Neutrinoless double beta decay

Status and challenges: A brief review

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Plan

• Introduction to NDBD
• Experimental challenges and novel techniques
• Some recent results
• Indian effort – TIN.TIN
• Summary
Nuclear Double Beta Decay: early history

\[ n \rightarrow p + e + \bar{\nu} \]

\[ Z^A \rightarrow Z+1^A \]

2νββ: 2\(^{nd}\) order weak interaction normal beta decay (βν) suppressed by Q-value or J\(^{π}\)

- First suggested by Maria Goeppert-Mayer (1935) \( T_{1/2} \approx 10^{17} \) yrs
- First geochemical observation of DBD \( T_{1/2}(^{130}\text{Te}) \approx 1.2 \times 10^{21} \) yrs (Ingram & Reynolds, 1950)
- First DBD Experimental evidence in laboratory: \(^{82}\text{Se}\) (Elliot et al. 1987)
Neutrinoless Double Beta Decay

- Majorana 1937: *neutrino is its own antiparticle*
- G. Racah (1937): *suggested testing Majorana theory with $0\nu\beta\beta$*

$0\nu\beta\beta$: Lepton number violating process occurs if neutrinos have mass and are their own antiparticles

**Importance of $0\nu\beta\beta$**

- only experiment to test the true nature of neutrino
  - whether it is a Dirac or a Majorana particle.
- enables the measurement of effective neutrino Majorana mass.
(Z,A) → (Z+2,A) + 2e⁻ + 2\bar{\nu}_e
(Z,A) → (Z−2,A) + 2e^+ + 2\nu_e

\textbf{2νββ Decay}
Conserves lepton number
\[ \Gamma^{2\nu} \propto Q^{11} \]

\textbf{0νββ Decay}
Violates lepton number conservation
\[ \Gamma^{0\nu} \propto Q^5 \]

- (β⁺β⁺/β⁺EC/ECEC) modes have additional experimental signal from β⁺ annihilation
- The half-lives of many β⁻β⁻ emitters are smaller due to the larger Q-values in comparison to the other modes.
\[ \Gamma_{0\nu2\beta} \propto [\text{phase-space } (\propto Q^5)] \times [\text{Nuclear ME}]^2 \times |\langle m_\nu \rangle|^2 \]

**High \( Q_{2\beta} \) and abundance desirable**

- Simultaneous emission of two electrons
- Constancy of the sum energy of the two emitted electrons
- Emission of two electrons from the same point inside the source.
- Angular correlation of emitted electrons

\[ \text{Identification experiments} \]

**Sum energy peak \( \Rightarrow \) High resolution**

**Extremely low event rates \( \Rightarrow \) very large sources and detector**
Experimental Methods

$2\nu\beta\beta$ & $0\nu\beta\beta$

1. DBD nuclei integral part of detector (active source)
   
   $-\ 76\text{Ge}, \ 128,130\text{Te}$
   
   Calorimetry (temperature, ionization, scintillation)
   
   $\Delta E_{\text{FWHM}}/E < 0.5 \% \ \text{at} \ 2 \text{MeV}$

2. Source external to detector (passive source)

   Tracking of $\beta^-$ (in magnetic field) + Vertex + Fast coincidence

   Poorer $\Delta E_{\text{FWHM}}/E \sim 4-10 \%$

Background reduction

- Underground location (reduce cosmic ray background)
- Careful choice of materials (detector & environs, shielding)
- Electronic rejection of background events

For a conclusive proof, $0\nu\beta\beta$ measurement in several isotopes is essential
Background issues

- Radioactivity of the surrounding materials (Natural Decay Chains)
  \[ T_{1/2} : \quad ^{238}\text{U} \sim 10^9 \text{ yrs}, \quad ^{235}\text{U} \sim 10^8 \text{ yrs}, \quad ^{232}\text{Th} \sim 10^{10} \text{ yrs} \]
- \(^{40}\text{K}\)
- radiative impurities

