Isotopes as Venues of Exotic Physics Phenomena
Neutrinoless Double Beta Decays- an example

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For

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Talk Plan

- Introduction

  Role of symmetries in physics
- Beta Decay symmetries
- Double Beta Decays
- Implications for astrophysics/cosmology
- Candidate Isotopes
- Experiments
- Future prospects

Symmetries play an important role

- Symmetrie, ob man ihre Bedeutung weit oder eng faβt, ist eine Idee, vermöge derer der Mensch durch die Jahrtausende seiner Geschichte versucht hat, Ordnung, Schönheit und Vollkommenheit zu begreifen und zu Schaffen.

  Hermann Weyl in Symmetrie

- *Symmetry, as wide or as narrow as you may define its meaning, is one idea by which man through the ages has tried to comprehend and create order, beauty, and perfection.*

In physics...

- Broken symmetries are good too

New degrees of freedom

New avenues to explore

New insights

eg: Parity violation in mid-1950s.

Also, in physics: For every symmetry, there is a conservation law /selection rule - *Emmy Nöther (~ 1918)*

Exception: Time reversal Symmetry

- Symmetries- Physical/spatial and Abstract types

Abstract Symmetries:

- Baryon number Conservation-- without this there is no matter

  Why is proton stable? (>10^{29} years)
- Lepton number conservation -- spin (a mathematical concept)
- Flavor Conservation -- Abstract
- Particle- Antiparticle Equivalence?

Fermions - Two types

- Baryon --- (1953) Abraham Pais
- Lepton --- (1947) Rosenfeld

Fermion number conservation --- Angular momentum (Spin)

Baryon and Lepton Number conservation ---- Abstract, mathematical

Particle – Antiparticle Symmetry

Can a particle be its own anti-particle?

Yes, if <u>ALL</u> additive quantum numbers are zero….

Photon, π^0, η, …. Mesons

Parity Symmetry

- Does a system remain unchanged if we invert the space in which it resides?
- Total inversion : $\vec{r} \rightarrow -\vec{r}$
- In 1950s, a problem in particle physics:

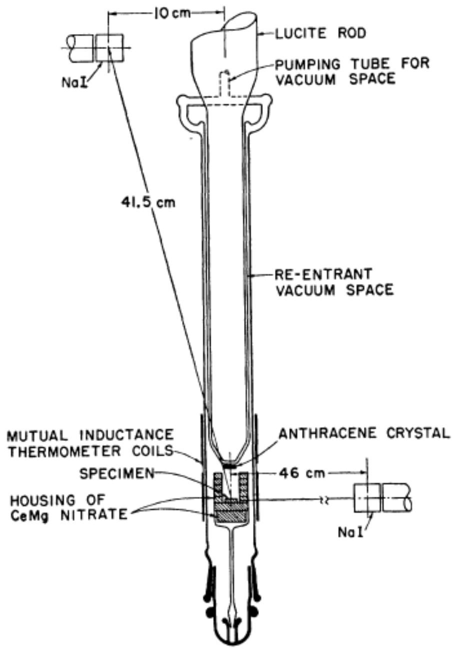
For the same species, some particles decayed by two emissions of negative values, while some others showed three emissions.

- Two times negative is +ve, while the three times negative is still negative.

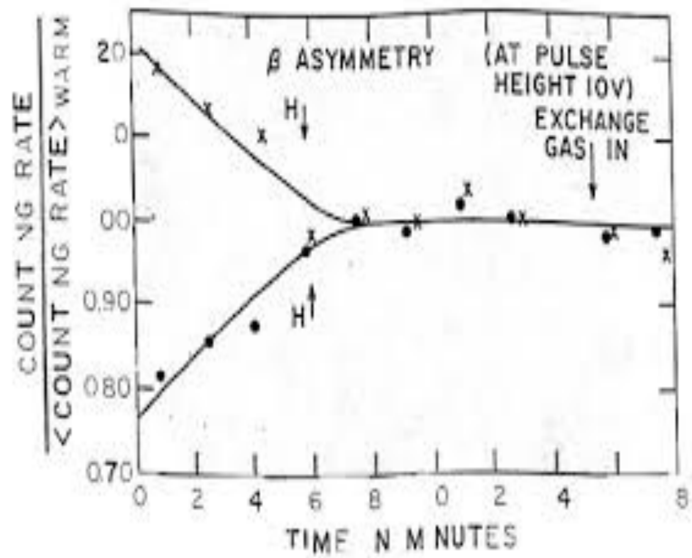
Theory: Some phenomena, especially β decays do not respect this symmetry.

