Neutrinoless Double Beta Decay

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https://www.nature.com/
Neutrinoless double beta decay

- Nuclear decay mode without emission of neutrinos ("forbidden" in the SM, since the lepton number is violated: $\Delta L = 2$)

\[
\begin{align*}
L = 0 & \quad 2n \rightarrow 2p + 2e^- \\
L = 2 & \quad 2p \rightarrow 2n + 2e^+
\end{align*}
\]

Expected: "peak" at the Q-value of the decay

\[Q = E_{e1} + E_{e2} - 2m_e\]
Neutrinoless double beta decay

• Why is this decay mode interesting?
  ➡ it can provide information about the nature of neutrinos

• Decision:
  ➡ neutrinos and antineutrinos are distinct particles (Dirac particles) or
  ➡ neutrinos are their own antiparticles (Majorana particles)

Paul Dirac  Ettore Majorana
What is the observable decay rate?

\[ \Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|\langle m_{eff} \rangle|^2}{m_e^2} \]

- with the effective Majorana neutrino mass:

\[ |\langle m_{eff} \rangle| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i(\alpha_1 - \alpha_2)} + U_{e3}^2 m_3 e^{i(-\alpha_1 - 2\delta)}| \]

- a coherent sum over mass eigenstates with potentially CP violating phases
- a mixture of \( m_1, m_2, m_3 \), proportional to the \( U_{ei}^2 \), with \( \alpha_1, \alpha_2 = \text{Majorana CPV phases} \)
Phase space

\[ \Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_{e}^2} \]

\[ G^{0\nu}(Q, Z) \propto (Z, Q^5) \]

| Transition       | G [10^{-14} yr^{-1}] | Q [keV]   |
|------------------|----------------------|-----------|
| \(^{48}\text{Ca} \rightarrow^{48}\text{Ti}\) | 6.35                 | 4373.7    |
| \(^{76}\text{Ge} \rightarrow^{76}\text{Se}\) | 0.63                 | 2039.1    |
| \(^{82}\text{Se} \rightarrow^{82}\text{Kr}\) | 2.7                  | 2995.5    |
| \(^{100}\text{Mo} \rightarrow^{100}\text{Ru}\) | 4.36                 | 3035      |
| \(^{116}\text{Cd} \rightarrow^{116}\text{Sn}\) | 4.62                 | 2809      |
| \(^{130}\text{Te} \rightarrow^{130}\text{Xe}\) | 4.09                 | 2530.3    |
| \(^{136}\text{Xe} \rightarrow^{136}\text{Ba}\) | 4.31                 | 2461.9    |
| \(^{150}\text{Nd} \rightarrow^{150}\text{Sm}\) | 19.2                 | 3367.3    |
Matrix elements

\[ \Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \left| \frac{m_{\beta\beta}}{m_e^2} \right|^2 \]

Matrix elements: vary by a factor of 2-3 for a given A
Which nuclei can decay via $0\nu\beta\beta$?

- Even-even nuclei
- Natural abundance is low (except $^{130}$Te)
- Must use enriched material

| Candidate* | Q [MeV] | Abund [%] |
|------------|---------|-----------|
| $^{48}$Ca $\rightarrow$ $^{48}$Ti | 4.271 | 0.187 |
| $^{76}$Ge $\rightarrow$ $^{76}$Se | 2.040 | 7.8 |
| $^{82}$Se $\rightarrow$ $^{82}$Kr | 2.995 | 9.2 |
| $^{96}$Zr $\rightarrow$ $^{96}$Mo | 3.350 | 2.8 |
| $^{100}$Mo $\rightarrow$ $^{100}$Ru | 3.034 | 9.6 |
| $^{110}$Pd $\rightarrow$ $^{110}$Cd | 2.013 | 11.8 |
| $^{116}$Cd $\rightarrow$ $^{116}$Sn | 2.802 | 7.5 |
| $^{124}$Sn $\rightarrow$ $^{124}$Te | 2.228 | 5.64 |
| $^{130}$Te $\rightarrow$ $^{130}$Xe | 2.530 | 34.5 |
| $^{136}$Xe $\rightarrow$ $^{136}$Ba | 2.479 | 8.9 |
| $^{150}$Nd $\rightarrow$ $^{150}$Sm | 3.367 | 5.6 |

* Q-value > 2 MeV
Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}^{0\nu}$ with a sensitivity (for non-zero background)

$$T_{1/2}^{0\nu} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T_{1/2}^{0\nu}}}$$

Minimal requirements:

