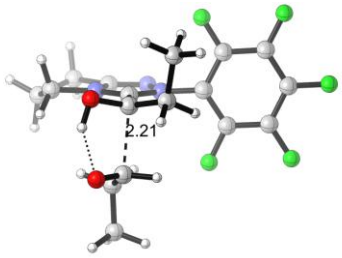


TS [V-VI]$^{(pyr)}_{(Z)P\text{-}(re)P}$



TS [V-VI]$^{(pyr)}_{(Z)P\text{-}(si)P}$

(*E*)-Propionaldehyde BI Attacking re Face of Propionaldehyde (**TS [V-VI]$^{(pyr)}_{(E)P\text{-}(re)P}$**)



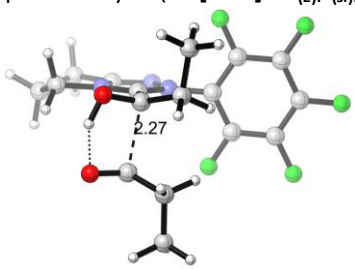
XYZ Coordinates

45

C	1.7575300	-3.3429840	-0.6780260
H	2.2131670	-4.1108780	-0.0521030
H	1.1249630	-3.8331660	-1.4250470
C	2.7896640	-2.3928630	-1.3334070
H	3.6647410	-2.3084150	-0.6829150
H	3.1187560	-2.7476130	-2.3106380
C	2.1009510	-1.0147760	-1.4314710
H	2.7848320	-0.1796390	-1.2885710
H	1.5545490	-0.8782000	-2.3687690
C	0.9304020	-2.3791990	0.1102180
N	1.1472230	-1.0995550	-0.3202590
N	0.0665140	-2.4437890	1.0693180
C	0.3544390	-0.2484170	0.3955330
N	-0.2965400	-1.1064000	1.2614610
C	0.3587640	1.1435010	0.3309350
O	0.9480520	1.6442180	-0.8192840
C	2.0531570	1.6124770	1.6712830
O	2.5809780	2.4977270	0.9487500
H	1.7154330	2.1809120	-0.4884150
C	-1.3316440	-0.8263580	2.1705870
C	-3.4010140	-0.3143590	3.9713320
C	-2.6626480	-0.9996690	1.7971180
C	-1.0582250	-0.4149830	3.4734320
C	-2.0812910	-0.1486750	4.3697120
C	-3.6965740	-0.7426000	2.6846160
F	-2.9551350	-1.4130920	0.5666080
F	-4.9649250	-0.9066390	2.3139640
F	-4.3855560	-0.0613300	4.8263810
F	-1.8084690	0.2605100	5.6074310
F	0.2017100	-0.2421410	3.8653020
C	-0.7252210	2.0204430	0.9048490
H	-1.0007740	1.7030630	1.9154540
H	-0.2826870	3.0195600	1.0131610
C	-1.9703550	2.1073480	0.0176370
H	-2.6965430	2.8184450	0.4248010

H -2.4622470 1.1321810 -0.0717220
H -1.6979160 2.4375640 -0.9893470
H 1.3340960 1.9126190 2.4562190
C 2.8020130 0.3275380 1.9538280
H 3.2917130 -0.0079380 1.0318000
H 2.1183640 -0.4574500 2.2939990
C 3.8545380 0.5932780 3.0370490
H 4.4082850 -0.3199790 3.2737780
H 3.3829680 0.9499980 3.9594570
H 4.5689140 1.3522850 2.7048770

(*E*)-Propionaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]**$^{(pyr)}_{(E)P\text{-}(si)P}$)

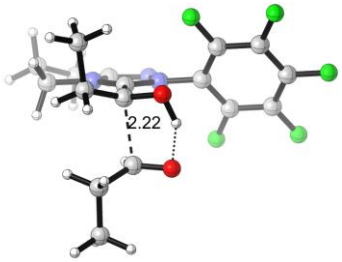


XYZ Coordinates

45

C 4.1404310 -0.3217120 0.2910410
H 4.7234530 0.6024260 0.3618380
C 3.8666470 -0.9325440 1.6861340
H 3.7186780 -2.0112080 1.5856200
H 4.6863750 -0.7588470 2.3839150
C 2.5546870 -0.2889740 2.1820760
H 1.9429000 -0.9678390 2.7725910
H 2.7230250 0.6378860 2.7373050
C 2.7555820 0.0144720 -0.1589020
N 1.8955650 0.0216050 0.9061810
N 2.1793720 0.3351740 -1.2699640
C 0.6559530 0.4018220 0.4740890
N 0.8586520 0.5816340 -0.8801690
C -0.0814820 0.9277510 -1.8644870
C -1.9535810 1.6178780 -3.8128360
C -0.2621340 2.2571030 -2.2392580
C -0.8325970 -0.0525340 -2.5101340
C -1.7741900 0.2839460 -3.4699990
C -1.1982060 2.6082450 -3.1997780
F -0.6607680 -1.3338260 -2.1936490
F -2.4976500 -0.6586230 -4.0716620
F -2.8501140 1.9480470 -4.7353010
F -1.3683470 3.8825730 -3.5463800
F 0.4661850 3.2125040 -1.6679690
C -0.5183150 0.4144460 1.2320350
O -0.2983700 0.3945650 2.6000080
C -1.7730100 1.1411370 0.8192650
H -2.5930800 0.7258230 1.4167970
H -2.0272980 0.9427760 -0.2265930
C -1.6937730 2.6529250 1.0594750
H -0.9080170 3.1095810 0.4482480
H -1.4651990 2.8611310 2.1091320
H -2.6427700 3.1414870 0.8143000
C -0.7807670 -1.8364880 1.0749250
O -0.4757040 -2.1145080 2.2628140
H 4.6511390 -1.0039440 -0.3892130
H -0.3956520 -0.5585050 2.8680000
H -0.0218990 -1.9742570 0.2833230
C -2.2131010 -1.9380470 0.6052420
H -2.8727400 -1.5739720 1.4002960
H -2.3709520 -1.3243080 -0.2872820
C -2.5295910 -3.4045870 0.2844880
H -3.5578950 -3.5090080 -0.0739000
H -2.4104570 -4.0298920 1.1742860
H -1.8606200 -3.7885940 -0.4936260

(*Z*)-Propionaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]**$^{(pyr)}_{(Z)P\text{-}(re)P}$)



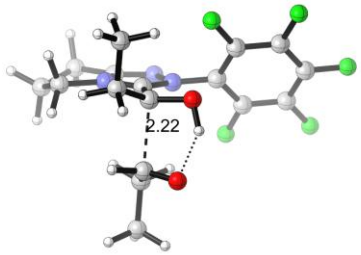
XYZ Coordinates

45

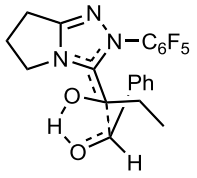
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H 1.7509720 -4.2631870 -0.6847110
H 0.8725530 -3.5655150 -2.0591890
C 2.7314800 -2.4872520 -1.5822120
H 3.5406700 -2.6762200 -0.8722520
H 3.0894910 -2.7190170 -2.5854970
C 2.2963170 -1.0095430 -1.4652690
H 3.0983700 -0.3632060 -1.1065110
H 1.8951040 -0.6122430 -2.4026510
C 0.7546190 -2.3829560 -0.3040400
N 1.2203200 -1.1050870 -0.4745520
N -0.2199530 -2.4491920 0.5409070
C 0.4608290 -0.2579460 0.2811010

N -0.4020500 -1.1179410 0.9230370
C 0.3997960 1.1414610 0.2512000
O -0.3569800 1.7307540 1.2425320
C -1.2531160 1.0983580 -1.2288460
H -1.1372180 0.0419090 -1.5393030
O -2.1900870 1.3926420 -0.4362020
H -1.2743830 1.8114970 0.8495430
C -1.3336040 -0.8289840 1.9331510
C -3.1976010 -0.2810490 3.9331960
C -2.6831550 -1.1145590 1.7442960
C -0.9327470 -0.2766570 3.1468400
C -1.8562870 0.0128520 4.1374580
C -3.6129440 -0.8518460 2.7387090
F -3.0983420 -1.6376820 0.5935520
F -4.9034410 -1.1314980 2.5500880
F -4.0872950 -0.0176250 4.8876790
F -1.4644800 0.5543450 5.2918900
F 0.3542430 -0.0195490 3.3656870
C -0.7644360 2.1060290 -2.2451420
H -0.6342510 3.0769630 -1.7545340
H 0.2015550 1.7902380 -2.6532590
C -1.7946980 2.2246570 -3.3753610
H -1.9578390 1.2566110 -3.8618350
H -1.4526710 2.9317960 -4.1368990
H -2.7547760 2.5758080 -2.9866520
C 1.5841050 1.9510810 -0.2097840
H 1.9598470 1.5838660 -1.1705060
H 1.2251890 2.9708920 -0.3877010
C 2.7178480 1.9789680 0.8200160
H 3.5299340 2.6387110 0.4968800
H 3.1350890 0.9764560 0.9701230
H 2.3506670 2.3377770 1.7866420

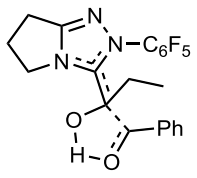
(*Z*)-Propionaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]$^{(pyr)}_{(Z)P\text{-}(si)P}$**)



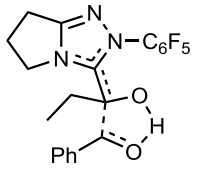
XYZ Coordinates
45
C -0.6028630 1.8540330 3.0859680
H -1.0314410 1.3699700 3.9636920
C 0.9421840 1.7789350 3.0378380
H 1.4139120 2.6401240 3.5115350
H 1.2757060 0.8753250 3.5546550
C 1.3280510 1.6750530 1.5429790
H 1.5607200 2.6440600 1.0918480
H 2.1588600 0.9865470 1.3793490
C -0.9724950 1.1678370 1.8127890
N 0.0962410 1.1394240 0.9575390
N -2.0290740 0.6202710 1.3112130
C -0.2840280 0.5231140 -0.2020180
N -1.6063200 0.2159040 0.0416450
C -2.5730860 -0.2604130 -0.8575570
C -4.5517170 -1.1870940 -2.5977230
C -3.3190910 -1.3947650 -0.5513750
C -2.8498710 0.4114080 -2.0468250
C -3.8177290 -0.0528340 -2.9205120
C -4.3068710 -1.8565450 -1.4088510
F -2.1818090 1.5207500 -2.3514900
F -4.0656020 0.5940750 -4.0605530
F -5.4954160 -1.6258130 -3.4279000
F -5.0107000 -2.9464470 -1.0998410
F -3.0830900 -2.0649640 0.5763700
C 0.4967550 0.1501500 -1.2968170
O -0.2057620 -0.3841750 -2.3598480
C 1.3401520 -1.7823540 -0.6073930
O 1.0891770 -2.4442310 -1.6475910
H -0.9605220 2.8879440 3.0468600
H 0.1214640 -1.3217410 -2.4285850
H 2.3324270 -1.3059220 -0.4995380
C 1.7320990 0.9272820 -1.6820390
H 2.3433580 0.2638930 -2.3076450
H 2.3365500 1.1618810 -0.8004140
C 1.4121540 2.2103020 -2.4544940
H 2.3285560 2.6999120 -2.8004110
H 0.8650200 2.9207700 -1.8246380
H 0.7938200 1.9880250 -3.3294010
C 0.6484010 -2.1293110 0.6924110
H -0.4313340 -2.2066640 0.5151500
H 0.8223240 -1.3414030 1.4348120
C 1.1864510 -3.4651050 1.2185500
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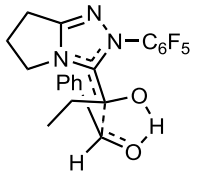
TS [V-VI]$^{(pyr)}_{(E)P\text{-}(re)B}$



TS [V-VI]$^{(pyr)}_{(E)P\text{-}(si)B}$

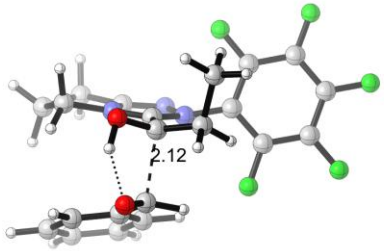


TS [V-VI]$^{(pyr)}_{(Z)P\text{-}(re)B}$



TS [V-VI]$^{(pyr)}_{(Z)P\text{-}(si)B}$

(*E*)-Propionaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]$^{(pyr)}_{(E)P\text{-}(re)B}$**)

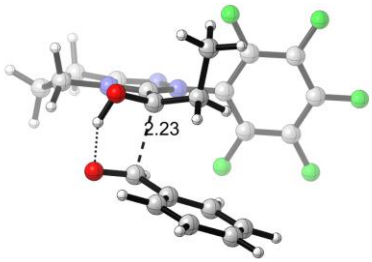


XYZ Coordinates

49

C	1.7180910	-3.3552930	-0.5696630
C	2.7062110	-2.4373330	-1.3309950
C	2.0791840	-1.0278370	-1.3354750
H	2.8117550	-0.2288000	-1.2483640
H	1.4423720	-0.8476720	-2.2059520
C	0.9705050	-2.3698690	0.2688470
N	1.2329680	-1.0887560	-0.1348230
N	0.1178830	-2.4177580	1.2391320
C	0.4815510	-0.2326180	0.6054950
N	-0.1828680	-1.0729690	1.4745780
C	0.5492700	1.1730890	0.5726590
O	1.0907410	1.6602010	-0.6031350
C	2.2115630	1.6577690	1.7929410
O	2.6054620	2.6672240	1.1299830
H	1.8195930	2.2666850	-0.2797790
C	-1.3479200	-0.8215240	2.2321850
C	-3.6860460	-0.4500540	3.7194100
C	-2.5943950	-1.1674730	1.7106170
C	-1.3001350	-0.2998660	3.5217020
C	-2.4569070	-0.0998010	4.2594890
C	-3.7578480	-0.9854930	2.4409090
F	-2.6799350	-1.6722840	0.4825760
F	-4.9395120	-1.3143640	1.9230870
F	-4.7963440	-0.2685550	4.4243730
F	-2.3919310	0.4199280	5.4836480
F	-0.1350790	0.0527600	4.0590880
C	-0.5154650	2.0632280	1.1683690
H	-0.7731740	1.7475910	2.1832650
H	-0.0471280	3.0506050	1.2710690
C	-1.7734450	2.1852820	0.3056140
H	-2.4666270	2.9205700	0.7266320
H	-2.3025070	1.2285880	0.2277180
H	-1.5108290	2.5061140	-0.7068310
C	3.0773220	0.4371270	1.8502490
C	4.7420290	-1.8168970	1.9510530
C	4.1742480	0.3277090	0.9888390
C	2.8254230	-0.5893480	2.7678060
C	3.6522720	-1.7114540	2.8175360
C	5.0017520	-0.7927900	1.0373850
H	4.3744430	1.1387610	0.2939790
H	1.9842690	-0.5047120	3.4496860
H	3.4496740	-2.5007410	3.5359710
H	5.8528160	-0.8663240	0.3658080
H	5.3883830	-2.6889600	1.9913190
H	1.5715440	1.7986010	2.6805580
H	2.2169670	-4.1154500	0.0332260
H	1.0187330	-3.8550690	-1.2469120
H	2.8982880	-2.7899970	-2.3448400
H	3.6551860	-2.4004540	-0.7896040

(*E*)-Propionaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$^{(pyr)}_{(E)P\text{-}(si)B}$**)



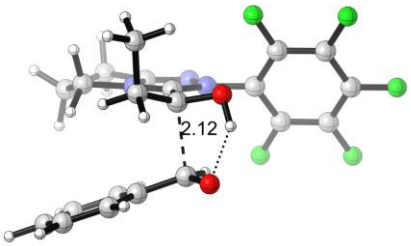
XYZ Coordinates

49

C	1.9251000	-2.9440730	-0.8486060
H	2.4674460	-3.7204470	-0.3081570
H	1.2967250	-3.4226560	-1.6068180
C	2.8428680	-1.8627420	-1.4656420
H	3.7342520	-1.7446250	-0.8432600
H	3.1572790	-2.1143520	-2.4789530

C	2.0324030	-0.5502530	-1.4352030
H	2.6530000	0.3255210	-1.2645300
H	1.4186080	-0.4128430	-2.3296400
C	1.0617200	-2.1182310	0.0479450
N	1.1511990	-0.7922080	-0.2797470
N	0.2345790	-2.3371910	1.0169400
C	0.3035560	-0.0825230	0.5191850
N	-0.2476240	-1.0631640	1.3142170
C	0.2127950	1.3231640	0.5822220
O	0.7235810	1.9521440	-0.5369520
C	2.1137510	1.5441060	1.7365070
H	2.0954630	0.5424870	2.1978200
O	2.8702630	1.7683620	0.7479720
H	1.6898450	2.1125010	-0.3243910
C	-1.2185550	-0.9364240	2.3232780
C	-3.1335100	-0.6615290	4.3306990
C	-2.5775250	-0.9544360	2.0168640
C	-0.8399850	-0.8380550	3.6596110
C	-1.7848340	-0.6834760	4.6619240
C	-3.5344280	-0.7999640	3.0086130
F	-2.9729230	-1.1207190	0.7575560
F	-4.8308430	-0.8042020	2.7061070
F	-4.0448840	-0.5200950	5.2862760
F	-1.4115860	-0.5649470	5.9344190
F	0.4497980	-0.8865430	3.9840430
C	-0.9365560	2.0473840	1.2310840
H	-1.1763700	1.6084080	2.2056790
H	-0.5937700	3.0681860	1.4368580
C	-2.1860110	2.1120120	0.3455770
H	-2.9858130	2.6737890	0.8394380
H	-2.5665020	1.1132400	0.1107550
H	-1.9541280	2.6115570	-0.5999980
C	1.6930320	2.6519980	2.6364390
C	0.8474230	4.7376620	4.3002570
C	1.8787680	3.9834540	2.2468210
C	1.0938800	2.3738630	3.8693810
C	0.6710880	3.4108270	4.6985920
C	1.4555870	5.0209670	3.0751400
H	2.3567750	4.1908010	1.2934030
H	0.9657260	1.3393620	4.1774960
H	0.2091250	3.1867720	5.6560320
H	1.6000860	6.0526680	2.7672440
H	0.5187230	5.5478000	4.9446770

(*Z*)-Propionaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]**$^{(pyr)}_{(Z)P\text{-}(re)B}$)



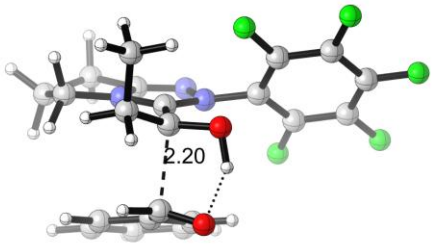
XYZ Coordinates

49

C	1.4626280	-2.8735260	-1.6466390
H	2.1965120	-3.4759710	-1.1017950
H	0.8265330	-3.5427960	-2.2266460
C	2.1411260	-1.7793110	-2.5040960
H	3.1237100	-2.0847990	-2.8641940
H	1.5108600	-1.5509000	-3.3680210
C	2.2343460	-0.5229100	-1.6116500
H	3.1718410	-0.4645580	-1.0505380
H	2.0813660	0.3941400	-2.1805290
C	0.6893460	-2.0514570	-0.6685410
N	1.1236450	-0.7509660	-0.6768720
N	-0.2361710	-2.2601490	0.2091030
C	0.4528170	-0.0632250	0.2899940
N	-0.3904780	-1.0145310	0.8122190
C	0.4621800	1.3151700	0.5603750
O	-0.1408540	1.6860480	1.7505640
C	-1.1803090	1.9373020	-0.6329550
H	-1.7426730	0.9987270	-0.4590760
O	-1.5087000	2.9703530	0.0197700
H	-0.8048750	2.3742140	1.4749670
C	-1.3121900	-0.8851990	1.8669970
C	-3.1574810	-0.6570540	3.9443720
C	-2.6742830	-1.0352740	1.6277040
C	-0.8871960	-0.6399520	3.1702950
C	-1.8003420	-0.5099230	4.2025480
C	-3.5979330	-0.9252810	2.6570280
F	-3.1089680	-1.2730360	0.3912260
F	-4.9006620	-1.0677690	2.4136240
F	-4.0354930	-0.5485810	4.9377010
F	-1.3856840	-0.2641930	5.4454990
F	0.4104060	-0.5236330	3.4338090
C	1.6433340	2.1752470	0.1883690
H	1.9997390	1.9459860	-0.8187640
H	1.2691960	3.2078460	0.1535080
C	2.7942150	2.0783040	1.1938410

H 3.5821380 2.8005630 0.9574170
H 3.2401910 1.0772790 1.1852440
H 2.4374950 2.2812600 2.2079120
C -0.5902330 2.0154660 -1.9986450
C 0.5380580 2.1149700 -4.5577000
C -0.0257540 3.2054230 -2.4727190
C -0.6114270 0.8859120 -2.8256100
C -0.0512510 0.9347960 -4.1013620
C 0.5440490 3.2510610 -3.7424150
H -0.0414020 4.0850500 -1.8354460
H -1.0833110 -0.0275310 -2.4671420
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H 0.9855480 4.1749840 -4.1050750
H 0.9759040 2.1566100 -5.5508020

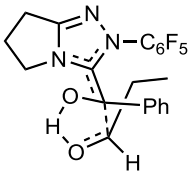
(*Z*)-Propionaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$^{(pyr)}_{(Z)P\text{-}(si)B}$**)



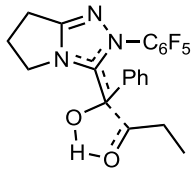
XYZ Coordinates

49

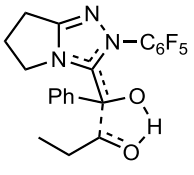
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H -0.9613010 1.1144050 3.9845360
C 0.9117600 1.7905220 3.0152470
H 1.2926200 2.7198730 3.4393050
H 1.3666160 0.9552890 3.5521910
C 1.2679580 1.6768540 1.5150080
H 1.3939870 2.6498510 1.0309500
H 2.1557780 1.0675040 1.3461680
C -0.9877910 1.0236310 1.8327820
N 0.0771490 1.0169220 0.9732650
N -2.0463550 0.4913550 1.3161440
C -0.3084270 0.4348650 -0.1956830
N -1.6278170 0.1202600 0.0392090
C -2.6136330 -0.2564800 -0.8904790
C -4.6209480 -0.9707580 -2.7054740
C -3.4829200 -1.3100260 -0.6189320
C -2.7999030 0.4575440 -2.0740870
C -3.7762160 0.0946740 -2.9855500
C -4.4802600 -1.6664720 -1.5156050
F -2.0442290 1.5206020 -2.3365930
F -3.9272900 0.7812870 -4.1190580
F -5.5710510 -1.3135090 -3.5720370
F -5.3003850 -2.6803110 -1.2354640
F -3.3748670 -2.0040760 0.5125290
C 0.4828460 0.0575620 -1.2965650
O -0.2169820 -0.4788450 -2.3494420
C 1.3241710 -1.8677530 -0.6388890
O 0.8852960 -2.5583640 -1.6065520
H -1.1061250 2.6764260 3.1581850
H 0.0711640 -1.4486030 -2.3580480
H 2.3438540 -1.4481120 -0.6870920
C 0.8214230 -2.0799450 0.7445980
C -0.1360300 -2.4444770 3.3489290
C 1.5923420 -1.6814260 1.8424260
C -0.4288690 -2.6710580 0.9597120
C -0.9093800 -2.8429350 2.2551510
C 1.1200350 -1.8709430 3.1406360
H 2.5717520 -1.2352520 1.6764550
H -1.0128160 -2.9864070 0.0992170
H -1.8863820 -3.2898790 2.4152050
H 1.7306710 -1.5770190 3.9897310
H -0.5087040 -2.5871690 4.3591020
C 1.7132220 0.8467690 -1.6781920
H 2.3118320 0.1992390 -2.3311120
H 2.3326920 1.0534190 -0.7995480
C 1.3879820 2.1497200 -2.4138800
H 2.3034390 2.6487680 -2.7483130
H 0.8414880 2.8432870 -1.7651090
H 0.7689570 1.9490030 -3.2933960



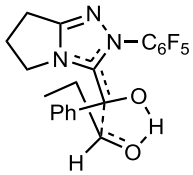
TS [V-VI]$^{(pyr)}_{(E)B\text{-}(re)P}$



TS [V-VI]$^{(pyr)}_{(E)B\text{-}(si)P}$

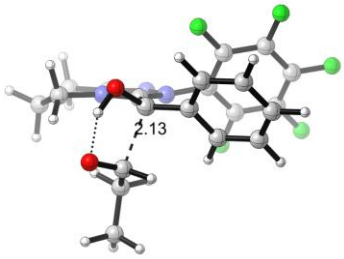


TS [V-VI]$^{(pyr)}_{(Z)B\text{-}(re)P}$



TS [V-VI]$^{(pyr)}_{(E)B\text{-}(si)P}$

(*E*)-Benzaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]$^{(pyr)}_{(E)B\text{-}(re)P}$**)

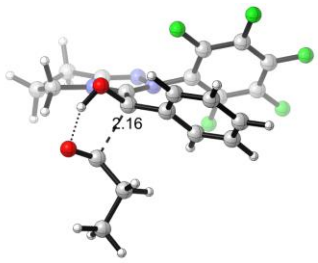


XYZ Coordinates

49

C -4.7201650 -1.0656380 0.8380970
H -5.5428270 -0.3439330 0.8110210
C -4.5438100 -1.7879230 -0.5215540
H -4.1025810 -2.7741890 -0.3524030
H -5.4910360 -1.9190850 -1.0452010
C -3.5579250 -0.9275630 -1.3418550
H -2.8831000 -1.5112130 -1.9683770
H -4.0583350 -0.1644080 -1.9430040
C -3.4234670 -0.3327030 0.9509050
N -2.8054020 -0.2649650 -0.2667090
N -2.7294570 0.2337330 1.8857620
C -1.6218920 0.3749240 -0.1232870
N -1.6020460 0.6931560 1.2083380
C -0.7659220 1.6202250 1.8575460
C 0.9506640 3.4266100 3.1035210
C -0.6539900 2.9284990 1.3939580
C -0.0206080 1.2384620 2.9680730
C 0.8303410 2.1340010 3.5957990
C 0.2115740 3.8260950 1.9978170
F -0.0890790 -0.0156300 3.4105360
F 1.5491790 1.7544530 4.6511210
F 1.7738870 4.2859670 3.6945530
F 0.3245610 5.0704920 1.5379120
F -1.3683710 3.3228210 0.3426500
C -0.6360990 0.5135340 -1.1428820
O -1.2104570 0.6743890 -2.3901440
C 0.0024670 -1.4920100 -1.4424310
O -0.5097310 -1.7080590 -2.5849490
H -4.8831550 -1.7474180 1.6732840
H -1.0205190 -0.1963360 -2.8544430
C 0.6150440 1.2735990 -0.8824810
C 2.9774360 2.7219770 -0.3869270
C 1.5200590 0.8596060 0.1087310
C 0.9339950 2.4029260 -1.6477810
C 2.1030010 3.1224740 -1.3978380
C 2.6837390 1.5807480 0.3627940
H 1.3063900 -0.0353890 0.6913300
H 0.2506590 2.7181120 -2.4306880
H 2.3288100 4.0033080 -1.9923290
H 3.3652660 1.2459710 1.1402220
H 3.8848440 3.2856700 -0.1913540
C -0.4237210 -2.3287450 -0.2511090
H -0.1879150 -1.8094790 0.6862750
H -1.5066500 -2.4954230 -0.2876890
C 0.3044450 -3.6769430 -0.2895020
H 1.3905100 -3.5351910 -0.2740540
H 0.0476500 -4.2314590 -1.1969570
H 0.0331500 -4.2900820 0.5751110
H 1.0604880 -1.1767640 -1.3965300

(*E*)-Benzaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]$^{(pyr)}_{(E)B\text{-}(si)P}$**)



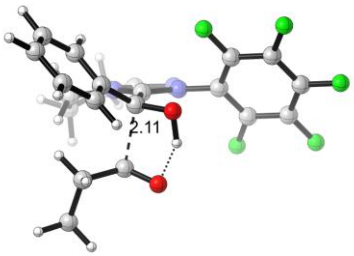
XYZ Coordinates

49

C -4.6820050 -1.0519320 0.6880440
H -5.4370000 -0.2600140 0.6426410
C -4.4932240 -1.7450010 -0.6848240
H -4.1428310 -2.7688680 -0.5291380
H -5.4183520 -1.7792910 -1.2605020
C -3.4009300 -0.9423020 -1.4228730
H -2.7498140 -1.5485060 -2.0534950
H -3.8068840 -0.1138410 -2.0088990
C -3.3392110 -0.4286220 0.8917700
N -2.6500460 -0.3845630 -0.2877070
N -2.6663250 0.0893190 1.8696690
C -1.4465110 0.1914380 -0.0726980
N -1.4807100 0.4917340 1.2609360
C -0.6626310 1.4068120 1.9522200
C 1.0068550 3.1939210 3.2855690
C -0.4753390 2.6988280 1.4681880
C -0.0191600 1.0322420 3.1267120
C 0.8096170 1.9177730 3.7966740
C 0.3680710 3.5860340 2.1171710
F -0.1604810 -0.2072240 3.5917850

F	1.4281410	1.5473890	4.9164120
F	1.8061310	4.0445490	3.9198640
F	0.5545920	4.8138270	1.6381000
F	-1.0916960	3.0863070	0.3546760
C	-0.4290390	0.3351430	-1.0747310
O	-0.9906200	0.7120460	-2.2789720
C	-0.1269030	-1.7154710	-1.6677360
O	-0.5416580	-1.6113270	-2.8683310
H	-4.9499180	-1.7414170	1.4887150
H	-0.8916600	-0.1134140	-2.8598940
H	-0.8134760	-2.1559820	-0.9188400
C	0.8738500	0.9659310	-0.7449300
C	3.3445330	2.2095770	-0.1851710
C	1.6547760	0.5639360	0.3535660
C	1.3741570	1.9799730	-1.5735610
C	2.5950210	2.5950880	-1.2959140
C	2.8676400	1.1849560	0.6371510
H	1.3130490	-0.2480850	0.9918620
H	0.7863250	2.2878760	-2.4317300
H	2.9567900	3.3841010	-1.9493190
H	3.4482970	0.8608240	1.4968560
H	4.2920460	2.6929690	0.0334430
C	1.3297260	-2.0357950	-1.4231730
H	1.9571880	-1.3194010	-1.9661200
H	1.5628670	-1.9552250	-0.3582470
C	1.6178580	-3.4619470	-1.9063790
H	2.6623290	-3.7298140	-1.7202730
H	1.4234490	-3.5516370	-2.9787630
H	0.9857390	-4.1895420	-1.3845880

(*Z*)-Benzaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]$^{(pyr)}_{(Z)B\text{-}(re)P}$**)

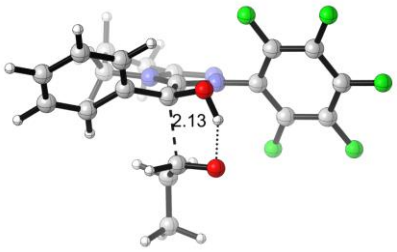


XYZ Coordinates

49

C	2.0640530	-2.9779170	2.0841340
H	2.7008920	-2.7297980	2.9390290
H	1.8078220	-4.0363090	2.1321740
C	2.7159350	-2.5612310	0.7432170
H	3.8002170	-2.6735380	0.7540430
H	2.3073520	-3.1759450	-0.0635750
C	2.3038080	-1.0913050	0.5203260
H	3.0076810	-0.3919640	0.9779610
H	2.1556620	-0.8274010	-0.5273930
C	0.8507330	-2.1081580	2.0860170
N	1.0232070	-1.0404560	1.2422640
N	-0.3365610	-2.1366030	2.5971600
C	-0.1374380	-0.3447680	1.1808320
N	-0.9508670	-1.0240360	2.0398410
C	-0.5382350	0.6677140	0.2463630
O	-1.8738940	0.9887930	0.3191240
C	-0.7274190	-0.6434380	-1.3971160
H	-0.2678420	-1.5332690	-0.9227810
O	-1.9988060	-0.6267820	-1.5138140
H	-2.2873200	0.4170920	-0.4135660
C	-2.2725270	-0.7316640	2.4315710
C	-4.8814090	-0.2034640	3.2550690
C	-3.2751320	-1.6804670	2.2602870
C	-2.5960140	0.4849420	3.0226690
C	-3.8926010	0.7571000	3.4246230
C	-4.5738950	-1.4246320	2.6740820
F	-3.0013540	-2.8450480	1.6764270
F	-5.5262830	-2.3417310	2.5064670
F	-6.1259240	0.0492630	3.6499170
F	-4.1946730	1.9293230	3.9817320
F	-1.6530580	1.4068120	3.1965910
C	0.3538930	1.8150380	-0.0532990
C	1.9443230	4.0450780	-0.7291730
C	-0.0768920	2.7464790	-1.0133140
C	1.5756940	2.0508240	0.5927300
C	2.3669010	3.1488840	0.2502200
C	0.7086310	3.8433290	-1.3500270
H	-1.0417590	2.6009060	-1.4900340
H	1.9003260	1.4048980	1.4026550
H	3.3068480	3.3127580	0.7698890
H	0.3537000	4.5465950	-2.0981030
H	2.5570340	4.9022670	-0.9912190
C	0.1280170	-0.0693570	-2.5090390
H	1.1147740	0.2238780	-2.1342640
H	-0.3588610	0.8276750	-2.9041700
C	0.2789110	-1.1186740	-3.6160360
H	0.8819770	-0.7290940	-4.4417660
H	-0.6985010	-1.4087480	-4.0133990
H	0.7716380	-2.0215530	-3.2367890

