DUNE Expanded Scope
Session: $0\nu\beta\beta$

Julieta Gruszko
Snowmass Community Summer Study
July 20, 2022
Outline

- Why look for $0\nu\beta\beta$?
- $0\nu\beta\beta$ sensitivity and discovery
- Current status and near-term future
Why look for $0\nu\beta\beta$?
Motivating BSM Physics

• Need answers to:
  – What is dark matter?
  – What is dark energy/the mechanism behind the cosmological constant?
  – What generates neutrino mass?
  – What created the matter/antimatter asymmetry?

• Would like answers to:
  – Naturalness problems
  – CP conservation in QCD
  – Unification, flavor, etc…
The Surprising Neutrino Mass

• A reminder: neutrino mass is not in the Standard Model!

• This is one of the few observations we have of Beyond-the-Standard Model physics

• Another surprise: neutrino mass is very small
The Surprising Neutrino Mass

Two options for neutrino mass terms:

• Dirac mass:
  – Requires two **non-interacting** new fields, $\nu_R$ and $\overline{\nu}_L$
  – Leads to hierarchy problem

• Majorana mass:
  – No new fields required; $\overline{\nu}_R = \nu_R$ and $\nu_L = \overline{\nu}_L$
  – Can be generated by new physics at TeV - GUT scale

• Both may be present; any non-zero Majorana mass makes the neutrino a Majorana fermion

• Majorana neutrino masses can be generated by a range of models
The Type I See-Saw Mechanism

• Including both Majorana and Dirac mass terms can generate two light neutrinos, $\nu$ and $\bar{\nu}$, and two heavy neutrinos, $N$ and $\bar{N}$

• If the Majorana mass term is of the GUT scale ($\sim 10^{14}$ GeV) and Dirac mass term is of EW scale ($\sim 100$ GeV):
  – $m_\nu \sim 0.1$ eV
  – $m_N \sim 10^{14}$ GeV

• This gives a “natural” neutrino of the correct mass by introducing a new GUT-scale particle
The Matter Asymmetry Problem

- Today, all the structure we see in the universe is made up of matter, with no significant quantity of antimatter.
- Baryon asymmetry measurements give $\eta \equiv \frac{n_B - n_B}{n_\gamma} \sim 6 \times 10^{-10}$
- We believe this asymmetry has to have been generated dynamically, not as an initial condition.
Making an Asymmetry: The Sakharov Conditions

In 1967, Sakharov proposed 3 conditions required for baryon-generating interactions that would generate an asymmetry:

1. Baryon number violation
2. Interactions out of thermal equilibrium
3. C and CP violation: need more than the CP violation observed in the SM (even if $\delta_{CP}$ is maximal)

From SM at high temperature

Majorana neutrinos can do this in many models

Majorana neutrinos could be a low-energy signature of the high-energy physics that generated baryon asymmetry
There are many mechanisms beyond Type I see-saw that would generate neutrino mass.

Some generate the baryon asymmetry or dark matter candidate particles.

Many of these also predict new particles that could be observed at accelerators (O(1-10’s of TeV)).

Many models of flavor predict Majorana neutrinos with specific Majorana phases.

Comparing LHC and 0νββ limits on TeV-scale Lepton number violation.
For certain even-even nuclei, single beta decay is disallowed because of energy or momentum. Instead, they double-beta decay, which is a second-order weak process. The half-life $T_{1/2}$ is approximately $10^{19}$ to $10^{21}$ years. The electron capture variant is the longest-lifetime process ever observed.
Double-Beta Decay Isotopes

- 35 naturally-occurring isotopes are capable of double-beta decay; we’ve observed it in 14 of these.
- These 14 “golden nuclei” are particularly well-suited to experiments:
  - High Q-values
  - High abundance or ability to enrich (with some exceptions)
  - Other abundant isotopes of the element not highly radioactive