Lee and Yang - Theory
C.S. Wu experiment (1956)

T= 0.003 K



ɜ. 1. Schematic drawing of the lower part of the cryostat.



Since then, particle physics has not been the same.

Are β decays trouble makers or fascinating ?

- First problem: Energy – Momentum conservation needs a new particle --- neutrino !!
- very light particle (nearly zero mass), spin ½ (Fermion), zero charge

- We know: For every particle there is an antiparticle
- Some particles(quanta) are their own antiparticles
  - photon, π^0 meson, η meson, ……

When can a particle be its own antiparticle?

Can neutrino be its own antiparticle?

Neutrino - Its own anti-particle?

- zero Charge ✓
- zero Mass - no consequence ✓
- non-zero spin - no consequence ✓
- Lepton number ??

Dirac : neutrino and antineutrino are distinct

Majorana : Not necessarily distinct

So, what do we have ?? Dirac neutrinos or Majorana neutrinos?

How to test??

Go back to beta decays, isotopes !!

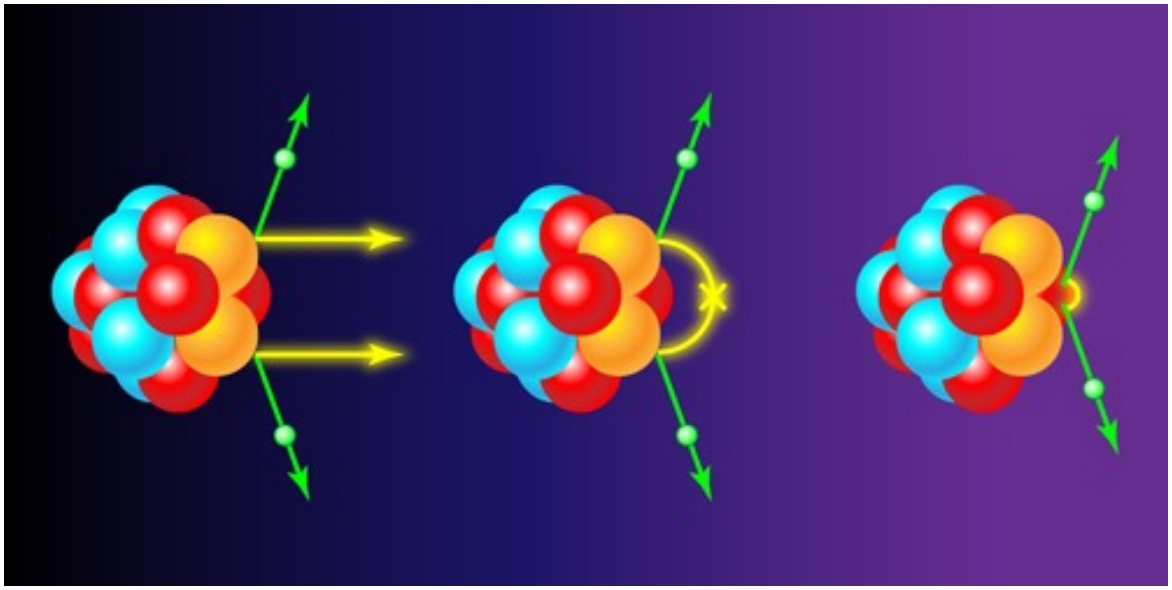
- ${}^{A}_{Z}X \rightarrow {}_{Z\pm1}^{\ \ A}X' \ + \beta^{\mp} + \bar{\nu}(\nu)$ A
- ${}^{A}_{Z}X \rightarrow {}_{Z\pm2}^{\ \ A}X' \ + 2\beta^{\mp} + 2\bar{\nu}(\nu)$ B
- ${}^{A}_{Z}X \rightarrow {}_{Z\pm2}^{\ \ A}X' \ + 2\beta^{\mp}$?? C
- 'C' can happen if only neutrino is its own antineutrino !!