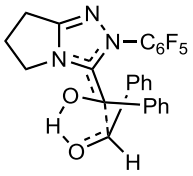
(*Z*)-Benzaldehyde BI Attacking *si* Face of Propionaldehyde (**TS [V-VI]$^{(pyr)}_{(Z)B\text{-}(si)P}$**)



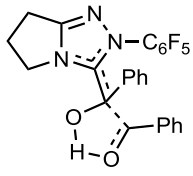
XYZ Coordinates

49

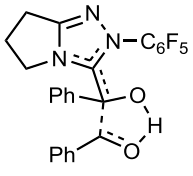
C	-0.7700860	1.7946370	3.0146710
H	-0.5163960	1.0106790	3.7361010
C	0.4672430	2.6385440	2.6313740
H	0.1426470	3.6251630	2.2906910
H	1.1594270	2.7673730	3.4637350
C	1.1357470	1.8922830	1.4585140
H	1.6028490	2.5588900	0.7348310
H	1.8632080	1.1516660	1.8030680
C	-1.0995360	1.1631900	1.7040640
N	-0.0162150	1.1975650	0.8616520
N	-2.1303160	0.6098880	1.1573210
C	-0.3594500	0.6015820	-0.3099320
N	-1.6733810	0.2583150	-0.1069000
C	-2.6165190	-0.2678650	-1.0143440
C	-4.5513680	-1.2825060	-2.7432580
C	-3.1752220	-1.5222500	-0.7938470
C	-3.0570790	0.4791270	-2.1026610
C	-4.0064470	-0.0262370	-2.9748470
C	-4.1400280	-2.0313100	-1.6506900
F	-2.5651950	1.6959090	-2.3158880
F	-4.4149870	0.6927350	-4.0213200
F	-5.4795550	-1.7644560	-3.5657970
F	-4.6705960	-3.2345140	-1.4306380
F	-2.7880090	-2.2528430	0.2475770
C	0.4247280	0.2077540	-1.4265270
O	-0.3305680	-0.0767960	-2.5476290
C	0.7586240	-1.8204090	-0.8848440
O	-0.1159200	-2.3723480	-1.6203860
H	-1.5953590	2.3848850	3.4132910
H	-0.4083080	-1.0809370	-2.5321930
C	1.7498550	0.8309290	-1.7004130
C	4.2446780	1.9801510	-2.3217060
C	2.8496210	0.6662040	-0.8472830
C	1.9333430	1.5484040	-2.8922200
C	3.1672800	2.1178990	-3.1985920
C	4.0807810	1.2484710	-1.1459110
H	2.7507400	0.0658950	0.0525840
H	1.0973620	1.6526270	-3.5768730
H	3.2871510	2.6727410	-4.1249160
H	4.9175260	1.1111930	-0.4667890
H	5.2059090	2.4260960	-2.5597170
H	1.7950070	-1.7464530	-1.2655020
C	0.6658300	-1.9593460	0.6215140
H	-0.3656880	-1.7718940	0.9421840
H	1.3212280	-1.2302630	1.1133240
C	1.0751570	-3.3807880	1.0222290
H	2.0925870	-3.6068650	0.6847030
H	0.3974620	-4.1134310	0.5744780
H	1.0444110	-3.5042180	2.1087920



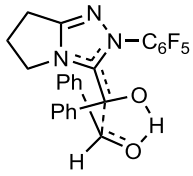
TS [V-VI]$^{(pyr)}_{(E)B\text{-}(re)B}$



TS [V-VI]$^{(pyr)}_{(E)B\text{-}(si)B}$

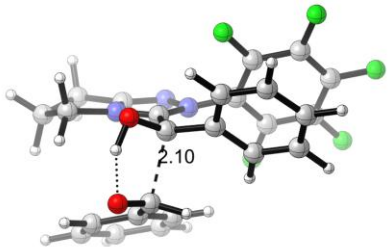


TS [V-VI]$^{(pyr)}_{(Z)B\text{-}(re)B}$



TS [V-VI]$^{(pyr)}_{(Z)B\text{-}(si)B}$

(*E*)-Benzaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]$^{(pyr)}_{(E)B\text{-}(re)B}$**)



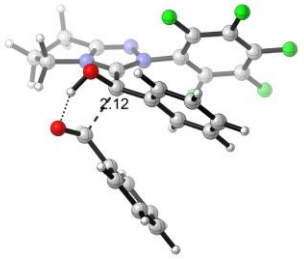
XYZ Coordinates

53

C	-4.6395930	-1.0607520	0.9579970
H	-5.4311350	-0.3098220	1.0389630
C	-4.5763420	-1.6952850	-0.4555210
H	-4.2655800	-2.7387310	-0.3699910
H	-5.5416940	-1.6617970	-0.9614140
C	-3.5072770	-0.9126600	-1.2486680

H	-2.9012190	-1.5386740	-1.9009120
H	-3.9258140	-0.0836630	-1.8238460
C	-3.3091650	-0.3892550	1.0551320
N	-2.6865500	-0.3584590	-0.1615220
N	-2.6103340	0.1962750	1.9757010
C	-1.5057850	0.2850040	-0.0313030
N	-1.4797100	0.6251760	1.2908490
C	-0.6285350	1.5478520	1.9306340
C	1.0872290	3.3644860	3.1629820
C	-0.5487510	2.8651450	1.4849000
C	0.1364370	1.1662260	3.0282000
C	0.9928120	2.0657750	3.6439330
C	0.3157440	3.7681410	2.0813750
F	0.0693850	-0.0812290	3.4863250
F	1.7307120	1.6865420	4.6857780
F	1.9125370	4.2268800	3.7456710
F	0.4030170	5.0190680	1.6343750
F	-1.2971700	3.2639340	0.4594560
C	-0.5166880	0.3848220	-1.0644230
O	-1.1061640	0.3926810	-2.3081800
C	0.2639370	-1.5628940	-1.2198480
O	0.0099270	-1.7640730	-2.4567850
H	-4.7815170	-1.7974600	1.7500810
H	-0.7432340	-0.4650100	-2.7287530
C	0.6572350	1.3025210	-0.9170750
C	2.8206820	3.0946260	-0.7117280
C	1.6742610	1.0982770	0.0278790
C	0.7653490	2.3998460	-1.7822960
C	1.8331400	3.2892980	-1.6786360
C	2.7391460	1.9912490	0.1385740
H	1.6359410	0.2385110	0.6910770
H	-0.0050240	2.5509070	-2.5317540
H	1.8912660	4.1391880	-2.3525800
H	3.5108360	1.8174260	0.8834770
H	3.6508110	3.7897900	-0.6287990
H	1.2736550	-1.2352460	-0.9290180
C	-0.4080670	-2.4101490	-0.1820900
C	-1.7131740	-3.9537890	1.7630320
C	-1.3658690	-3.3571290	-0.5555890
C	-0.0909250	-2.2641070	1.1740720
C	-0.7444660	-3.0212400	2.1426430
C	-2.0118510	-4.1280340	0.4110310
H	-1.5887770	-3.4852590	-1.6113330
H	0.6728650	-1.5507590	1.4740870
H	-0.4980670	-2.8867990	3.1921440
H	-2.7495130	-4.8663780	0.1081030
H	-2.2219660	-4.5479700	2.5165590

(*E*)- Benzaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$^{(pyr)}_{(E)B\text{-}(si)B}$**)



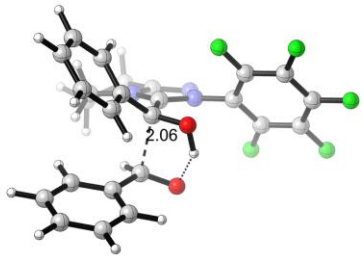
XYZ Coordinates

53

C	-4.6642540	-1.1676690	0.7342590
H	-5.4602340	-0.4249070	0.6215080
C	-4.4326590	-1.9647080	-0.5745380
H	-4.0297800	-2.9517960	-0.3321800
H	-5.3521160	-2.0953990	-1.1455800
C	-3.3794100	-1.1715000	-1.3763880
H	-2.7049240	-1.7906520	-1.9684090
H	-3.8218560	-0.4036120	-2.0161600
C	-3.3543570	-0.4648650	0.8859500
N	-2.6534080	-0.5002430	-0.2866230
N	-2.7093030	0.1679740	1.8155040
C	-1.4791680	0.1390580	-0.1148240
N	-1.5382090	0.5561370	1.1811090
C	-0.7098180	1.4958020	1.8274570
C	0.9845890	3.3219000	3.0681190
C	-0.5144430	2.7617790	1.2832570
C	-0.0586830	1.1639740	3.0104120
C	0.7814390	2.0706230	3.6360250
C	0.3398490	3.6693210	1.8886300
F	-0.2046590	-0.0543510	3.5263180
F	1.4078520	1.7429490	4.7643580
F	1.7941770	4.1922580	3.6603370
F	0.5361180	4.8719000	1.3535950
F	-1.1303240	3.1001220	0.1541210
C	-0.4563910	0.2431770	-1.1316910
O	-1.0231590	0.5475040	-2.3461780
C	-0.1086900	-1.7898840	-1.6078560
O	-0.4818460	-1.7421380	-2.8355320
H	-4.8976520	-1.7987810	1.5921420
H	-0.8889820	-0.3201850	-2.8843410
H	-0.7993310	-2.2307180	-0.8662230
C	0.8350550	0.9106970	-0.8280960
C	3.3310500	2.1296350	-0.3533050

C	1.6119970	0.5557490	0.2882450
C	1.3430250	1.8702830	-1.7120780
C	2.5786030	2.4756290	-1.4747160
C	2.8400450	1.1620070	0.5287270
H	1.2583990	-0.2170140	0.9660850
H	0.7577440	2.1387950	-2.5854340
H	2.9519030	3.2216720	-2.1706330
H	3.4233830	0.8673970	1.3972930
H	4.2927610	2.6000040	-0.1708620
C	1.3200850	-2.0413060	-1.2730880
C	4.0019200	-2.4691840	-0.5975740
C	1.6548880	-2.6514290	-0.0617690
C	2.3376690	-1.6606950	-2.1552080
C	3.6719120	-1.8655570	-1.8147090
C	2.9905000	-2.8698730	0.2758230
H	0.8619200	-2.9513730	0.6219030
H	2.0693850	-1.1940700	-3.0994550
H	4.4586980	-1.5563990	-2.4970790
H	3.2409180	-3.3506360	1.2172740
H	5.0435060	-2.6317080	-0.3358350

(*Z*)- Benzaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]$^{(pyr)}_{(Z)B\text{-}(re)B}$**)

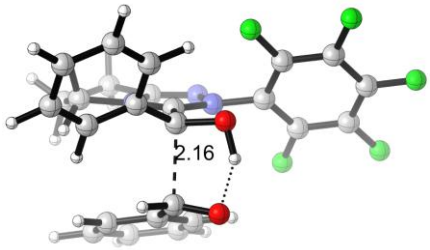


XYZ Coordinates

53

C	2.0503600	-2.9955130	2.4183860
H	2.5548520	-2.6758240	3.3362850
H	1.8194190	-4.0578570	2.4951330
C	2.8734770	-2.6301370	1.1585530
H	3.9477460	-2.7138980	1.3233580
H	2.5906860	-3.2924020	0.3358900
C	2.4691980	-1.1832240	0.8090960
H	3.0830010	-0.4445800	1.3303400
H	2.4699210	-0.9647400	-0.2591620
C	0.8320850	-2.1593890	2.2093430
N	1.0978960	-1.1373130	1.3369680
N	-0.4011890	-2.1506990	2.6023160
C	-0.0373910	-0.4281760	1.1423330
N	-0.9414050	-1.0660190	1.9324800
C	-0.3249440	0.5625980	0.1235130
O	-1.6536110	0.9202900	0.0713060
C	-0.4595170	-0.8166440	-1.4031010
H	0.3255650	-1.5190920	-1.0760760
O	-1.6902200	-1.1484120	-1.2499350
H	-2.0638840	0.1699630	-0.4797250
C	-2.2702880	-0.6983140	2.2267580
C	-4.8899860	0.0017510	2.8612510
C	-3.2998140	-1.6243880	2.0950120
C	-2.5702650	0.5799110	2.6869070
C	-3.8721760	0.9371140	2.9930790
C	-4.6048260	-1.2809020	2.4172930
F	-3.0484860	-2.8500040	1.6445930
F	-5.5849870	-2.1750950	2.2916050
F	-6.1403470	0.3370580	3.1647250
F	-4.1505360	2.1661850	3.4259340
F	-1.5978200	1.4747880	2.8366460
C	0.6221990	1.6985330	-0.0349730
C	2.3657630	3.8933340	-0.3667660
C	0.4133980	2.6384190	-1.0589780
C	1.6880770	1.9177590	0.8498880
C	2.5594970	2.9931680	0.6783980
C	1.2765170	3.7173720	-1.2235520
H	-0.4346930	2.5195890	-1.7255770
H	1.8208410	1.2767330	1.7160500
H	3.3735840	3.1377350	1.3828470
H	1.0965580	4.4271470	-2.0261150
H	3.0394680	4.7345650	-0.4991770
C	-0.0712580	-0.0328950	-2.6180210
C	0.6209460	1.4629320	-4.8826040
C	-1.0661190	0.5328300	-3.4215540
C	1.2711020	0.1410370	-2.9679160
C	1.6179590	0.8843870	-4.0943870
C	-0.7220560	1.2812700	-4.5460510
H	-2.1065300	0.3753130	-3.1519610
H	2.0503520	-0.3018350	-2.3508490
H	2.6638840	1.0161680	-4.3563510
H	-1.5006780	1.7207000	-5.1632960
H	0.8892710	2.0457710	-5.7589080

(*Z*)- Benzaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$^{(pyr)}_{(Z)B\text{-}(si)B}$**)

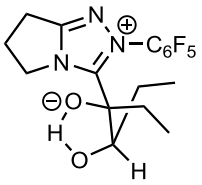


XYZ Coordinates

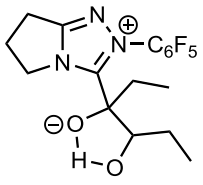
53

C	-0.6760800	1.8855690	2.9949570
H	-1.0931150	1.3858870	3.8703960
C	0.8701200	1.8860940	2.9757560
H	1.2879170	2.8036550	3.3906210
H	1.2385990	1.0403510	3.5609090
C	1.2970830	1.6966260	1.5038160
H	1.4780400	2.6396440	0.9809560
H	2.1689750	1.0528810	1.4122990
C	-0.9965930	1.1648950	1.7289960
N	0.1102450	1.0471380	0.9275600
N	-2.0561660	0.6750220	1.1748550
C	-0.2600180	0.4607620	-0.2388310
N	-1.5985000	0.2266870	-0.0555620
C	-2.5792890	-0.1801210	-0.9858760
C	-4.6022000	-0.9263750	-2.7612200
C	-3.4434580	-1.2269750	-0.6819120
C	-2.7756920	0.5153680	-2.1772040
C	-3.7628770	0.1365030	-3.0699940
C	-4.4485530	-1.6029400	-1.5620920
F	-2.0167370	1.5686730	-2.4647560
F	-3.9274050	0.8000150	-4.2148580
F	-5.5605780	-1.2844230	-3.6113160
F	-5.2659700	-2.6099740	-1.2539540
F	-3.3265360	-1.8912660	0.4662460
C	0.5342310	0.0088260	-1.3377060
O	-0.2266000	-0.4570620	-2.3835520
C	1.1835120	-1.9549080	-0.7156290
O	0.5072000	-2.6302160	-1.5551950
H	-1.0874570	2.8982290	2.9435300
H	-0.0863430	-1.4659230	-2.3417840
C	1.7340770	0.8065610	-1.7577970
C	3.9167950	2.3320130	-2.6776920
C	2.9622240	0.7793100	-1.0884590
C	1.6277570	1.5902260	-2.9187060
C	2.7048700	2.3467360	-3.3720080
C	4.0413850	1.5429740	-1.5366240
H	3.0936600	0.1425960	-0.2202270
H	0.6884010	1.5946440	-3.4636170
H	2.5993650	2.9489840	-4.2700260
H	4.9850550	1.5031580	-1.0000520
H	4.7584200	2.9205820	-3.0307180
H	2.2354250	-1.7187070	-0.9419340
C	0.8754430	-2.0352140	0.7417450
C	0.2474650	-2.1061190	3.4707020
C	-0.3848640	-2.4688060	1.1657930
C	1.8293360	-1.6662590	1.6960820
C	1.5194530	-1.7057870	3.0550340
C	-0.7022610	-2.4932400	2.5219820
H	-1.1052580	-2.7873550	0.4190920
H	2.8230290	-1.3599590	1.3745650
H	2.2699900	-1.4270090	3.7897460
H	-1.6887620	-2.8180170	2.8412240
H	0.0024200	-2.1294580	4.5287070

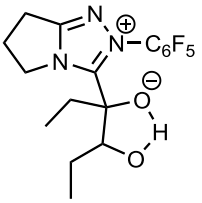
Tetrahedral Intermediates



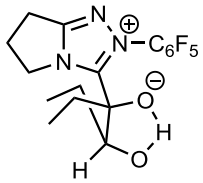
Int. VI$^{(pyr)}_{(E)P\text{-}(re)P}$



Int. VI$^{(pyr)}_{(E)P\text{-}(si)P}$

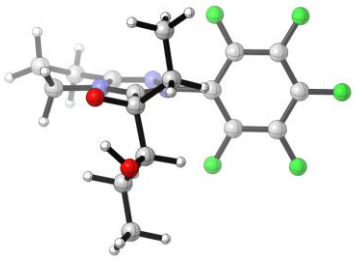


Int. VI$^{(pyr)}_{(Z)P\text{-}(re)P}$



Int. VI$^{(pyr)}_{(Z)P\text{-}(si)P}$

(*E*)-Propionaldehyde BI + *re* Face of Propionaldehyde (**Int. VI$^{(pyr)}_{(E)P\text{-}(re)P}$**)



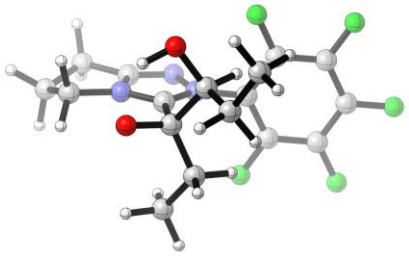
XYZ Coordinates

45

C	-3.1392470	-2.5158180	-1.8923480
H	-3.4196740	-2.0243070	-2.8295310
H	-2.9217020	-3.5636660	-2.0999370
C	-4.2111850	-2.3116220	-0.7924200
C	-3.8308650	-1.0119310	-0.0530040
H	-4.2682480	-0.1195730	-0.5068450
H	-4.0282530	-1.0094810	1.0147810
C	-1.9736160	-1.7990600	-1.2959710
N	-2.3732530	-0.9718020	-0.2816440
N	-0.6901920	-1.7317940	-1.4843600
C	-1.3070740	-0.3312080	0.1992290
N	-0.2851360	-0.8101090	-0.5445880
C	1.0981650	-0.5194180	-0.4466020
C	3.8192510	0.0207260	-0.2380240
C	1.9496610	-1.4163930	0.1936430
C	1.6342660	0.6304920	-1.0169100
C	2.9876120	0.9117670	-0.9019430
C	3.3039230	-1.1476430	0.3088770
F	0.8527620	1.4790980	-1.6767800
F	3.4941310	2.0173820	-1.4405570
F	5.1154920	0.2824370	-0.1321910
F	4.1112610	-2.0013110	0.9319180
F	1.4636230	-2.5404030	0.7099480
C	-1.2433170	2.1553970	0.6432150
C	-1.3664540	0.7238130	1.3171660
O	-2.5641440	0.6318670	1.9317420
O	-1.7681890	3.0347390	1.6167020
H	-2.4163760	2.4391700	2.0691420
H	-5.2182190	-2.2523920	-1.2057090
H	-4.1721200	-3.1482800	-0.0900240
H	-0.1866580	2.4138180	0.4787970
C	-0.1775380	0.5339780	2.2941530
H	0.7861750	0.6531830	1.7838110
H	-0.2634930	1.3697690	2.9972620
C	-0.2303890	-0.7868040	3.0517690
H	0.5726490	-0.8494690	3.7928810
H	-0.1245120	-1.6467810	2.3796880
H	-1.1887390	-0.8813380	3.5694060
C	-2.0226100	2.2976030	-0.6649790
H	-1.6387920	1.5943530	-1.4155850
H	-3.0675210	2.0264450	-0.4623090
C	-1.9440170	3.7149530	-1.2254170
H	-2.5245820	3.8104200	-2.1483660
H	-0.9061520	3.9855370	-1.4529760
H	-2.3298750	4.4378680	-0.5015300

(*E*)-Propionaldehyde BI + *si* Face of Propionaldehyde

(**Int. VI$^{(pyr)}_{(E)P\text{-}(si)P}$**)



XYZ Coordinates

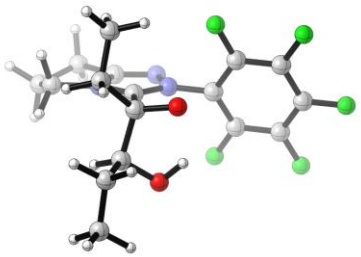
45

C	-3.4908670	-2.6311000	-1.3706000
H	-3.6412050	-2.4985140	-2.4467110
H	-3.4213760	-3.6980150	-1.1564810
C	-4.5790630	-1.9046760	-0.5411400
C	-4.0463850	-0.4808280	-0.2765470
H	-4.3139070	0.2289350	-1.0618800
H	-4.3077310	-0.0632630	0.6912500
C	-2.2659150	-1.8903550	-0.9504350
N	-2.5885000	-0.7064510	-0.3434420
N	-0.9792960	-2.0594460	-1.0039190
C	-1.4657650	-0.0773910	0.0032420
N	-0.4911690	-0.9191010	-0.4036980
C	0.9146660	-0.7962300	-0.2708180
C	3.6867100	-0.6813070	-0.0698490
C	1.5630760	-1.3025040	0.8516240
C	1.6757490	-0.2569120	-1.3040870
C	3.0564950	-0.1865640	-1.2043220
C	2.9433800	-1.2383560	0.9618970
F	1.0781570	0.2096910	-2.3946440
F	3.7786390	0.3393240	-2.1894000
F	5.0081580	-0.6194770	0.0304100
F	3.5570760	-1.7165390	2.0407430
F	0.8569880	-1.8479930	1.8358530
C	-0.5825840	2.2691070	-0.1191910
C	-1.4281760	1.2829130	0.7691670
O	-2.6926180	1.7328390	0.8520580
O	-1.4488860	2.6320140	-1.1791010
H	-2.3248620	2.5596000	-0.7248000
H	-5.5394060	-1.8786180	-1.0565350
H	-4.7110160	-2.4213150	0.4131320
C	-0.7711590	0.9971780	2.1406470
H	0.2847980	0.7155150	2.0201960
H	0.2949410	1.7768580	-0.5591290
H	-0.7865580	1.9465450	2.6848840

C	-1.5268840	-0.0553330	2.9470430
H	-2.5609730	0.2655320	3.1019010
H	-1.0630080	-0.2055240	3.9265820
H	-1.5450360	-1.0290510	2.4422040
C	-0.1052920	3.5006720	0.6477390
H	-0.9661730	3.9529710	1.1565000
H	0.6067410	3.1893960	1.4215380
C	0.5603210	4.5201390	-0.2732750
H	-0.1394590	4.8714460	-1.0361730
H	1.4232700	4.0795600	-0.7870690
H	0.9147550	5.3883210	0.2911180

(*Z*)-Propionaldehyde BI + *re* Face of Propionaldehyde

(**Int. VI$^{(pyr)}_{(Z)P\text{-}(re)P}$**)



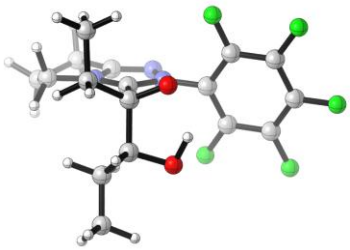
XYZ Coordinates

45

C	2.8763070	-3.2870170	-0.9902030
H	2.9287390	-4.0497580	-0.2066170
H	2.7278140	-3.7820860	-1.9500620
C	4.1119270	-2.3513100	-0.9690600
H	5.0111550	-2.8640560	-0.6280730
H	4.2910590	-1.9650810	-1.9753260
C	3.7495210	-1.1767130	-0.0344640
H	4.0211300	-1.3616740	1.0083690
H	4.1554620	-0.2192810	-0.3606030
C	1.7780230	-2.3306870	-0.6653370
N	2.2809910	-1.1714420	-0.1392190
N	0.4800830	-2.2999490	-0.7083760
C	1.2627550	-0.3631240	0.1751480
N	0.1753920	-1.0659580	-0.1798470
C	-1.1885980	-0.6814970	-0.1189370
C	-3.8772490	0.0106010	-0.0380560
C	-1.8629600	-0.3504270	-1.2854920
C	-1.8784400	-0.6927910	1.0870820
C	-3.2142390	-0.3373260	1.1334010
C	-3.2056130	0.0016940	-1.2501060
F	-1.2607640	-1.0461290	2.2071980
F	-3.8726620	-0.3326410	2.2929410
F	-5.1645930	0.3416790	0.0062920
F	-3.8477810	0.3188360	-2.3745110
F	-1.2256480	-0.3619590	-2.4535970
C	1.7543830	1.9643070	-0.4506260
C	1.2738820	1.0665240	0.7612140
O	0.0213340	1.4152330	1.1066170
O	0.6132670	2.0828560	-1.2798500
H	-0.1064890	2.0304490	-0.6022640
H	2.5458300	1.4658250	-1.0316030
C	2.2893290	1.0772830	1.9264810
H	3.3130390	0.9291890	1.5557470
H	2.2450410	2.0882940	2.3430020
C	1.9620550	0.0663640	3.0213330
H	2.6480400	0.1731480	3.8672090
H	2.0417580	-0.9693410	2.6655820
H	0.9426870	0.2211680	3.3854710
C	2.2543500	3.3369150	-0.0041040
H	3.1821540	3.2165770	0.5677040
H	1.5078480	3.7759930	0.6700230
C	2.5052410	4.2649860	-1.1899660
H	3.2527380	3.8401680	-1.8707290
H	2.8731840	5.2398710	-0.8550780
H	1.5857390	4.4225730	-1.7595640

(*Z*)-Propionaldehyde BI + *si* Face of Propionaldehyde

(**Int. VI$^{(pyr)}_{(Z)P\text{-}(si)P}$**)

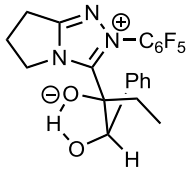


XYZ Coordinates

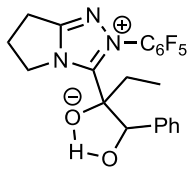
45

C	3.2184660	-1.5733380	-2.5615620
H	3.3407150	-2.6599640	-2.5164980
H	3.1276830	-1.2766130	-3.6066640
C	4.3535870	-0.8346320	-1.8128410
C	3.8743020	-0.6736440	-0.3555480
H	4.1510440	-1.5194840	0.2788880
H	4.2027550	0.2584370	0.1003960
C	2.0304400	-1.1749920	-1.7511930
N	2.4075850	-0.6779670	-0.5300090
N	0.7388640	-1.1803990	-1.8786090
C	1.3036440	-0.3634360	0.1621740
N	0.3014240	-0.6756250	-0.6778850

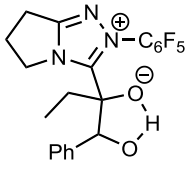
C	-1.0927380	-0.4772300	-0.5026110
C	-3.8214860	-0.0701010	-0.2101670
C	-1.6991850	0.6353800	-1.0682690
C	-1.8661620	-1.4024480	0.1875790
C	-3.2259010	-1.1978750	0.3430770
C	-3.0624860	0.8474040	-0.9197960
F	-1.3078800	-2.4876460	0.7084650
F	-3.9699280	-2.0770720	1.0153480
F	-5.1302650	0.1199350	-0.0697460
F	-3.6424240	1.9185980	-1.4620450
F	-0.9757100	1.5111260	-1.7589410
C	1.1022610	1.8281430	1.3869110
C	1.1059910	0.2504070	1.5657220
O	-0.1036380	-0.1260430	2.0351540
O	-0.2345750	2.1699400	1.1033770
H	-0.6885400	1.3831200	1.5239570
H	5.2994790	-1.3741480	-1.8582550
H	4.4942040	0.1554120	-2.2536420
H	1.3881200	2.2253040	2.3779220
C	2.2838160	-0.1744550	2.4656990
H	3.2363660	0.2129100	2.0815780
H	2.1051150	0.3280720	3.4227180
C	2.3500320	-1.6808300	2.6966490
H	3.1471340	-1.9357000	3.4016910
H	2.5388960	-2.2382150	1.7707420
H	1.3990140	-2.0328050	3.1052540
C	2.0318810	2.4217040	0.3402800
H	3.0551470	2.0762470	0.5380690
H	1.7426620	2.0519990	-0.6531840
C	1.9975530	3.9485950	0.3422220
H	2.6830940	4.3619360	-0.4040270
H	2.2890760	4.3424650	1.3223120
H	0.9903950	4.3113850	0.1183210



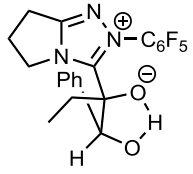
Int. VI$^{(pyr)}_{(E)P\text{-}(re)B}$



Int. VI$^{(pyr)}_{(E)P\text{-}(si)B}$



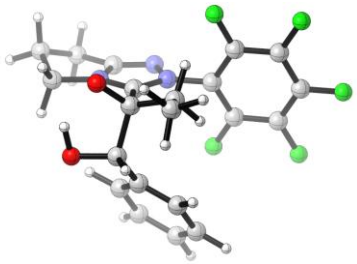
Int. VI$^{(pyr)}_{(Z)P\text{-}(re)B}$



Int. VI$^{(pyr)}_{(Z)P\text{-}(si)B}$

(*E*)-Propionaldehyde BI + *re* Face of Benzaldehyde

(Int. VI$^{(pyr)}_{(E)P\text{-}(re)B}$)



XYZ Coordinates

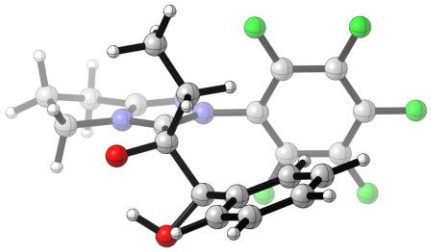
49

C	-3.1153520	-1.6832080	-2.7491280
H	-3.4081790	-0.7875000	-3.3067010
H	-2.9120170	-2.4845190	-3.4595110
C	-4.1630320	-2.0588150	-1.6738260
C	-3.7671900	-1.2792180	-0.4036980
H	-4.2099230	-0.2822300	-0.3560750
H	-3.9438140	-1.8094040	0.5298060
C	-1.9340610	-1.3609950	-1.8958070
N	-2.3122470	-1.1246250	-0.6028200
N	-0.6496730	-1.2420410	-2.0411340
C	-1.2279200	-0.8290650	0.1224990
N	-0.2204290	-0.9114300	-0.7746580
C	1.1714660	-0.7081260	-0.5985150
C	3.9045360	-0.2839250	-0.3131070
C	1.9961480	-1.7247240	-0.1274550
C	1.7405800	0.5012800	-0.9809810
C	3.1001290	0.7254410	-0.8241530
C	3.3559050	-1.5120710	0.0328270
F	0.9799240	1.4462000	-1.5139070
F	3.6374910	1.8900390	-1.1779030
F	5.2074920	-0.0795660	-0.1657060
F	4.1385380	-2.4800310	0.5034970
F	1.4844760	-2.9086160	0.1945210
C	-1.8397440	0.9462830	1.8312420
C	-1.2841200	-0.5431170	1.6516700
O	-2.2014170	-1.3865650	2.1643650
O	-3.2372120	0.8253110	1.7505750
H	-3.3294180	-0.1292120	2.0381620
H	-5.1794760	-1.8179370	-1.9856400
H	-4.1051910	-3.1313850	-1.4715090
H	-1.5457290	1.2364750	2.8501830
C	-1.3275260	1.9998060	0.8825180
C	-0.4218360	4.0480650	-0.8154850
C	-2.0088790	2.2951630	-0.3037480
C	-0.1805580	2.7372750	1.2011680