- large detector masses
- high isotopic abundance
- ultra-low background noise
- good energy resolution

Additional tools to distinguish signal from background:

- event topology
- pulse shape discrimination
- particle identification
Experimental techniques

Ionisation
- Tracking: SuperNEMO
- Crystals: GERDA, Majorana, COBRA, LEGEND

Scintillation
- Isotope in LS: KamLAND-Zen, SNO+
- Crystals: CANDLES

Phonons
- Bolometer: CUORE

TPC:
- NEXT (tracking)
- EXO, nEXO, DARWIN

Scintillating bolometers:
- AMoRE
- Lucifer
- Lumineu

\{ CUPID \}
One Slide Current Status of the Field

- No observation of this extremely rare nuclear decay (so far)
- Best lower limits on $T_{1/2}$: $1.07 \times 10^{26}$ y ($^{136}$Xe), $0.9 \times 10^{26}$ y ($^{76}$Ge), $2.7 \times 10^{24}$ y ($^{130}$Te)

$$\left| \langle m_{eff} \rangle \right| = \left| \sum_i U_{ei}^2 m_i \right| \leq 0.06 - 0.4 \text{ eV}$$

- Running and upcoming experiments (a selection):
  - $^{130}$Te: CUORE, SNO+
  - $^{136}$Xe: KAMLAND-Zen, KAMLAND2-Zen, EXO-200, nEXO, NEXT, DARWIN
  - $^{76}$Ge: GERDA Phase-II, Majorana, LEGEND (GERDA & Majorana + new groups)
  - $^{100}$Mo AMoRE, LUMINEU; $^{82}$Se: LUCIFER, CUPID = CUORE with light read-out
  - $^{82}$Se ($^{150}$Nd, $^{48}$Ca): SuperNEMO
Effective Majorana neutrino mass

\[ T_{1/2} \sim 10^{26} \text{y} \]

\[ T_{1/2} \sim 10^{27} \text{y} \]

Fig. 1 (color online). Updated predictions on neutrino masses (\( m_{\nu} \)) in the two cases of \( m_{1} \approx m_{2} \approx m_{3} \) (current sensitivities), \( m_{3} < m_{1} < m_{2} \) (IH, \( \Delta m^{2} < 0 \)), and \( m_{1} < m_{2} < m_{3} \) (NH, \( \Delta m^{2} > 0 \)). The shaded areas correspond to the 90\% C.L. bound, and the solid lines represent the theoretical expression of the half-life in an exchange of ordinary neutrinos with Majorana mass, the phase space factor, and the expression of the number of active counts per year. The 90\% C.L. bound gives \( T_{1/2} = 3.5 \times 10^{25} \text{y} \), which differs a little bit from the combined theoretical expression of the half-life in an exchange of ordinary neutrinos with Majorana mass, the phase space factor, and the expression of the number of active counts per year.

For the parameter \( m_{\nu} \), we can write the following:\n
\[ m_{\nu} \approx m_{1} \approx m_{2} \approx m_{3} \]

Furthermore, the measure of the dependence of the Majorana effective mass on the uncertainties on the oscillation parameters.

The result of the plotting in this case is shown in the right part of Table 1.

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Physics goal of GERDA and LEGEND

- Search for the neutrinoless double beta decay ($0\nu\beta\beta$) of $^{76}\text{Ge}$
- Observe the 2 final-state $e^-$, expect sharp “peak” at the Q-value
- Excellent energy resolutions and ultra-low background: essential for a discovery

\[ Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e = 2039 \text{ keV} \]
The GERDA Experiment: Overview

HPGe detectors, enriched to ~86% in $^{76}$Ge
Liquid argon as cooling medium and shielding
(U/Th in LAr < 7x10^{-4} μBq/kg)
A minimal amount of surrounding materials

Phase I (2011-2014)
~18 kg HPGe detectors

Phase II (2015-2019)
~ 36 kg HPGe detectors
The GERDA Collaboration

16 Institutes
~132 Members

GERDA presents the first results on neutrinoless double beta decay of $^{76}$Ge from GERDA Phase I

Stefan Schönert (TUM) for the GERDA collaboration

LNGS, Seminar July 16, 2013

S. Schönert (TUM): First GERDA results

LNGS, July 16, 2013
GERDA Phase II

- Started science run in December 2015
- 37 detectors (35.6 kg) enriched in $^{76}$Ge
- Improve phase I sensitivity by factor 10:
  - 100 kg y exposure
  - background: 0.001 events/(kg y keV)
- LAr veto: 0.5 m diameter, 2 m high
- Viewed by optical fibres + SiPMs and 16 (7 + 9) 3-inch PMTs (R11065-10/20)
- 7 detector strings (one out of nat Ge detectors) fully operational
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GERDA Detectors