3 modes of double beta decays

a) 2- neutrinos.

b) Neutrino-antineutrino one and same

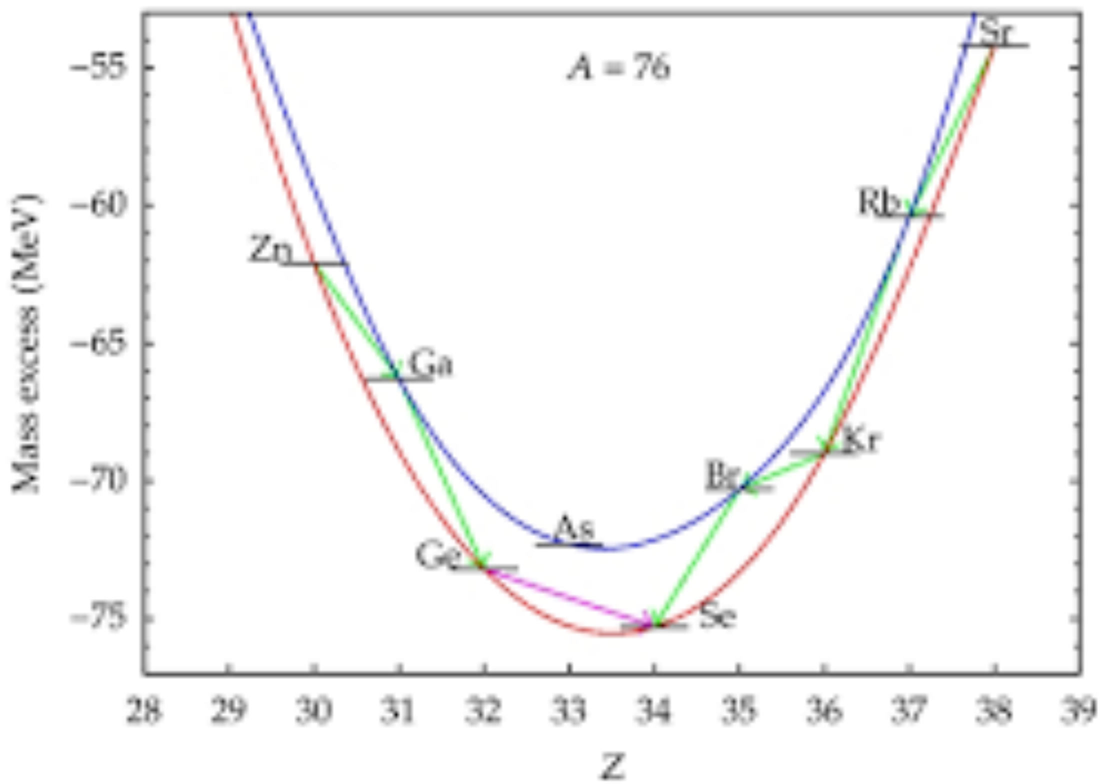
c) No neutrino at all



• Process a) can be distinguished from b), c) by kinematics

Double β decay: Not a sequential decay

Decay Energetics



Why study this process??