C	0.2705470	3.7539790	0.3595980
C	-1.5592770	3.3109530	-1.1471450
H	-2.9166690	1.7458230	-0.5409180
H	0.3421280	2.5346770	2.1342860
H	1.1545660	4.3256520	0.6282120
H	-2.1070120	3.5376320	-2.0577260
H	-0.0788560	4.8468880	-1.4665640
C	0.1191900	-0.6753430	2.2824020
H	0.7970330	0.0976500	1.8958860
H	0.5222920	-1.6520340	1.9931440
C	0.0795270	-0.6206260	3.8077350
H	-0.6488370	-1.3403840	4.1889110
H	-0.1913400	0.3701700	4.1841290
H	1.0634230	-0.8699600	4.2165000

(*E*)-Propionaldehyde BI + *si* Face of Benzaldehyde

(**Int. VI$^{(pyr)}_{(E)P\text{-}(si)B}$**)



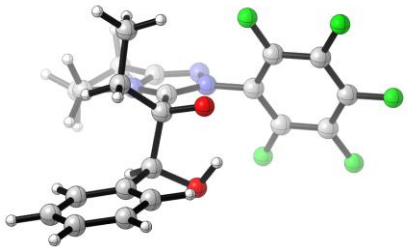
XYZ Coordinates

49

C	-4.7983790	-1.6264800	-0.4005380
H	-5.0323950	-1.7912640	-1.4571620
H	-5.1275900	-2.4954200	0.1695360
C	-5.3836050	-0.2891820	0.1192350
C	-4.3029310	0.7850420	-0.1279450
H	-4.3841300	1.2586110	-1.1078740
H	-4.2347650	1.5513260	0.6392080
C	-3.3341890	-1.3755510	-0.2592380
N	-3.0774080	-0.0382960	-0.1178270
N	-2.2377520	-2.0720080	-0.2437220
C	-1.7607880	0.1393760	-0.0230500
N	-1.2614080	-1.1129330	-0.0905810
C	0.0912510	-1.5341160	-0.0462960
C	2.7217630	-2.4378240	0.0068590
C	0.7375180	-1.7501680	1.1667010
C	0.7683210	-1.8121870	-1.2314510
C	2.0801430	-2.2581980	-1.2122770
C	2.0546520	-2.1829650	1.1978690
F	0.1557560	-1.6356430	-2.3968400
F	2.7246270	-2.5101430	-2.3474940
F	3.9774480	-2.8638940	0.0348380
F	2.6727910	-2.3772540	2.3593350
F	0.0947350	-1.5465630	2.3114330
C	-0.0143280	1.6958230	-1.0319830
C	-1.0749450	1.5108700	0.1828930
O	-2.0160140	2.4656830	0.0511680
O	-0.7243290	2.4337810	-1.9804640
H	-1.4984260	2.7400440	-1.3836940
H	-6.3187090	-0.0303780	-0.3776960
H	-5.5722170	-0.3700490	1.1929140
C	-0.4179270	1.4893530	1.5791580
H	0.4176230	0.7801700	1.6154850
H	0.2632650	0.7205180	-1.4508290
C	1.2618770	2.3796260	-0.5942380
C	3.6129010	3.6211980	0.3060950
C	2.3639570	1.6159780	-0.1958350
C	1.3534300	3.7729860	-0.5486700
C	2.5208380	4.3905570	-0.0985900
C	3.5325570	2.2285770	0.2544440
H	2.3037690	0.5279670	-0.2376990
H	0.5033560	4.3673890	-0.8711690
H	2.5795100	5.4749940	-0.0659410
H	4.3818660	1.6219920	0.5564630
H	4.5226400	4.1026420	0.6530210
H	0.0164840	2.4851040	1.7157470
C	-1.4213720	1.2061570	2.6927280
H	-2.2305740	1.9418080	2.6644880
H	-0.9395800	1.2634040	3.6732870
H	-1.8640870	0.2063380	2.6045230

(*Z*)-Propionaldehyde BI + *re* Face of Benzaldehyde

(**Int. VI$^{(pyr)}_{(Z)P\text{-}(re)B}$**)



XYZ Coordinates

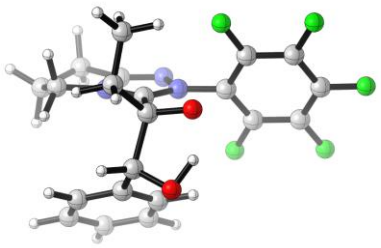
49

C	-0.4148660	4.6607480	-0.4927290
H	-0.2054040	5.2534830	0.4032900
H	0.0411910	5.1535460	-1.3514960
C	-1.9314700	4.3974700	-0.6716100
H	-2.5411710	5.2170400	-0.2914860

H	-2.1518850	4.2613530	-1.7331410
C	-2.2329060	3.0817060	0.0780310
H	-2.4979760	3.2380160	1.1271730
H	-2.9887400	2.4658610	-0.4098990
C	0.0990200	3.2738850	-0.2943480
N	-0.9201770	2.4162680	0.0226290
N	1.2394000	2.6528650	-0.3240930
C	-0.4108340	1.1944070	0.2117070
N	0.9046600	1.3575240	-0.0035620
C	1.9370860	0.3842750	-0.0083880
C	4.0171850	-1.4531830	-0.0636290
C	2.4903800	-0.0125940	-1.2175230
C	2.4477440	-0.1289810	1.1779980
C	3.4783800	-1.0514770	1.1532030
C	3.5293550	-0.9321340	-1.2517690
F	1.9549680	0.2647920	2.3451200
F	3.9635990	-1.5550440	2.2882340
F	5.0150750	-2.3319010	-0.0851740
F	4.0613950	-1.3059390	-2.4148440
F	2.0255600	0.4877340	-2.3599090
C	-1.1192120	-0.1348460	0.5436200
O	-0.2016440	-1.0672350	0.8491330
C	-2.1519230	0.1447410	1.6528040
H	-2.6172130	-0.8218640	1.8705390
H	-2.9505090	0.8031970	1.2850930
C	-1.5248020	0.7119160	2.9221050
H	-2.2697080	0.8000830	3.7185380
H	-1.0984890	1.7105390	2.7619950
H	-0.7240110	0.0551330	3.2725280
C	-1.8125130	-0.5445380	-0.8474520
H	-2.1588160	0.3486670	-1.3866480
C	-2.9939530	-1.4642890	-0.6394910
C	-5.1993540	-3.1313160	-0.1487920
C	-2.8081510	-2.8229040	-0.3634580
C	-4.2954800	-0.9559160	-0.6815460
C	-5.3937070	-1.7801200	-0.4364000
C	-3.9034890	-3.6501410	-0.1173190
H	-1.8002450	-3.2266770	-0.3405160
H	-4.4513510	0.0967750	-0.9110820
H	-6.3988790	-1.3699810	-0.4763570
H	-3.7452670	-4.7027150	0.1003030
H	-6.0512710	-3.7772940	0.0427490
O	-0.7715680	-1.1567550	-1.5661070
H	-0.1960680	-1.4568700	-0.8015250

(*Z*)-Propionaldehyde BI + *si* Face of Benzaldehyde

(**Int. VI$^{(pyr)}_{(Z)P\text{-}(si)B}$**)

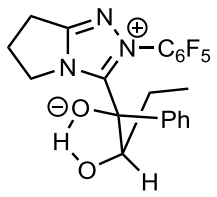


XYZ Coordinates

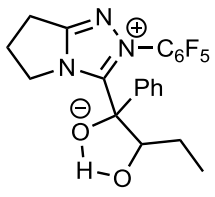
49

C	2.7121930	-0.4423220	-3.0999410
H	2.8671020	0.4823900	-3.6561930
C	3.8822610	-0.7817610	-2.1441800
H	4.6379850	-1.4072570	-2.6193390
H	4.3539680	0.1449870	-1.8060880
C	3.2506860	-1.4924410	-0.9303090
H	3.1633630	-2.5740200	-1.0674130
H	3.7525680	-1.2737350	0.0110700
C	1.5708370	-0.3505040	-2.1429960
N	1.8931210	-0.9188190	-0.9396010
N	0.3432850	0.0727480	-2.1468500
C	0.8295830	-0.8461090	-0.1318270
N	-0.1097210	-0.2489410	-0.8883450
C	-1.4703630	0.0215600	-0.5908830
C	-4.1610870	0.5566040	-0.1242310
C	-1.9301460	1.3304240	-0.5443360
C	-2.3816130	-1.0204530	-0.4465260
C	-3.7167860	-0.7586280	-0.1980190
C	-3.2704650	1.6023830	-0.3028740
F	-1.9819430	-2.2793290	-0.5694830
F	-4.5843500	-1.7599780	-0.0493020
F	-5.4472060	0.8092400	0.0993350
F	-3.7007810	2.8629350	-0.2537780
F	-1.0922520	2.3484560	-0.7309420
C	0.6826080	-1.2862510	1.3214770
O	-0.6150090	-1.2330380	1.6818230
C	1.5085880	-0.2398700	2.2971010
O	0.5487990	0.1633150	3.2180090
H	2.5173780	-1.2514300	-3.8109830
H	-0.2692810	-0.3288890	2.8157040
H	2.3065970	-0.8225940	2.7811460
C	2.1382020	0.9325490	1.5817780
C	3.2579400	3.0566370	0.1254160
C	3.5126460	0.9777690	1.3342730
C	1.3342850	1.9802010	1.1184310

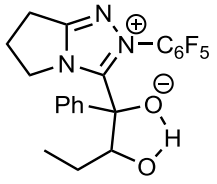
C	1.8856630	3.0309790	0.3885850
C	4.0718680	2.0319360	0.6084240
H	4.1525770	0.1873680	1.7227050
H	0.2712070	1.9623040	1.3450500
H	1.2466250	3.8326890	0.0286820
H	5.1432060	2.0567960	0.4284200
H	3.6909740	3.8778210	-0.4384350
C	1.3198550	-2.6836150	1.4775310
H	1.2184670	-2.9243350	2.5423800
H	2.3961570	-2.6374760	1.2675150
C	0.6461140	-3.7578300	0.6321450
H	1.0949900	-4.7387750	0.8158070
H	0.7396680	-3.5485350	-0.4416700
H	-0.4190940	-3.8139260	0.8698720



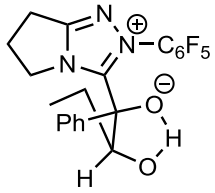
Int. VI$^{(pyr)}_{(E)B\text{-}(re)P}$



Int. VI$^{(pyr)}_{(E)B\text{-}(si)P}$



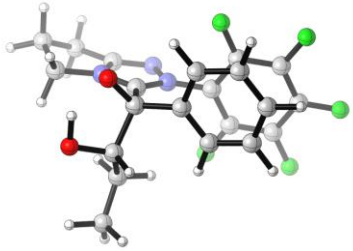
Int. VI$^{(pyr)}_{(Z)B\text{-}(re)P}$



Int. VI$^{(pyr)}_{(Z)B\text{-}(si)P}$

(*E*)-Benzaldehyde BI + *re* Face of Propionaldehyde

(Int. VI$^{(pyr)}_{(E)B\text{-}(re)P}$)



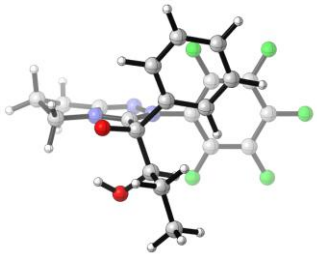
XYZ Coordinates

49

C	3.7405110	-2.9109650	-0.4215850
H	4.1029160	-3.1322130	0.5876690
H	3.6340940	-3.8485120	-0.9676810
C	4.6379420	-1.8734970	-1.1414450
C	4.0655630	-0.4856400	-0.7839120
H	4.4940170	-0.0613180	0.1270560
H	4.1100130	0.2472150	-1.5868110
C	2.4551820	-2.1597930	-0.3183420
N	2.6548920	-0.8221410	-0.5145810
N	1.2060190	-2.4190700	-0.0727110
C	1.4907770	-0.1828040	-0.3726110
N	0.6144210	-1.1752020	-0.1084450
C	-0.7893620	-1.1076890	0.0756150
C	-3.5396020	-0.9660390	0.4380440
C	-1.6399390	-1.0328310	-1.0226000
C	-1.3331680	-1.1528800	1.3537840
C	-2.7044390	-1.0801180	1.5407460
C	-3.0107920	-0.9408200	-0.8457070
F	-0.5344370	-1.2398880	2.4142260
F	-3.2211370	-1.1034450	2.7673640
F	-4.8525800	-0.8713670	0.6114390
F	-3.8204990	-0.8352960	-1.8956310
F	-1.1394670	-1.0388910	-2.2526460
C	2.0048360	2.0123030	0.8002090
C	1.3608530	1.3537100	-0.5200880
O	2.1203870	1.6993400	-1.5824810
O	3.3162790	2.3504370	0.4341420
H	3.2202230	2.2795950	-0.5714080
H	5.6836190	-1.9589300	-0.8458350
H	4.5684490	-2.0233450	-2.2217840
H	1.4223360	2.9284340	0.9933840
C	2.0173710	1.1560650	2.0624670
H	1.0282690	0.7148430	2.2344580
H	2.7170050	0.3229240	1.9107940
C	2.4417670	1.9613560	3.2885390
H	2.4833610	1.3328940	4.1834450
H	1.7334360	2.7749660	3.4809440
H	3.4304320	2.4043890	3.1361090
C	-0.1183370	1.7483220	-0.6677140
C	-2.8120170	2.4399570	-1.0735210
C	-0.9694130	1.9730960	0.4216530
C	-0.6280680	1.8981300	-1.9590840
C	-1.9669250	2.2353720	-2.1637290
C	-2.3071100	2.3126630	0.2219230
H	-0.5991970	1.8773230	1.4393050
H	0.0476210	1.7469880	-2.7951430
H	-2.3495450	2.3401430	-3.1751320
H	-2.9536690	2.4820620	1.0789330
H	-3.8547470	2.7017960	-1.2300400

(*E*)-Benzaldehyde BI + *si* Face of Propionaldehyde

(**Int. VI$^{(pyr)}_{(E)B\text{-}(si)P}$**)



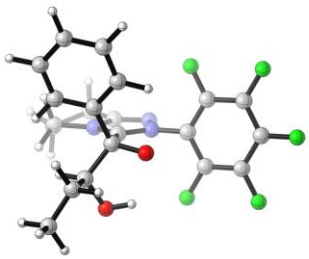
XYZ Coordinates

49

C	3.7557590	-3.0304060	-0.3817580
H	4.0607520	-3.3981810	0.6033120
H	3.6624500	-3.8802110	-1.0582710
C	4.7068900	-1.9261020	-0.9038760
C	4.1431880	-0.5891450	-0.3806000
H	4.5250050	-0.3269330	0.6090290
H	4.2595710	0.2558960	-1.0517640
C	2.4808260	-2.2684810	-0.2408280
N	2.7092550	-0.9187680	-0.2427420
N	1.2184490	-2.5355140	-0.0907790
C	1.5477690	-0.2838230	-0.0736770
N	0.6488320	-1.2871170	0.0127700
C	-0.7557240	-1.2050460	0.1714240
C	-3.5132230	-1.0554390	0.4761950
C	-1.5860550	-1.1682770	-0.9435290
C	-1.3228130	-1.1926700	1.4416860
C	-2.6976340	-1.1065810	1.5995350
C	-2.9609540	-1.0875270	-0.7975070
F	-0.5466560	-1.2608760	2.5186350
F	-3.2384870	-1.0926420	2.8150540
F	-4.8296490	-0.9714030	0.6221070
F	-3.7502600	-1.0151650	-1.8659070
F	-1.0596530	-1.1604450	-2.1619010
C	1.0919740	1.6137400	1.4874740
C	1.4174660	1.2855060	-0.0113970
O	2.6172950	1.7825860	-0.3313610
O	2.2261030	1.1680970	2.2189120
H	2.9655220	1.4418170	1.6385660
H	5.7353350	-2.0787300	-0.5758900
H	4.6880490	-1.9198990	-1.9969490
H	0.2290850	1.0466470	1.8634560
C	0.8681720	3.1076860	1.7142740
H	1.7644620	3.6327300	1.3642260
H	0.0317470	3.4589940	1.1013850
C	0.5989070	3.4221200	3.1838150
H	1.4322800	3.0950010	3.8119750
H	-0.3068860	2.9133650	3.5348270
H	0.4581210	4.4964540	3.3376920
C	0.2842980	1.6717950	-0.9889930
C	-1.6647250	2.3470420	-2.8995160
C	-1.0571980	1.8137200	-0.6192860
C	0.6371180	1.8881030	-2.3244640
C	-0.3269730	2.2163690	-3.2757850
C	-2.0253160	2.1531930	-1.5665630
H	-1.3660190	1.6616980	0.4133520
H	1.6863320	1.8090930	-2.5946880
H	-0.0353810	2.3762910	-4.3101160
H	-3.0623080	2.2642410	-1.2601640
H	-2.4192150	2.6061780	-3.6367700

(*Z*)-Benzaldehyde BI + *re* Face of Propionaldehyde

(**Int. VI$^{(pyr)}_{(Z)B\text{-}(re)P}$**)



XYZ Coordinates

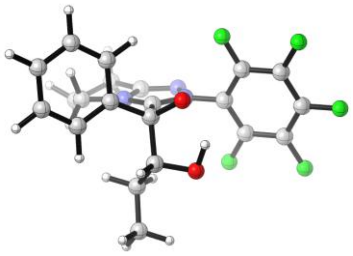
49

C	1.8048190	3.5697570	-2.0440520
H	1.9044410	3.3168040	-3.1044660
H	1.4095580	4.5823130	-1.9614250
C	3.1322720	3.3654770	-1.2767660
C	3.1224820	1.9003450	-0.7980460
H	3.5240250	1.2095440	-1.5434460
H	3.6254720	1.7535770	0.1560420
C	0.9297740	2.5597410	-1.3811290
N	1.6724930	1.6492660	-0.6736720
N	-0.3374810	2.2896130	-1.3089770
C	0.8406470	0.7503600	-0.1310920
N	-0.3769560	1.1627770	-0.5225860
C	-1.6503780	0.5820370	-0.2785870
C	-4.2005820	-0.4533670	0.1046360
C	-2.3321950	0.8178380	0.9083500
C	-2.2669860	-0.1543940	-1.2781090
C	-3.5370460	-0.6819140	-1.0902560
C	-3.5971680	0.2961360	1.1081470
F	-1.6297700	-0.3837360	-2.4266960
F	-4.1198330	-1.3966580	-2.0529400

F -5.4212600 -0.9478470 0.2929260
F -4.2442110 0.5109550 2.2540660
F -1.7585480 1.5288040 1.8744530
C 1.9642070 -0.0786570 1.9485250
C 1.0764440 -0.5248080 0.7364430
O -0.1136940 -0.9462370 1.1804380
O 1.1513100 0.8072360 2.7017490
H 0.2638710 0.4005710 2.6293730
C 1.7963390 -1.5073430 -0.2163090
C 2.9767860 -3.3227620 -2.0024750
C 3.1690690 -1.4514980 -0.4828260
C 1.0248410 -2.4853440 -0.8467920
C 1.6087210 -3.3874810 -1.7364350
C 3.7572360 -2.3549840 -1.3687650
H 3.7963870 -0.7178690 0.0183140
H -0.0343110 -2.5281870 -0.6098810
H 0.9967940 -4.1444840 -2.2190820
H 4.8260300 -2.3075920 -1.5578200
H 3.4333890 -4.0268350 -2.6920310
H 4.0055960 3.5727410 -1.8950900
H 3.1543810 4.0258560 -0.4064620
C 2.4048090 -1.2737220 2.7906300
H 3.0315850 -1.9358540 2.1829510
H 1.5071290 -1.8400090 3.0649720
C 3.1695320 -0.8424960 4.0393250
H 3.4707430 -1.7104360 4.6339650
H 2.5533780 -0.1955060 4.6698890
H 4.0774360 -0.2877110 3.7738840
H 2.8476550 0.4922880 1.6366870

(*Z*)-Benzaldehyde BI + *si* Face of Propionaldehyde

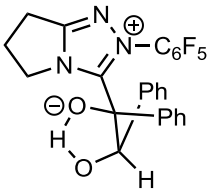
(**Int. VI$^{(pyr)}_{(Z)B\text{-}(si)P}$**)



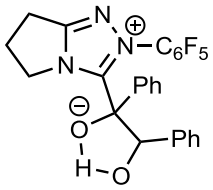
XYZ Coordinates

49

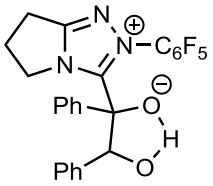
C -2.0196060 -2.2327740 -3.1078990
H -2.1839520 -1.6277770 -4.0054160
H -1.6679650 -3.2189190 -3.4119370
C -3.2783680 -2.2819570 -2.2070590
H -4.2017440 -2.2294950 -2.7838010
H -3.2775570 -3.2128000 -1.6344160
C -3.1607010 -1.0909080 -1.2331740
H -3.6052990 -0.1709210 -1.6218120
H -3.5563150 -1.2998140 -0.2407930
C -1.0501160 -1.5318460 -2.2162280
N -1.6966710 -0.9093480 -1.1807700
N 0.2303720 -1.3190310 -2.1655430
C -0.7910370 -0.2607950 -0.4410280
N 0.3751470 -0.5242820 -1.0535170
C 1.6808110 -0.1217950 -0.6726520
C 4.2426570 0.6333690 0.0724490
C 2.4991700 -1.0078910 0.0133300
C 2.1601450 1.1391110 -1.0054810
C 3.4351590 1.5227430 -0.6270410
C 3.7803270 -0.6337210 0.3924930
F 1.4016920 1.9863050 -1.6883360
F 3.8970100 2.7350590 -0.9341850
F 5.4719240 0.9974160 0.4255210
F 4.5655670 -1.4848400 1.0523830
F 2.0579700 -2.2245080 0.3154070
C -0.7350660 -0.3798930 2.0753720
C -0.9470120 0.5941280 0.8382620
O 0.0329810 1.5237450 0.8539880
O 0.6528890 -0.3637040 2.3158580
H 0.8768420 0.5210830 1.9019890
H -1.2597600 0.0950150 2.9211680
C -1.2151930 -1.8169300 1.9201430
H -2.2582610 -1.8243080 1.5789690
H -0.6148600 -2.3056270 1.1406570
C -1.0910560 -2.6025800 3.2234500
H -1.6917890 -2.1405610 4.0150610
H -0.0505190 -2.6255700 3.5595960
H -1.4326760 -3.6347780 3.1002600
C -2.3593830 1.2048430 0.7765300
C -4.8711760 2.4395490 0.5098900
C -2.5584120 2.2330580 -0.1536470
C -3.4324190 0.8111840 1.5793720
C -4.6806820 1.4275960 1.4482590
C -3.8014430 2.8440500 -0.2928670
H -1.7153390 2.5564080 -0.7591320
H -3.3154660 0.0223730 2.3165270
H -5.5032930 1.1141510 2.0847880
H -3.9360330 3.6377310 -1.0221860
H -5.8419670 2.9159910 0.4085760



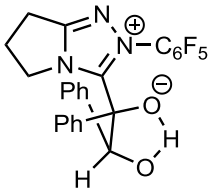
Int. VI$^{(pyr)}_{(E)B\text{-}(re)B}$



Int. VI$^{(pyr)}_{(E)B\text{-}(si)B}$



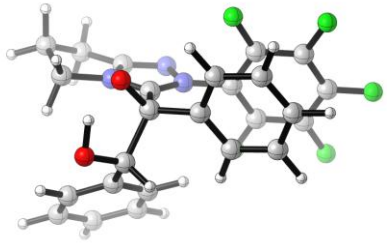
Int. VI$^{(pyr)}_{(Z)B\text{-}(re)B}$



Int. VI$^{(pyr)}_{(Z)B\text{-}(si)B}$

(*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde

(**Int. VI$^{(pyr)}_{(E)B\text{-}(re)B}$**)



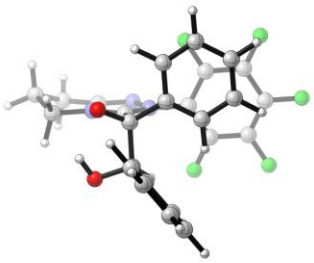
XYZ Coordinates

53

C	3.2011940	0.8995020	3.0130000
H	2.9899790	1.1630200	4.0494110
C	1.9607230	0.6756720	2.2155390
N	2.1099130	-0.3890700	1.3735900
N	0.7842610	1.2128790	2.0941520
C	0.9938770	-0.5334880	0.6547130
N	0.1867820	0.4446130	1.1181740
C	-1.1730740	0.7107290	0.8192690
C	-3.8423220	1.2314570	0.2420420
C	-2.1746740	-0.1260770	1.3026300
C	-1.5287610	1.8424630	0.0938200
C	-2.8579300	2.1028350	-0.2021940
C	-3.5039560	0.1148220	0.9956630
F	-0.5930410	2.6830520	-0.3401960
F	-3.1903960	3.1784140	-0.9126870
F	-5.1152580	1.4644260	-0.0546520
F	-4.4567220	-0.7043080	1.4322090
F	-1.8602310	-1.1696120	2.0625500
C	0.8327910	-1.6482720	-0.3913320
O	1.2939970	-2.7722400	0.1983070
C	1.8355150	-1.3281150	-1.6735040
O	2.7202650	-2.3973340	-1.6682390
H	3.7759280	1.7098300	2.5530170
H	2.3507780	-2.9037540	-0.8451660
C	-0.6240580	-1.7641610	-0.8740670
C	-3.3161280	-2.0516890	-1.6348930
C	-1.1993070	-0.8967990	-1.8115650
C	-1.4072270	-2.7925490	-0.3472630
C	-2.7450050	-2.9351150	-0.7196040
C	-2.5356570	-1.0328660	-2.1842500
H	-0.6118600	-0.1018240	-2.2629930
H	-0.9480590	-3.4731190	0.3623060
H	-3.3407650	-3.7370010	-0.2924350
H	-2.9636870	-0.3457710	-2.9091310
H	-4.3579590	-2.1581610	-1.9238420
H	1.2023190	-1.3570330	-2.5703770
C	3.9109060	-0.4687210	2.8558480
C	2.5599240	0.0096230	-1.6605240
C	3.9090050	2.4825710	-1.6512510
C	3.9559120	0.0621680	-1.7167080
C	1.8511080	1.2176630	-1.6260230
C	2.5138850	2.4429770	-1.6114290
C	4.6251110	1.2876940	-1.7109790
H	4.5099160	-0.8699620	-1.7618970
H	0.7655330	1.2063860	-1.6008150
H	1.9400460	3.3647770	-1.5724260
H	5.7106390	1.3068570	-1.7557390
H	4.4302250	3.4353390	-1.6432840
H	4.9963600	-0.3695200	2.8602810
H	3.6177820	-1.1249230	3.6787800
C	3.4096700	-1.0679230	1.5225350
H	3.2455060	-2.1433310	1.5382820
H	4.0382170	-0.7983190	0.6722110

(*E*)-Benzaldehyde BI + *si* Face of Benzaldehyde

(**Int. VI$^{(pyr)}_{(E)B\text{-}(si)B}$**)



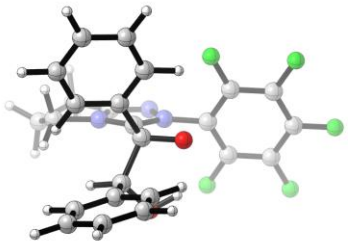
XYZ Coordinates

53

C	0.8410310	5.0608540	-0.6554420
H	1.1255380	5.2565340	-1.6943390
H	0.1202750	5.8163700	-0.3416300
C	2.0772210	4.9633550	0.2723400
C	2.5112740	3.4834640	0.2513950
H	3.2026320	3.2578870	-0.5640240
H	2.9034280	3.1031640	1.1905920
C	0.2937690	3.6769290	-0.5497670
N	1.2287030	2.8150170	-0.0450340
N	-0.8241390	3.0659820	-0.8054000
C	0.6995690	1.5916620	0.0188310
N	-0.5540700	1.7639210	-0.4503570
C	-1.6061250	0.8192510	-0.5337740
C	-3.6750850	-1.0267400	-0.6775100
C	-2.5269430	0.7134310	0.5046400
C	-1.7492800	0.0122360	-1.6546160
C	-2.7773680	-0.9145800	-1.7301880
C	-3.5531250	-0.2144140	0.4427550
F	-0.8771170	0.1007480	-2.6554190
F	-2.9017390	-1.6991220	-2.7982010
F	-4.6520290	-1.9236750	-0.7363790
F	-4.4163790	-0.3368740	1.4477030
F	-2.4150850	1.4967970	1.5717110
C	2.1448990	-0.2936320	-0.7315480
C	1.4752960	0.3341700	0.5585720
O	2.4283420	0.7952340	1.3812260
O	3.1819840	0.6136270	-1.0673030
H	3.4730250	0.9119990	-0.1740910
H	2.8870510	5.6183480	-0.0494070
H	1.7889310	5.2389690	1.2900270
H	1.4421760	-0.3229340	-1.5738330
C	0.4448440	-0.5907470	1.2325830
C	-1.4835090	-2.1313480	2.5755740
C	-0.1718310	-1.6733800	0.5949560
C	0.0955860	-0.3016950	2.5537310
C	-0.8676410	-1.0583630	3.2207530
C	-1.1262880	-2.4410610	1.2621960
H	0.0789630	-1.9245280	-0.4320720
H	0.5963250	0.5247130	3.0498490
H	-1.1346580	-0.8125000	4.2447370
H	-1.5937060	-3.2802260	0.7536500
H	-2.2324890	-2.7242690	3.0927860
C	2.7086400	-1.6880680	-0.5240530
C	3.8045260	-4.2579150	-0.2399390
C	2.5174050	-2.6586530	-1.5114920
C	3.4624090	-2.0156500	0.6104760
C	4.0024600	-3.2932280	0.7505110
C	3.0605330	-3.9372370	-1.3747440
H	1.9348270	-2.4105300	-2.3969140
H	3.6064740	-1.2617480	1.3791140
H	4.5803490	-3.5386550	1.6371580
H	2.9032420	-4.6793110	-2.1523090
H	4.2290850	-5.2513110	-0.1273160

(*Z*)- Benzaldehyde BI + *re* Face of Benzaldehyde

(**Int. VI$^{(pyr)}_{(Z)B\text{-}(re)B}$**)



XYZ Coordinates

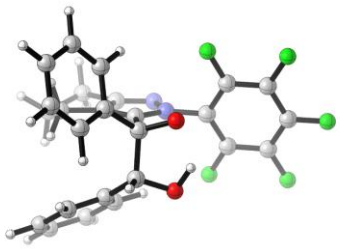
53

C	0.1504700	4.7282070	-0.6138140
H	0.2331950	5.2539910	0.3426210
H	0.7601400	5.2490990	-1.3524400
C	-1.3235300	4.5520840	-1.0513930
H	-1.9557260	5.3749610	-0.7179230
H	-1.3743230	4.4917040	-2.1412820
C	-1.7918610	3.2113840	-0.4491500
H	-2.2024410	3.3157870	0.5578890
H	-2.4962280	2.6770800	-1.0847670
C	0.5700780	3.3082440	-0.4321670
N	-0.5161730	2.4764600	-0.3549210
N	1.6783930	2.6434700	-0.3110290
C	-0.0828560	1.2237720	-0.1674270
N	1.2556050	1.3464080	-0.1465360
C	2.2594080	0.3502700	-0.0105340
C	4.3339840	-1.4784140	0.2499680
C	3.0074440	-0.0241520	-1.1168270
C	2.5760520	-0.1777860	1.2341950
C	3.6000380	-1.0979450	1.3676270
C	4.0404640	-0.9428580	-0.9942180
F	1.8796210	0.1862980	2.3063680
F	3.8922960	-1.6181400	2.5595910
F	5.3244720	-2.3570430	0.3789220
F	4.7506670	-1.3052770	-2.0623510
F	2.7238790	0.4839060	-2.3149960
C	-1.5880840	-0.3332780	-1.4091960
C	-0.8326050	-0.1336310	-0.0256040

