Discovery Potential of Future Neutrinoless Double-Beta Decay Experiments

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Neutrinoless Double-Beta Decay

- Matter creation process
- The peak in the plot exceeds current limits
- Must measure summed electron kinetic energy to distinguish from Standard-Model $2\nu$ process: scintillation, ionization, and/or heat
- Some experiments can also measure electron momenta (tracking), provides a handle on the LNV process
Pure-Majorana SM Neutrino Exchange

- "Minimal" model: add just one parameter to the SM Lagrangian
- Simple goal post for future experiments

$$\Gamma_{1/2}^{0\nu} = G^{0\nu}|M^{0\nu}|^2 \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

$$e^- \nu_i m_i \rightarrow e^- W^- W^-$$

(A, Z) (A, Z + 2)

Nuclear Process

Excluded by current 0νββ experiments
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- Excluded by current $0\nu\beta\beta$ experiments
- Next-generation goal

\[ m_{\text{lightest}} \]

\[ m_{\beta\beta} \]
$\text{IO}_{\text{min}}$ is still a reasonable goal

- NO preferred at $\sim 3\sigma$ in global oscillation analyses. Also preferred by cosmology. However:
  - Visibility of such preference in the data is still poor: large $\Delta \chi^2$ but small $\Delta \text{G.O.F}$
  - Phenomenologists cannot reproduce the strong contribution from SK ($>3\sigma$ global analyses just use the SK $\chi^2$ map)
  - Cosmological limits are systematic-dominated, still favor $\Sigma \rightarrow 0$

- Also: $\text{IO}_{\text{min}}$ still represents $\sim 2$ orders-of-magnitude improvement in $T_{1/2}$ sensitivity
  - Significant potential for discovery even in the case of NO (this talk)
  - Non-minimal models open up the entire parameter space for discovery anywhere below current limits!


Bari, PPNP 102, 48 (2018)

Planck, arXiv:1807.06209

J. Detwiler
**IO_{\text{min}}** is still a reasonable goal

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  - Visibility of such preference in the data is still poor: large \(\Delta \chi^2\) but small \(\Delta \text{G.O.F}\)
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- Also: \(IO_{\text{min}}\) still represents \(\sim 2\) orders-of-magnitude improvement in \(T_{1/2}\) sensitivity
  - Significant potential for discovery even in the case of NO (this talk)
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Alternative Mechanisms

Flavor Models

King, Merle, Stuart, JHEP 1312, 005 (2013)

\(0\nu\beta\beta\): Qualitative Experimental Description

- Energy is the only observable quantity that is both a necessary and sufficient condition for discovery of \(0\nu\beta\beta\) decay.

- Sensitivity is dominated by Poisson counting in the region-of-interest (ROI): observing some number of counts during an exposure in the presence of background.

- Relevant parameters:

  \[
  \mathcal{E} = \epsilon m_{iso}^{FV} t
  \]

  \[
  B = \frac{N_{bg}}{\mathcal{E}}
  \]

  - In most (all) experiments, background is well-constrained, either from energy or volumetric side-bands.

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Experimental Focus: Discovery

- Discovery sensitivity: the value of $T_{1/2}$ for which an experiment has a 50% chance to observe a signal above background with $3\sigma$ significance:

$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma} (B \mathcal{E})}$$

- $S_{3\sigma}(B) =$ Poisson signal expectation at which 50% of experiments report $3\sigma$ fluctuation above $B = B \mathcal{E}$
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Requirements:

- high exposure
- low bg

Target sensitivity

- $0$ cts/t$_{iso}$ ROI yr
- $10^{-2}$ cts/t$_{iso}$ ROI yr
- $10^{-1}$ cts/t$_{iso}$ ROI yr
- $10^{0}$ cts/t$_{iso}$ ROI yr
- $10^{1}$ cts/t$_{iso}$ ROI yr
- $10^{2}$ cts/t$_{iso}$ ROI yr

high exposure → low bg
Poisson + BG Uncertainty

- Shortcut: approximate the Poisson CDF using the $\Gamma$ function
  \[CDF(C|\mu) \approx \frac{\Gamma(C + 1|\mu)}{\Gamma(C + 1)}\]

- Extremely fast calculation (avoid lengthy MC)

- Better approximation when BG uncertainty is considered
ROI Optimization

- Optimize ROI to maximize discovery sensitivity

- $x_c \approx 1.4$ solves

  $$x_c e^{-\frac{x_c^2}{2}} = \frac{\sqrt{2\pi}}{4} \text{erf}\left(\frac{x_c}{\sqrt{2}}\right)$$