- BEGe and coaxial
  - p+ electrodes:
    - 0.3 μm boron implantation
  - n+ electrodes:
    - 1-2 mm lithium layer (biased up to +4.5 kV)
- Low-mass detector holders (Si, Cu, PTFE)
Background Suppression Methods

- Example: calibration data with $^{228}$Th sources, background rejection via:
  - Muon Veto (MV)
  - Anti-coincidence detector array (AC)
  - Anti-coincidence liquid argon veto (LAr)
  - Pulse shape discrimination (PSD)

Peaks from $^{208}$Tl line
BEGe Pulse Shape Spectra

- Mono-parametric event selection based on $A/E$:
  - current pulse amplitude $A$
  - total energy $E$
- Tuned by calibration data (DEP from 2615 keV)
- Efficiencies:
  - DEP: ~87%
  - $2\nu\beta\beta$: ~85%
- All surface $\alpha$'s removed
- $\gamma$-lines: factor 6 lower
Energy calibration

- Weekly calibrations with low neutron emission Th-228 sources
- Energy scale and resolution monitoring

Energy (keV)

Counts / 5 keV

500 1000 1500 2000 2500 3000

• Weekly calibration with three $^{228}$Th sources

• FWHM at $Q_{\beta\beta}$: (3.0 ± 0.1) keV for BEGe, (3.6 ± 0.1) keV for coaxial

Counts / 5 keV

500 1000 1500 2000 2500 3000

Energy (keV)

Energy (keV)

FWHM (keV)

$^{208}$Tl

$^{40}$K

$^{42}$K

Counts / 5 keV

500 1000 1500 2000 2500 3000

Energy (keV)
Data taking and analysis overview

- Total exposure for June 2018 release: 82.4 kg y
- Blind analysis: events at \((2039 \pm 25)\) keV unmasked after selections frozen
Background model

- Dominant background at $Q_{\beta\beta}$:

  - degraded alphas, betas from $^{42}$K, gammas from U/Th chain

![Graph showing background model with enriched detectors - 60.2 kgyr.](image-url)
Energy Spectra in Phase II: 53.9 kg y

- Measured half-life of the $2\nu\beta\beta$- decay: $1.92 \times 10^{21}$ y

- LAr veto effect: ~ factor 5 background suppression at 1525 keV ($^{42}$K)
Latest results

- **Blind analysis:** 82.4 kg y

- **New limit on the 0νββ-decay of $^{76}$Ge**
  \[ T_{1/2}^{0\nu} > 0.9 \times 10^{26} \text{ y (90\%C.L.)} \]
  \[ m_{\beta\beta} < 0.11 - 0.26 \text{ eV (90\%C.L.)} \]

- **New background index:**
  - 5.6 x $10^{-4}$ events/(keV kg y)
  - in 230 keV energy window around $Q_{\beta\beta}$

- **GERDA will stay “background-free” hence the motivation for LEGEND-200**

- **Current median sensitivity:**
  \[ T_{1/2}^{0\nu} > 1.1 \times 10^{26} \text{ y (90\%C.L.)} \]
Beyond GERDA: LEGEND

- Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay
- Collaboration formed in October 2016
- 219 members, 48 institutions, 16 countries (legend-exp.org)
- Background goal:
  \[ \sim 10^{-4} \text{ events/(kg y keV)} \]
- Detector mass: 200 kg -> 1 t
- Discovery potential:
  \[ T_{1/2}^{0\nu} > 10^{27} \text{ y} \]
Beyond GERDA: LEGEND

- **First stage**: LEGEND-200 at LNGS
- Reuse GERDA infrastructure
- Start data taking in 2021
- Obtain 1 ton x year exposure
- Mass sensitivity
- 30 - 70 meV discovery potential
## LEGEND and other experiments