<table>
<thead>
<tr>
<th>Double-beta candidate</th>
<th>Q-value (MeV)</th>
<th>Phase space $G_{01}(y^{-1})$</th>
<th>Isotopic abundance (%)</th>
<th>Enrichable by centrifugation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4.27226 (404)</td>
<td>$6.05 \times 10^{-14}$</td>
<td>0.187</td>
<td>No</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2.03904 (16)</td>
<td>$5.77 \times 10^{-15}$</td>
<td>7.8</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.99512 (201)</td>
<td>$2.48 \times 10^{-14}$</td>
<td>9.2</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>3.35037 (289)</td>
<td>$5.02 \times 10^{-14}$</td>
<td>2.8</td>
<td>No</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.03440 (17)</td>
<td>$3.89 \times 10^{-14}$</td>
<td>9.6</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.81350 (13)</td>
<td>$4.08 \times 10^{-14}$</td>
<td>7.5</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2.52697 (23)</td>
<td>$3.47 \times 10^{-14}$</td>
<td>33.8</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{126}$Xe</td>
<td>2.45783 (37)</td>
<td>$3.56 \times 10^{-14}$</td>
<td>8.9</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3.37138 (20)</td>
<td>$1.54 \times 10^{-13}$</td>
<td>5.6</td>
<td>No</td>
</tr>
</tbody>
</table>
If neutrinos are Majorana, $0\nu\beta\beta$ could occur.
Lepton number conservation is violated by 2 units.
In this case, I’ve drawn the exchange of a light neutrino, but you can think of that “x” as a contracted diagram of any sort (with new physics in it).
The Decay Signature

- **2νββ**: Standard Model process
  - In non-gaseous detectors, looks like a single-site event (modulo Cherenkov light)

- **0νββ**: Only if ν is Majorana
  - No missing energy

- **νββ**: Only if ν is Majorana
  - No missing energy

---

**Diagram Notes**

- **2νββ**
- **0νββ (B.R. = 10^-4)**
- HPGGe resolution
Majorana Neutrinos and $0\nu\beta\beta$

Model-independent implications of $0\nu\beta\beta$:
- Lepton number violation
- Neutrino-antineutrino oscillation, implying a non-zero Majorana mass term

The mechanism of $0\nu\beta\beta$ determines the rate along with the parameters of the model.
0νββ Sensitivity and Discovery
The 0νββ Rate for Light Majorana Neutrino Exchange

**Effective Majorana mass for light neutrino exchange:**

\[
(T_{1/2}^{0ν})^{-1} = G^{0ν}|M_{0ν}|^2 \left( \frac{\langle m_{ββ} \rangle}{m_e} \right)^2
\]

Even under simple assumptions, the 0νββ rate depends on:
- ν mixing angles
- ν masses
- mass hierarchy
- 2 totally unknown phases

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{μ1} & U_{μ2} & U_{μ3} \\
U_{τ1} & U_{τ2} & U_{τ3}
\end{pmatrix}
\]

\[
c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}, \delta = \text{Dirac CP violation}, \alpha_i = \text{Majorana CP violation}
\]
Interpretation of Half-Life Sensitivity

\[
(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left( \frac{<m_{\beta\beta}>}{m_e} \right)^2
\]

\[
<m_{\beta\beta}> = |\sum_{i=1}^{3} U_{ei}^2 m_i |
\]

- Light Majorana neutrino exchange: assumes new physics is at GUT scale, $0\nu\beta\beta$ mediated by dim. 5 operator
- Used to compare and set goals for future experiments
Translating Half-Life to $m_{\beta\beta}$

- Need to use a particular model, the phase space factor and a nuclear matrix element to turn half-life into $m_{\beta\beta}$
- Results are generally reported for the full set of NMEs, so the upper limit in $m_{\beta\beta}$ has a range

This area excluded
Upper limit for a single NME
Excluded for larger NME
Information from Other Neutrino Experiments

- Light-colored edges are $3\sigma$ uncertainty on neutrino mixing and mass splittings.
- Measuring hierarchy would tell us which branch we need to look in.
- Mass measurement would tell us which vertical band to look in.
Discovery and Sensitivity

After you run a $0\nu\beta\beta$ search…

• You either see an excess at the Q value, and fit a peak with some rate to it.