O	0.0873680	-1.0955750	0.1185980
O	-0.5641560	-0.6800800	-2.3202400
H	0.0715330	-1.1547010	-1.7335600
C	-1.7915490	0.0190040	1.1727060
C	-3.4361230	0.2316750	3.4385880
C	-3.0461480	0.6314140	1.0859220
C	-1.3748540	-0.4941940	2.4032100
C	-2.1887620	-0.3868220	3.5305290
C	-3.8654730	0.7356250	2.2105400
H	-3.4081080	1.0100690	0.1341960
H	-0.4113470	-0.9916220	2.4488630
H	-1.8510640	-0.7918690	4.4803510
H	-4.8430170	1.2014070	2.1228880
H	-4.0745720	0.3087980	4.3138960
H	-2.0497350	0.5985110	-1.7598160
C	-2.6609520	-1.4014120	-1.3376420
C	-4.6630320	-3.3673710	-1.2303070
C	-2.3568210	-2.7017870	-0.9148290
C	-3.9723630	-1.1048560	-1.7159870
C	-4.9712620	-2.0786970	-1.6626250
C	-3.3523280	-3.6752800	-0.8583680
H	-1.3383000	-2.9324080	-0.6166700
H	-4.2171320	-0.0990390	-2.0526440
H	-5.9862170	-1.8303300	-1.9599180
H	-3.1050000	-4.6786670	-0.5229580
H	-5.4365560	-4.1287700	-1.1851770

(*Z*)- Benzaldehyde BI + *si* Face of Benzaldehyde

(**Int. VI$^{(pyr)}_{(Z)B\text{-}(si)B}$**)

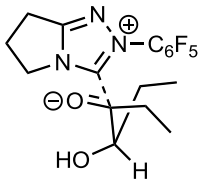


XYZ Coordinates

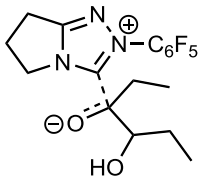
53

C	1.7488850	-1.2985690	3.4671400
H	1.7261600	-0.6040330	4.3130750
H	1.5484080	-2.3046250	3.8363980
C	3.0704130	-1.1925710	2.6648530
H	3.9176020	-0.9267700	3.2971210
H	3.2791630	-2.1513360	2.1838070
C	2.8312230	-0.1243270	1.5754210
H	3.0882590	0.8862180	1.9033830
H	3.3246930	-0.3433650	0.6280120
C	0.7537150	-0.8585180	2.4465630
N	1.3684430	-0.2027780	1.4152430
N	-0.5326300	-0.9131590	2.2655940
C	0.4386870	0.1810450	0.5363640
N	-0.7130650	-0.2570130	1.0720360
C	-2.0342240	-0.1267320	0.5713620
C	-4.6381300	0.1001370	-0.3601910
C	-2.6740010	-1.2223230	0.0097800
C	-2.7163770	1.0783530	0.6892140
C	-4.0114260	1.1984600	0.2173170
C	-3.9748890	-1.1129830	-0.4621280
F	-2.1303310	2.1235780	1.2594580
F	-4.6646950	2.3557950	0.3191310
F	-5.8872370	0.2108700	-0.8021850
F	-4.5876180	-2.1672950	-0.9997580
F	-2.0459980	-2.3910130	-0.0803460
C	0.8574200	-0.2646090	-1.9018180
C	0.5745330	0.8981220	-0.8289190
O	-0.6060330	1.4590290	-1.1545970
O	-0.4196390	-0.7955580	-2.1611800
H	-0.9740840	0.0174630	-1.9901810
H	1.2382010	0.2464870	-2.7959860
C	1.6990890	1.9359840	-0.6872540
C	3.5841080	4.0091260	-0.3821470
C	1.6546650	2.7984260	0.4181000
C	2.6880460	2.1502580	-1.6503050
C	3.6267440	3.1741490	-1.4953690
C	2.5847210	3.8219330	0.5754460
H	0.8716390	2.6716240	1.1640960
H	2.7373800	1.5394020	-2.5440070
H	4.3882540	3.3186610	-2.2562160
H	2.5286020	4.4750440	1.4415320
H	4.3149220	4.8035340	-0.2642600
C	1.8161640	-1.3639990	-1.5128190
C	3.6102160	-3.3793860	-0.7181120
C	3.1591240	-1.3199420	-1.9024580
C	1.3765860	-2.4506070	-0.7448980
C	2.2656450	-3.4470240	-0.3464630
C	4.0521280	-2.3161670	-1.5043470
H	3.5137420	-0.5057210	-2.5283400
H	0.3263950	-2.5147780	-0.4702060
H	1.9074250	-4.2811180	0.2508620
H	5.0909800	-2.2641450	-1.8174200
H	4.3029230	-4.1564880	-0.4082360

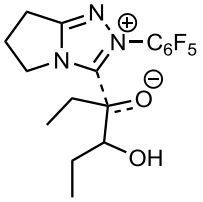
Ejection Transition States



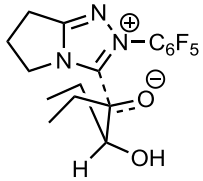
TS [VI-I]$^{(pyr)}_{(E)P\text{-}(re)P}$



TS [VI-I]$^{(pyr)}_{(E)P\text{-}(si)P}$

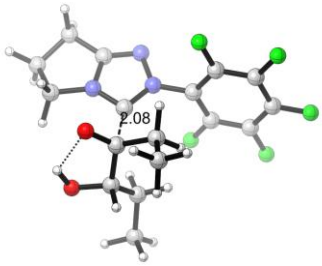


TS [VI-I]$^{(pyr)}_{(Z)P\text{-}(re)P}$



TS [VI-I]$^{(pyr)}_{(Z)P\text{-}(si)P}$

(*E*)-Propionaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]$^{(pyr)}_{(E)P\text{-}(re)P}$**)

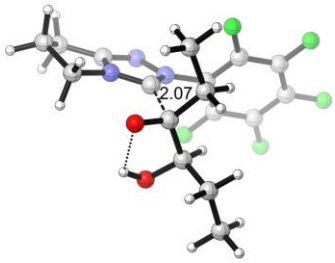


XYZ Coordinates

45

N	-0.9182170	-0.5113580	-1.1725420
C	-0.3816520	0.4823810	-0.4271300
N	-0.7608910	1.5631670	-1.1319580
C	-1.4918430	1.1932180	-2.2299020
N	-1.6162680	-0.0969530	-2.2966380
C	-0.8151850	-1.8949010	-0.9073920
C	-0.6183390	-4.6166680	-0.3464580
C	-1.8987160	-2.5906290	-0.3795760
C	0.3618380	-2.5879200	-1.1693990
C	0.4695130	-3.9405640	-0.8800910
C	-1.8072050	-3.9441690	-0.0957080
F	1.4030050	-1.9611370	-1.7095670
F	1.6028090	-4.5946360	-1.1283670
F	-0.5224740	-5.9139740	-0.0767400
F	-2.8465770	-4.5997400	0.4166680
F	-3.0369310	-1.9503270	-0.1242450
C	-0.6238360	3.0191840	-1.0029710
H	0.3990290	3.2763690	-0.7299430
H	-1.3085580	3.3654900	-0.2256230
C	-1.9422400	2.3901260	-3.0011410
H	-2.9962400	2.5861710	-2.7795710
H	-1.8326700	2.2607720	-4.0784190
C	-1.0183080	3.4913720	-2.4200080
H	-1.5054980	4.4665060	-2.3952020
H	-0.1189180	3.5696100	-3.0364420
C	0.0749940	0.7901600	1.5805520
O	-0.5387660	1.8598570	1.8250000
C	1.6127450	0.9161070	1.5294960
O	1.9367310	2.2419450	1.1541030
H	1.1573860	2.7610110	1.4273730
C	-0.4859880	-0.5176540	2.1352380
H	0.0510480	-1.3773100	1.7198630
H	-1.5332570	-0.5908390	1.8233250
C	-0.4130370	-0.5363500	3.6653100
H	0.6213810	-0.5145340	4.0217210
H	-0.8809570	-1.4447470	4.0560440
H	-0.9378850	0.3260420	4.0859510
H	1.9230100	0.7519500	2.5790090
C	2.3846290	-0.0536910	0.6523020
H	2.1825330	0.1946290	-0.3944080
H	2.0126820	-1.0718670	0.8214850
C	3.8880770	-0.0007090	0.9185130
H	4.4272010	-0.6896230	0.2609230
H	4.1161070	-0.2763730	1.9541090
H	4.2783540	1.0065830	0.7445120

(*E*)-Propionaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]$^{(pyr)}_{(E)P\text{-}(si)P}$**)



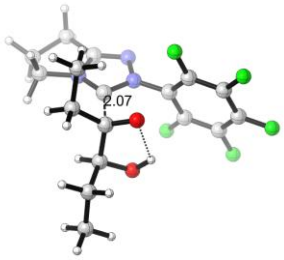
XYZ Coordinates

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N	-1.4841440	0.0160820	-0.4596160
C	-0.2529650	0.5644810	-0.5514290
N	-0.3174730	1.1499210	-1.7579290
C	-1.5409920	0.9255900	-2.3355830
N	-2.3054010	0.2221340	-1.5572170
C	-1.9692210	-0.7278800	0.6374970
C	-2.8945370	-2.2173190	2.8025980

C	-2.2528260	-0.1108510	1.8517430
C	-2.1652750	-2.1011750	0.5220120
C	-2.6268800	-2.8476250	1.5945430
C	-2.7024510	-0.8495030	2.9363960
F	-1.8865710	-2.7147260	-0.6244760
F	-2.8061270	-4.1613060	1.4764250
F	-3.3359790	-2.9273900	3.8349270
F	-2.9664710	-0.2516690	4.0967870
F	-2.0919760	1.2029720	1.9878740
C	0.5863660	1.9246240	-2.6202340
H	1.3059980	1.2411490	-3.0769820
H	1.1214400	2.6702950	-2.0352950
C	-1.6081060	1.5420930	-3.6946410
H	-2.5592720	2.0395320	-3.8865090
H	-1.4637850	0.7638390	-4.4508910
C	-0.4064140	2.5200900	-3.6416720
H	-0.7505410	3.4936950	-3.2825360
H	0.0571810	2.6567210	-4.6190290
C	1.5827240	0.4726310	0.3941190
O	2.3635280	1.0241530	-0.4216550
C	1.6602690	-1.0674400	0.4464500
H	0.7077960	-1.4898170	0.7935170
O	1.8888000	-1.5339910	-0.8705030
H	2.3718550	-0.8036910	-1.2997250
C	1.2282760	1.1752820	1.6961740
H	2.1171270	1.0978980	2.3372230
H	0.4201580	0.6294970	2.1988290
C	0.8737420	2.6434340	1.5048090
H	1.6962250	3.1735070	1.0163980
H	0.6748990	3.1267190	2.4658490
H	-0.0197300	2.7522640	0.8798360
C	2.7784590	-1.5226120	1.3900460
H	2.5654300	-1.1545250	2.4007330
H	3.7200070	-1.0608400	1.0654020
C	2.9155580	-3.0423600	1.4149020
H	3.7175530	-3.3543650	2.0908070
H	3.1402450	-3.4283690	0.4168520
H	1.9861300	-3.5124280	1.7570570

(*Z*)-Propionaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]**$^{(pyr)}_{(Z)P\text{-}(re)P}$)



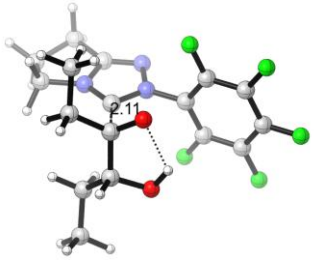
XYZ Coordinates

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N	-1.1644870	-0.9172700	-0.7470050
C	-0.1427430	-0.0399450	-0.7034250
N	-0.2975800	0.5994710	-1.8773130
C	-1.3768320	0.0976710	-2.5603960
N	-1.9521020	-0.8492200	-1.8850280
C	-1.5446240	-1.7956900	0.2936890
C	-2.2765280	-3.4645170	2.3924880
C	-2.5841700	-1.4427450	1.1464440
C	-0.8836750	-3.0011130	0.4945370
C	-1.2414770	-3.8333440	1.5441060
C	-2.9547090	-2.2694970	2.1952760
F	0.0948930	-3.3719710	-0.3226320
F	-0.6035270	-4.9877910	1.7400760
F	-2.6285690	-4.2665940	3.3934560
F	-3.9513490	-1.9258240	3.0115360
F	-3.2326440	-0.2964250	0.9620910
C	0.4011360	1.6563320	-2.6175280
H	1.3068250	1.2358830	-3.0645690
H	0.6667430	2.4774310	-1.9515310
C	-1.5404510	0.7852840	-3.8763700
H	-2.5812030	1.0219160	-4.0995700
H	-1.1512270	0.1435490	-4.6733040
C	-0.6590800	2.0436710	-3.6711770
H	-1.2754460	2.8551830	-3.2756670
H	-0.1976430	2.3813030	-4.5994290
C	1.2717800	-0.0749340	0.8030950
O	1.1948340	-1.2136120	1.3318230
C	0.6731560	1.0754890	1.6409650
H	0.3568200	1.9037090	0.9949560
O	-0.4789170	0.5697820	2.2920790
H	-0.2690820	-0.3725210	2.4349370
C	2.4799950	0.2746830	-0.0570790
H	3.3136740	0.4223110	0.6425690
H	2.3108710	1.2364670	-0.5568980
C	2.8509570	-0.8185050	-1.0510020

H	2.0506780	-0.9861070	-1.7814510
H	3.0274120	-1.7633130	-0.5300450
H	3.7588800	-0.5536500	-1.6009390
C	1.6938770	1.5944230	2.6601420
H	2.5579940	2.0057320	2.1247070
H	2.0539260	0.7473270	3.2583070
C	1.0968720	2.6654230	3.5690100
H	1.8376080	3.0300030	4.2873190
H	0.2446960	2.2692130	4.1277280
H	0.7463420	3.5237700	2.9841170

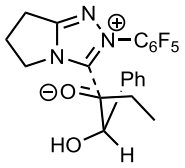
(*Z*)-Propionaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]$^{(pyr)}_{(Z)P\text{-}(si)P}$**)



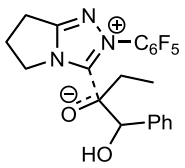
XYZ Coordinates

45

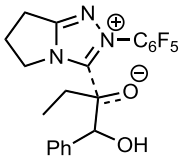
N	-0.1946100	-0.8160070	-1.2433140
C	0.0522420	0.2252550	-0.4236440
N	-0.1791460	1.2632030	-1.2507320
C	-0.5306700	0.8178240	-2.4990670
N	-0.5584480	-0.4791960	-2.5376260
C	-0.1296830	-2.1815070	-0.8822760
C	0.0223030	-4.8499180	-0.1186290
C	-1.2344360	-2.8198470	-0.3324530
C	1.0484970	-2.8978450	-1.0559330
C	1.1320230	-4.2267090	-0.6742140
C	-1.1637830	-4.1504490	0.0536910
F	2.1131380	-2.3073850	-1.5881000
F	2.2652060	-4.9097850	-0.8381830
F	0.0959460	-6.1274990	0.2428910
F	-2.2256580	-4.7598820	0.5815520
F	-2.3751790	-2.1567450	-0.1687770
C	-0.0979330	2.7248210	-1.1684130
H	0.9546410	3.0230130	-1.1854530
H	-0.5659810	3.0813360	-0.2501630
C	-0.7307840	1.9634210	-3.4362900
H	-1.6083970	1.8409480	-4.0718240
H	0.1515590	2.0620520	-4.0768120
C	-0.8565610	3.1497940	-2.4457370
H	-1.9103120	3.3063680	-2.2013830
H	-0.4567430	4.0764100	-2.8581860
C	1.1029920	-0.0575490	1.3783070
O	1.7202120	-1.1384400	1.2155740
C	-0.0770460	-0.1246460	2.3706500
O	-0.6067850	-1.4370270	2.3402200
H	0.1447370	-1.9900850	2.0559210
C	1.8803410	1.2535460	1.3378810
H	2.3347240	1.3604330	2.3331950
H	1.1969890	2.0990490	1.2121930
C	2.9712210	1.2629410	0.2751880
H	2.5497600	1.1261310	-0.7276930
H	3.6822940	0.4509390	0.4456840
H	3.5179450	2.2104540	0.2878090
H	0.4051420	0.0515440	3.3521220
C	-1.2119690	0.8743270	2.2203180
H	-1.7696570	0.6334220	1.3083780
H	-0.7922920	1.8797600	2.0970810
C	-2.1543710	0.8515550	3.4230600
H	-2.9757130	1.5626050	3.2917740
H	-1.6234380	1.1172940	4.3438340
H	-2.5871810	-0.1441410	3.5572480



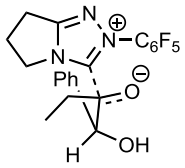
TS [VI-I]$^{(pyr)}_{(E)P\text{-}(re)B}$



TS [VI-I]$^{(pyr)}_{(E)P\text{-}(si)B}$

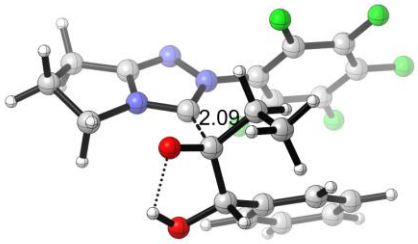


TS [VI-I]$^{(pyr)}_{(Z)P\text{-}(re)B}$



TS [VI-I]$^{(pyr)}_{(Z)P\text{-}(si)B}$

(*E*)-Propionaldehyde BI + *re* Face of Benzaldehyde Eject (**TS [VI-I]$^{(pyr)}_{(E)P\text{-}(re)B}$**)

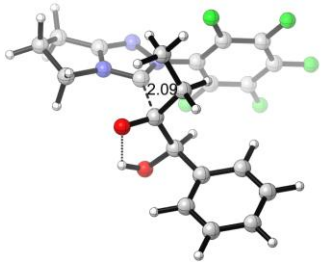


XYZ Coordinates

49

N	-1.4696040	-0.3555370	-0.3337740
C	-0.8144170	0.7954450	-0.0450600
N	-1.6311390	1.7037970	-0.6130660
C	-2.6925430	1.0843270	-1.2206890
N	-2.6338530	-0.2019630	-1.0679750
C	-1.0323000	-1.6727010	-0.0665780
C	-0.1672210	-4.2824440	0.3912650
C	-1.1251450	-2.2372190	1.2017520
C	-0.5453900	-2.4542410	-1.1110190
C	-0.1097570	-3.7506880	-0.8892320
C	-0.6766580	-3.5282060	1.4387310
F	-0.5112770	-1.9602250	-2.3448420
F	0.3685000	-4.4834260	-1.8927330
F	0.2612910	-5.5211390	0.6132670
F	-0.7565300	-4.0556610	2.6598160
F	-1.6649110	-1.5515340	2.2060830
C	-1.6437540	3.1622700	-0.8193980
H	-0.9216910	3.4045850	-1.6041520
H	-1.3718940	3.6732900	0.1008730
C	-3.5797180	2.0722560	-1.9034990
H	-4.6383670	1.8707980	-1.7366240
H	-3.3862610	2.0459620	-2.9807160
C	-3.1012520	3.4004400	-1.2661270
H	-3.7127720	3.6213210	-0.3874100
H	-3.1752940	4.2405660	-1.9572640
C	0.6338990	1.5700660	1.2409440
O	0.2847670	2.7701770	1.3638150
C	1.8979630	1.3823330	0.3571760
O	1.8410610	2.3374130	-0.6775090
H	1.3310220	3.0734240	-0.2916620
C	0.4461190	0.6346240	2.4254290
H	0.5966070	-0.4063470	2.1258610
H	-0.5880490	0.7413450	2.7653090
C	1.3988920	1.0070550	3.5657410
H	2.4486850	0.8844800	3.2786870
H	1.2141060	0.3705500	4.4360750
H	1.2494180	2.0482450	3.8659080
H	2.7245800	1.6352360	1.0454370
C	2.1937960	0.0131380	-0.2041340
C	2.9039920	-2.5027410	-1.2400410
C	2.0631710	-0.2558570	-1.5689450
C	2.6878320	-0.9944130	0.6362110
C	3.0280620	-2.2458280	0.1275440
C	2.4235730	-1.5032530	-2.0840610
H	1.7009710	0.5253990	-2.2297040
H	2.8300350	-0.7904590	1.6950920
H	3.4101830	-3.0130910	0.7952500
H	2.3251870	-1.6929880	-3.1493670
H	3.1856590	-3.4719570	-1.6420230

(*E*)-Propionaldehyde BI + *si* Face of Benzaldehyde Eject (**TS [VI-I]$^{(pyr)}_{(E)P\text{-}(si)B}$**)



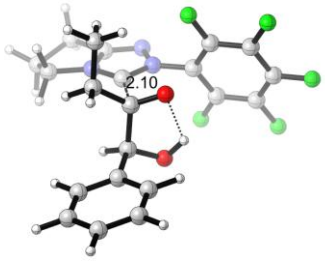
XYZ Coordinates

49

N	-1.5951030	0.1261600	-1.3369950
C	-0.4699440	0.7627510	-0.9450710
N	-0.3380220	1.6795380	-1.9172090
C	-1.3492890	1.5558680	-2.8352630
N	-2.1624130	0.5972700	-2.5105430
C	-2.2148400	-0.9360010	-0.6428150
C	-3.3958170	-3.0440350	0.7457780
C	-2.8854510	-0.7085110	0.5551630
C	-2.1578360	-2.2342640	-1.1417380
C	-2.7448310	-3.2868350	-0.4566040
C	-3.4642310	-1.7555610	1.2571170
F	-1.5147150	-2.4787540	-2.2797510
F	-2.6799920	-4.5260710	-0.9382230
F	-3.9512500	-4.0505250	1.4112180
F	-4.0953850	-1.5281990	2.4074380
F	-2.9749290	0.5250230	1.0468290
C	0.6109410	2.7500620	-2.2547060
H	1.5085690	2.3007400	-2.6867090
H	0.8833800	3.3108020	-1.3627610
C	-1.1997030	2.5631770	-3.9286170
H	-2.1485320	3.0211060	-4.2101680
H	-0.7716820	2.0802710	-4.8129680
C	-0.2040750	3.5622460	-3.2842010
H	-0.7632520	4.3442930	-2.7634330
H	0.4424460	4.0346320	-4.0243840
C	1.0534780	0.6075440	0.4774610
O	1.9167500	1.4175310	0.0695600
C	1.3732670	-0.8914940	0.2135120
H	0.4415810	-1.4529510	0.0845440
O	2.1219330	-0.9633850	-0.9771190

H	2.5041760	-0.0704420	-1.0784520
C	2.1172080	-1.4781560	1.3996330
C	3.4459280	-2.5018290	3.6459850
C	3.4847870	-1.2497760	1.5761930
C	1.4238320	-2.2270600	2.3543210
C	2.0813710	-2.7355500	3.4743830
C	4.1458970	-1.7599120	2.6927800
H	4.0325480	-0.6765810	0.8330020
H	0.3600390	-2.4152620	2.2164740
H	1.5314430	-3.3189730	4.2072740
H	5.2095370	-1.5788630	2.8193180
H	3.9624570	-2.9011380	4.5139460
C	0.2418530	0.9121800	1.7241160
H	0.9184850	0.7424800	2.5728300
H	-0.5715100	0.1824240	1.8150870
C	-0.2817400	2.3407410	1.7657050
H	0.5446470	3.0539220	1.6992630
H	-0.8225960	2.5284240	2.6977310
H	-0.9676150	2.5345160	0.9333320

(*Z*)-Propionaldehyde BI + *re* Face of Benzaldehyde Eject (**TS [VI-I]**$^{(pyr)}_{(Z)P\text{-}(re)B}$)

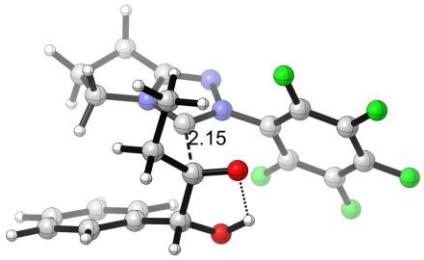


XYZ Coordinates

49

N	-1.3147600	-0.9548320	-1.5045420
C	-0.2109950	-0.2686810	-1.1486480
N	0.1529040	0.2663630	-2.3284300
C	-0.7176330	-0.1120350	-3.3189300
N	-1.6544330	-0.8751060	-2.8453590
C	-2.1339250	-1.7059690	-0.6312870
C	-3.7185200	-3.1518880	1.1368010
C	-3.3649340	-1.2080350	-0.2199630
C	-1.7117670	-2.9426510	-0.1574700
C	-2.4939200	-3.6634550	0.7305950
C	-4.1595310	-1.9236060	0.6629130
F	-0.5483160	-3.4465230	-0.5522700
F	-2.0831890	-4.8450970	1.1912660
F	-4.4762410	-3.8425810	1.9836040
F	-5.3403240	-1.4448640	1.0542540
F	-3.7866040	-0.0280020	-0.6670400
C	1.2508560	1.1028840	-2.8238290
H	2.1523920	0.4893260	-2.9106380
H	1.4358010	1.9337970	-2.1425850
C	-0.2972500	0.4482430	-4.6382670
H	-1.1366660	0.8364310	-5.2161600
H	0.1965600	-0.3337600	-5.2238490
C	0.7002480	1.5501040	-4.1964110
H	0.1640110	2.4947610	-4.0751090
H	1.5006940	1.6969280	-4.9216530
C	0.5465380	-0.2933620	0.8075590
O	0.0422960	-1.2937400	1.3674030
C	-0.0752530	1.0708030	1.2193700
H	0.0219060	1.7915070	0.4003720
O	-1.4452990	0.8478420	1.4694350
H	-1.4939620	-0.0966860	1.7140150
C	0.6538240	1.6139640	2.4354000
C	2.0901480	2.5544110	4.6523680
C	0.4147280	1.0869970	3.7083440
C	1.6122250	2.6198340	2.2855510
C	2.3302610	3.0880140	3.3863950
C	1.1283050	1.5543220	4.8106410
H	-0.3323550	0.3079360	3.8336060
H	1.7950680	3.0413440	1.2989400
H	3.0708070	3.8719240	3.2566490
H	0.9356460	1.1370290	5.7949870
H	2.6450060	2.9178010	5.5124690
C	2.0228270	-0.2799020	0.4468740
H	2.5592670	-0.1386200	1.3951200
H	2.2419370	0.5975810	-0.1736360
C	2.4910070	-1.5684290	-0.2153880
H	2.2622410	-2.4288410	0.4191320
H	3.5706930	-1.5462230	-0.3892830
H	1.9953720	-1.7222660	-1.1807210

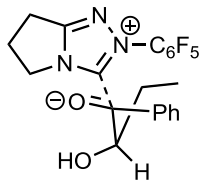
(*Z*)-Propionaldehyde BI + *si* Face of Benzaldehyde Eject (**TS [VI-I]**$^{(pyr)}_{(Z)P\text{-}(si)B}$)



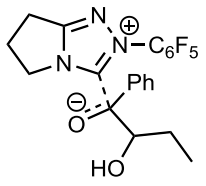
XYZ Coordinates

49

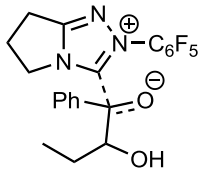
N	-0.6584890	-1.3640070	-0.8730710
C	0.1254440	-0.3063510	-0.5783080
N	-0.4744610	0.6615590	-1.2958720
C	-1.5635700	0.1680630	-1.9642960
N	-1.7196950	-1.0987540	-1.7251980
C	-0.5090600	-2.6659740	-0.3447950
C	-0.1743510	-5.1927650	0.7685210
C	-1.3695130	-3.1196260	0.6489630
C	0.5142690	-3.4980610	-0.7825730
C	0.6897690	-4.7554130	-0.2254090
C	-1.2092170	-4.3781180	1.2079410
F	1.3391230	-3.0954320	-1.7426880
F	1.6763530	-5.5489780	-0.6430310
F	-0.0144310	-6.4016470	1.2995370
F	-2.0345860	-4.8079150	2.1625620
F	-2.3514230	-2.3338430	1.0841210
C	-0.2636150	2.0940510	-1.5181890
H	0.5654100	2.2291460	-2.2190070
H	-0.0356040	2.5914630	-0.5732920
C	-2.2298870	1.2421280	-2.7604760
H	-3.3173840	1.2019210	-2.6910420
H	-1.9455770	1.1462440	-3.8132530
C	-1.6244260	2.5169960	-2.1160330
H	-2.2767980	2.8559150	-1.3064820
H	-1.5134760	3.3295240	-2.8345190
C	1.8221450	-0.4714890	0.7370900
O	2.1437170	-1.6777680	0.7183140
C	1.0973700	-0.0287310	2.0413400
O	0.3243240	-1.1177190	2.4924190
H	0.7956140	-1.9013370	2.1524740
C	2.6881270	0.5616350	0.0376460
H	3.5210610	0.7717420	0.7247100
H	2.1324890	1.4966830	-0.0834860
C	3.2278760	0.0623710	-1.2953260
H	3.7919370	-0.8642350	-1.1613640
H	3.8862270	0.8067060	-1.7523980
H	2.4073090	-0.1437610	-1.9922480
H	1.9314010	0.1576100	2.7418500
C	0.2590350	1.2238890	1.9834290
C	-1.2726340	3.5732090	1.8367840
C	-1.1251940	1.1576250	1.7922680
C	0.8626410	2.4774780	2.1246540
C	0.1050100	3.6467510	2.0449110
C	-1.8854100	2.3241990	1.7162410
H	-1.6012300	0.1847320	1.7060720
H	1.9339980	2.5388360	2.3041080
H	0.5895070	4.6124660	2.1568550
H	-2.9597040	2.2573450	1.5672760
H	-1.8659310	4.4814140	1.7819440



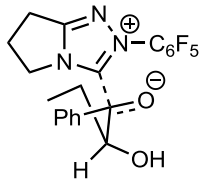
TS [VI-I]$^{(pyr)}_{(E)B\text{-}(re)P}$



TS [VI-I]$^{(pyr)}_{(E)B\text{-}(si)P}$

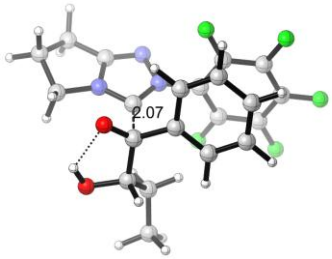


TS [VI-I]$^{(pyr)}_{(Z)B\text{-}(re)P}$



TS [VI-I]$^{(pyr)}_{(Z)B\text{-}(si)P}$

(*E*)-Benzaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]$^{(pyr)}_{(E)B\text{-}(re)P}$**)



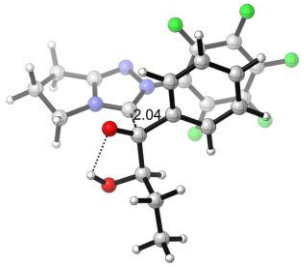
XYZ Coordinates

49

N	-1.2988010	0.0045460	-0.8019320
C	-0.0107780	0.3962810	-0.9352370
N	-0.0515040	1.0260800	-2.1210950
C	-1.3194510	0.9895520	-2.6423390
N	-2.1338320	0.3667920	-1.8465430
C	-1.8517240	-0.6534100	0.3204560
C	-2.8790000	-1.9029030	2.5880500
C	-2.5564270	0.0754610	1.2741910
C	-1.7114670	-2.0262310	0.4957140
C	-2.2086520	-2.6508320	1.6304650
C	-3.0600630	-0.5380280	2.4101750
F	-1.1058060	-2.7644900	-0.4313040
F	-2.0615850	-3.9645720	1.7955960
F	-3.3566690	-2.4963150	3.6770910
F	-3.7125920	0.1717540	3.3284700
F	-2.7552690	1.3781010	1.0976420