| Experiment          | Iso   | Iso. mass | FWHM [keV] | BI [cts/(FWHM·t·yr)] | $T_{1/2}^{0
u}$ [yr] | $\langle m_{\beta\beta} \rangle$ [meV] |
|---------------------|-------|-----------|------------|----------------------|-----------------|----------------------|
| LEGEND-200          | $^{76}$Ge | 175       | 3          | 0.6                  | $10^{27}$      | 34 – 74               |
| LEGEND-1000         | $^{76}$Ge | 873       | 3          | 0.1                  | $6 \cdot 10^{27}$ | 14 – 30               |
| SuperNEMO           | $^{82}$Se | 100       | 120        | 6                    | $10^{26}$      | 58 – 144              |
| CUPID               | $^{82}$Se | 336       | 5          | 0.02                 | $2.1 \cdot 10^{27}$ | 13 – 31              |
| AMoRE-I             | $^{100}$Mo | 2.5       | 5          | 5                    | $2.8 \cdot 10^{25}$ | 74 – 126              |
| AMoRE-II            | $^{100}$Mo | 100       | 5          | 0.5                  | $10^{27}$      | 12 – 21               |
| CUPID               | $^{130}$Te | 543       | 5          | 0.02                 | $2.6 \cdot 10^{27}$ | 8 – 38                |
| SNO+ Phase I        | $^{130}$Te | 1357      | 193        | 23                   | $1.9 \cdot 10^{26}$ | 31 – 139              |
| SNO+ Phase II       | $^{130}$Te | 7960      | 134        | 5.4                  | $7.4 \cdot 10^{26}$ | 16 – 71               |
| KamLAND-Zen 800     | $^{136}$Xe | 750       | 268        | 64.3                 | $4.6 \cdot 10^{26}$ | 24 – 77               |
| KamLAND2-Zen        | $^{136}$Xe | 1000      | 141        | 3.3                  | $1.4 \cdot 10^{27}$ | 14 – 44               |
| nEXO                | $^{136}$Xe | 4507      | 59         | 0.4                  | $6 \cdot 10^{27}$ | 7 – 21                |
| NEXT-100            | $^{136}$Xe | 91        | 18         | 7.2                  | $8.5 \cdot 10^{25}$ | 56 – 180              |
| PandaX-III 200      | $^{136}$Xe | 180       | 73         | 7.3                  | $1.3 \cdot 10^{26}$ | 45 – 145              |
| PandaX-III 1000     | $^{136}$Xe | 901       | 24         | 0.8                  | $1.3 \cdot 10^{27}$ | 14 – 46               |
LEGEND: Physics Reach

- Ton-scale experiments are indeed required to explore the inverted mass hierarchy scale
- Several other technologies also move into this direction
- $^{76}$Ge experiments: the advantage of an excellent energy resolution coupled to ultra-low backgrounds
The end
Allowed parameter space for $m_{\beta\beta}$
FIG. 16. Schematical cross section through the array of the 19 detector strings. Sketched are possible positions of the LAr veto fibers and calibration sources.
GERDA Pulse Shape Discrimination

• Signal-like: Single Site Events (SSE)
• Background-like: Multiple Site Events (MSE)
• BEGe detectors: E-field and weighting potential has special shape: pulse-height nearly independent of position
GERDA Pulse Shape Discrimination

- A/E: amplitude of the current pulse over energy
- Multiple energy depositions: multiple peaks in current pulse => decreasing A/E
- p+ surface events: shorter signals => higher A/E
LEGEND Physics Reach

- 60% efficiency, including isotope fraction, active volume fraction, analysis cuts
- GERDA-II/MJD: 3 events/(ROI t y)
- LEGEND-200 (LEGEND-1000): 0.6 events/(ROI t y) (0.1 events/(ROI t y))

N.B.: background-free operation is a prerequisite for a discovery
Isotopes and sensitivity to $0\nu\beta\beta$

Isotopes have comparable sensitivities in terms of rates per unit mass

$$
\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}
$$

$$
g_A^4 \ln(2) \frac{N_A}{G^{0\nu} Am_e^2}
$$

Effective value for the axial vector coupling constant $g_A$: $\sim 0.6 - 1.269$ (free nucleon value)
GERDA phase II and beyond

- Demonstrated that a background of $\leq 10^{-3}$ events/(keV kg yr) is feasible
- Will explore $T_{1/2}$ values in the $10^{26}$ yr range, probing the degenerate mass region
- LEGEND, a ton-scale experiment (in collaboration with Majorana) is in design phase

Exposure [kg yr] vs. 90% prob. lower limit $T_{1/2}$ [10^{25} yr]

- Phase I
- Phase II

$1.4 \cdot 10^{26}$ yr

100 kg yr

Theory: neutrino mixing and masses from a minimum principle

Gerda, Gavela, Isidori, Maiani, JHEP 1311 (2013) 187
Blankenburg, Isidori, Jones-Perez, EPJC 72 (2012) 2126