DBD events \( T_{1/2} \geq 10^{20} \text{ yrs} \), overwhelmed by natural background

\[ N_a = N_A (M/A)i \quad \text{number of } \beta\beta \text{ atoms} \]
\[ t : \text{measurement time} \]
\[ \varepsilon : \text{detection efficiency} \]

\[ \frac{T_{1/2} \sim \ln 2 \cdot N_a \cdot t \cdot \varepsilon}{N_{0\nu\beta\beta}} \]

\[ N_{\text{bkg}} = B(c/kev/t) \cdot \Delta E \cdot t \]

\[ T_{1/2} \sim \ln 2 \cdot N_A \cdot M \cdot i \cdot \varepsilon \cdot t / A(B\Delta Et)^{1/2} \]

- low energy neutrons – induced by Uranium/Thorium activities in the surrounding rocks and concrete by the fission and \((\alpha,n)\) reactions.
- high energy neutrons – interaction of muons in the rocks or with the heavy metal shielding around the detector

The neutron background is quite difficult to suppress.

Background reduction is very crucial
Present Status

- Many small scale experiments ~ kg
  \[ T_{1/2} \approx 10^{24} - 10^{25} \text{ years}, \quad \langle m_\nu \rangle \approx 0.75 \text{ eV} \]
- A few large scale experiments: Cuoricino, NEMO3
- Some of these experiments have capability to upscale
- Improvement in sensitivity possible by background reduction in some cases
- Many new experiments are planned/proposed, R&D in progress
- 2νββ detected in several nuclei, half life measured.
- Search for other DBD modes
- Scintillating Bolometers (Lucifer)
### Neutrinoless Double beta decay Experiments & Proposals

<table>
<thead>
<tr>
<th>experiment</th>
<th>isotope</th>
<th>mass [kg]</th>
<th>method</th>
<th>location</th>
<th>time</th>
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<tr>
<td><strong>past experiments</strong></td>
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<td>Heidelberg-Ms.</td>
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<td>LNGS</td>
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<td>Cuoricino</td>
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<td>NEMO-3</td>
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<td>Modane</td>
<td>-2011</td>
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<td><strong>current experiments</strong></td>
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<td>EXO</td>
<td>$^{136}$Xe</td>
<td>175</td>
<td>liquid TPC</td>
<td>WIPP</td>
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<td>[15]</td>
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<td>Kamland-Zen</td>
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<td>liquid scintil.</td>
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<td>[39]</td>
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<td>CANDLES</td>
<td>$^{48}$Ca</td>
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<td>scint. crystal</td>
<td>Oto Cosmo</td>
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<td><strong>funded experiments</strong></td>
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<td>NEXT</td>
<td>$^{136}$Xe</td>
<td>100</td>
<td>gas TPC</td>
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<td>Majorana Demo.</td>
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<td>30</td>
<td>ionization</td>
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<td><strong>proposal, proto-typing</strong></td>
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<td>Cobra</td>
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<td>DCBA/MTD</td>
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<td>32</td>
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<td>MOON</td>
<td>$^{82}$Se, $^{100}$Mo</td>
<td>30-480</td>
<td>track.+scint.</td>
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<td>liquid scint.</td>
<td>Kamioka</td>
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<td>AMoRE</td>
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<td>100</td>
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<tr>
<td>Cd exp.</td>
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<td></td>
<td>scint.</td>
<td></td>
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*Arxiv:1201.4916v1*
Recent results & Status

- GERDA ($^{76}\text{Ge}$, HPGe detector)
- EXO ($^{136}\text{Xe}$, TPC + Ba$^+$)
- KamLAND-Xe ($^{136}\text{Xe}$, liquid scintillator)
- CUORE ($^{130}\text{Te}$, cryogenic thermal detector)
GERDA ($^{76}$Ge)
Located at LNGS

Phase 1 (2013)

- ~86% enriched liquid Ar – detector coolant + shield
- Muon veto – water Cernekov

• Energy resolution (ROI)~0.15%
• Background ~ 0.02 cts/(keV-Kg-yr)
• Detector segmentation
• Pulse shape discrimination

http://www.mpi-hd.mpg.de/gerda/
First results from GERDA


21.6 Kg-yr exposure

Open histogram without PSD, solid histograms with PSD cut

Blue solid line – upper limit obtained by the GERDA collaboration

\[ T_{1/2} > 2.1 \times 10^{25} \text{ yr (90\% C.L.)}, \text{ effective neutrino mass } 200-400 \text{ meV} \]
EXO-200 ($^{136}\text{Xe}$)
Located at WIPP, USA (1580 mwe)