- A) settle the question of Dirac vs Majorana
- B) virtual processes required to mediate this phenomenon:

  nuclear structure, interactions, virtual particles, Dark Matter etc..

  from symmetry, structure to cosmological imp;ications

Some Double Beta decay candidates

Isotope	Natural abundance (%)[a]	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

2ν decays: ^{100}Mo - 6 x 10^{20} ; ^{150}Nd – 1.3x 10^{20} years

2νββ Decay of ^{116}Cd – Barabash et al.

https://arxiv.org/pdf/1811.06398.pdf

Experiment	$T_{1/2}(\times 10^{19}$ yr)	Year, Reference
ELEGANT V, ^{116}Cd foil, drift chambers, plastic scintillators	$2.6^{+0.9}_{-0.5}$	1995 [40]
Solotvina, $^{116}CdWO_4$ scintillators	$2.7^{+0.5}_{-0.4}(\text{stat})^{+0.9}_{-0.6}(\text{sys})$	1995 [41]
NEMO-2, ^{116}Cd foils, track reconstruction by Geiger cells, plastic scintillators	$3.75 \pm 0.35(\text{stat}) \pm 0.21(\text{sys})^{a}$	1995 [42, 43]
Solotvina, $^{116}CdWO_4$ scintillators	$2.6 \pm 0.1(\text{stat})^{+0.7}_{-0.4}(\text{sys})$	2000 [44]
Solotvina, $^{116}CdWO_4$ scintillators	$2.9 \pm 0.06(\text{stat})^{+0.4}_{-0.3}(\text{sys})$	2003 [32]
NEMO-3, ^{116}Cd foils, track reconstruction by Geiger cells, plastic scintillators	$2.74 \pm 0.04(\text{stat}) \pm 0.18(\text{sys})$	2017 [45]
$^{116}CdWO_4$ scintillators	$2.63 \pm 0.01(\text{stat})^{+0.11}_{-0.12}(\text{sys})$	2018, Present work

[a)] The result of NEMO-2 was re-estimated as $T_{1/2} = [2.9 \pm 0.3(\text{stat}) \pm 0.2(\text{sys})] \times 10^{19}$ yr in [46].

Current Lower Limits on Neutrinoless Decays:

M. Dolinski et al, *Annu. Rev. Nucl. Part. Sci. 2019. 69:219–51*

Isotope	$T_{1/2}^{0\nu}$ (x10^{25} years)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment	Reference
^{48}Ca	$>5.8 \times 10^{-3}$	$<$3.5–22	ELEGANT-IV	159
^{76}Ge	$>$8.0	$<$0.12–0.26	GERDA	160
	$>$1.9	$<$0.24–0.52	MAJORANA DEMONSTRATOR	161
^{82}Se	$>3.6 \times 10^{-2}$	$<$0.89–2.43	NEMO-3	162
^{96}Zr	$>9.2 \times 10^{-4}$	$<$7.2–19.5	NEMO-3	163
^{100}Mo	$>1.1 \times 10^{-1}$	$<$0.33–0.62	NEMO-3	164
^{116}Cd	$>2.2 \times 10^{-2}$	$<$1.0–1.7	Aurora	165
^{128}Te	$>1.1 \times 10^{-2}$	NE	C. Arnaboldi et al.	166
^{130}Te	$>$1.5	$<$0.11–0.52	CUORE	126
^{136}Xe	$>$10.7	$<$0.061–0.165	KamLAND-Zen	167
	$>$1.8	$<$0.15–0.40	EXO-200	168
^{150}Nd	$>2.0 \times 10^{-3}$	$<$1.6–5.3	NEMO-3	169

Acronyms of the collaborations

- **CUORE, Italy:** Cryogenic Underground Observatory for Rare Events
- **NEMO-3, France:** Neutrino Ettore Majorana Observatory
- **GERDA, Italy:** *The GERmanium Detector Array*
- **ELEGANT, Japan:** ElEctron Gamma ray Neutrino Telescope
- **KamLAND-Zen, Japan**: Kamioka Liquid scintillatorANtineutrino Detector for Zero-Neutrino Double-Beta Decay
- **EXO-200, USA:** Enriched Xenon Observatory – 200 kg liquid Xe