- Kink: “Truly” BG-free at $-\ln[\text{erf}(3/\sqrt{2})] = 0.0027$ cts / ROI

- Typical approximations
  - “Nearly” BG-free: $Q_{bb} \pm 2\sigma$
  - Large, flat BG: $Q_{bb} \pm 1.4\sigma$
  - Poor resolution: $[Q_{bb}, Q_{bb} + 1.4\sigma]$

Red fit: sub-percent accuracy

$$\text{ROI}_{\text{opt}} = 2.8 + 10^{a_0 + a_1 \log_{10} b + a_2 (\log_{10} b)^2}$$

$a_0 = -0.48, a_1 = -0.32, a_2 = -0.046$
Signal Extraction and Shape Uncertainties

• Sensitivity doesn’t capture well systematic background shape uncertainties

• Several illustrative examples:

KamLAND-Zen: O(10) c/ROI, complex shape

CUORE: O(10) c/ROI, simple shape

GERDA: O(0.1) c/ROI, simple shape
Experimental Techniques

- Scintillators (KamLAND-Zen, SNO+, CANDLES)
  - Measure energy (\(\sigma \sim 3-10\%\)) + position from scintillation light; some PID

- TPCs (EXO, NEXT, PandaX)
  - Collect scintillation + ionization: measure energy (\(\sigma \sim 1-3\%\)) + tracks / position + PID

- Bolometers (CUORE, CUPID, AMORE)
  - Measure energy (\(\sigma \sim 0.2\%\)) from phonons; some PID
  - R&D underway for instrumenting with photon detectors for background rejection

- Semiconductors (GERDA, Majorana, COBRA, SELENA)
  - Measure energy (~0.1-0.3%) from ionization; some PID and tracking / position sensitivity

- External detectors (NEMO, SuperNEMO, DCBA)
  - Trackers + calorimeters, measure energy (\(\sigma \sim 3-10\%\)) + tracks / positions + PID
## Experiments

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Isotope</th>
<th>Technique</th>
<th>mass (0νββ isotope)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMoRE</td>
<td>Mo-100</td>
<td>CaMoO₄ bolometers (+ scint.)</td>
<td>5 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>CANDLES</td>
<td>Ca-48</td>
<td>305 kg CaF₂ crystals - liq. scint.</td>
<td>0.3 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>CARVEL</td>
<td>Ca-48</td>
<td>⁸⁶CaWO₄ crystal scint.</td>
<td>16 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>GERDA I</td>
<td>Ge-76</td>
<td>Ge diodes in LAr</td>
<td>15 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>GERDA II</td>
<td>Ge-76</td>
<td>Point contact Ge in active LAr</td>
<td>20 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>MAJORANA DEMONSTRATOR</td>
<td>Ge-76</td>
<td>Point contact Ge in Lead</td>
<td>30 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>LEGEND 200</td>
<td>Ge-76</td>
<td>Best of GERDA + MJD</td>
<td>200 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>LEGEND 1000</td>
<td>Ge-76</td>
<td>Best of GERDA + MJD</td>
<td>1 tonne</td>
<td>R&amp;D</td>
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<tr>
<td>NEMO3</td>
<td>Mo-100</td>
<td>Foils with tracking</td>
<td>6.9 kg</td>
<td>Complete</td>
</tr>
<tr>
<td></td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>0.9 kg</td>
<td></td>
</tr>
<tr>
<td>SuperNEMO Demonstrator</td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>7 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>100 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>COBRA</td>
<td>Cd-116, Te-130</td>
<td>CdZnTe detectors</td>
<td>10 kg</td>
<td>Operating / Construction</td>
</tr>
<tr>
<td>CUORICINO</td>
<td>Te-130</td>
<td>TeO₂ Bolometer</td>
<td>11 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>CUORE-0</td>
<td>Te-130</td>
<td>TeO₂ Bolometer</td>
<td>11 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>CUORE</td>
<td>Te-130</td>
<td>TeO₂ Bolometer</td>
<td>206 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>CUPID</td>
<td>Several</td>
<td>Scintillating Bolometers</td>
<td>~tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>SNO+</td>
<td>Te-130</td>
<td>0.3% natTe in liquid scint.</td>
<td>800 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>370 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>KamLAND-Zen 800</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>750 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>KamLAND2-ZEN</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>~tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>NEXT-100</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>10 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>PandaX</td>
<td>Xe-136</td>
<td>2 phase Xe liquid TPC</td>
<td>~tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>EXO-200</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>160 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>nEXO</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>5 tonnes</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>DCBA</td>
<td>Nd-150</td>
<td>Nd foils &amp; tracking chambers</td>
<td>30 kg</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>
Future Experiments