Liquid Xenon TPC
~80% enriched
TPC – ionization and scintillation signal.
Electronic rejection of multihit background signals

Background ~ 0.0017 cts/(keV-Kg-yr) – considerably smaller than GERDA

J.B. Albert et al. (EXO Collaboration), Nature 510, 229 (2014)
With 123.7 Kg-yr exposure

$T_{1/2} > 1.1 \times 10^{25}$ yr (90% C.L.), effective neutrino mass 190-450 meV
Kamland-Zen ($^{136}\text{Xe}$)

Located in Japan (2700 mwe)

Liquid Xenon loaded scintillator

~91% enriched

Water Cerenkov for muon veto

Resolution ~ 4%

Phase I: Background in the ROI limited by $^{110}\text{mAg}$

Phase II: after purification with improved background

Phase I+II:

$T_{1/2} > 2.6 \times 10^{25} \text{ yr (90\% C.L.)}$, effective neutrino mass 140-280 meV

arXiv:1409.0077v1
GERDA, EXO and KAMLAND - ZEN
proved the feasibility of a large bolometric array with the tower-like structure

Detector performances are not affected by the increase in crystal size (from 340 g to 760 g)
Cryogenic Underground Observatory (for) Rare Events

- M = 0.75 ton
- bkg ~ 0.01 counts/(keV-kg-yr)
- $T_{1/2} \sim 2.5 \times 10^{26}$ yrs, $\langle m_\nu \rangle \sim 0.04$ eV

- Pulse Tubes
- Internal lead shielding
- External lead shielding
- PET shielding

Array of 988 detectors:
19 towers, 13 modules/tower, 4 detectors/module

Nucciotti et al., JOLT, 151 (2008) 662
Initiative for DBD experiment in India

A multi-institutional effort

Proposal for an experiment at site of the INO

$^{124}\text{Sn} (Q = 2288.1 \pm 1.6 \text{ keV})$

- Sn has $T_C \sim 3.7 \text{ K}$
- Electronic specific heat falls off exponentially below $T_C$
- Only lattice specific heat ($\sim T^3$) present below $\sim 500 \text{ mK}$
- Z=50 shell is closed
- Simple metallurgy

$^{124}\text{Sn}: T_{1/2} > (0.8-1.2) \times 10^{21} \text{ yrs}$ Nucl. Phys. A 807, 269(2008)

Strongly Multi-disciplinary project

Nuclear Physics, Particle Physics, Low Temperature Physics, Material Science, Physical Chemistry
A bolometer is a calorimetric detector.

Energy of particle $\rightarrow$ Thermal energy in detector
$\rightarrow$ measurable temperature rise if net heat capacity is very low

Resolution of Bolometer
- Limited by Thermodynamical fluctuation noise $\{\delta E = (kT^2 C(T))^{1/2}\}$
- Depends only on operating temperature and specific heat
- Independent of incident Energy

Challenge: to make measurements in time domain at mK temperature
$^{124}\text{Sn bolometer}$


0.95 x 0.95 x.25 mm$^3$ Sn sample

*Large Size Sn Bolometers have not yet been made.*
Cryogen Free Dilution Refrigerator @TIFR
(Custom built CFDR-1200: M/S Leiden Cryogenics)

- Cryogen Free Dilution preferable for experiments with long timescales at remote underground location
- Reduced vibration (compressor mounted at distance, linear drive)

Our Design requirement

- A cylindrical sample space of 30 cm dia x 30 cm long for housing an array of natural/enriched Tin crystals (~3x3x3 cm$^3$ each) together with lead shielding.
- Readout wires for 75 sensors:
  - Total of 300 wires (75x 4)
  - phosphor –bronze till 3K
  - NbTi between 3K and 10 mK stage, to minimize the heat load
  - Provision for mounting preamp stage of pulse processing at 50K
- Total mass Sn+Pb ~ 100 Kg
- Large cooling Power to cool down to 10mK (1.4mW @ 120mK)
- Provision for top mounting probe for easy sample changes during R&D
Cryogen free dilution refrigerator installed at TIFR

Base Temp. ~7 mK
cooling power
1.4 mW @ 120 mK

V. Singh et. al. Pramana 81 (2013) 719

http://www.tifr.res.in/~tin.tin/
Diagnostic thermometry & wiring

Stable within 0.5% of the base temperature (12.2±0.05 mK).