C	0.9059820	1.7064800	-3.0050600
H	1.4949340	0.9491620	-3.5290540
H	1.5617140	2.3451260	-2.4161460
C	-1.3663950	1.6668460	-3.9730650
H	-2.2516340	2.2915090	-4.0966570
H	-1.3604830	0.9116490	-4.7659130
C	-0.0450840	2.4765790	-3.9452200
H	-0.2379940	3.4673680	-3.5253790
H	0.3854960	2.5997100	-4.9392090
C	1.6243510	0.7436750	0.2895870
O	2.0376290	1.8615090	-0.1135050
C	2.5174420	-0.4604480	-0.0873350
C	0.9019510	0.7087090	1.6272060
C	-0.4308890	0.8227570	4.0964550
C	1.0145440	-0.3433170	2.5426310
C	0.1342520	1.8258970	1.9733140
C	-0.5326930	1.8836260	3.1938290
C	0.3489710	-0.2858230	3.7697930
H	1.6323310	-1.2086560	2.3239240
H	0.0623500	2.6470480	1.2652330
H	-1.1358140	2.7528450	3.4404960
H	0.4479750	-1.1081760	4.4726730
H	-0.9521830	0.8630350	5.0486440
C	1.8471080	-1.8036890	-0.3319560
H	1.3402640	-1.7502490	-1.3014240
H	1.0719030	-1.9751890	0.4206440
C	2.8445130	-2.9595370	-0.3261940
H	3.6230550	-2.8078100	-1.0801120
H	2.3443230	-3.9083640	-0.5433090
H	3.3341140	-3.0538250	0.6497330
H	3.2132360	-0.5566880	0.7671640
O	3.2522510	-0.1100580	-1.2444380
H	3.2630490	0.8652060	-1.2414520

(*E*)-Benzaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]$^{(pyr)}_{(E)B\text{-}(si)P}$**)



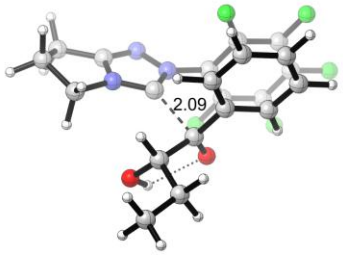
XYZ Coordinates

49

N	-1.5010420	-0.3905590	-0.8122150
C	-0.1697080	-0.6067630	-0.9029150
N	-0.0723620	-1.1280390	-2.1374670
C	-1.3098460	-1.2115060	-2.7219350
N	-2.2321770	-0.7536340	-1.9320250
C	-2.1820860	0.2137920	0.2681420
C	-3.5253220	1.4329710	2.3794630
C	-2.6240150	1.5288000	0.1612460
C	-2.4270920	-0.4831080	1.4455950
C	-3.0921010	0.1205020	2.5019300
C	-3.2928500	2.1415240	1.2090510
F	-2.0098110	-1.7404520	1.5792860
F	-3.3116290	-0.5488400	3.6332860
F	-4.1456470	2.0213080	3.3977320
F	-3.6901740	3.4082910	1.1078720
F	-2.4004520	2.2136650	-0.9571180
C	0.9981090	-1.6367790	-3.0066810
H	1.2708870	-2.6405830	-2.6716190
H	1.8626250	-0.9766810	-2.9512970
C	-1.2144730	-1.8102220	-4.0867410
H	-1.8554260	-1.3082420	-4.8121410
H	-1.5011900	-2.8660110	-4.0406610
C	0.2972570	-1.6409830	-4.3815890
H	0.4632490	-0.6779590	-4.8719740
H	0.6836550	-2.4301270	-5.0273220
C	1.5128400	0.1406290	-0.0303170
O	2.2539100	0.3999880	-1.0138820
C	1.9173130	-1.1018630	0.7863720
H	1.0723780	-1.4853630	1.3678390
O	2.2765770	-2.1213910	-0.1293740
H	2.7609990	-1.6594460	-0.8358970
C	0.8654020	1.2948340	0.7201860
C	-0.3128390	3.4838770	2.0206060
C	0.3648220	1.1623470	2.0210580
C	0.7690940	2.5320560	0.0797950
C	0.1757870	3.6196120	0.7207360
C	-0.2130270	2.2524330	2.6704990
H	0.4170930	0.2079650	2.5393580
H	1.1639790	2.6281760	-0.9274870
H	0.0969970	4.5736740	0.2072280
H	-0.5908440	2.1381930	3.6831510
H	-0.7725690	4.3302830	2.5231500
C	3.0924990	-0.7755040	1.7148040
H	2.8382810	0.0833440	2.3461750
H	3.9436630	-0.4734410	1.0917170
C	3.4705230	-1.9686170	2.5879950
H	4.3308240	-1.7352250	3.2226200

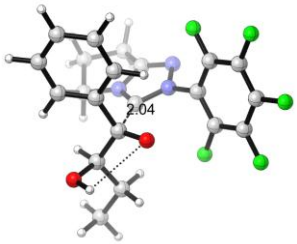
H 3.7266850 -2.8354650 1.9720450
H 2.6378730 -2.2523880 3.2419610

(*Z*)-Benzaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]**$^{(pyr)}_{(Z)B\text{-}(re)P}$)



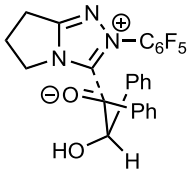
XYZ Coordinates
49
N -1.4006380 -0.8286670 -1.0302060
C -0.6930540 0.2613910 -0.6731460
N -1.1715060 1.1771290 -1.5327400
C -2.1313350 0.6219670 -2.3403900
N -2.3049280 -0.6343060 -2.0614010
C -1.2764290 -2.1043770 -0.4345400
C -0.9714940 -4.5734830 0.8097940
C -2.1490490 -2.4980120 0.5749560
C -0.2523840 -2.9639870 -0.8120890
C -0.0930710 -4.1956880 -0.1944780
C -2.0026050 -3.7268700 1.1978350
F 0.6095670 -2.6015640 -1.7588740
F 0.8996660 -5.0097100 -0.5534120
F -0.8268140 -5.7529990 1.4067350
F -2.8396450 -4.1017750 2.1652700
F -3.1342110 -1.6910810 0.9513440
C -0.9679220 2.6075170 -1.7848150
H 0.0965820 2.8436280 -1.7962730
H -1.4601230 3.1732610 -0.9902280
C -2.6993320 1.6449530 -3.2697540
H -3.6761640 1.9692180 -2.8969800
H -2.8242550 1.2676880 -4.2852400
C -1.6412050 2.7740850 -3.1654230
H -2.0830060 3.7642600 -3.2787530
H -0.8914040 2.6385000 -3.9491490
C 0.2084780 0.2393840 1.2091190
O -0.6620190 -0.2768370 1.9474710
C 0.3658620 1.7662040 1.3282540
H 0.8370730 2.1858590 0.4320340
O -0.9286770 2.3297710 1.4293350
H -1.4562230 1.6602060 1.9004590
C 1.4517950 -0.5579670 0.8636980
C 3.7339920 -2.0790380 0.3002130
C 2.3778360 -0.1169100 -0.0877350
C 1.6797840 -1.7600630 1.5339960
C 2.8152870 -2.5223980 1.2499490
C 3.5143730 -0.8701810 -0.3666460
H 2.1977510 0.8078810 -0.6312730
H 0.9524820 -2.0921420 2.2705290
H 2.9800540 -3.4622370 1.7697820
H 4.2247920 -0.5217740 -1.1105990
H 4.6166300 -2.6708250 0.0760120
C 1.2176700 2.1077130 2.5548030
H 2.1994370 1.6294500 2.4517680
H 0.7371020 1.6748760 3.4412430
C 1.3870300 3.6143570 2.7253420
H 1.9881620 3.8453140 3.6098680
H 0.4150720 4.1031750 2.8369160
H 1.8891080 4.0530330 1.8552970

(*Z*)-Benzaldehyde BI + *si* Face of Propionaldehyde Eject (**TS [VI-I]**$^{(pyr)}_{(Z)B\text{-}(si)P}$)

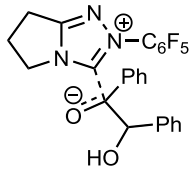


XYZ Coordinates
49
N -1.5236280 -0.6775800 -0.4296700
C -0.5388110 0.2315760 -0.2819880
N -0.5363290 0.8199980 -1.4894990
C -1.4950590 0.2618970 -2.2966110
N -2.1343210 -0.6799750 -1.6746090
C -1.9188610 -1.6434640 0.5229530
C -2.6537130 -3.5718560 2.3923100
C -2.4732420 -1.2693770 1.7416640
C -1.7438850 -2.9968000 0.2517460
C -2.1116010 -3.9617250 1.1759450
C -2.8321320 -2.2256810 2.6781830
F -1.1943710 -3.3797320 -0.8996410
F -1.9393280 -5.2559400 0.9068050
F -3.0068800 -4.4923320 3.2847130
F -3.3602970 -1.8603970 3.8461350
F -2.6763510 0.0130780 2.0227430
C 0.1971260 1.9094540 -2.1431890

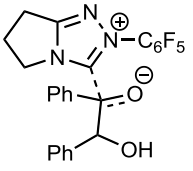
H	1.2636110	1.8313730	-1.9296940
H	-0.1860350	2.8649020	-1.7741820
C	-1.5164970	0.9313000	-3.6319560
H	-2.3505930	1.6392480	-3.6697510
H	-1.6237100	0.2249330	-4.4555040
C	-0.1481740	1.6597870	-3.6274960
H	-0.1724230	2.5894980	-4.1960690
H	0.6098860	1.0041080	-4.0637500
C	0.7678000	0.1316690	1.2833200
O	0.2413180	-0.5334520	2.2067380
C	0.9322830	1.6478430	1.4982310
C	1.8560540	-0.5553640	0.4580000
C	3.7826660	-1.9436280	-1.0376800
C	2.8762780	0.1388000	-0.2003350
C	1.8237410	-1.9513250	0.3754730
C	2.7732500	-2.6430440	-0.3722570
C	3.8349660	-0.5534650	-0.9429470
H	2.9480560	1.2189740	-0.1195590
H	1.0446750	-2.4830290	0.9154540
H	2.7311290	-3.7269610	-0.4324070
H	4.6291820	-0.0044590	-1.4408510
H	4.5295810	-2.4797790	-1.6158360
C	-0.3075750	2.2886370	2.1068460
H	-0.4880020	1.8266040	3.0849670
H	-1.1726450	2.0396570	1.4818090
C	-0.1683010	3.8022870	2.2387900
H	-1.0577090	4.2409480	2.7012760
H	-0.0368430	4.2713350	1.2563930
H	0.6974090	4.0656490	2.8538550
H	1.1731960	2.1465510	0.5518530
O	2.0767370	1.8411710	2.3274020
H	1.9153940	1.3725770	3.1604240



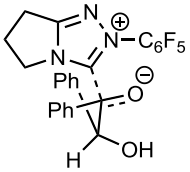
TS [VI-I]$^{(pyr)}_{(E)B\text{-}(re)B}$



TS [VI-I]$^{(pyr)}_{(E)B\text{-}(si)B}$



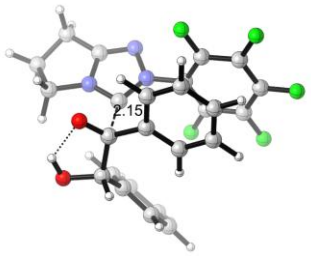
TS [VI-I]$^{(pyr)}_{(Z)B\text{-}(re)B}$



TS [VI-I]$^{(pyr)}_{(Z)B\text{-}(si)B}$

(*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde Eject

(TS [VI-I]$^{(pyr)}_{(E)B\text{-}(re)B}$)



XYZ Coordinates

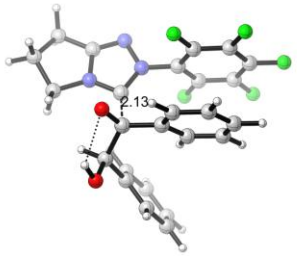
53

N	-0.7071360	0.2658500	-1.4004300
C	0.3626900	0.7024940	-0.6981930
N	1.0015170	1.4290450	-1.6341960
C	0.3143410	1.4067720	-2.8198990
N	-0.7649590	0.6932610	-2.7196610
C	-1.7712360	-0.5124580	-0.8937370
C	-3.8897530	-2.0043610	0.1285570
C	-3.0104050	0.0787940	-0.6647420
C	-1.6111760	-1.8637360	-0.6085670
C	-2.6619590	-2.6102260	-0.0959440
C	-4.0683800	-0.6581590	-0.1576770
F	-0.4415870	-2.4589890	-0.8212330
F	-2.4973180	-3.9027240	0.1851130
F	-4.8946500	-2.7114520	0.6371840
F	-5.2425630	-0.0769510	0.0833730
F	-3.1857490	1.3709700	-0.9286300
C	2.1966980	2.2783810	-1.6872360
H	3.0298140	1.7994380	-1.1719220
H	1.9692120	3.2301600	-1.2006940
C	1.0029530	2.2417560	-3.8497960
H	0.4810090	3.1995800	-3.9446960
H	1.0323530	1.7639190	-4.8295950
C	2.4050660	2.4140180	-3.2110130
H	2.8631960	3.3688300	-3.4702070
H	3.0604220	1.6099360	-3.5571570
C	0.7531580	1.2358380	1.3511490
O	1.0751540	2.4348240	1.2181030
C	1.9544490	0.2981360	1.7301550
O	3.1315160	0.9958920	1.3835750
H	2.8425450	1.9254020	1.2897450
C	-0.6405940	0.9310550	1.8607300
C	-3.2485300	0.5310430	2.8169130
C	-1.0296530	-0.3171270	2.3561740
C	-1.5722950	1.9744180	1.8455820
C	-2.8689710	1.7768500	2.3156230

C	-2.3252880	-0.5143800	2.8347400
H	-0.3339800	-1.1469100	2.3669880
H	-1.2643540	2.9415000	1.4605120
H	-3.5832880	2.5948670	2.2901990
H	-2.6125710	-1.4891700	3.2196540
H	-4.2582410	0.3744950	3.1862130
H	1.8736050	0.2203220	2.8289290
C	2.0691530	-1.1079230	1.1760270
C	2.4325680	-3.7178460	0.1930080
C	2.5460330	-1.3230950	-0.1228400
C	1.8213260	-2.2187510	1.9862860
C	1.9869560	-3.5161200	1.4976510
C	2.7221470	-2.6146970	-0.6124360
H	2.8037690	-0.4712520	-0.7441140
H	1.5088960	-2.0709810	3.0177870
H	1.7824710	-4.3650330	2.1436280
H	3.0930180	-2.7611460	-1.6229780
H	2.5687610	-4.7251280	-0.1894770

(*E*)- Benzaldehyde BI + *si* Face of Benzaldehyde Eject

(TS [VI-I]$^{(pyr)}_{(E)B\text{-}(si)B}$)



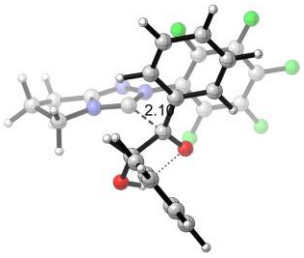
XYZ Coordinates

53

N	-1.4842520	-0.0464190	-1.0267730
C	-0.1933570	-0.4153170	-0.8653600
N	-0.0470840	-1.2766340	-1.8923640
C	-1.2130420	-1.3889700	-2.6021100
N	-2.1395660	-0.6334640	-2.0983650
C	-2.1816400	0.9239380	-0.2711680
C	-3.5116730	2.8512900	1.2283630
C	-2.1659770	2.2587800	-0.6632200
C	-2.8874600	0.5652890	0.8703110
C	-3.5496230	1.5218170	1.6243440
C	-2.8206170	3.2252610	0.0837260
F	-2.9138890	-0.7058200	1.2653320
F	-4.2067540	1.1773400	2.7312260
F	-4.1275950	3.7744470	1.9599630
F	-2.7833070	4.5053230	-0.2809310
F	-1.5044340	2.6188640	-1.7592570
C	1.0388170	-2.0916600	-2.4516520
H	1.1779330	-2.9789730	-1.8275440
H	1.9597660	-1.5089430	-2.4833870
C	-1.0603540	-2.3466280	-3.7370600
H	-1.5393880	-1.9902980	-4.6495760
H	-1.5024560	-3.3104300	-3.4645910
C	0.4833010	-2.4338590	-3.8518920
H	0.8352040	-1.6861680	-4.5670900
H	0.8183320	-3.4161900	-4.1860120
C	1.5781050	0.6002700	-0.2592470
O	2.0995640	0.8579340	-1.3632540
C	2.2861180	-0.5840540	0.4823390
H	2.2408800	-1.4336470	-0.2104430
O	3.6342490	-0.1661640	0.6398990
H	3.8960620	0.2297920	-0.2058590
C	1.7596730	-1.0269160	1.8219750
C	0.6633010	-1.7680480	4.2933490
C	2.2565040	-0.4788150	3.0080320
C	0.7362230	-1.9772610	1.8872060
C	0.1809500	-2.3382450	3.1140910
C	1.7105620	-0.8473360	4.2369200
H	3.0636700	0.2456840	2.9605070
H	0.3642060	-2.4279650	0.9697080
H	-0.6219690	-3.0691430	3.1509600
H	2.1010740	-0.4119780	5.1523500
H	0.2341950	-2.0498690	5.2505470
C	0.9763600	1.7446710	0.5405290
C	0.0060070	3.9767960	1.9418250
C	0.1592260	1.5777190	1.6669080
C	1.2890380	3.0409450	0.1214280
C	0.8025940	4.1521540	0.8120470
C	-0.3137950	2.6849710	2.3667670
H	-0.1368820	0.5834940	1.9863390
H	1.9146290	3.1656780	-0.7569840
H	1.0513390	5.1523950	0.4694340
H	-0.9425120	2.5384270	3.2412790
H	-0.3711460	4.8389540	2.4850820

(*Z*)- Benzaldehyde BI + *re* Face of Benzaldehyde Eject

(**TS [VI-I]**$^{(pyr)}_{(Z)B\text{-}(re)B}$)



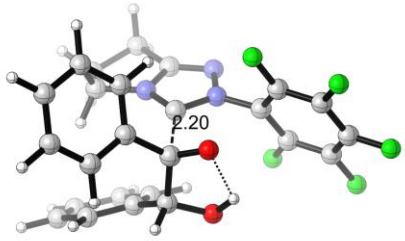
XYZ Coordinates

53

N	-1.7743280	0.5833730	-1.5133990
C	-1.1932240	-0.3693910	-0.7574830
N	-1.9459880	-1.4401400	-1.0617950
C	-2.9105310	-1.1046420	-1.9779910
N	-2.8408360	0.1544430	-2.2868800
C	-1.3457450	1.9273770	-1.5962020
C	-0.4031620	4.5420770	-1.7459600
C	-0.6161550	2.3550650	-2.7013010
C	-1.5920240	2.8262980	-0.5656080
C	-1.1214250	4.1303460	-0.6336610
C	-0.1501770	3.6558630	-2.7858960
F	-2.2738030	2.4446100	0.5113810
F	-1.3531640	4.9838920	0.3633000
F	0.0450790	5.7919840	-1.8202390
F	0.5487360	4.0597550	-3.8463420
F	-0.3477760	1.5028980	-3.6856590
C	-1.9554350	-2.8648670	-0.7152270
H	-1.8313810	-2.9967600	0.3600110
H	-1.1333020	-3.3553680	-1.2425510
C	-3.7252770	-2.3004240	-2.3523510
H	-3.4066360	-2.6654790	-3.3335750
H	-4.7932120	-2.0837640	-2.3945990
C	-3.3505520	-3.2942640	-1.2219200
H	-3.3499150	-4.3283460	-1.5670400
H	-4.0731020	-3.2021250	-0.4068560
C	0.7709220	0.0081730	-0.1125080
O	1.2908490	0.5673510	-1.1018240
C	1.1470150	-1.4821630	0.0850230
H	0.3844020	-1.9978140	0.6762080
O	1.1979910	-2.0809670	-1.1910580
H	1.4287690	-1.3593640	-1.8044720
C	2.4764480	-1.5637320	0.8166400
C	4.9232350	-1.6563670	2.1823970
C	2.5193760	-1.9006930	2.1716830
C	3.6711370	-1.2746190	0.1492110
C	4.8874660	-1.3219210	0.8270280
C	3.7360670	-1.9459430	2.8538840
H	1.5949080	-2.1326000	2.6963950
H	3.6479540	-1.0118630	-0.9049400
H	5.8089640	-1.0974380	0.2975290
H	3.7555560	-2.2130990	3.9065580
H	5.8718170	-1.6945470	2.7099880
C	0.4739010	0.8111420	1.1355060
C	-0.0037790	2.3535500	3.4205360
C	-0.3052890	0.3028820	2.1797340
C	1.0204990	2.0896770	1.2473540
C	0.7784350	2.8622300	2.3854380
C	-0.5422130	1.0674360	3.3175820
H	-0.7507490	-0.6855090	2.0918100
H	1.6325060	2.4693520	0.4335660
H	1.2011920	3.8600250	2.4618150
H	-1.1556200	0.6682980	4.1201110
H	-0.1974800	2.9536530	4.3048730

(*Z*)- Benzaldehyde BI + *si* Face of Benzaldehyde Eject

(**TS [VI-I]**$^{(pyr)}_{(Z)B\text{-}(si)B}$)



XYZ Coordinates

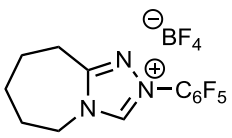
53

N	1.4205490	-1.4131070	-0.5373110
C	0.3155750	-0.6817210	-0.2816070
N	-0.1810480	-1.3379490	0.7823450
C	0.6208290	-2.3942340	1.1228240
N	1.6406910	-2.4798510	0.3228550
C	2.3533870	-1.1472280	-1.5645070
C	4.1575990	-0.5279110	-3.5899160
C	3.6006350	-0.6125270	-1.2605540
C	2.0260330	-1.3784370	-2.8955130
C	2.9182520	-1.0645110	-3.9090930
C	4.5055840	-0.3042870	-2.2643910
F	0.8475090	-1.9037410	-3.2116440
F	2.5944440	-1.2774520	-5.1841460
F	5.0192760	-0.2309520	-4.5582850
F	5.6992600	0.2085220	-1.9673400
F	3.9321090	-0.3792560	0.0068140

C	-1.3399540	-1.1839670	1.6634990
H	-2.2307660	-1.5570480	1.1497940
H	-1.4789220	-0.1319110	1.9217480
C	0.0688140	-3.1148900	2.3103960
H	0.8414570	-3.3908760	3.0289690
H	-0.4402460	-4.0265890	1.9819430
C	-0.9314880	-2.0657620	2.8653190
H	-0.4254420	-1.4423620	3.6078610
H	-1.7977400	-2.5310940	3.3365610
C	-0.2360070	1.0814080	-1.4732220
O	0.3391580	0.9117730	-2.5639210
C	0.4435290	2.1256420	-0.5327460
O	1.8277880	2.0732820	-0.7961520
H	1.8932190	1.7558320	-1.7159060
C	-1.7382060	0.8985800	-1.4224450
C	-4.5250870	0.5959210	-1.5563830
C	-2.5797160	2.0064300	-1.2866550
C	-2.3070650	-0.3561650	-1.6658100
C	-3.6892750	-0.5101170	-1.7247020
C	-3.9665770	1.8547460	-1.3474890
H	-2.1620930	2.9994040	-1.1541530
H	-1.6562330	-1.2148290	-1.8093420
H	-4.1154810	-1.4929920	-1.9039680
H	-4.6068150	2.7251930	-1.2381320
H	-5.6035850	0.4765740	-1.5994820
H	0.0388620	3.0942160	-0.8731310
C	0.2044180	2.0173750	0.9569440
C	-0.2365770	1.8104450	3.7264900
C	1.1151720	1.3389380	1.7755850
C	-0.9075800	2.6229480	1.5506110
C	-1.1333190	2.5137280	2.9239100
C	0.8943080	1.2308070	3.1472030
H	2.0011250	0.8985540	1.3272050
H	-1.6008000	3.1963250	0.9429740
H	-2.0046940	2.9887850	3.3651910
H	1.6106100	0.6969460	3.7658990
H	-0.4078760	1.7273910	4.7959100

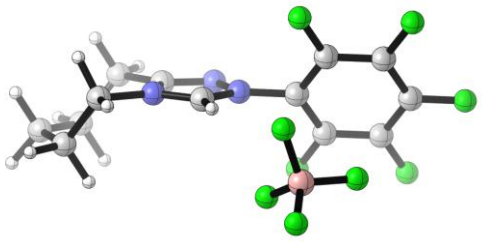
Caprolactam-Derived Catalyst System Structures:

Starting Materials



157

2-(perfluorophenyl)-6,7,8,9-tetrahydro-5H-[1,2,4]triazolo[4,3-a]azepin-2-ium tetrafluoroborate (*Caprolactam-Based Triazolium Salt*) (**157**)

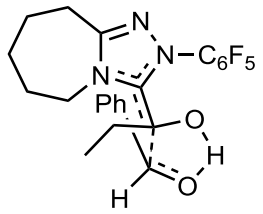


XYZ Coordinates

37

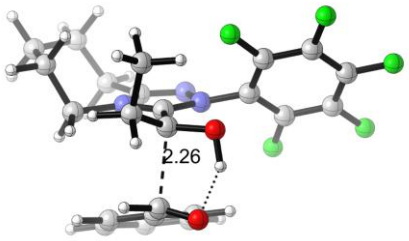
H	5.6949350	-2.0837320	-1.0364840
C	4.9353120	-1.3227150	-0.8342410
H	4.3762700	-1.1764410	-1.7665310
C	5.6432930	-0.0271140	-0.4307840
H	6.3749580	0.2187710	-1.2073390
H	6.2120200	-0.2049390	0.4920550
C	4.7405530	1.1924810	-0.2274100
H	5.3708620	2.0681720	-0.0419230
H	4.1593270	1.4040450	-1.1332810
C	3.7894670	1.0967660	0.9609610
H	3.3496370	2.0672550	1.1954640
H	4.2954910	0.7152880	1.8530260
N	2.6530710	0.1966320	0.6887440
C	2.7229990	-1.1440770	0.3719090
C	3.9972450	-1.8994120	0.2390760
H	4.5019580	-1.9076360	1.2135340
H	3.7234390	-2.9290770	-0.0014710
N	1.5225550	-1.6281390	0.1935990
N	0.6894030	-0.5697360	0.4010800
C	1.3673140	0.5319170	0.6962650
H	0.9328680	1.5041760	0.8933910
C	-0.7130460	-0.7223140	0.2791980
C	-3.4544440	-1.0706100	0.0257360
C	-1.2620490	-1.0991070	-0.9419100
C	-1.5500500	-0.5090020	1.3677280
C	-2.9198910	-0.6790680	1.2444250
C	-2.6282210	-1.2819000	-1.0697150
F	-0.4753070	-1.2754230	-1.9969870
F	-3.1539480	-1.6354260	-2.2395650
F	-4.7657560	-1.2355700	-0.0974050
F	-3.7183260	-0.4784680	2.2897840
F	-1.0390730	-0.1497370	2.5419050
B	-1.2945000	2.4211500	-0.5943390
F	-2.5206650	1.7728980	-0.7824870
F	-0.2881690	1.7399550	-1.3127310
F	-1.3703480	3.7475520	-1.0236240
F	-0.9556720	2.3844410	0.7810950

Carbon-Carbon Bond Formation Transition States



TS [V-VI]$^{(cap)}_{(Z)P\text{-}(si)B}$

(*Z*)-Propionaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]$^{(cap)}_{(Z)P\text{-}(si)B}$**)

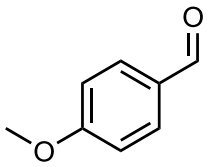


XYZ Coordinates

55

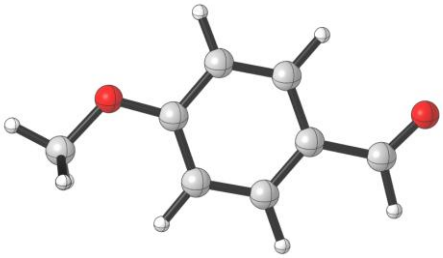
C	2.7253610	0.1927190	-2.6440560
H	3.5415770	0.8093450	-2.2454790
C	3.2278580	-1.0198710	0.0122320
H	3.1972440	-1.2091400	1.0817160
H	3.8991850	-0.1683930	-0.1377720
C	1.6665540	0.0392540	-1.6091380
N	1.8908480	-0.5890440	-0.4047590
N	0.4280040	0.3906810	-1.7453940
C	0.6997780	-0.6558370	0.2750480
N	-0.1810450	-0.0290130	-0.5738770
C	-1.5882280	-0.0181820	-0.5476390
C	-4.3855550	0.0092030	-0.5925040
C	-2.2888530	1.1658810	-0.7585580
C	-2.3207450	-1.1934860	-0.3905860
C	-3.7044510	-1.1835860	-0.3904180
C	-3.6765040	1.1836330	-0.7846110
F	-1.6870840	-2.3535030	-0.2377580
F	-4.3862250	-2.3173170	-0.2195180
F	-5.7169390	0.0216520	-0.6092080
F	-4.3272370	2.3304680	-0.9864350
F	-1.6391130	2.3161020	-0.9320010
C	0.4165840	-1.0710980	1.5913790
O	-0.9062910	-0.9033320	1.9414010
C	1.1069690	0.6912320	2.8227210
O	0.0181660	0.8470980	3.4414240
H	2.2726720	0.7379930	-3.4752750
H	-0.8838180	-0.1952540	2.6564700
H	1.9087340	0.0773620	3.2683830
C	1.5731020	1.6848210	1.8204920
C	2.4553330	3.5072560	-0.1099320
C	2.9352720	1.7952810	1.5247130
C	0.6542270	2.5043290	1.1537150
C	1.0934030	3.4052760	0.1873740
C	3.3773660	2.7058230	0.5657380
H	3.6495530	1.1658560	2.0524540
H	-0.4016000	2.4188540	1.3975910
H	0.3759410	4.0286650	-0.3382430
H	4.4381390	2.7912900	0.3460020
H	2.7966230	4.2127290	-0.8620040
C	1.0565010	-2.2560420	2.2813440
H	0.9356040	-2.0884030	3.3597380
H	2.1304180	-2.3227840	2.0983190
C	0.3925750	-3.5850280	1.9044610
H	0.8012270	-4.4042610	2.5051670
H	0.5585340	-3.8235410	0.8484930
H	-0.6859680	-3.5371830	2.0772740
C	3.7205100	-2.2253310	-0.7869060
H	2.9108480	-2.9605600	-0.8734300
H	4.5257970	-2.6990230	-0.2152070
C	3.2689630	-1.1687620	-3.1214690
H	2.4245860	-1.8400530	-3.3227970
H	3.7736210	-1.0020890	-4.0783260
C	4.2625740	-1.8425210	-2.1685340
H	4.6483860	-2.7451100	-2.6549820
H	5.1208830	-1.1712020	-2.0273910

***p*-Anisaldehyde System Structures: Starting Materials**



39

p-Anisaldehyde (**39**)



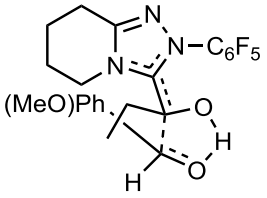
XYZ Coordinates

18

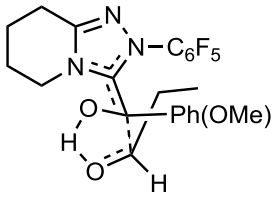
C	2.8905490	-0.5224740	-0.0000250

H	3.1498350	-1.5987710	-0.0002240
O	3.7703560	0.3203510	0.0002540
C	1.4502020	-0.2245400	-0.0000940
C	-1.2931450	0.2885240	-0.0000500
C	0.9807100	1.1001390	-0.0000960
C	0.5337790	-1.2768760	-0.0000920
C	-0.8383850	-1.0352920	-0.0000550
C	-0.3760100	1.3567920	-0.0000880
H	1.6963990	1.9173750	-0.0001040
H	0.8956520	-2.3026950	-0.0001050
H	-1.5322590	-1.8669230	-0.0000260
H	-0.7615240	2.3714880	-0.0000970
O	-2.5957650	0.6392250	-0.0000080
C	-3.5715610	-0.3971850	0.0001620
H	-4.5382490	0.1053280	0.0002560
H	-3.4815910	-1.0184160	0.8974300
H	-3.4818220	-1.0185100	-0.8970660

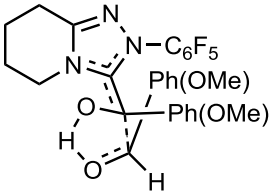
Carbon-Carbon Bond Formation Transition States