Neutrino Research in India

- INO- India Neutrino Observatory
- Muon Background of INO

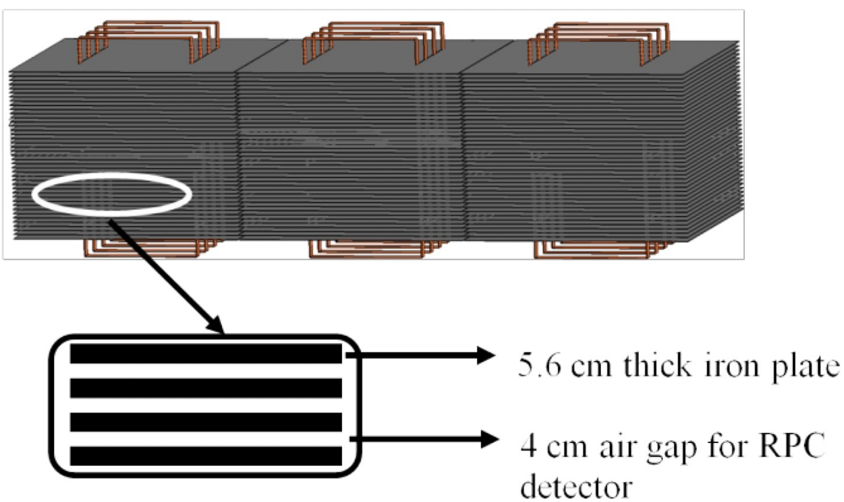
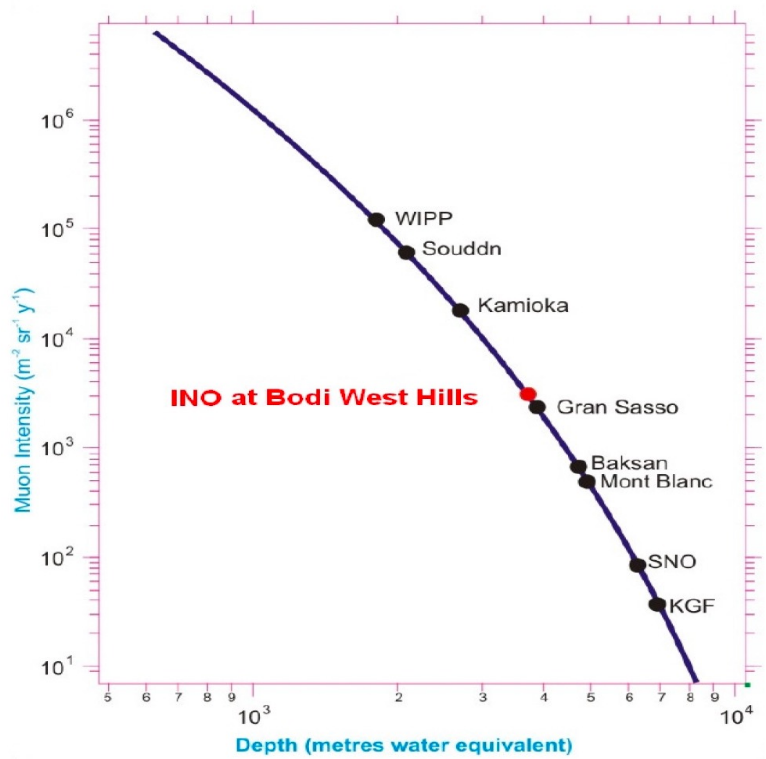


Figure 1.3: Schematic view of the 50 kt ICAL detctor



TIN TIN https://www.tifr.res.in/~tin.tin/

The INdia-based TIN Detector (TIN.TIN)

- TIFR, BARC, IIT/Ropar . VECC etc…
- Sn Cryogenic bolometer in development to be located at INO

cooling power:1.4 mW at 120 mK

Stay Tuned for Exciting Astrophysics and Cosmology in the coming Decade (s) from India and elsewhere

Thanks/Merci