- R&D on bolometer
- Choice of materials, mounting of sensors, Readout wires and making connections
- RF shielding & low temperature sensor readout, vibration issues
- Physics issues with SC bolometers (measurements in 10 mK to 4 K range)
Specific Heat of Tin

V. Singh et al. JOLT 175, 604 (2014)

Large Size Sn Bolometers should be feasible

Specific Heat for Torlon, Teflon (support materials)

V. Singh et al. submitted to Cryogenics
### NTD Ge Sensor R&D

Neutron irradiation at Dhurva Reactor (BARC, Mumbai)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Isotopic Abundance (%)</th>
<th>Products (half-life)</th>
<th>Stable end product (mode)</th>
<th>Dopant Type</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Set 1</td>
<td>Set 2</td>
<td></td>
<td></td>
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<tr>
<td>$^{70}\text{Ge}$</td>
<td>21.5</td>
<td>21.9</td>
<td>$^{71}\text{Ge}^*$ (11.43d)</td>
<td>$^{71}\text{Ga}$ (e$^-$ capture)</td>
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<tr>
<td>$^{72}\text{Ge}$</td>
<td>26.8</td>
<td>27.0</td>
<td>$^{73}\text{Ge}$ (stable)</td>
<td>$^{73}\text{Ge}$</td>
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<tr>
<td>$^{73}\text{Ge}$</td>
<td>10.8</td>
<td>8.8</td>
<td>$^{74}\text{Ge}$ (stable)</td>
<td>$^{74}\text{Ge}$</td>
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<td>$^{74}\text{Ge}$</td>
<td>34.1</td>
<td>35.1</td>
<td>$^{75}\text{Ge}^*$ (82.78min)</td>
<td>$^{75}\text{As}$ (β-decay)</td>
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<tr>
<td>$^{76}\text{Ge}$</td>
<td>6.8</td>
<td>7.2</td>
<td>$^{77}\text{Ge}^*$ (11.3,38.8hrs)</td>
<td>$^{77}\text{As}^*,^{77}\text{Se}$ (β-decay)</td>
</tr>
</tbody>
</table>

- Radioactive impurity studies
- Fast neutron induced defect studies (PALS, Channeling)
  - Annealing at 600 C for 2 hrs in vacuum cures defects

S. Mathimalar et. al., NIM B  in press
Study for radioactive impurities in NTD Ge
Study for radioactive impurities in NTD Ge

The samples were etched with $\text{H}_2\text{O}_2$ at 80°C in ultrasonic bath and HF for removing surface impurities.

After 20 $\mu$m impurities nearly remained constant (bulk contribution)
## Study for radioactive impurities in NTD Ge

<table>
<thead>
<tr>
<th>Sample</th>
<th>Activity (mBq/gm) (t&lt;sub&gt;0&lt;/sub&gt; + 150 days)</th>
<th>T&lt;sub&gt;cool&lt;/sub&gt; (yrs)</th>
<th>¹²³Sb Conc. (ppt)</th>
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<tbody>
<tr>
<td>¹¹⁰Ag</td>
<td>²⁴⁴Sb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>3018 ± 465</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>743 ± 222</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>D-B1</td>
<td>-</td>
<td>420 ± 9</td>
<td>1.9</td>
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<tr>
<td>E-T3L</td>
<td>-</td>
<td>201 ± 20</td>
<td>1.7</td>
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<tr>
<td>F-B5</td>
<td>-</td>
<td>344 ± 12</td>
<td>1.8</td>
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</tbody>
</table>