TS [V-VI]$_{(Z)P\text{-}(si)A}$

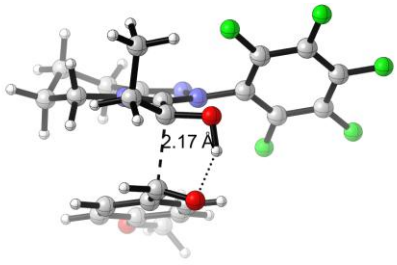


TS [V-VI]$_{(E)A\text{-}(re)P}$



TS [V-VI]$_{(E)A\text{-}(re)A}$

(*Z*)-Propionaldehyde BI Attacking *si* Face of Anisaldehyde (**TS [V-VI]$_{(Z)P\text{-}(si)A}$**)



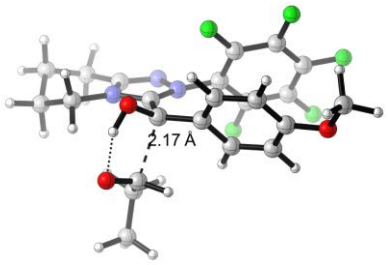
XYZ Coordinates

56

C	2.5812340	-0.1102520	-2.6753480
H	3.2533290	0.6338460	-2.2289370
C	3.3352150	-1.4266750	-2.8739650
C	3.6790260	-2.0138630	-1.5072210
H	4.2903180	-2.9149810	-1.6047340
H	4.2598780	-1.2789460	-0.9373430
C	2.4292200	-2.3941970	-0.7193150
H	1.9964040	-3.3261210	-1.0984680
H	2.6705080	-2.5222580	0.3367690
C	1.4345650	-0.3141300	-1.7419370
N	1.4030040	-1.3462920	-0.8302690
N	0.3738420	0.4257600	-1.6639840
C	0.2383850	-1.2493720	-0.1183780
N	-0.3740140	-0.1483780	-0.6512710
C	-1.7073680	0.2817620	-0.5094450
C	-4.3529910	1.1658800	-0.3218850
C	-1.9970660	1.6221470	-0.2727630
C	-2.7717150	-0.6009380	-0.6843580
C	-4.0829730	-0.1728720	-0.5731850
C	-3.3091990	2.0658430	-0.1799230
F	-2.5352340	-1.8772600	-0.9743450
F	-5.0890200	-1.0350010	-0.7273250
F	-5.6131830	1.5832920	-0.2258610
F	-3.5652920	3.3544430	0.0493660
F	-1.0160240	2.5115460	-0.1256440
C	-0.1691510	-1.9615340	1.0364730
O	-1.4084480	-1.5800220	1.4975210
C	0.9346270	-0.9810770	2.6303880
O	-0.0764410	-0.6728330	3.3397630
H	2.1997890	0.3041810	-3.6113410
H	-1.1934130	-1.1438430	2.3906100
H	1.4936300	-1.9050040	2.8603740
C	1.7570230	0.0767650	1.9861640
C	3.2731780	2.0414440	0.6755040
C	3.1018520	-0.1543910	1.6649440
C	1.1972860	1.3146360	1.6650650
C	1.9375190	2.2964500	1.0073120
C	3.8589110	0.8163620	1.0238180
H	3.5623850	-1.1045880	1.9303450
H	0.1617260	1.5078710	1.9328480
H	1.4704070	3.2424900	0.7589670
H	4.9042040	0.6481790	0.7812640
C	0.1163620	-3.4350380	1.2362020
H	-0.0999370	-3.6406050	2.2920120
H	1.1719920	-3.6737350	1.0893130
C	-0.7526390	-4.3364090	0.3544870
H	-0.5682450	-5.3929990	0.5751350
H	-0.5407850	-4.1689280	-0.7078000

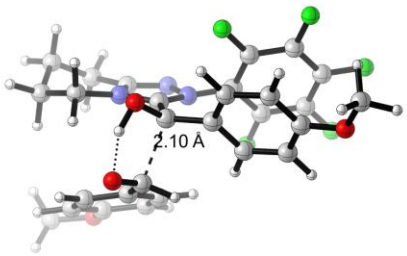
H -1.8136000 -4.1314420 0.5235890
H 2.7220940 -2.1323780 -3.4474600
H 4.2462300 -1.2388540 -3.4472780
O 4.0791610 2.9208960 0.0251630
C 3.5110450 4.1554720 -0.3896100
H 3.1784630 4.7459010 0.4712080
H 2.6703620 3.9905500 -1.0732260
H 4.3049650 4.6904570 -0.9106300

(*E*)-Anisaldehyde BI Attacking *re* Face of Propionaldehyde (**TS [V-VI]$_{(E)A\text{-}(re)P}$**)



XYZ Coordinates
56
C 4.3165540 -2.3636240 -0.5147800
H 4.1456590 -3.3525220 -0.9470330
C 5.3129600 -0.0955620 -0.8279270
H 5.5072190 -0.0645960 0.2519770
H 6.0925050 0.4938250 -1.3180420
C 3.9777480 0.5709140 -1.1299740
H 3.8815240 1.5239150 -0.6104190
H 3.8571200 0.7393420 -2.2035190
C 3.0058420 -1.6496710 -0.4293910
N 2.8719600 -0.3041060 -0.6861600
N 1.8791680 -2.1839780 -0.0729790
C 1.5661420 0.0422130 -0.4723270
N 0.9773230 -1.1345910 -0.1087790
C -0.3929210 -1.4495850 -0.0404350
C -3.1085840 -2.0525980 0.1317210
C -1.2330450 -1.2587040 -1.1343730
C -0.9313740 -1.9702490 1.1317800
C -2.2795620 -2.2778750 1.2219210
C -2.5878510 -1.5364760 -1.0478680
F -0.1543220 -2.1344390 2.2007190
F -2.7876830 -2.7651120 2.3530000
F -4.4049350 -2.3332180 0.2175030
F -3.3866910 -1.3353160 -2.0942730
F -0.7383140 -0.7898320 -2.2774580
C 1.0235610 1.3574620 -0.5124630
O 1.5988690 2.1501760 -1.4914740
C 1.9599470 2.3667440 1.1666810
O 2.6826360 3.1908250 0.5342200
H 4.6836330 -2.5106750 0.5076120
H 2.0974900 2.8506220 -0.9838590
C -0.4326290 1.5736980 -0.2861200
C -3.2002360 1.9637260 0.0944780
C -1.0468590 1.2739240 0.9433300
C -1.2322750 2.1114030 -1.2967720
C -2.6049850 2.3067820 -1.1221130
C -2.4088160 1.4537150 1.1330260
H -0.4472350 0.8794540 1.7626910
H -0.7746920 2.3688620 -2.2473590
H -3.1903830 2.7155260 -1.9378240
H -2.8801330 1.2115400 2.0814410
C 2.5885110 1.3129920 2.0550390
H 1.8645500 0.5141090 2.2599470
H 3.4552910 0.8710940 1.5503760
C 3.0349610 1.9593110 3.3713830
H 2.1888050 2.4297650 3.8838710
H 3.7905550 2.7289990 3.1886760
H 3.4631000 1.2119840 4.0459230
H 0.9664820 2.7019200 1.5130680
C 5.3314900 -1.5434080 -1.3137640
H 6.3242730 -1.9822010 -1.1891800
H 5.0875040 -1.5774520 -2.3824390
O -4.5257900 2.0969860 0.3663710
C -5.3631160 2.5969250 -0.6656270
H -6.3707370 2.6215090 -0.2503920
H -5.3464190 1.9386920 -1.5416680
H -5.0662620 3.6100440 -0.9593240

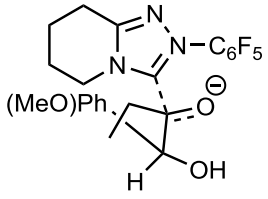
(*E*)-Anisaldehyde BI Attacking *re* Face of Anisaldehyde (**TS [V-VI]$_{(E)A\text{-}(re)A}$**)



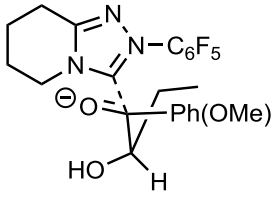
XYZ Coordinates
64
C 3.5177430 0.9910530 2.4065010
H 3.3509640 1.8211790 3.0964820
C 4.1521620 -1.4008850 2.1061940
H 4.7121130 -1.1091210 1.2098420

H	4.6523890	-2.2710960	2.5400970
C	2.7469690	-1.8390470	1.7133460
H	2.7586890	-2.4875830	0.8386660
H	2.2589560	-2.3696170	2.5343680
C	2.2163260	0.6294490	1.7727470
N	1.9086670	-0.6595360	1.3978620
N	1.2577100	1.4535110	1.4801640
C	0.6758500	-0.6448440	0.8187610
N	0.2935020	0.6583460	0.8922430
C	-1.0032670	1.1942760	0.7551040
C	-3.5744380	2.2277230	0.4672040
C	-2.0542180	0.7084140	1.5289010
C	-1.2544170	2.2259380	-0.1420680
C	-2.5315080	2.7467140	-0.2869210
C	-3.3390030	1.2027520	1.3748850
F	-0.2717800	2.6968790	-0.9066580
F	-2.7641140	3.7244520	-1.1609280
F	-4.8032150	2.7119820	0.3218310
F	-4.3419730	0.7171510	2.1034130
F	-1.8302400	-0.2571250	2.4174970
C	0.0426830	-1.7484550	0.1528870
O	0.3225040	-2.9570580	0.7489340
C	1.2227960	-2.0651550	-1.5591460
O	1.5446310	-3.2846570	-1.3357830
H	4.1878810	1.3454350	1.6126830
H	0.8371050	-3.4475630	0.0159660
C	-1.3628640	-1.6114420	-0.3434630
C	-4.0418390	-1.3926670	-1.2041430
C	-1.7250960	-0.7344520	-1.3798330
C	-2.3714120	-2.3949750	0.2216850
C	-3.7016710	-2.2949390	-0.1930190
C	-3.0410280	-0.6145850	-1.8012650
H	-0.9681160	-0.1200540	-1.8601060
H	-2.1118700	-3.0911370	1.0132740
H	-4.4536620	-2.9175730	0.2780410
H	-3.3128980	0.0703460	-2.5995090
H	0.3731850	-1.8571850	-2.2279120
C	4.1301130	-0.2330180	3.0899920
C	2.2951270	-1.0211360	-1.6293570
C	4.3086580	0.9406910	-1.7098380
C	3.6331240	-1.3600600	-1.4386150
C	1.9837310	0.3214150	-1.8976720
C	2.9683240	1.2956190	-1.9278480
C	4.6449910	-0.3967390	-1.4846000
H	3.8865810	-2.4009240	-1.2552770
H	0.9519920	0.6100330	-2.0796800
H	2.7250310	2.3368310	-2.1185880
H	5.6760780	-0.6976970	-1.3374840
H	5.1430250	0.0081770	3.4213810
H	3.5458770	-0.4998940	3.9788940
O	5.2056800	1.9601730	-1.7424560
O	-5.3018560	-1.2076600	-1.6770060
C	6.5672380	1.6537240	-1.4802200
H	6.9710270	0.9655290	-2.2308560
H	6.6882580	1.2207190	-0.4802360
H	7.1030780	2.6015300	-1.5325830
C	-6.3392920	-2.0037480	-1.1223880
H	-7.2507520	-1.7148160	-1.6458090
H	-6.4572570	-1.8079290	-0.0505340
H	-6.1472940	-3.0700010	-1.2857640

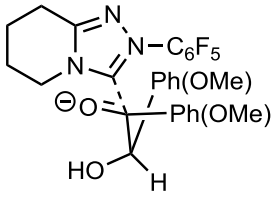
Ejection Transition States



TS [VI-I]$_{(Z)\text{P-}(si)\text{A}}$

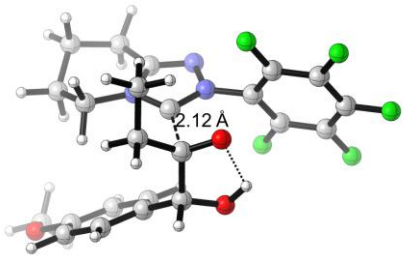


TS [VI-I]$_{(E)\text{A-}(re)\text{P}}$



TS [VI-I]$_{(E)\text{A-}(re)\text{A}}$

(*Z*)-Propionaldehyde BI + *si* Face of Anisaldehyde Eject (**TS [VI-I]$_{(Z)\text{P-}(si)\text{A}}$**)



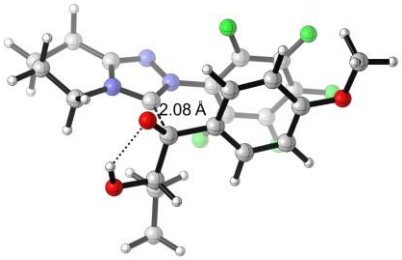
XYZ Coordinates

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N	-1.1930310	1.5009380	-0.2196920

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N 0.3656580 1.6595750 -1.7622030
C 2.0756420 0.3862140 -0.6598610
C 4.6217510 -0.7274860 -0.6093580
C 2.3641820 -0.7462470 -1.4114690
C 3.0812070 0.9660220 0.1033620
C 4.3496610 0.4102930 0.1383610
C 3.6311270 -1.3093080 -1.3883210
F 2.8329890 2.0607230 0.8137190
F 5.3098690 0.9612980 0.8812000
F 5.8403130 -1.2598600 -0.5853930
F 3.9024710 -2.3984390 -2.1079150
F 1.4151340 -1.3084600 -2.1554990
C -2.4884270 1.7315030 0.4377430
H -2.3364210 2.4860480 1.2169270
H -2.7919040 0.7931800 0.9054390
C -1.7990570 2.7914140 -2.3031230
H -2.1909400 2.1268270 -3.0820440
H -1.2460840 3.5910520 -2.8019370
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C -3.5186410 2.2057170 -0.5799080
H -3.8209100 1.3612240 -1.2128120
H -4.4040730 2.5383510 -0.0315660
C 0.3256270 -0.2403370 2.0801430
O 1.5775670 -0.2308660 2.1397400
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O 0.6309700 -2.2543170 0.8187610
H 1.4958110 -1.8741850 1.0635480
C -0.4757520 0.6109840 3.0515010
H -0.4411720 0.0758840 4.0116360
H -1.5251350 0.6489390 2.7463200
C 0.1030480 2.0092240 3.2206680
H 1.1473960 1.9588710 3.5397820
H -0.4601380 2.5767690 3.9672470
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H -0.3007160 -2.1640920 2.6623890
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C -4.2723550 -1.5838260 0.0627860
C -1.8802190 -1.6327490 -0.2572480
C -2.7850280 -1.6640230 1.9643250
C -4.0745580 -1.6252120 1.4490170
C -3.1686270 -1.5988110 -0.7956380
H -1.0233570 -1.6479410 -0.9255090
H -2.6434770 -1.7061740 3.0422390
H -4.9418740 -1.6356680 2.1022020
H -3.2968180 -1.5870070 -1.8720300
H -2.6037280 4.1491300 -0.8172560
H -3.7293630 3.7291330 -2.1110360
O -5.5654260 -1.5388380 -0.3546180
C -5.8088350 -1.5537100 -1.7535610
H -5.3722010 -0.6748870 -2.2420780
H -6.8922000 -1.5306880 -1.8705920
H -5.4116080 -2.4655530 -2.2132140

(*E*)-Anisaldehyde BI + *re* Face of Propionaldehyde Eject (**TS [VI-I]**$_{(E)\text{A-}(re)\text{P}}$)

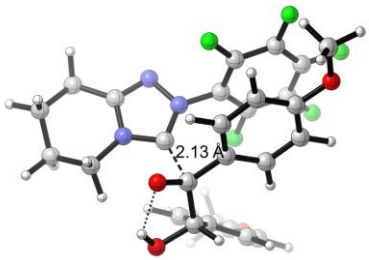


XYZ Coordinates
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C 2.9338340 -1.7581100 -0.8420540
N 1.7602950 -2.2586420 -0.5833630
C -0.3481480 -1.3445540 0.0935560
C -3.0316550 -1.7364400 0.7271080
C -1.3225220 -1.3069090 -0.8983480
C -0.7328770 -1.6205990 1.4013380
C -2.0682310 -1.8102030 1.7237030
C -2.6612150 -1.4880500 -0.5871030
F 0.1839200 -1.7126590 2.3629870
F -2.4318760 -2.0604510 2.9807790
F -4.3142640 -1.8998760 1.0342680
F -3.5897500 -1.4209390 -1.5390680
F -0.9710720 -1.1095120 -2.1655520
C 4.1034520 0.4744440 -0.8291410
H 4.4608570 0.7265900 0.1737150
H 3.7702990 1.3894940 -1.3185640
C 4.1474960 -2.5134870 -1.2786470
H 4.0336000 -2.7590900 -2.3407710
H 4.1915160 -3.4563330 -0.7280270
C 5.4053740 -1.6638210 -1.0755940
C 5.1756250 -0.2566120 -1.6264870
H 4.8764060 -0.3170820 -2.6804600
H 6.0920440 0.3376090 -1.5788510
C 1.1782130 2.0156310 -0.1340150

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C	1.7207050	2.3371760	1.2874470
C	-0.3264720	1.8816600	-0.2755770
C	-3.1038330	1.6831310	-0.6865180
C	-1.2111830	1.8257450	0.8124640
C	-0.8655830	1.8644490	-1.5607320
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H	2.5523750	0.5398430	2.0742300
H	0.8081090	0.6391190	2.2637260
C	1.9171290	1.7621490	3.7422500
H	2.8435140	2.3395900	3.8204640
H	1.9624680	0.9475190	4.4714750
H	1.0856070	2.4186750	4.0224530
H	1.0664810	3.1521120	1.6475970
O	3.0379340	2.8332010	1.1512430
H	3.0970720	3.1001630	0.2137700
H	5.6491090	-1.6056290	-0.0075410
H	6.2479150	-2.1441140	-1.5790450
O	-4.4512850	1.5537510	-0.7819780
C	-5.0249720	1.5436490	-2.0821510
H	-4.8254110	2.4847300	-2.6068180
H	-6.0989710	1.4308620	-1.9344600
H	-4.6493160	0.7029860	-2.6751520

(*E*)-Anisaldehyde BI + *re* Face of Anisaldehyde Eject

(**TS [VI-I]**$_{(E)\text{A-}(re)\text{A}}$)



XYZ Coordinates

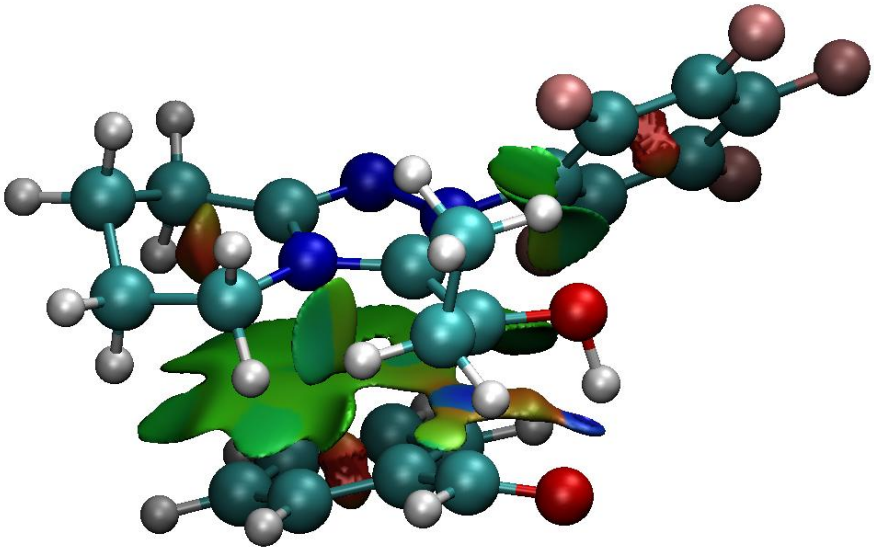
64

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C	0.7428700	-0.1477480	-1.2964830
C	2.9531170	1.5218260	-1.6074640
C	2.0190450	-0.6805080	-1.4511120
C	0.5880120	1.2336800	-1.3215900
C	1.6861680	2.0691530	-1.4642970
C	3.1218470	0.1443810	-1.6055880
F	-0.6220100	1.7735590	-1.2148620
F	1.5278700	3.3926750	-1.4750920
F	4.0099580	2.3183770	-1.7356870
F	4.3417690	-0.3778400	-1.7240360
F	2.1922960	-2.0001560	-1.4470270
C	-2.9755290	-2.8732460	0.3485300
H	-3.3975800	-2.1474150	1.0447780
H	-2.4504290	-3.6364230	0.9294240
C	-2.5943900	-3.3983620	-2.5962640
H	-1.9511450	-3.9587880	-3.2791930
H	-3.2837570	-2.8047830	-3.2081170
C	-3.3896900	-4.3176520	-1.6645520
C	-4.0366710	-3.4978480	-0.5476750
H	-4.6756740	-4.1266490	0.0780730
H	-4.6693580	-2.7131090	-0.9817340
C	-0.5840420	-1.1744070	2.0275600
O	-0.8488240	-2.3437630	2.3926190
C	-1.5719920	-0.0929970	2.5998000
O	-2.7349610	-0.7851400	3.0051340
H	-2.4405320	-1.7141790	3.0899740
C	0.8735350	-0.8130530	1.8515100
C	3.6207450	-0.2907290	1.5474750
C	1.3589910	0.5016420	1.8586940
C	1.7915730	-1.8528250	1.7032670
C	3.1569900	-1.6096790	1.5488940
C	2.7134850	0.7640480	1.7144040
H	0.6814650	1.3391900	1.9682760
H	1.4257190	-2.8751970	1.7047050
H	3.8385870	-2.4428690	1.4212570
H	3.0891750	1.7833870	1.7175110
H	-1.0376050	0.2858950	3.4889500
C	-1.9982560	1.1037820	1.7770940
C	-2.9069630	3.3537120	0.3410340
C	-2.9700700	0.9836300	0.7820590
C	-1.5285570	2.3897320	2.0724110
C	-1.9603890	3.5020140	1.3604940
C	-3.4284350	2.0869710	0.0624930
H	-3.4078420	0.0117990	0.5757870
H	-0.8200870	2.5309130	2.8856950
H	-1.5881710	4.4954520	1.5923880

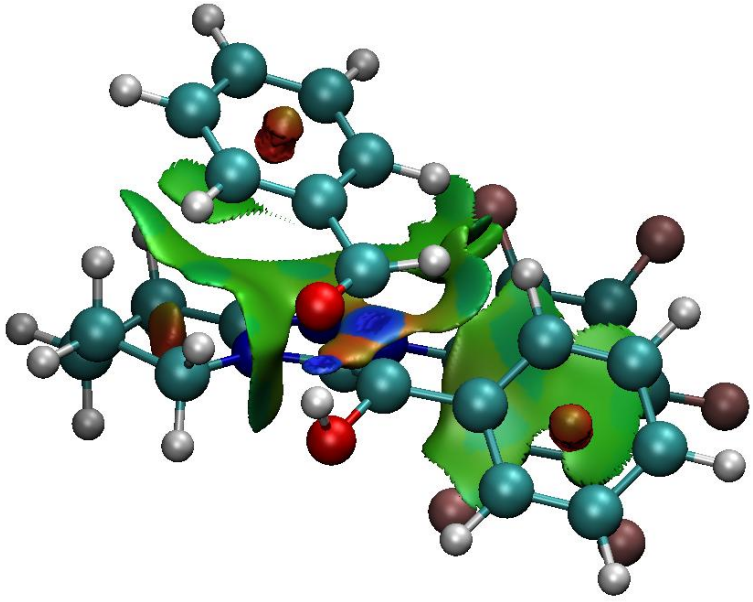
H	-4.1859000	1.9471370	-0.6997150
H	-4.1494440	-4.8475170	-2.2445730
H	-2.7242790	-5.0714480	-1.2263050
O	-3.2724120	4.4912000	-0.3072980
O	4.9184040	0.0641740	1.3757370
C	-4.2375630	4.3802630	-1.3428170
H	-5.1922590	4.0073450	-0.9552950
H	-3.8825890	3.7230250	-2.1448060
H	-4.3742820	5.3878540	-1.7356250
C	5.8722340	-0.9760800	1.2041600
H	5.9165950	-1.6164630	2.0921730
H	6.8333720	-0.4817610	1.0640360
H	5.6414240	-1.5827730	0.3222720

5.2.7. Modelled and Visualized Non-Covalent Interactions

NCI Plot for (*Z*)-Propionaldehyde BI Attacking *si* Face of Benzaldehyde (**TS [V-VI]**$_{(Z)P\text{-}(si)B}$)

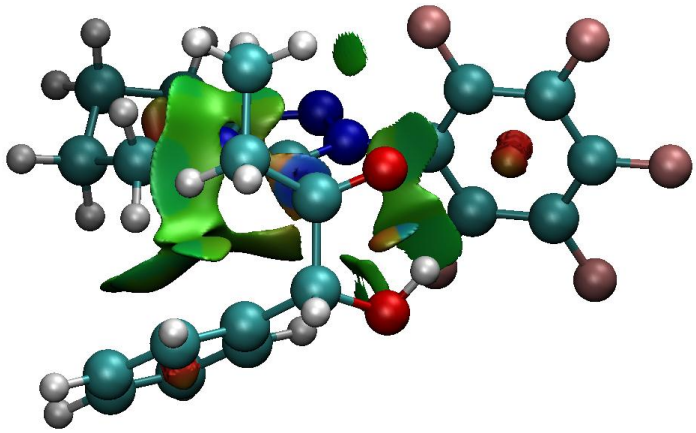


NCI Plot for (*E*)-Benzaldehyde BI Attacking *re* Face of Benzaldehyde (**TS [V-VI]**$_{(E)B\text{-}(re)B}$)

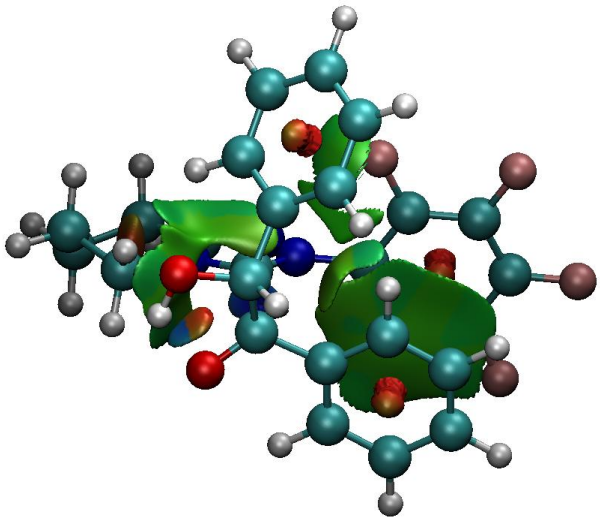


(Note: Mirror image shown)

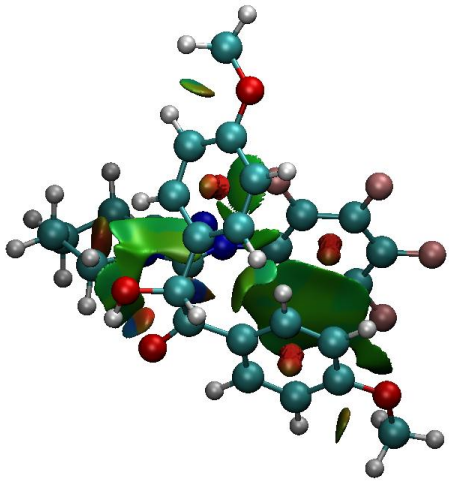
NCI Plot for (*Z*)-Propionaldehyde BI + *si* Face of Benzaldehyde Eject (**TS [VI-I]$_{(Z)P\text{-}(si)B}$**)



NCI Plot for (*E*)-Benzaldehyde BI + *re* Face of Benzaldehyde Eject (**TS [VI-I]$_{(E)B\text{-}(re)B}$**)



NCI Plot for (*E*)-Anisaldehyde BI + *re* Face of Anisaldehyde Eject (**TS [VI-I]$_{(E)A\text{-}(re)A}$**)



5.3. Experimental Procedures for Total Synthesis of Sparteine

Preparation of Zinc Chloride Solution:

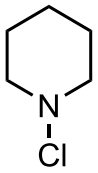
A round bottom flask with a Schlenk take-off was pre-weighed and a mass of zinc (II) chloride was added. The vessel was capped with a pre-weighed glass stopper and placed under vacuum (≤1 torr.). The mixture was then heated to 300 °C. After 24 h the vessel was cooled to room temperature (23 °C), placed under inert (argon) atmosphere, and re-weighed to determine the mass of dry zinc chloride. Anhydrous tetrahydrofuran was added to afford a 0.8 M solution. A magnetic stirbar was added to the solution and it was stirred vigorously for 48 h to dissolve all solids. The solution was stored under inert (argon) atmosphere and may be for several months after preparation.

Preparation of Copper Cyanide + Lithium Chloride Solution:

A round bottom flask with a Schlenk take-off was pre-weighed and a mass of lithium chloride is added. The vessel was capped with a pre-weighed glass stopper and placed under vacuum (≤1 torr.). The mixture was then heated to 200 °C. After 72 h the vessel was cooled to room temperature (23 °C), placed under inert (argon) atmosphere, and re-weighed to determine the mass of dry lithium chloride. Anhydrous tetrahydrofuran was added to afford a 0.6 M solution. Copper cyanide (0.5 equiv.) was added to the solution. A magnetic stir bar was added to the solution and it was stirred vigorously for 48 h to dissolve all solids. The solution was stored under inert (argon) atmosphere and may be used until particulate or a green hue is visible.

5.3.1. Procedures for the Imine Acceptor Approaches

Synthesis of *N*-chloropiperidine (297):[131]



A round bottom flask was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Methyl *tert*-butyl ether

was added (150 mL, 0.4 M). The flask was brought to 0 °C. Sodium hypochlorite (75 mL of a 6% w/w solution in water, 60 mmol, 1.00 equiv.) and acetic acid (3.4 mL, 60 mmol, 1.00 equiv.) were added slowly while stirring. The reaction mixture was stirred for 20-30 min. and then piperidine (5.9 mL, 60 mmol, 1.00 equiv.) was added dropwise while stirring. The reaction mixture was stirred for 1 h at 0 °C and was then warmed to room temperature (23 °C). The organic component was washed with water three times and brine once. The organic component was dried over Na_2SO_4. Volatiles were then removed *in vacuo* (ca. 50 torr.) affording 5.49 g (77% yield) of the product as a pale yellow oil. All spectra are consistent with those previously reported.[131]

General Procedure:[57c]

N-Chloropiperidine (typically 2.00 equiv.) and water (0.6 M) were added to a round bottom flask. Solid sodium hydroxide (to pH ca. 13) was added. 3-Oxopentanedioic acid (1.00 equiv.) was added in one portion while stirring at room temperature (23 °C). Additional water was added to adjust the concentration (to 0.2 M) and the pH was re-adjusted to ca. 13 with additional sodium hydroxide as needed. The flask was then brought to the desired temperature (23-100 °C). The reaction mixture was stirred for the desired amount of time (1-72 h) and was then quenched by slow addition of 2 M HCl (to pH ca. 6). The organic component was dried over Na_2SO_4. Volatiles were then removed *in vacuo* (ca. 50 torr.).

5.3.2. Procedures for Alkyl and Allyl Halide Acceptor Approaches

General Procedure 1:[148]

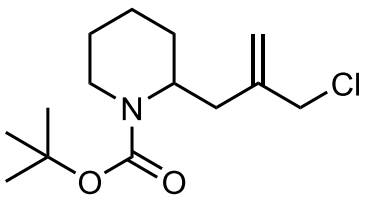
N-Boc piperidine (*tert*-butyl piperidine-1-carboxylate (**299**); 1.00 equiv.) was added to a round bottom flask with a Schlenk take-off. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Tetramethylethylenediamine (2.00-4.00 equiv.) and solvent (typically diethyl ether, 0.2 M) were added. The flask was then brought to the desired temperature (-78 °C) and stirred for 20 min. *sec*-Butyllithium (1.00-1.10 equiv.) was added dropwise while stirring. The reaction mixture was stirred for 3

h. An electrophile (epichlorohydrin, allyl bromide, allyl chloride; 0.50-4.00 equiv.) was added dropwise while stirring. The reaction mixture was stirred for the desired amount of time, typically 2-3 h, and was then warmed to room temperature (23 °C). The reaction was quenched by slow addition of water. The mixture was extracted 3-5 times with diethyl ether. The organic components were combined and dried over Na_2SO_4. Volatiles were then removed *in vacuo* (ca. 50 torr.).