• Compiled using quoted stats in publications, presentations

• Tune sensitive exposure and sensitive background when necessary to match published sensitivities
Discovery Sensitivity of Future Experiments

![Graph showing discovery sensitivity for different elements and exposure levels.](image-url)
Discovery Probability

What are the chances that these next-generation experiments will make a discovery? How much should humanity invest in $0\nu\beta\beta$?

• Bayesian methods are the only tools available by which such a “value” question can be approached:
  • Quantify the “volume” in the available parameter space (assign priors). Equal volumes = equal relative probability of discovery
  • Compute the amount of volume left to be explored (apply constraints from available measurements)
  • Compute the fraction of the remaining volume that will be explored by next-generation experiments. This is the “discovery probability” (DP).

• Equivalent / technical description:
  • Compute the posterior PDF for $m\beta\beta$ given all experiments to date, and use it as a prior for next-generation experiments
  • For each value of $m\beta\beta$, compute the probability that a next-generation experiment will make a $3\sigma$ discovery. Then sum up those probabilities weighted by the $m\beta\beta$ PDF.
Priors and Basis

• Neutrino mass scale is unknown: use log-flat prior for all mass parameters

• Angles and phases: use flat prior in $[0, 2\pi)$

• Constrain with all available data: NuFit (osc.), $\beta$-decay, $\beta\beta$-decay

• Evaluate for multiple NME, with/without $g_A$ quenching, with/without cosmological limits

• Basis choice: $\Sigma$ vs. $m_l$
  
  • $m_l$: represents theoretical prejudice for the hierarchical scenario $m_l \ll m_2$. Results are trivial: DP $\sim 100\%$ for IO, and $< \sim$few$\%$ for NO
  
  • $\Sigma$: represents theoretical prejudice that neutrino masses are generated by a different mechanism than the other SM fermions
  
  • We choose $\Sigma$ as our “reference” basis. One can re-weight our results according to his or her own prejudice for this vs. extreme hierarchical scenarios
$m_{\beta\beta}$ PDF

a) NO, QRPA

limited $\Sigma$ volume

Flat $\text{ln}\Sigma$ prior

b) IO, QRPA

limited $\Sigma$ volume

Flat $\text{ln}\Sigma$ prior

Flat current $m_{\beta\beta}$ limits

Flat phase priors
$m_{\beta\beta}$ PDF

Shaded bands: NME variation (QRPA, LSM, IBM, EDM)
Discovery Probabilities

• Fold $m_{\beta\beta}$ PDF with discovery sensitivity

• These plots: flat $\ln \Sigma$ prior

• Flat $\ln m_l$ prior:
  • IO $\sim$ unchanged
  • NO $\rightarrow$ $\sim$ few%
Impact of $g_A$ Quenching

- $g_A$ quenching could be up to tens of percent: could suppress $T_{1/2}$ by $g_A^2$ or $g_A^4$, depending on the model.

- Might be partially mitigated by higher $q^2$ in virtual exchange loop.

- Sensitivity is suppressed accordingly. But would also relax current 0νββ limits.

- Phase degeneracy gives larger posterior at higher $m_{ββ}$: affect on discovery probability is weak until degradation reaches the main peak.
Alternative Analyses (flat $\ln \Sigma$)

• Adding 30% $g_A$ quenching: DP drops by only ~15% (25%) for IO (NO)

• Adding cosmological constraints: NO DP reduced by ~30%. No effect for IO.

• Both cosmological limits + $g_A$ quenching: Planck rules out the region opened up at high $m_{\beta\beta}$ from relaxed GERDA / KLZ limits. IO DP drops to ~50%, NO DP drops to 10-20%.

• If KATRIN sees a positive signal: DP $\rightarrow$ 100% regardless of ordering, mass model, NME, quenching, cosmology.

Many scenarios have significant discovery probability for either mass ordering!
Summary

• Promising future $0\nu\beta\beta$ experiments must have high sensitive exposure with low sensitive background

• Proposed experiments balance exposure and background using different techniques in different nuclei with different systematics

• These experiments have good discovery probability: discovery may be just around the corner!
Backup