**Channeling studies of NTD Ge**

**First sensor results**

**Mathi et al. 10.1109/WOLTE.2014.6881014**
Bolometer Detector - Initial Tests

- NTD Ge sensor
- Teflon: weak thermal link
- Tin ~ 3.3 g
- Am-Pu alpha source (5.5 MeV)
- Copper: Thermal Bath

For 5.5 MeV alpha - expected temperature rise at 100 mK ~ 130 μK.
Thermal pulses are characterized by sharp rise time and very slow decay time. Since the pulses are slow, high frequency noise can be filtered. Count rate matched with the alpha source. Need to improve on Signal to Noise ratio to achieve good resolution and generate an energy spectrum.
Low bkg HPGe detector (70%, ORTEC)

Expt (red filled) and MC (blue lines) for 834.8keV

Screening of materials and their selection on the basis of radio purity levels

- \(^{124}\text{Sn}, \text{natSn}, ^{122}\text{Sn}\)
- ETP Cu, OFHC Cu, Torlon, Teflon, FET
- Neutron Transmutation Doped Ge sensors, \text{natZr} foils

N. Dokania et al., NIM A 745 (2014) 119-127
Low Background Counting Facility

Ambient background spectra

Cosmic Veto added

Cryo-free low Bkg HPGe setup is underway

Setup can also be used for rare decay studies
### $n$-induced background in $^{124}\text{Sn}$

- $^{124}\text{Sn} (\text{n, } \gamma) \quad ^{125}\text{Sn}$
- $^{125}\text{Sn} : \beta$ decay $Q_\beta = 2357 \text{ keV}$
  - (very close to $Q_{\beta\beta}$ of $^{124}\text{Sn} = 2293 \text{ keV}$)
- $T_{1/2} = 9.52\text{m}, 9.64\text{ days}$

- $^{124}\text{Sn} (2\text{n, } \gamma) \quad ^{126}\text{Sn}$
- $^{126}\text{Sn}$ undergoes $\beta$-decay to $^{126}\text{Sb}$
  - ($T_{1/2} = 2.3 \times 10^5 \text{ years}, Q_\beta = 378 \text{ keV}$)
- $^{126}\text{Sb}$ undergoes $\beta$-decay to $^{126}\text{Te}$
  - ($T_{1/2} = 12.35 \text{ days}, Q_\beta = 3673 \text{ keV}$)

Simulation studies to estimate neutron flux at INO site based on rock composition and design of layered shield (Paraffin + lead) are in progress.
Fast neutron activation setup at PLF, Mumbai

<table>
<thead>
<tr>
<th>Production Target</th>
<th>E_p (MeV)</th>
<th>E_max (MeV)</th>
<th>&lt;E_n&gt; (MeV)</th>
<th>( \phi_n ) (n cm^{-2} s^{-1})</th>
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<tr>
<td>(^9)Be</td>
<td>12</td>
<td>9.9</td>
<td>3.9</td>
<td>2.3(0.2) x 10^5</td>
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<td>20</td>
<td>17.9</td>
<td>5.6</td>
<td>9.9(0.7) x 10^5</td>
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<tr>
<td>natLi</td>
<td>12</td>
<td>10.1</td>
<td>9.85</td>
<td>1.3(0.2) x 10^5</td>
</tr>
</tbody>
</table>

- \(^{124}\)Sn, natCu, natPb, Torlon & Teflon
- \(^{56}\)Fe(n,p) for neutron flux
$E_n^{\text{max}} \sim 18 \text{ MeV}$