General Procedure 2:[138a]

N-Boc piperidine (*tert*-butyl piperidine-1-carboxylate (**299**); 1.00 equiv.) was added to a round bottom flask with a Schlenk take-off. The vessel was fitted with a septum, purged under vacuum (≤1 torr.) three times, and placed under inert (argon) atmosphere. Tetramethylethylenediamine (1.20 equiv.) and diethyl ether (0.25 M) were added. The flask was then brought to the desired temperature (-78 °C) and stirred for 20 min. *sec*-Butyllithium (1.20 equiv.) was added dropwise while stirring. The reaction mixture was stirred for 3 h. Zinc chloride (1.30 equiv. from a 0.8 M solution in terahydrofuran) was added dropwise while stirring. The reaction mixture was stirred for 40 min. Copper cyanide and lithium chloride (1.20 and 2.40 equiv. respectively from a 0.3/0.6 M solution in terahydrofuran) were added dropwise while stirring. The reaction mixture was stirred for 30 min. An electrophile was added dropwise while stirring. The reaction mixture was stirred for 30 min. and was then warmed slowly to room temperature (23 °C). The reaction was quenched by slow addition of ammonium hydroxide. The mixture was extracted five times with diethyl ether. The organic components were combined and dried over Na_2SO_4. Volatiles were then removed *in vacuo* (ca. 50 torr.).

Synthesis of *tert*-butyl 2-(2-(chloromethyl)allyl)piperidine-1-carboxylate (317):



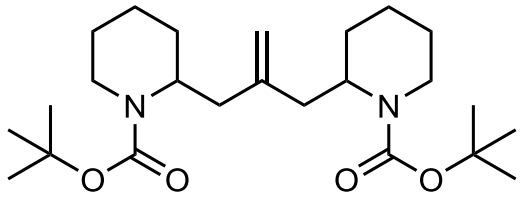
Following the *General Procedure 2*, using 3-chloro-2-(chloromethyl)prop-1-ene (1.20 equiv.) as the electrophile. Purification is accomplished *via* distillation (110 °C at 0.1 torr.) which removes the starting materials, leaving the purified product in the residue.

Reaction carried out on 1.00 equiv. = 0.54 mmol scale. Affords 0.095 g (64% yield) of the product as a pale yellow oil.

Reaction carried out on 1.00 equiv. = 39.45 mmol scale. Affords 4.29 g (40% yield) of the product as a pale yellow oil.

Yellow oil (4.29 g, 40% yield). **FTIR** (KBr; thin film) ν_{max} (cm^{-1}): 2975, 2933, 2361, 1689, 1413, 1365, 1161; **^{1}H NMR** (600 MHz, d_6-DMSO) δ 5.17 (s, 1H), 4.99 (s, 1H), 4.55-4.3 (m, 1H), 4.30-4.12 (m, 1H), 4.07 (app. d, *J* = 12.0 Hz, 1H), 4.08-3.88 (m, 1H), 2.81 (app. t, *J* = 12.6 Hz, 1H), 2.59 (dd, *J* = 13.8, 10.8 Hz, 1H), 2.34 (dd, *J* = 13.8, 6.0 Hz, 1H), 1.72-1.52 (m, 6H), 1.46 (s, 9H); **^{13}C NMR** (125 MHz, $CDCl_3$) δ 155.2, 117.1, 48.1 (br.), 48.0, 39.0 (br.), 33.7, 28.6 (sept.), 25.7, 19.1; **HRMS** (TOF^+) *m*/*z* calculated for $C_{14}H_{24}NO_2NaCl$ $[M+Na]^+$: 296.1388; found: 296.1375.

Synthesis of di-*tert*-butyl 2,2'-(2-methylenepropane-1,3-diyl)bis(piperidine-1-carboxylate) (306):



Following the *General Procedure 2*, using *tert*-butyl 2-(2-(chloromethyl)allyl)piperidine-1-carboxylate (1.00 equiv.) as the electrophile. Purification is accomplished *via* passing the mixture through a short silica plug (30% ethyl acetate, 70% hexanes) to remove the electrophile followed by distillation (110 °C at 0.1 torr.) to remove the *N*-Boc piperidine.

Reaction carried out on 1.00 equiv. = 2.70 mmol scale. Affords 0.250 g (22% yield) of the product as a pale yellow oil.

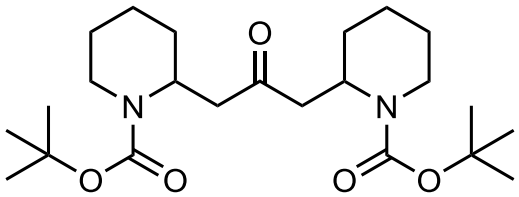
Reaction carried out on 1.00 equiv. = 15.70 mmol scale. Affords 4.96 g (75% yield) of the product as a pale yellow oil.

Yellow oil (4.96 g, 75% yield). **FTIR** (KBr; thin film) ν_{max} (cm^{-1}): 2933, 2859, 1691, 1413, 1365, 1269, 1160, 1042, 893, 766; **^{1}H NMR** (600 MHz, $CDCl_3$, 330 K) δ 4.79

(d, *J* = 3.4 Hz, 2H), 4.36 (br. d, *J* = 24.5 Hz, 2H), 3.96 (br. t, *J* = 10.3 Hz, 2H), 2.85-2.75 (m, 2H), 2.40 (ddd, *J* = 18.8, 14.0, 8.7 Hz, 2H), 2.28-2.19 (m, 2H), 1.65-1.51 (m, 12H), 1.44 (s, 18H); **^{13}C NMR** (125 MHz, $CDCl_3$, 330 K) δ 155.1, 114.3, 114.1, 49.4, 39.1, 36.3, 36.1, 28.3, 25.7, 19.3, 19.1; **HRMS** (EI^+) *m*/*z* calculated for $C_{24}H_{42}N_2O_4$ $[M]^+$: 422.3145; found: 422.3140.

5.3.3. Procedure for Ozonolysis

Synthesis of di-tert-butyl 2,2'-(2-oxopropane-1,3-diyl)bis(piperidine-1-carboxylate) (319):

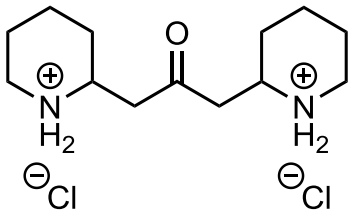


Di-*tert*-butyl 2,2'-(2-methylenepropane-1,3-diyl)bis(piperidine-1-carboxylate) (4.33 g, 10.25 mmol, 1.00 equiv.) was added to a round bottom flask. Anhydrous dichloromethane (43 mL) and methanol (8.25 mL) were added. The flask was then brought to the desired temperature (-78 °C). The mixture was then stirred while ozone from a T-408 Welsbach Ozone Generator was bubbled through the reaction. When the solution developed a deep blue hue the ozone was replaced by oxygen gas, which was bubbled until the hue dissipated. The reaction was quenched by addition of thiourea (0.38 g, 5.13 mmol, 0.50 equiv.) and stirred while slowly being brought to room temperature (23 °C, typically over 3 h). Starch iodide paper was used to confirm the absence of reactive intermediates/by-products. Volatiles were then removed *in vacuo* (ca. 50 torr.). Affords 4.35 g (99% yield) of the product as a colourless oil with minor impurities. The compound is used without purification (see Section 5.3.4).

Colourless oil (4.35 g, 99% yield). **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 2936, 2857, 1680, 1447, 1407, 1248, 1138, 769, 536; **^{1}H NMR** (500 MHz, $CDCl_3$) δ 4.67 (br. s, 2H), 3.93 (br. s, 2H), 2.88-2.50 (m, 6H), 1.72-1.45 (m, 12H), 1.40 (s, 18H); **^{13}C NMR** (125 MHz, $CDCl_3$) δ 207.2, 155.1, 79.8, 47.7, 43.8, 39.9, 28.7, 25.6, 19.3, 19.2; **HRMS** (EI^+) *m*/*z* calculated for $C_{23}H_{40}N_2O_5$ $[M]^+$: 424.2937; found: 424.2954.

5.3.4. Procedure for Deprotection and Reduction

Synthesis of 2,2'-(2-oxopropane-1,3-diyl)bis(piperidin-1-ium) chloride (132):

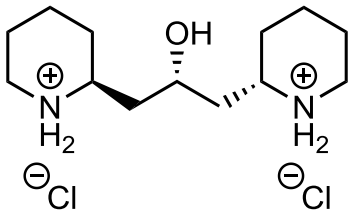


Di-*tert*-butyl 2,2'-(2-oxopropane-1,3-diyl)bis(piperidine-1-carboxylate) (0.531 g, 1.25 mmol, 1.00 equiv.) was added to a round bottom flask. Hydrochloric acid (30 mL, 2.0 M in diethyl ether) was added. The reaction mixture was stirred for 48 h, open to air. A suspension was formed and the mixture was filtered. The resulting solid was dried *in vacuo* (≤1 torr.). Affords 0.306 g (82% yield) of the product as a white solid. Diethyl ether (14 mol % by ^{1}H NMR spectroscopy) contaminates the compound and cannot be removed.

Note: Only six ^{13}C NMR signals are observed in d_4-MeOH. It is probable that one signal is obscured by the residual solvent signal. Seven ^{13}C NMR signals are observed if the spectrum is instead collected in D_2O. However, an unusual splitting of some of the signals is also observed.

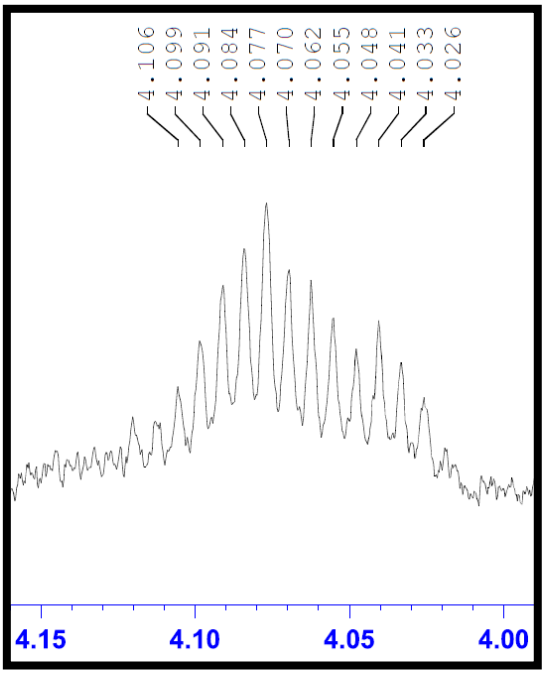
White solid (0.306 g, 82% yield). **m.p.**: 202.5-203.6 °C; **FTIR** (ATR; neat) ν_{max} (cm^{-1}): 2935, 2723, 2567, 2511, 1712, 1586, 1448, 1385, 1022, 453; **^{1}H NMR** (600 MHz, d_4-MeOH) δ 3.60-3.54 (m, 2H), 3.41-3.36 (m, 2H), 3.05 (ddd, *J* = 12.4, 12.4, 2.5 Hz, 2H), 2.98-2.92 (m, 4H), 1.97-1.84 (m, 6H), 1.74-1.49 (m, 6H); **^{13}C NMR** (125 MHz, d_4-MeOH) δ 206.2, 53.5, 45.9, 29.5, 23.2, 22.8; **^{13}C NMR** (125 MHz, D_2O) δ (uncalibrated) 207.5 (app. d, *J* = 5 Hz), 52.2, 44.9 (app. d, *J* = 2.5 Hz), 44.7 (app. d, *J* = 2.5 Hz), 28.0 (app. d, *J* = 2.5 Hz), 21.7, 21.3; **HRMS** (ESI) *m*/*z* calculated for $C_{13}H_{26}N_2O$ $[M]^{+2}$: 113.1017; found: 113.1013.

Synthesis of (2*S*,2'*S*)-2,2'-(2-hydroxypropane-1,3-diyl)bis(piperidin-1-ium) chloride (322):



Di-*tert*-butyl 2,2'-(2-oxopropane-1,3-diyl)bis(piperidine-1-carboxylate) (spatula tip, ca. 5 mg) was added to a vial. Methanol (ca. 2 mL) was added. The mixture was then stirred while sodium borohydride (ca. 30 mg) was added portionwise. The reaction mixture was stirred for 3 h at room temperature (23 °C) open to air. An ethereal solution of hydrochloric acid (ca. 20 mL (2 M in Et_2O)) was added. The mixture was then stirred for 48 h at room temperature (23 °C). All volatiles were thoroughly removed *in vacuo* (≤1 torr.).

Colourless oil. **^{1}H NMR** (500 MHz, D_2O) δ 4.08 (app. tt, *J* = 8.6, 4.5, 1H), 3.45-3.30 (m, 4H), 3.08-2.97 (m, 2H), 2.12-1.97 (m, 2H), 1.95-1.74 (m, 7H), 1.73-1.45 (m, 7H).



5.3.5. General Computational Methods

All reported calculations were performed with the Gaussian 09 software package.[116] The M06-2X exchange-correlation functional with the polarized diffuse split-valence 6-31+G(d,p) basis set was used for all geometry optimizations (including those with constraints), transition state calculations, infrared frequency calculations, and IRC calculations. Solvent effects were added using the integral equation formalism model (IEFPCM)[118] with radii and nonelectrostatic terms for Truhlar and co-workers' SMD solvation model (CH_2Cl_2).[119]

For each species a broad conformational search was performed using the MMFF94 force field in Spartan '08.[147] Additional conformers were generated by hand as needed. The lowest energy structures (typically 2−5) were carried forward for full optimization. The conformer with the lowest energy had its vibrational frequencies computed using the same level of theory to confirm that it was an energy minimum and to evaluate its zero-point vibrational energy (ZPVE) and thermal corrections at 298.15 K.

Transition states were found using a similar conformer search, but with a single constrained interatomic distance. The lowest energy conformers found with this process were optimized without the constraint and confirmed to be first-order saddle points by harmonic vibrational frequency analysis (*viz*. they contain only one imaginary frequency). The imaginary frequency was inspected to ensure it represented the desired reaction coordinate/transition. All three-dimensional representations were generated using CYLview.[121]

Energies for the various steps on the reaction coordinate were calculated using the summed Gibbs Free Energy values for materials at that stage. The sum of the energies of the starting materials was then subtracted from each of the totals to relativize them (see Section 5.2.6).

All tabular values reported in hartrees. Values may be converted to kcal/mol using the conversion factor:

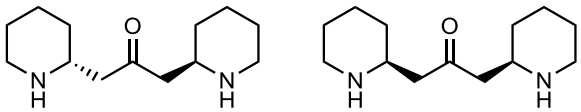
1 hartree = 627.509469 kcal/mol

All values reported with all calculated significant figures.

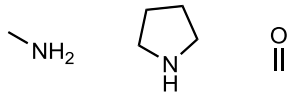
Thermochemical Parameters:

Structure/Filename	SCF	ZPE	Hcorr	Gcorr	SCFZPE	H298	G298
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formaldehyde (**334**)	-114.4590996040	0.0273510000	0.0311600000	0.0063400000	-114.4317486040	-114.4279396040	-114.4527596040
meso_anaferine (***meso*-69**)	-694.3226972710	0.3668490000	0.3834070000	0.3220490000	-693.9558482710	-693.9392902710	-694.0006482710
methylamine (**335**)	-95.8172437520	0.0644590000	0.0688140000	0.0415430000	-95.7527847520	-95.7484297520	-95.7757007520
pyrrolidine (**336**)	-212.4999831800	0.1305330000	0.1363480000	0.1026290000	-212.3694501800	-212.3636351800	-212.3973541800
TS_enol_genisteine (**TS 289**)	-770.9069908950	0.3931820000	0.4089590000	0.3528550000	-770.5138088950	-770.4980318950	-770.5541358950
TS_enol_sparteine_chel (**TS 288**)	-770.8906250760	0.3934030000	0.4090500000	0.3532490000	-770.4972220760	-770.4815750760	-770.5373760760
TS_enol_sparteine_nonchel (**TS 287**)	-770.8943268470	0.3936730000	0.4094640000	0.3530070000	-770.5006538470	-770.4848628470	-770.5413198470
TS_methylamine_genisteine (**TS 295**)	-790.3449995950	0.4345140000	0.4521470000	0.3921020000	-789.9104855950	-789.8928525950	-789.9528975950
TS_methylamine_sparteine_chel (**TS 294**)	-790.3294329370	0.4332930000	0.4509840000	0.3907110000	-789.8961399370	-789.8784489370	-789.9387219370
TS_methylamine_sparteine_nonchel (**TS 293**)	-790.3379031380	0.4346290000	0.4521410000	0.3922300000	-789.9032741380	-789.8857621380	-789.9456731380
TS_pyrrol_genisteine (**TS 292**)	-907.0304132300	0.5002180000	0.5197570000	0.4551870000	-906.5301952300	-906.5106562300	-906.5752262300
TS_pyrrol_sparteine_chel (**TS 291**)	-907.0151990630	0.4994890000	0.5190680000	0.4543620000	-906.5157100630	-906.4961310630	-906.5608370630
TS_pyrrol_sparteine_nonchel (**TS 290**)	-907.0271269220	0.5000740000	0.5196750000	0.4550210000	-906.5270529220	-906.5074519220	-906.5721059220
water (**337**)	-76.4034656115	0.0213010000	0.0250820000	0.0036500000	-76.3821646115	-76.3783836115	-76.3998156115
genisteine (**67**)	-696.5120749720	0.4007130000	0.4154090000	0.3613270000	-696.1113619720	-696.0966659720	-696.1507479720
pusilline (**68**)	-696.5006716610	0.4009340000	0.4156530000	0.3625120000	-696.0997376610	-696.0850186610	-696.1381596610
sparteine_chelating_conf (**66_{chel}**)	-696.5064243900	0.4007290000	0.4155500000	0.3610820000	-696.1056953900	-696.0908743900	-696.1453423900
sparteine_nonchelating_conf (**$66_{nonchel}$**)	-696.5109051590	0.4011740000	0.4158710000	0.3618640000	-696.1097311590	-696.0950341590	-696.1490411590

Starting Materials

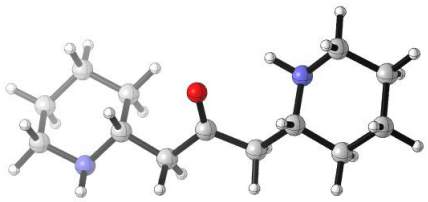


C_2-69 ***meso*-69**



335 **336** **334**

C_2-symmetric anaferine (**C_2-69**)



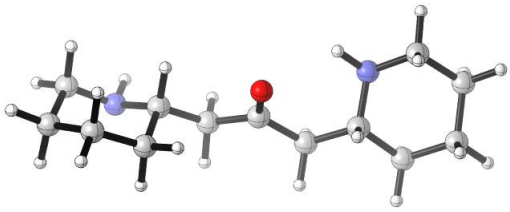
XYZ Coordinates

40

Final Energy = -694.3226726600

H	-4.1266500	2.4777760	-0.9896650
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C	-4.9691050	-0.5560490	0.4506990
C	-2.5515610	-0.3576680	0.2578480
N	-3.7225260	-1.2201760	0.0601290
C	-2.6994560	0.8867190	-0.6203870
C	-5.1968660	0.6736970	-0.4222330
H	-4.9435570	-0.2408090	1.5101500
H	-2.4817330	-0.0261200	1.3097520
H	-2.6944740	0.5660970	-1.6717880
H	-5.3188140	0.3511240	-1.4645090
H	-3.9566990	2.0279110	0.7076320
H	-5.7900270	-1.2705440	0.3364800
H	-1.8389300	1.5468060	-0.4671780
H	-6.1221890	1.1760020	-0.1197200
H	5.1883410	-0.8515380	1.0729430
C	5.0804650	-0.6476850	-0.0017060
C	2.5644560	-0.4650150	0.1379830
C	3.9220960	1.5357040	0.3968190
N	2.6902570	0.9665730	-0.1561720
C	5.1379130	0.8635570	-0.2320700
C	3.7441430	-1.2118950	-0.4872190
H	3.9255920	2.6109230	0.1930960
H	6.0557390	1.2854210	0.1921060
H	3.6654770	-2.2786040	-0.2468380
H	5.9122400	-1.1495090	-0.5077960
H	2.5887320	-0.6376070	1.2318240
H	3.9697010	1.4035260	1.4938590
H	5.1424480	1.0736350	-1.3096560
H	3.6756110	-1.1127780	-1.5796900
C	-1.2966940	-1.1497410	-0.0862750
H	-1.2940960	-2.1094980	0.4535400
H	-1.2834920	-1.4032830	-1.1536640
C	1.2442990	-0.9968030	-0.4041230
H	1.2170970	-2.0929820	-0.3402530
H	1.1539230	-0.7524250	-1.4726120
C	0.0040650	-0.4700210	0.2837010
O	0.0521320	0.4284270	1.1073720
H	1.8939680	1.4422450	0.2611620
H	-3.6076990	-2.0645170	0.6171110

meso-anaferine (***meso*-69**)



XYZ Coordinates

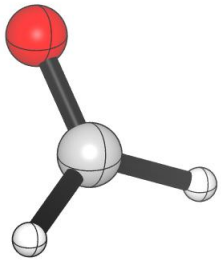
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Final Energy = -694.3226972710

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C	4.0373940	1.5251540	0.0986800
C	2.5424500	-0.3914030	0.1938060
N	2.8326970	0.8949140	-0.4494550
C	3.7141430	-1.3465430	-0.0400410
C	5.2523270	0.6392820	-0.1521100
H	3.9405920	1.6977270	1.1865630
H	2.4205940	-0.2569160	1.2854260
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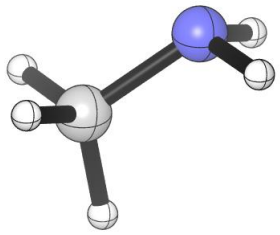
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C -4.2554640 0.1277060 1.5033740
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N -3.5949960 -0.1244450 -1.2934090
C -5.3322300 -0.0393570 0.4297780
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H -5.5578410 -1.1053140 0.2955290
H -3.0340030 -1.5578960 0.9143120
H -4.1138030 1.1981850 1.7080480
H -5.5854590 0.3691070 -1.6853240
H -6.2595320 0.4616630 0.7284520
H -2.1376580 -0.2833780 1.7618060
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H 1.0557670 -1.9568850 0.0667430
H 1.3340100 -1.1167700 -1.4519200
C -1.2347360 -0.5161600 -0.8514200
H -1.0591890 -0.2081920 -1.8938040
H -1.3203530 -1.6103990 -0.8723390
C 0.0162380 -0.1292320 -0.0932270
O 0.0381800 0.8113990 0.6827070
H -3.3058380 0.2341070 -2.2012900
H 2.0435120 1.5153790 -0.2843280

formaldehyde (**334**)



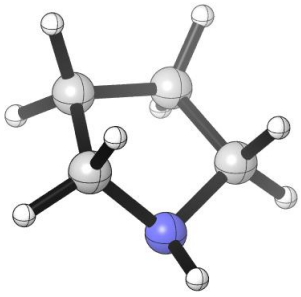
XYZ Coordinates
4
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H 0.0000000 0.9410470 -1.1087070
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O 0.0000000 0.0000000 0.6768010

methylamine (**335**)



XYZ Coordinates
7
Final Energy = -95.8172437520
C -0.0519800 0.7054030 0.0000000
H -0.5873020 1.0669180 0.8821190
H -0.5873020 1.0669180 -0.8821190
H 0.9491730 1.1581850 0.0000000
N -0.0519800 -0.7592620 0.0000000
H 0.4505860 -1.1048040 -0.8130850
H 0.4505860 -1.1048040 0.8130850

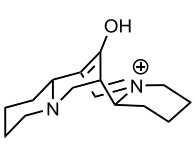
pyrrolidine (**336**)



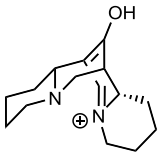
XYZ Coordinates
7
Final Energy = -95.8172437520
C -0.0519800 0.7054030 0.0000000
H -0.5873020 1.0669180 0.8821190
H -0.5873020 1.0669180 -0.8821190
H 0.9491730 1.1581850 0.0000000
N -0.0519800 -0.7592620 0.0000000

H 0.4505860 -1.1048040 -0.8130850
H 0.4505860 -1.1048040 0.8130850

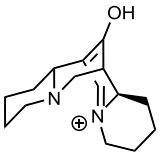
Transition States



TS 287

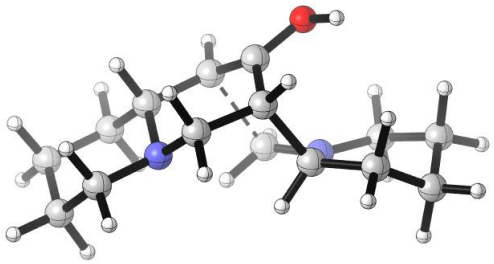


TS 288



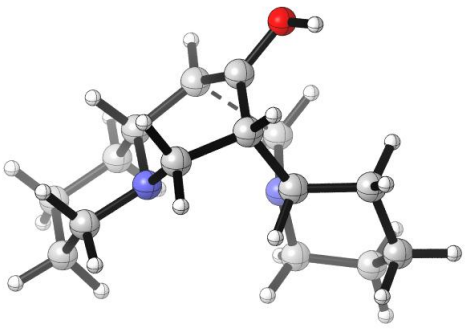
TS 289

Cyclization of 2-(8-hydroxy-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)-1-methylenepiperidin-1-ium leading to the non-chelating conformer of oxo-sparteine (**TS 287**)



XYZ Coordinates
43
Final Energy = -770.8943268470
H -1.1018150 1.2706630 1.9546260
C -0.5163470 0.7838100 1.1697950
N 1.7217890 0.7629630 0.1092860
C 0.6341950 -1.3370430 0.7534240
C 1.9623550 -0.6190510 0.5382430
C -0.3633300 -0.6498080 1.4233440
C 0.8439730 1.4719260 1.0332480
H 2.4906600 -0.6188780 1.5133450
H 1.2999320 1.5600980 2.0355900
H 0.6894350 2.4865630 0.6506690
C 2.8546860 -1.3624890 -0.4582920
H 2.3411120 -1.4637740 -1.4227570
H 3.0312990 -2.3727490 -0.0729210
C 2.9759630 1.5013910 -0.0625830
H 2.7218320 2.5164730 -0.3848200
H 3.5049890 1.5840600 0.9068600
C 3.8862520 0.8259160 -1.0800050
H 3.3971640 0.8383800 -2.0625730
H 4.8155080 1.3983860 -1.1660320
C 4.1708590 -0.6159970 -0.6635040
H 4.7825410 -1.1256520 -1.4144350
H 4.7404500 -0.6173420 0.2757030
C -1.3979560 0.8720830 -0.2158920
H -0.7439210 1.4570890 -0.8724280
C -0.3575300 -1.0906730 -0.9658450
H -0.4272280 -2.1135950 -1.3283130
N -1.5312110 -0.4404360 -0.8150210
C -2.7929720 -1.1980750 -0.9874630
H -2.8607320 -1.4347100 -2.0545300
H -2.7239700 -2.1403950 -0.4357530
C -2.7268940 1.6025200 0.0119140
H -2.5557970 2.6738650 -0.1249670
H -3.0511320 1.4607110 1.0501960
C -4.0256620 -0.4035040 -0.5743000
H -4.2096680 -0.5127630 0.5021750
H -4.8893800 -0.8266850 -1.0944700
C -3.8387610 1.0771580 -0.8906260
H -3.5852000 1.2158850 -1.9494690
H -4.7612370 1.6314280 -0.6959660
H 0.6807660 -2.4156740 0.8929430
H 0.4581860 -0.4791240 -1.3432540
O -1.3914920 -1.3299610 1.8972100
H -2.0988840 -0.7392440 2.2143020

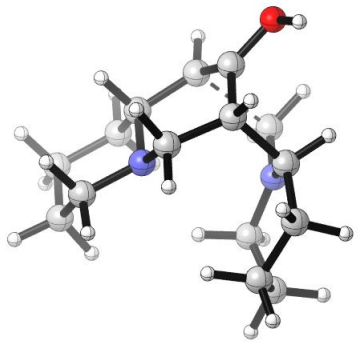
Cyclization of 2-(8-hydroxy-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)-1-methylenepiperidin-1-ium leading to the chelating conformer of oxo-sparteine (**TS 288**)



XYZ Coordinates
43
Final Energy = -770.8906250760
H 1.2466670 1.9871450 1.7095770
C 0.6491580 1.3497440 1.0488810

N	-1.4135760	0.0751430	0.8389740
C	-0.6727620	1.5371260	-1.0184820
C	-1.8019180	0.7240440	-0.4157730
C	0.3212130	2.0484440	-0.2194420
C	-0.6777790	0.9621160	1.7251160
H	-2.6111390	1.4602990	-0.2156160
H	-1.2443020	1.8751140	1.9811440
H	-0.8839670	2.0378880	-1.9621830
H	-0.4679030	0.4273060	2.6562040
C	-2.3707350	-0.3144290	-1.3840980
H	-1.5917970	-1.0542870	-1.6090150
H	-2.6470210	0.1812330	-2.3214310
C	-2.5724480	-0.5286720	1.4945980
H	-2.2338470	-0.9684890	2.4381810
H	-3.3271740	0.2452000	1.7375630
C	-3.2005440	-1.5961240	0.6037910
H	-2.4758810	-2.4094160	0.4675000
H	-4.0794790	-2.0161490	1.1040480
C	-3.5784560	-1.0120720	-0.7577490
H	-3.9542310	-1.7951330	-1.4239200
H	-4.3882360	-0.2812620	-0.6285170
C	1.4767190	0.0457030	0.7386440
H	1.2014950	-0.6698450	1.5234830
C	0.8713250	0.1915810	-1.5963110
H	1.5284030	1.0309610	-1.8269330
H	0.4796470	-0.3347380	-2.4670860
N	1.0386210	-0.5573680	-0.5098070
C	3.0021270	0.1131920	0.7031750
H	3.3944810	0.5702670	1.6171890
H	3.3338540	0.7182230	-0.1511260
C	1.3064800	-1.9910200	-0.5829250
H	0.8433800	-2.4761800	0.2833140
H	0.8715510	-2.3951070	-1.5004680
C	2.8403890	-2.1308520	-0.5708400
H	3.1122850	-3.1889610	-0.5008640
H	3.2134850	-1.7554850	-1.5322900
C	3.4963610	-1.3453560	0.5801280
H	3.2789160	-1.8555630	1.5277060
H	4.5830110	-1.3611220	0.4531980
O	1.1306490	2.9881000	-0.7075850
H	1.8625120	3.1783360	-0.0954350

Cyclization of 2-(8-hydroxy-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)-1-methylenepiperidin-1-ium leading to oxo-genisteine (**TS 289**)



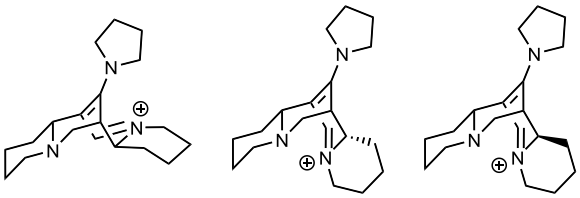
XYZ Coordinates

43

Final Energy = -770.9069908950

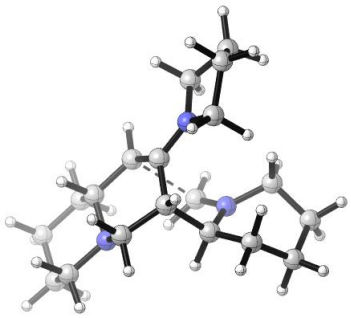
H	-1.8627330	1.3466690	-1.8805280
C	-1.1583350	1.0096330	-1.1133100
N	0.9945050	-0.1309040	-0.7757820
C	0.4696780	1.9468890	0.4536650
C	1.5538290	1.0039880	-0.0407290
C	-0.6544630	2.1416980	-0.3194640
C	0.0090630	0.2701740	-1.7667160
H	2.1791190	1.6180060	-0.7259710
H	0.4497620	0.9302110	-2.5376220
H	0.7985330	2.7658270	1.0925680
H	-0.3569450	-0.6235270	-2.2817240
C	2.4723380	0.5134730	1.0792710
H	1.8869490	-0.0758530	1.7966160
H	2.8758580	1.3820360	1.6121100
C	2.0510800	-0.9370890	-1.3867760
H	1.5729490	-1.7604220	-1.9288100
H	2.6141910	-0.3352160	-2.1276960
C	3.0113550	-1.4818250	-0.3351780
H	2.4697290	-2.1797930	0.3161250
H	3.8063350	-2.0469910	-0.8325490
C	3.5972530	-0.3454120	0.5021940
H	4.2265540	-0.7398160	1.3062320
H	4.2380800	0.2809920	-0.1330080
C	-2.0538790	0.1388070	-0.0900650
C	-0.8223910	0.9405390	1.7451970
H	-1.4856360	1.7972440	1.8605500
H	-0.1320010	0.7594310	2.5659090
N	-1.3008600	-0.1383880	1.1184990
C	-0.7264120	-1.4639640	1.4327950
H	0.2538810	-1.5428340	0.9565410
H	-2.8609070	0.8281740	0.1893770
C	-2.6763090	-1.0942200	-0.7570230
H	-2.8125960	-0.8764770	-1.8211240