• Or you don’t see an excess. In that case, you set a lower limit on half-life:

$$T^{0\nu}_{1/2} > \ln(2) \frac{N_a T \epsilon}{S}$$

- Number of $\beta\beta$ atoms
- Upper limit on the number of signal counts
- Livetime
- Efficiency
Sensitivity vs. Discovery

90% confidence-level exclusion

3σ median discovery sensitivity

Background demands are more stringent if you want to make a discovery
Reaching Ultra-Long Half-Life

• Best-case scenario: quasi-background-free experiment, $3\sigma = 3$ counts
• Long half-lives mean you need large exposures. For 3-4 counts of $0\nu\beta\beta$ at…
  – $10^{26}$ years: 100 kg-years
  – $10^{27}$ years: 1 ton-year
  – $10^{28}$ years: 10 ton-years
• Goal of the next generation of experiments: cover the bottom of the IO region in discovery mode for most nuclear matrix elements
• Implies required discovery sensitivities of $10^{27}$ to $10^{28}$ years
Current status and near-term future
Current Best Limits on $0\nu\beta\beta$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Exposure [kg yr]</th>
<th>$T_{1/2}^{0\nu}$ [10$^{25}$ yr]</th>
<th>$m_{\beta\beta}$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gerda</td>
<td>$^{76}\text{Ge}$</td>
<td>127.2</td>
<td>18</td>
<td>79-180</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}\text{Ge}$</td>
<td>26</td>
<td>8.3</td>
<td>113-269</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}\text{Xe}$</td>
<td>970</td>
<td>23</td>
<td>36-156</td>
</tr>
<tr>
<td>EXO-200</td>
<td>$^{136}\text{Xe}$</td>
<td>234.1</td>
<td>3.5</td>
<td>93-286</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}\text{Te}$</td>
<td>1038.4</td>
<td>2.2</td>
<td>90-305</td>
</tr>
</tbody>
</table>

NSAC recommendation: quote a range of $m_{\beta\beta}$ using the largest and smallest available NME from the 4 main calculation methods; $g_A=1.27$; no contribution from the contact term

J. Gruszko – DUNE Expanded Scope: $0\nu\beta\beta$ – Snowmass CSS 2022
The Ton-Scale Generation

- Covering the IO in discovery mode requires $O(1 \text{ ton})$ of isotope
- 3 candidate experiments with US participation, in addition to other ongoing efforts: LEGEND, nEXO, and CUPID
- All 3 experiments cover the IO for some matrix elements, and miss for others
- All 3 were evaluated by the DOE in Summer 2021. DOE-NP is seeking international support to pursue all 3 experiments.

Discovery Sensitivity for the “Big 3”
Discovery and Sensitivity

- Larger background = more difference between discovery and exclusion
- Liquid scintillator experiments will have competitive sensitivity, but generally don’t publish discovery projections:
  - KL2Z: $T_{1/2} > 2 \times 10^{27}$
  - SNO+ with increased Te loading: $T_{1/2} > 1 \times 10^{27}$

From Agostini et al., PRC 104, L042501 (2021)
Timeline for Ton-Scale Experiments

- Depends on funding availability
- The 3 ton-scale experiments are moving towards CD-1, hoping for projected construction start in ~2024-2025
- Construction estimate: ~5 to 10 years*
- All plan for 10 years of running, full-exposure results in ~2040

* Just my guess, 0νββ collaborations may disagree
Conclusion

• $0\nu\beta\beta$ is some of the most exciting physics we can look for! It could provide insight into…
  – The origin of neutrino mass
  – The mechanism that drove baryogenesis
  – The origin of flavor/particle generations, dark matter, etc…

• Regardless of the mechanism, $0\nu\beta\beta$ would be a direct observation of lepton number violation and prove that neutrinos have Majorana mass

• The coming generation of experiments is exploring very rich parameter space and (hopefully) beginning very soon

• For a competitive $0\nu\beta\beta$ search, an experiment would need to have high $\beta\beta$ isotope mass and ultra-low backgrounds at $Q_{\beta\beta}$