(a) Torlon 4203
- $t_i = 10 \text{ min}$
- $t_i = 40 \text{ h} (\pm 0.1)$

(b) Torlon 4301
- $t_i = 10 \text{ min}$
- $t_i = 80 \text{ h} (\pm 0.1)$

(c) Teflon
- $t_i = 14 \text{ min}$
- $t_i = 117 \text{ h}$

$E_n^{\text{max}} \sim 18 \text{ MeV} (8 \text{ MeV})$

(a) $^{208}\text{Pb}$
- $t_i = 14 \text{ min}$
- $t_i = 117 \text{ h} (\pm 0.1)$

(b) $^{64}\text{Cu}$
- $t_i = 1.7 \text{ h}$
- $t_i = 80 \text{ h} (\pm 0.1)$

(c) $^{64}\text{Cu}$
- $t_i = 10 \text{ min}$

(Images and graphs depicting energy spectra for different materials and time intervals.)
**Estimated neutron-induced background**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Neutron Fluence (n cm(^{-2}) x (10^{10}))</th>
<th>Reaction Product</th>
<th>(T_{1/2})</th>
<th>(E_\gamma) (keV)</th>
<th>Expected Activity (E_\gamma) (Bq g(^{-1}))</th>
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<tbody>
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<td>natPb</td>
<td>0.30(2)</td>
<td>(^{124})Sb</td>
<td>60.2 d</td>
<td>2182.6 2294.0</td>
<td>0.0007(3) 00005(2)</td>
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<tr>
<td>natCu</td>
<td>0.33(2)</td>
<td>(^{62m})Co</td>
<td>13.91 min</td>
<td>2301.9 2882.3</td>
<td>6(2) 4(1)</td>
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<tr>
<td>(^{124})Sn</td>
<td>1.6(1)</td>
<td>(^{116m})In</td>
<td>54.29 min</td>
<td>2112.3</td>
<td>5(1)</td>
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<tr>
<td>natSn</td>
<td>0.84(6)</td>
<td>(^{116m})In</td>
<td>54.29 min</td>
<td>2112.3</td>
<td>24(6)</td>
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</tbody>
</table>

- Most of the activities are short-lived and can be minimized by storage in an underground location prior to use in the detector setup.
- Typical neutron flux in underground locations ~10\(^{-6}\) n/cm\(^2\)/s, \(E_n < 10\) MeV the required overall background level <10\(^{-2}\) counts/(keV kg year).

Contribution from Cu and Pb samples would be negligible

\(nat\)Sn produces higher background of 2112.3 keV and can be of concern.

N. Dokania et. al., JINST 9, P11002 (2014)
Nuclear Structure Aspect

• Several nuclear models to calculate the NTME
  – Shell-model and variants
  – QRPA and extensions
  – Alternative models
• The NTME ($M_{2\nu}$) is sensitive to details of the nuclear structure
  – Spectroscopic properties of the initial and final nucleus
  – Pairing and Deformation

Observed physical properties of nuclei: *Test of nuclear models*

Uncertainty in estimated neutrino mass upto a factor of 10 due to uncertainty in NTMEs.

Experiments to constrain NTME are essential
• Measurements with $^{\text{nat}}$Sn bolometer using Am-Pu source
• Rare decay studies using low BKG setup (DBD to excited state in $^{94}$Zr).
• NTD Ge Sensor development
• Neutron capture background studies
• $2\nu\beta\beta$ measurements in $^{124}$Sn

After prototype demonstration

Build a large scale detector (~ 1 ton) at INO lab

(3phases: 100 Kg, 500 Kg, 1000 Kg)

$F_n = G^{0\nu} |M^{0\nu}|^2 = 8.569 \times 10^{-13} \text{ yr}^{-1} (\text{PHFB})$

$= 1.382 \times 10^{-13} \text{ yr}^{-1} (\text{SM})$

*With 90 % enrichment, background ~ 0.01 counts/ keV.kg.yr
$m_\nu \sim 100 \text{ meV in 1 yr (SM)} , \quad m_\nu \sim 50 \text{ meV in 1 yr (PHFB)}$*
Majorana neutrino mass as a function of the smallest neutrino mass in the normal hierarchy (NS) and in the inverted hierarchy scenario (IS) (Figure from S. Bilenky, C Giunti, Mod. Phys. Lett. A 27 (2012) 1230015)

- **Degenerate**: can be tested
- **Inverted**: can be tested by next generation of 2β experiments.
- **Normal**: inaccessible (new approach is needed)
Summary

- Neutrinoless Double Beta Decay to test true nature of neutrino – Majorana or Dirac?
- Several large scale experiments with increased sensitivity are proposed and some are underway
- No peak seen in expected energy region yet!
- Feasibility study for NDBD with $^{124}\text{Sn}$ bolometer in India is underway
Tin.Tin Collaboration