H	-0.6109820	-1.4995500	2.5183870
C	-1.6255880	-2.5825150	0.9364930
H	-2.5739320	-2.5861430	1.4885720
O	-1.4267970	3.2017920	-0.0890700
H	-2.2513390	3.1626060	-0.6049400
C	-1.8909110	-2.3894350	-0.5521650
H	-3.6758710	-1.2343360	-0.3314460
H	-0.9333910	-2.3667350	-1.0878450
H	-2.4723860	-3.2232680	-0.9568490
H	-1.1222030	-3.5339770	1.1315270



TS 290 **TS 291** **TS 292**

Cyclization of 1-methylene-2-(8-(pyrrolidin-1-yl)-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)piperidin-1-ium leading to the non-chelating conformer of oxo-sparteine (**TS 290**)



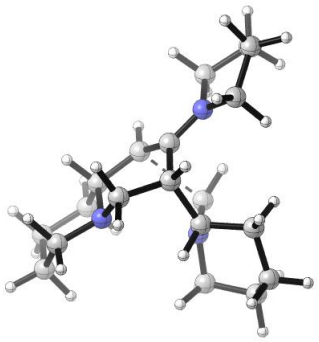
XYZ Coordinates

54

Final Energy = -907.0271269220

H	-0.7116560	0.1998370	2.1734500
C	-0.0548540	0.2249290	1.3002990
N	2.3197320	0.2380260	0.6506290
C	0.7639590	-1.3408830	-0.4133260
C	2.2057020	-1.0486200	-0.0461200
C	-0.2698380	-0.9751450	0.4276950
C	1.3970540	0.2945710	1.7768760
H	2.5468540	-1.8539370	0.6418240
H	1.5896110	-0.5222000	2.4967130
H	1.5520000	1.2428570	2.3045060
C	3.1312080	-1.0963230	-1.2651670
H	2.8058640	-0.3599130	-2.0111930
H	3.0399860	-2.0858790	-1.7272560
C	3.6933850	0.4867400	1.0902210
H	3.7100090	1.4487970	1.6132420
H	4.0110600	-0.2901530	1.8136310
C	4.6566690	0.5021720	-0.0904970
H	4.3942160	1.3366890	-0.7536250
H	5.6735720	0.6790890	0.2753800
C	4.5774020	-0.8149470	-0.8615500
H	5.2230980	-0.7888300	-1.7451360
H	4.9387970	-1.6309730	-0.2207240
C	-0.4257640	1.5443420	0.4741170
H	0.4886680	2.1485780	0.4524190
C	0.2024750	0.6126190	-1.6073240
H	-0.0399720	0.2394320	-2.5985350
N	-0.7370170	1.2178410	-0.9193430
C	-2.1323880	1.3372310	-1.3583330
H	-2.1892670	0.9925490	-2.3921720
H	-2.7575640	0.6876360	-0.7405340
C	-1.5610800	2.3700630	1.0743520
H	-1.2015530	2.8213720	2.0036090
H	-2.4083350	1.7250510	1.3349020
C	-2.5795460	2.7977020	-1.2116600
H	-3.6733590	2.8066480	-1.1844100
H	-2.2704380	3.3679830	-2.0920480
C	-1.9968500	3.4392540	0.0688770
H	-1.1217160	4.0477870	-0.1871180
H	-2.7289210	4.1119670	0.5228310
H	0.6240710	-2.1671030	-1.1053140
H	1.2287400	0.8353940	-1.3405150
N	-1.5263650	-1.4305010	0.2799080
C	-1.8792340	-2.4015300	-0.7616170
C	-3.3872470	-2.5775570	-0.5926100
C	-3.5819090	-2.3833200	0.9123170
C	-2.6346940	-1.2265700	1.2296430
H	-1.3387380	-3.3442220	-0.5998000
H	-1.5961470	-2.0094910	-1.7461070
H	-3.9189410	-1.7935900	-1.1434520
H	-3.7321850	-3.5477530	-0.9547260
H	-3.2652300	-3.2819010	1.4523250
H	-4.6125510	-2.1547310	1.1910160
H	-2.2719260	-1.2437930	2.2596190
H	-3.1291880	-0.2631230	1.0516750

Cyclization of 1-methylene-2-(8-(pyrrolidin-1-yl)-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)piperidin-1-ium leading to the chelating conformer of oxo-sparteine (**TS 291**)



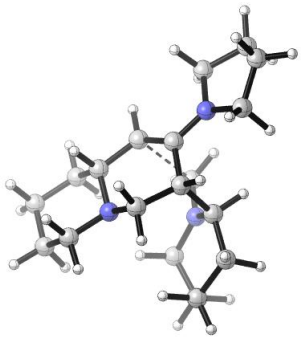
XYZ Coordinates

54

Final Energy = -907.0151990630

H	-1.1315390	0.2178430	2.1214070
C	-0.4035020	0.0505060	1.3247030
N	1.8717330	-0.6592250	0.8675550
C	0.0107020	-1.5115620	-0.5266620
C	1.4630940	-1.6552530	-0.1271800
C	-0.9267850	-0.9144950	0.2966210
C	0.8830640	-0.5336130	1.9242290
H	1.5678310	-2.6688510	0.3242270
H	0.6678730	-1.5002610	2.4159260
H	-0.3164660	-2.2085620	-1.2936370
H	1.2718230	0.1486250	2.6871320
C	2.4175640	-1.6102110	-1.3230990
H	2.3500330	-0.6190150	-1.7912850
H	2.0984950	-2.3520100	-2.0643250
C	3.2074990	-0.9528220	1.3806370
H	3.4480760	-0.2086390	2.1473090
H	3.2263920	-1.9497150	1.8652520
C	4.2370580	-0.9121750	0.2559750
H	4.2882160	0.1115130	-0.1374790
H	5.2251950	-1.1599810	0.6579360
C	3.8523440	-1.8758360	-0.8674110
H	4.5474930	-1.7849520	-1.7084970
H	3.9257590	-2.9080510	-0.4984960
C	-0.0681570	1.4489710	0.7024910
H	0.7860650	1.8169590	1.2837510
C	-0.1632210	0.6119880	-1.5689650
H	-1.2223710	0.3810300	-1.5012060
H	0.2942920	0.5898720	-2.5566410
N	0.4313810	1.3568860	-0.6695700
C	-1.1081190	2.5698000	0.7047620
H	-1.5550210	2.6798820	1.6983360
H	-1.9123390	2.3408210	-0.0065780
C	1.3309650	2.4551830	-1.0230420
H	2.1408340	2.4944020	-0.2876130
H	1.7471670	2.2769820	-2.0172710
C	0.4556270	3.7231690	-0.9929180
H	1.0892760	4.6050980	-1.1304970
H	-0.2274630	3.6698480	-1.8498620
C	-0.3595740	3.8591900	0.3066230
H	0.3187440	4.1217650	1.1287420
H	-1.0667740	4.6874210	0.2006140
N	-2.2526160	-0.9665720	0.0555890
C	-3.3059850	-0.3919820	0.9167520
C	-4.5556140	-1.1766120	0.5132430
C	-4.3073770	-1.5002050	-0.9613570
C	-2.8176380	-1.8329110	-0.9885010
H	-3.4220530	0.6795010	0.7149500
H	-3.0625970	-0.5243090	1.9730400
H	-4.6112610	-2.1037480	1.0937080
H	-5.4702090	-0.6055580	0.6851880
H	-4.5042600	-0.6181410	-1.5805780
H	-4.9187910	-2.3254110	-1.3314890
H	-2.3508220	-1.6219740	-1.9565500
H	-2.6267390	-2.8867840	-0.7419280

Cyclization of 1-methylene-2-(8-(pyrrolidin-1-yl)-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)piperidin-1-ium leading to oxo-genisteine (**TS 292**)



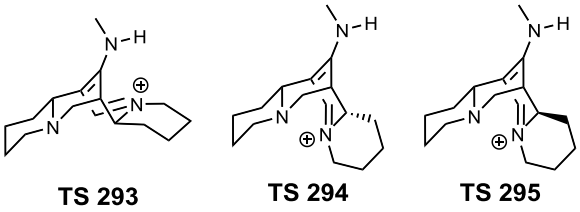
XYZ Coordinates

54

Final Energy = -907.0304132300

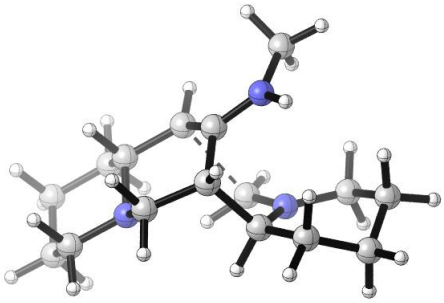
H	1.1720460	1.0326430	-1.8237260
C	0.5340200	0.5734060	-1.0632150
N	-1.5799680	-0.6457670	-0.8022360
C	0.4883860	-1.4955280	0.2564430

C -0.9195550 -1.8041660 -0.1999910
C 1.2596670 -0.5313110 -0.3548130
C -0.7177140 0.0354460 -1.7511640
H -0.8299950 -2.6057630 -0.9698880
H -0.4039130 -0.6370370 -2.5731870
H 0.9683660 -2.2926460 0.8187630
H -1.2756210 0.8587080 -2.2088820
C -1.7935810 -2.3672370 0.9223650
H -1.9008810 -1.5980410 1.7000290
H -1.2882320 -3.2282030 1.3749900
C -2.8574580 -1.0215150 -1.4027070
H -3.2899790 -0.1271220 -1.8660470
H -2.7032480 -1.7686380 -2.2069830
C -3.8084910 -1.5867840 -0.3517620
H -4.0533050 -0.7937060 0.3668050
H -4.7431700 -1.8910770 -0.8343760
C -3.1678760 -2.7649860 0.3833890
H -3.8150440 -3.1103120 1.1963150
H -3.0500880 -3.6055320 -0.3141530
C 0.2984800 1.7435360 -0.0156000
C 0.2976000 0.3323980 1.8759890
H 1.3830130 0.3385530 1.8435800
H -0.2077470 -0.1677600 2.6970090
N -0.3594700 1.2350350 1.1981230
C -1.7984050 1.4525350 1.4751340
H -2.3561390 0.6951680 0.9177570
H 1.3070800 2.0277090 0.3025320
C -0.3835720 2.9807970 -0.6159060
H -0.1133120 3.0325340 -1.6757420
H -1.9338060 1.2995170 2.5476950
C -2.2344040 2.8412170 1.0441470
H -1.7322480 3.6063930 1.6494500
C -1.9003110 3.0363210 -0.4303350
H 0.0457300 3.8674590 -0.1360090
H -2.4038700 2.2584190 -1.0178070
H -2.2657000 4.0033140 -0.7884500
H -3.3099790 2.9274160 1.2237840
N 2.5870920 -0.3884630 -0.1199550
C 3.3306810 -1.3601460 0.6873770
C 4.7414250 -0.7792670 0.7285100
C 4.8707690 -0.1164330 -0.6448810
C 3.4899350 0.5056060 -0.8706210
H 3.3102280 -2.3489940 0.2058240
H 2.8775920 -1.4581950 1.6803990
H 4.8112280 -0.0259550 1.5208900
H 5.4976780 -1.5452260 0.9108800
H 5.0599400 -0.8784350 -1.4082350
H 5.6679410 0.6280250 -0.6948670
H 3.2212500 0.5304860 -1.9297990
H 3.4430250 1.5273310 -0.4742310



TS 293 **TS 294** **TS 295**

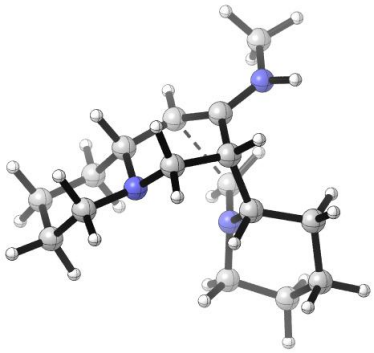
Cyclization of 2-(8-(methylamino)-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)-1-methylenepiperidin-1-ium leading to the non-chelating conformer of oxo-sparteine (**TS 293**)



XYZ Coordinates
47
Final Energy = -790.3379031380
H -0.9637820 -0.6760140 -2.2264320
C -0.4041780 -0.5000190 -1.3023890
N 1.8771160 -0.7326400 -0.3705760
C 0.7116690 1.4266470 -0.2531860
C 2.0557930 0.7231180 -0.3060150
C -0.3452140 0.9613670 -1.0117720
C 0.9921070 -1.0981690 -1.4685590
H 2.5826320 1.0597620 -1.2250890
H 1.4076840 -0.7685520 -2.4391470
H 0.9108690 -2.1906590 -1.5006890
C 2.9359380 1.1112630 0.8848670
H 2.4191720 0.8597220 1.8203740
H 3.0752210 2.1980720 0.8721640
C 3.1611720 -1.4255970 -0.4852660
H 2.9578630 -2.4998850 -0.5453460
H 3.6736970 -1.1313830 -1.4226600
C 4.0625300 -1.1165070 0.7042160

H 3.5919810 -1.5010140 1.6184480
H 5.0165620 -1.6393460 0.5799050
C 4.2813920 0.3904550 0.8293090
H 4.8766400 0.6257170 1.7175580
H 4.8467310 0.7462400 -0.0429880
C -1.2532780 -1.1759570 -0.1182180
H -0.6315480 -1.9935710 0.2641910
C -0.2907830 0.3071320 1.4408610
H -0.3691400 1.0716390 2.2099640
N -1.4150220 -0.2269050 0.9951090
C -2.7019190 0.2509010 1.5531730
H -2.7447630 -0.1166250 2.5842260
H -2.6755750 1.3447710 1.5864060
C -2.5814300 -1.7310640 -0.6509500
H -2.3921230 -2.7369520 -1.0374660
H -2.9119830 -1.1224540 -1.5020430
C -3.9174050 -0.2614410 0.7986150
H -4.1007720 0.3449620 -0.0975030
H -4.7869150 -0.1497160 1.4524580
C -3.7006640 -1.7129980 0.3826970
H -3.4432860 -2.3253460 1.2567100
H -4.6119220 -2.1297480 -0.0552430
H 0.7374100 2.4717230 0.0469280
H 0.6080760 -0.2962670 1.3741050
N -1.4935690 1.6284310 -1.1722770
C -1.7153170 2.9754840 -0.6871130
H -1.0205530 3.6813330 -1.1531370
H -1.5776530 3.0185400 0.4010020
H -2.7366820 3.2688440 -0.9279460
H -2.2599830 1.1563080 -1.6361680

Cyclization of 2-(8-(methylamino)-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)-1-methylenepiperidin-1-ium leading to the chelating conformer of oxo-sparteine (**TS 294**)

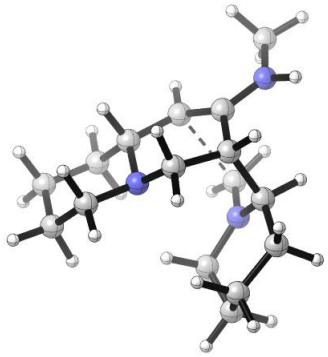


XYZ Coordinates

47
Final Energy = -790.3294329370
H 1.3084720 1.0975840 2.1967740
C 0.6675460 0.7278420 1.3890530
N -1.4960490 -0.2322240 0.8524520
C -0.6202320 1.6464850 -0.5000770
C -1.8186010 0.7964000 -0.1409730
C 0.4398360 1.8026690 0.3687170
C -0.6995730 0.3042150 1.9447910
H -2.5744100 1.4884190 0.2961830
H -1.1893900 1.1622990 2.4407150
H -0.7977490 2.3953190 -1.2685300
H -0.5638030 -0.4798770 2.6961470
C -2.4701520 0.1473040 -1.3635640
H -1.7499740 -0.5458530 -1.8184830
H -2.6985110 0.9244730 -2.1021350
C -2.7089400 -0.8993990 1.3205790
H -2.4217300 -1.6264260 2.0876040
H -3.3953550 -0.1686380 1.7931460
C -3.4213300 -1.5974920 0.1658730
H -2.7706650 -2.3943090 -0.2172010
H -4.3379030 -2.0685860 0.5363360
C -3.7358380 -0.6069840 -0.9564920
H -4.1698940 -1.1242380 -1.8183870
H -4.4850130 0.1143700 -0.6025150
C 1.3686460 -0.5269670 0.7664120
H 0.9761830 -1.3854050 1.3256570
C 0.9273530 0.2136060 -1.4954440
H 1.5846990 1.0747140 -1.4079990
H 0.5840370 -0.0518720 -2.4940720
N 0.9631400 -0.7632650 -0.6181840
C 2.8923220 -0.6444050 0.7944540
H 3.2747710 -0.4601460 1.8034350
H 3.3398110 0.0967570 0.1195410
C 1.0539990 -2.1688390 -1.0115620
H 0.4763360 -2.7700250 -0.3022300
H 0.6416890 -2.2914730 -2.0158570
C 2.5573900 -2.5037470 -0.9703610
H 2.6960360 -3.5769660 -1.1344130
H 3.0332390 -1.9764430 -1.8068270
C 3.2285890 -2.0848040 0.3520340
H 2.9015280 -2.7656440 1.1484490
H 4.3119920 -2.2054920 0.2563800
N 1.4125250 2.7176820 0.1962310
C 1.3110570 3.8058250 -0.7596340
H 1.2489980 3.4216970 -1.7837770

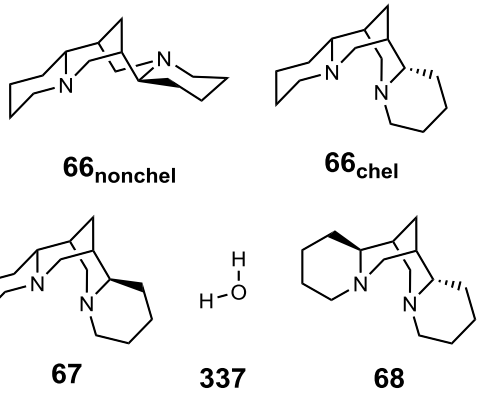
H 0.4224790 4.4171560 -0.5643100
H 2.2011270 4.4280070 -0.6735960
H 2.1632570 2.7449920 0.8736370

Cyclization of 2-(8-(methylamino)-1,3,4,6,7,9a-hexahydro-2H-quinolizin-7-yl)-1-methylenepiperidin-1-ium leading to oxo-genisteine (**TS 295**)



XYZ Coordinates
47
Final Energy = -790.3449995950
H 1.9537950 0.3665740 -1.9936520
C 1.2434300 0.1535710 -1.1867140
N -1.1250120 -0.3454400 -0.7599340
C 0.6410100 -1.7806180 0.2071510
C -0.8178020 -1.6488120 -0.1689100
C 1.6206560 -1.1179820 -0.4975660
C -0.1603830 0.0397100 -1.7770630
H -1.0178620 -2.4419270 -0.9259010
H -0.1315710 -0.6927150 -2.6068610
H 0.8962080 -2.6773590 0.7676200
H -0.4679580 0.9982140 -2.2080480
C -1.7555240 -1.9158900 1.0090480
H -1.5879140 -1.1431650 1.7720010
H -1.5053010 -2.8850390 1.4554680
C -2.4913920 -0.3140990 -1.2785910
H -2.6587260 0.6704350 -1.7301230
H -2.6172570 -1.0710530 -2.0786890
C -3.5069470 -0.5687040 -0.1681270
H -3.4600600 0.2583060 0.5522900
H -4.5153870 -0.5745980 -0.5950000
C -3.2116430 -1.8868180 0.5475110
H -3.8886410 -2.0250880 1.3967260
H -3.3856680 -2.7228370 -0.1437380
C 1.4728730 1.3341550 -0.1496010
C 1.1209440 -0.0177110 1.7453140
H 2.1557580 -0.3414110 1.6773160
H 0.5275490 -0.3300190 2.6002690
N 0.7587020 1.0663130 1.1027290
C -0.5114110 1.7411610 1.4537660
H -1.3194030 1.2180470 0.9347140
H 2.5375180 1.2572950 0.0998150
C 1.2110980 2.7301560 -0.7294030
H 1.4199000 2.6945790 -1.8035230
H -0.6326950 1.6303480 2.5336250
C -0.4858520 3.2009220 1.0338560
H 0.2733810 3.7502480 1.6047160
C -0.1861830 3.2877490 -0.4585240
H 1.9392830 3.4194140 -0.2873710
H -0.9517840 2.7286670 -1.0104700
H -0.2272870 4.3249130 -0.8039100
H -1.4610150 3.6370810 1.2692740
N 2.9388420 -1.3896140 -0.3862380
C 3.4467170 -2.5586720 0.3051850
H 3.0288780 -3.4804460 -0.1165480
H 3.1969910 -2.5216110 1.3717610
H 4.5311920 -2.5797510 0.2018280
H 3.5827970 -0.8546270 -0.9534730

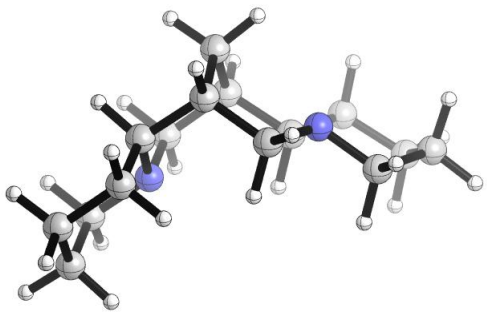
By-product and Final Products



66$_{nonchel}$ **66$_{chel}$**

67 **337** **68**

The non-chelating conformer of sparteine (**66$_{nonchel}$**)



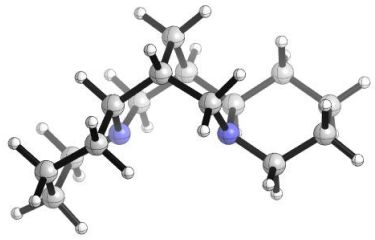
XYZ Coordinates

43

Final Energy = -696.5109051590

H	-1.0839550	2.1835510	1.3482770
C	-0.5807000	1.3021190	0.9318510
N	1.5151740	0.7113870	-0.2843030
C	0.5460310	-0.8176180	1.3870020
C	1.8406860	-0.2785520	0.7494570
C	-0.1919790	0.3426290	2.0560390
C	0.6959440	1.7980400	0.2491760
H	2.4204560	0.2212510	1.5572000
H	0.4694220	0.8464770	2.7716940
H	1.2776370	2.3943750	0.9818110
H	0.8443130	-1.5583670	2.1377970
H	-1.0749290	-0.0073210	2.5976130
H	0.4399690	2.4658570	-0.5832820
C	2.7164210	-1.3973550	0.1810900
H	2.1412380	-1.9741680	-0.5543620
H	2.9769150	-2.0793310	0.9993470
C	2.7142860	1.2661950	-0.9081660
H	2.3948340	1.9935290	-1.6632130
H	3.3148240	1.8190820	-0.1559150
C	3.5836970	0.1873740	-1.5401690
H	3.0242970	-0.2987660	-2.3500890
H	4.4708740	0.6519890	-1.9843650
C	3.9754020	-0.8498650	-0.4896050
H	4.5554190	-1.6629490	-0.9394660
H	4.6160020	-0.3743200	0.2665490
C	-1.5486970	0.6038170	-0.0605510
H	-1.1267480	0.6891090	-1.0844560
C	-0.3889080	-1.4835300	0.3443250
H	-0.5688600	-2.5311160	0.6081820
H	0.0878680	-1.4731590	-0.6523640
N	-1.6929920	-0.8219960	0.2701750
C	-2.5465280	-1.5043490	-0.6974330
H	-2.1059770	-1.4372670	-1.7141590
H	-2.5820630	-2.5666480	-0.4301390
C	-2.9244060	1.2707400	-0.0550740
H	-2.8030250	2.3292270	-0.3158790
H	-3.3216760	1.2298200	0.9693930
C	-3.9513770	-0.9133720	-0.7169320
H	-4.4197800	-1.0766400	0.2621870
H	-4.5570690	-1.4379110	-1.4642340
C	-3.8924570	0.5839770	-1.0165740
H	-3.5410240	0.7319520	-2.0474450
H	-4.8887280	1.0345010	-0.9483970

The chelating conformer of sparteine (**66$_{chel}$**)



XYZ Coordinates

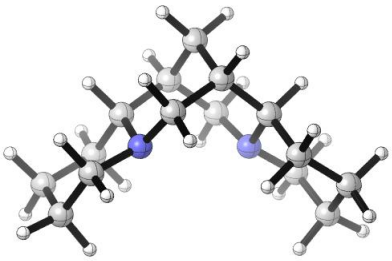
43

Final Energy = -696.5064243900

H	-1.0476840	2.7131180	-0.0019250
C	-0.5836620	1.7232190	0.0934270
N	1.5401260	0.5652650	-0.5456690
C	0.3414120	0.0256980	1.5932490
C	1.6788480	0.0654650	0.8279790
C	-0.2964030	1.4136980	1.5638320
C	0.7566150	1.7923650	-0.6416800
H	2.3237920	0.7736320	1.3991710
H	0.3884630	2.1654910	1.9757670
H	1.3254700	2.6489110	-0.2204660
H	0.5863130	-0.2552030	2.6257100
H	-1.2091630	1.4314340	2.1693390
H	0.5967870	2.0055670	-1.7060630
C	2.3956470	-1.2855650	0.8090740
H	1.7807990	-2.0030810	0.2501770
H	2.4882110	-1.6564180	1.8373740
C	2.8455630	0.7525200	-1.1687080
H	2.6883080	1.1595170	-2.1740500
H	3.4402530	1.5015470	-0.6024320
C	3.6229450	-0.5563990	-1.2438010
H	3.0812590	-1.2521070	-1.8973440
H	4.6044450	-0.3742730	-1.6953790
C	3.7689260	-1.1698650	0.1477270
H	4.2544290	-2.1503460	0.0912180
H	4.4128950	-0.5257060	0.7626960
C	-1.5751450	0.7041760	-0.4999320
H	-1.5836360	0.8402040	-1.5945520
C	-0.6983520	-0.9807350	1.0857640
H	-1.5303750	-0.9794090	1.8174910
H	-0.2882280	-1.9977980	1.0833090
N	-1.1371080	-0.6810770	-0.2716140

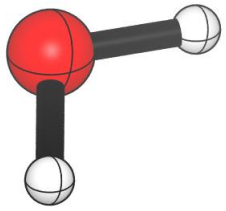
C -3.0107480 0.9649180 -0.0031740
H -3.3004120 1.9889400 -0.2696140
H -3.0454090 0.8934180 1.0922290
C -2.0894310 -1.6486380 -0.8068490
H -2.0935260 -1.5423750 -1.9022260
H -1.7160480 -2.6541400 -0.5804020
C -3.5250230 -1.4694810 -0.3001220
H -4.1789850 -2.2076590 -0.7788170
H -3.5675460 -1.6532030 0.7818840
C -3.9949680 -0.0449330 -0.5980240
H -4.0446910 0.0961850 -1.6876520
H -5.0041820 0.1257860 -0.2070260

Genisteine (**67**)



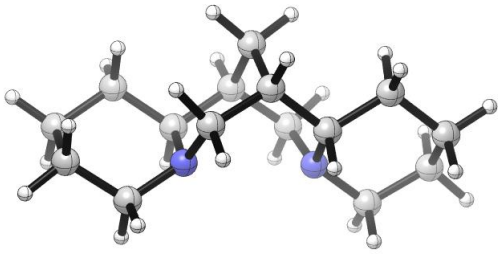
XYZ Coordinates
43
Final Energy = -696.5120749720
H -1.1042360 2.0751200 -1.8363600
C -0.6230220 1.4817710 -1.0481890
N 1.2865790 -0.1093100 -0.7781020
C 0.6230220 1.4817710 1.0481890
C 1.7423740 0.6465100 0.3955570
C 0.0000000 2.4014360 0.0000000
C 0.5059080 0.6905560 -1.7149990
H 2.5094450 1.3846140 0.0639020
H 0.7607240 3.0468790 -0.4565440
H 1.1562510 1.4264280 -2.2342550
H 1.1042360 2.0751200 1.8363600
H -0.7607240 3.0468790 0.4565440
H 0.1136780 0.0172830 -2.4862590
C 2.4206730 -0.3070950 1.3784070
H 1.6862950 -1.0523640 1.7097980
H 2.7447240 0.2574740 2.2614420
C 2.4119850 -0.7326750 -1.4652500
H 2.0252520 -1.2500510 -2.3506270
H 3.1213440 0.0437250 -1.8245490
C 3.1504900 -1.7125950 -0.5594540
H 2.4751240 -2.5407910 -0.3095290
H 4.0053880 -2.1349200 -1.0992820
C 3.6059180 -1.0167240 0.7230990
H 4.0570560 -1.7359420 1.4152640
H 4.3790740 -0.2750820 0.4780660
C -1.7423740 0.6465100 -0.3955570
C -0.5059080 0.6905560 1.7149990
H -1.1562510 1.4264280 2.2342550
H -0.1136780 0.0172830 2.4862590
N -1.2865790 -0.1093100 0.7781020
C -2.4119850 -0.7326750 1.4652500
H -2.0252520 -1.2500510 2.3506270
C -3.6059180 -1.0167240 -0.7230990
H -2.5094450 1.3846140 -0.0639020
H -4.0570560 -1.7359420 -1.4152640
C -2.4206730 -0.3070950 -1.3784070
H -1.6862950 -1.0523640 -1.7097980
H -2.7447240 0.2574750 -2.2614420
H -3.1213440 0.0437250 1.8245490
H -4.3790740 -0.2750820 -0.4780660
C -3.1504900 -1.7125960 0.5594540
H -4.0053880 -2.1349200 1.0992810
H -2.4751240 -2.5407910 0.3095280

Water (**337**)



XYZ Coordinates
3
Final Energy = -76.4034656115
H 0.0000000 0.7684290 -0.4676740
O 0.0000000 0.0000000 0.1169190
H 0.0000000 -0.7684290 -0.4676740

pusilline (**68**)



XYZ Coordinates

43

Final Energy = -696.5006716610

H 1.9560830 0.8798830 1.5106980
C 1.1188920 0.5016050 0.9103770
N 0.6061950 -1.3358860 -0.6863360
C -1.1188920 -0.5016050 0.9103770
C -0.6254380 -1.6749540 0.0420450
C 0.0000000 0.0000000 1.8257900
C 1.6464980 -0.6957450 0.1103640
H 0.3780120 -0.7962780 2.4766310
H 2.1226480 -1.3888840 0.8317190
H -1.9560830 -0.8798830 1.5106980
H -0.3780120 0.7962780 2.4766310
H 2.4335640 -0.3679580 -0.5812940
C 1.0902040 -2.4544720 -1.4882390
H 2.0162550 -2.1425390 -1.9853020
C 0.6254380 1.6749540 0.0420450
C -1.6464980 0.6957450 0.1103640
H -2.1226480 1.3888840 0.8317190
H -2.4335640 0.3679580 -0.5812940
N -0.6061950 1.3358860 -0.6863360
C -1.0902040 2.4544720 -1.4882390
H -2.0162550 2.1425390 -1.9853020
H 1.3891280 1.8694200 -0.7298580
H -0.3465300 2.6470220 -2.2763920
C 0.4862770 2.9673410 0.8720810
H 1.4536190 3.2051250 1.3317760
H -0.2293130 2.8088370 1.6897630
C 0.0000000 4.1328670 0.0075620
H 0.7633240 4.3665390 -0.7488870
H -0.1328570 5.0339320 0.6167020
C -1.3014310 3.7518860 -0.6995570
H -1.6273540 4.5475320 -1.3796210
H -2.0984890 3.6137840 0.0432500
H -1.3891280 -1.8694200 -0.7298580
H 0.3465300 -2.6470220 -2.2763920
C -0.4862770 -2.9673410 0.8720810
H -1.4536190 -3.2051250 1.3317760
H 0.2293130 -2.8088370 1.6897630
C 0.0000000 -4.1328670 0.0075620
H -0.7633240 -4.3665390 -0.7488870
H 0.1328570 -5.0339320 0.6167020
C 1.3014310 -3.7518860 -0.6995570
H 1.6273540 -4.5475320 -1.3796210
H 2.0984890 -3.6137840 0.0432500

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