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Yashwant G.(visiting fellow)
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IIT Kharagpur, IIT Ropar
P. K. Raina, S. Ghourai, Soumik Das

Univ. of Lucknow
P. K. Rath, Akhilesh Ranjan, Dr. Ramesh Chandra

PRL
V. K. B. Kota

VECC
Parnika Das

Thanks to
INO collaboration
Backup slides
**GERDA phase II**
20 Kg enriched detectors
Expected background 0.001 cts/(keV-Kg-yr)
100 Kg-yr exposure expected

**Majorana demonstrator (1500 m depth)**
30 Kg enriched detectors

**Kamland-Zen upgrade**
1 ton mass, resolution $\sim 2.5\%$
Expected sensitivity 20 meV
Table 1. Summary of $T_{1/2}^{0\nu\beta\beta}$ lower limits

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ [yr]</th>
<th>$\langle m_{\beta\beta} \rangle$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{136}$Xe</td>
<td>EXO-200</td>
<td>$&gt; 1.6 \cdot 10^{25}$</td>
<td>$&lt; 140$–$380$</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>KamLAND-Zen</td>
<td>$&gt; 1.9 \cdot 10^{25}$</td>
<td>$&lt; 120$–$250$</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>GERDA phase I</td>
<td>$&gt; 2.1 \cdot 10^{25}$</td>
<td>$&lt; 200$–$400$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>CUORICINO</td>
<td>$&gt; 2.8 \cdot 10^{24}$</td>
<td>$&lt; 300$–$700$</td>
</tr>
</tbody>
</table>

Table 2. Sensitivity of future experiments

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ sensitivity [yr]</th>
<th>$\langle m_{\beta\beta} \rangle$ sensitivity [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{136}$Xe</td>
<td>EXO-200 (4 yr)</td>
<td>$5.5 \cdot 10^{25}$</td>
<td>75–200</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>nEXO (5 yr)</td>
<td>$3 \cdot 10^{27}$</td>
<td>12–29</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>nEXO (5 yr + 5 yr w/ Ba tagging)</td>
<td>$2.1 \cdot 10^{28}$</td>
<td>5–11</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>KamLAND-Zen (300 kg, 3 yr)</td>
<td>$2 \cdot 10^{26}$</td>
<td>45–110</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>KamLAND2-Zen (1 ton, post 2016)</td>
<td>IH</td>
<td>IH</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>GERDA phase II</td>
<td>$2 \cdot 10^{26}$</td>
<td>90–290</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>CUORE-0 (2 yr)</td>
<td>$5.9 \cdot 10^{24}$</td>
<td>204–533</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>CUORE (5 yr)</td>
<td>$9.5 \cdot 10^{25}$</td>
<td>51–133</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>SNO+</td>
<td>$4 \cdot 10^{25}$</td>
<td>70–140</td>
</tr>
</tbody>
</table>

D. Tosi, arxiv:1402.1170v1
- 50K and 3K plates are cooled by a high cooling capacity pulsed tube cooler (1.5W @4.2K).
- 3He/ 4He mixture is condensed using a Joule-Thomson heat exchanger which is installed between the 3K plate and the Still.
- Turbo +roots pump for high flow rate and effectively higher cooling power
- Significantly smaller amount of 3He
Possible issues for finite size Superconducting bolometer

- Energy thermalization
- Anomalous heat capacity arising from impurities which can trap quasi-particles (degradation of resolution)
- Comparison of polycrystal and single crystal bolometers

Important to measure and quantify the heat capacity of Tin absorbers and other materials used in bolometers (sensor, heater, epoxy)

- Measured the heat capacity of high purity Tin samples (~ 3gm) in the range of 60-400 mK, Extracted Debye temperature consistent with values at higher T

- No differences observed for single and polycrystal sample

*Should be possible to make large size Sn bolometer: tests in progress*

V Singh et. al., *JOLT* (DOI: 10.1007/s10909-013-1081-5)
Specific Heat Measurement of Tin

### Relaxation Calorimetry

\[
C = \frac{T}{G}
\]

\[
P = I^2 \cdot R = G \cdot \Delta T
\]

\[
C = \frac{P \cdot T}{G} = I^2 \cdot R \cdot \frac{T}{\Delta T}
\]

- **Sensor**: Commercial Ruthenium Oxide chip resistor (Dale 1kΩ).
- **Heater**: NiCr chip resistor (100 Ω)
- **Thermal links**: NbTi wires.
- **Current Source for heater**: Keithley 220 programmable unit.
- **Resistance readout**: AVS-47B A.C Resistance Bridge

Typical Decay Pulse

\[ T = \Delta T \exp(-t/\tau) \]
How do we get mK temperature?

$^3$He-$^4$He Dilution Refrigerator

- Liquid $^4$He $\sim 4.2$ K, $^3$He $\sim 3.2$ K
- Pumping on liq. $^4$He $\sim 1.2$ K, $^3$He $\sim 0.3$ K
- Cooling through the continuous cycle of a $^3$He / $^4$He mixture for lower temperatures
- When a mixture of the two isotopes of helium is cooled below a critical temperature, it separates into two phases.

  - The lighter "concentrated phase" is rich in $^3$He and the heavier "dilute phase" is rich in $^4$He. Since the enthalpies of the $^3$He in the two phases are different, it is possible to obtain cooling by "evaporating" the $^3$He from the concentrated phase into the dilute phase.

  - This process continues to work even at the lowest temperatures because the equilibrium concentration of $^3$He in the dilute phase is still finite even as the temperature approaches absolute zero.

(originally proposed by H. London in 1951)
Has $0\nu\beta\beta$ been observed?

**Heidelberg-Moscow expt.**

11 Kg $^{76}$Ge (1990-2003)

Controversial !!

![Graphical representation of data]

$$T_{1/2} \geq 1.12 \times 10^{25} \text{ yrs} , \langle m_\nu \rangle \sim 0.1-0.9 \text{ eV}$$


Mod. Phys. Lett. A **21** (2006) 1547,

Old data, new pulse shape analysis.

$$\tau_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25} \text{ y (6 } \sigma)$$,

$$m_\nu = 0.32 \pm 0.03 \text{ eV}$$

$$n = 11 \pm 1.8 \text{ events}$$

**Recent results from CUORICINO**

Bolometric detector operated at 8 mK

40.7 Kg $^{130}$Te

![Graphical representation of data]

$$T_{1/2} \geq 1.8 \times 10^{24} \text{ yrs} , \langle m_\nu \rangle \leq 0.2-1.1 \text{ eV}$$

PRL **95**, 142501 (2005)

$$T_{1/2} \geq 3 \times 10^{24} \text{ yrs} , \langle m_\nu \rangle \leq 0.38-0.46 \text{ eV}$$

PRC **78**, 35502 (2008)

FIG. 2. Anticoincidence spectrum of the sum of the two electron energies in the region of neutrinoless $0\nu\beta\beta$ decay.
Neutron Transmutation Doped more homogeneous than chemically doped

$\sigma(n,\gamma)$ low, n-flux constant over sample $\Rightarrow$ uniform distribution of dopant

$^{71}\text{Ge}, \; ^{75}\text{Ge} \rightarrow$ decay As, Se, Ga

$$ R (T) = R_0 \exp( T_0/T)^{0.5} $$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Plane</th>
<th>Thickness (mm)</th>
<th>Resistivity ((\Omega)cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>&lt;100&gt;</td>
<td>1.0</td>
<td>&gt;35</td>
</tr>
<tr>
<td>Sample 2</td>
<td>&lt;111&gt;</td>
<td>0.4</td>
<td>&gt;30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NTD Ge</th>
<th>Neutron Flux/cm²</th>
<th>Calculated carrier concentration/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTD A</td>
<td>$1.9 \times 10^{18}$</td>
<td>$5.868 \times 10^{16}$</td>
</tr>
<tr>
<td>NTD B</td>
<td>$1.6 \times 10^{19}$</td>
<td>$4.94 \times 10^{17}$</td>
</tr>
<tr>
<td>NTD C</td>
<td>$0.97 \times 10^{19}$</td>
<td>$2.99 \times 10^{17}$</td>
</tr>
</tbody>
</table>