Neutrinoless Double Beta Decay

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Resources and Acknowledgements

- 2016 NNPSS Lectures of Vincenzo Cirigliano at MIT
- Writeup of Lectures by Petr Vogel, Massive Neutrinos, 1997 Mexican Summer School on Astrophysics and Cosmology
- Slides from the opening workshop of the INT Program on Neutrinoless Double-Beta Decay, June 2017: http://www.int.washington.edu/talks/WorkShops/int_17_2a/

The EXO-200 and nEXO collaborations and many other colleagues:
Plan for Lectures

- **Lecture 1**
  - Nomenclature, Theoretical Overview, Physics Motivation, Goal for Experiments

- **Lecture 2**
  - Overview of Experimental Techniques, Overview of Experimental Program Worldwide, Details of 2 Initiatives aiming for the Ton-Scale, Detailed Description of EXO-200 and nEXO (the 3rd ton-scale initiative)
Recap
Postulate the Right-Handed Neutrino Neutrinoless Double-Beta Decay: Lecture 2

$\nu_L \rightarrow \nu_R$

Lorentz boost

helicity: conserved but not Lorentz invariant

$\nu_L \rightarrow \nu_R$

chirality: not conserved but Lorentz invariant

CPT transformation: left-handed particle to right-handed anti-particle

A profound question:

Dirac OR Majorana
What is the Discovery Measurement?

The most pragmatic approach to discover the Majorana nature of neutrinos is to search for Lepton Number Violation (LNV)

Practically: discover Neutrinoless Double-Beta Decay

(0νββ)
Neutrinoless Double-Beta Decay: Lecture 2

Double Beta Decay

A free neutron, or a neutron inside a nucleus

n \rightarrow p + 2e^+ + 2\nu^0

Nuclear Double-Beta Decay with the emission of two neutrinos

First direct observation by Moe, Elliott, and Hahn in $^{100}$Mo (1988)

Two neutrons convert to two protons and four leptons.
**0ν Double Beta Decay**

\[ (N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^- \]

“Neutrino mass mechanism” for double beta decay

Forbidden if neutrino mass is Dirac only (violates lepton number conservation).
0ν Double Beta Decay

Experimental Signature

0νββ

2n → 0νββ → 2p

Majorana neutrino mass term

Forbidden if neutrino mass is Dirac only (violates lepton number conservation).

"Neutrino mass mechanism" for double beta decay

Experimentally observed with 2% energy resolution

\[(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-\]
0ν Double Beta Decay

Experimental Signature

"Neutrino mass mechanism" for double beta decay

Forbidden if neutrino mass is Dirac only (violates lepton number conservation).

If observed, it would unambiguously signal that Lepton Number is NOT a conserved quantity, and that neutrinos are Majorana particles i.e. their own anti-particles.
Choosing a Nuclide

Typical $2\nu\beta\beta$ half-life is very long: second-order weak process

\[
\frac{1}{T^{0\nu}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2
\]

\[
\frac{1}{G^{2\nu}} \sim 10^{20} \text{ years}
\]

Atomic mass affected by nuclear pairing term:
even A nuclei occupy 2 parabolas,
even-even below odd-odd

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Q (MeV)</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Choose nuclei where single beta decay forbidden
but double-beta decay is possible

Candidate nuclei with $Q>2$ MeV

Choose a second-order process only detectable if first order beta decay is energetically forbidden

Double-beta decay:

\[
\frac{1}{T^{0\nu}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2
\]
Decay Rate for $0\nu\beta\beta$

$$\Gamma^{0\nu} = G(Q,Z)|M(A,Z)\eta|^2$$

Transition Probability

$$\alpha \frac{m}{Q^2} \quad (Q \sim m_e)$$

Phase Space Factor

$$G \sim G_F^4 g_A^4 m_e^5$$

Nuclear Matrix Element

Particle Physics of the Black Box
Decay Rate for $0\nu\beta\beta$

$\Gamma^{0\nu} = G(Q,Z) |M(A,Z)\eta|^2$

Transition Probability

Phase Space Factor

Nuclear Matrix Element

Particle Physics of the Black Box

For light neutrino exchange

All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta} \rangle = \sum_i U_{ie}^2 m_i$
Decay Rate for $0\nu\beta\beta$

\[ \Gamma^{0\nu} = G(Q,Z) |M(A,Z)\eta|^2 \]

Transition Probability
\[ \alpha \frac{m}{Q^2} (Q \sim m_e) \]

Phase Space Factor
\[ G \sim G_F^4 g_A^4 m_e^5 \]

Nuclear Matrix Element
\[ M(A,Z) \]

Particle Physics of the Black Box
\[ \eta \]

For light neutrino exchange

All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta} \rangle = \sum_i U_{ie}^2 m_i$

\[ m_{\beta\beta} \sim 1 \text{ eV} \quad \Rightarrow \quad T_{1/2} \sim 10^{24} \text{ years} \]
\[ m_{\beta\beta} \sim 0.1 \text{ eV} \quad \Rightarrow \quad T_{1/2} \sim 10^{26} \text{ years} \]
\[ m_{\beta\beta} \sim 0.01 \text{ eV} \quad \Rightarrow \quad T_{1/2} \sim 10^{28} \text{ years} \]
Absolute Neutrino Mass Scale

- \( \sim 2 \text{ eV} \) from tritium endpoint (Mainz and Troitsk)
- \( \sim 0.1 \text{ eV} \) from \( 0\nu\beta\beta \) if \( \nu \) is Majorana
- \( \sim 7.6 \cdot 10^{-5} \text{ eV}^2 \) solar from cosmology (PDG 2002)
- \( \Sigma \sim 0.25 \text{ eV} \) from cosmology
- \( \sim 20 \text{ eV} \) from time of flight from SN1987A (PDG 2002)
Discovery Reach

• Strong correlation of $0\nu\beta\beta$ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

\[ \langle m_{\beta\beta} \rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2 \]

Dark bands: unknown phases
Light bands: uncertainty from oscillation parameters (90% CL)

KamLAND-Zen 2016

Assume most "pessimistic" values for nuclear matrix elements

• Discovery possible for inverted spectrum OR $m_{\text{lightest}} > 50$ meV
Other Possibilities for the Black Box

- **In summary**: ton-scale $0\nu\beta\beta$ probes LNV from variety mechanisms, involving different scales ($M$) and coupling strengths ($g$)

![Diagram]

- $M_{GUT}$
- TeV
- eV

- Standard Mechanism (see-saw)
- Left-Right SM RPV SUSY ...
- Light sterile $\nu$’s
Towards Discovery Experiments
Nuclear Matrix Elements

\[
M_{0\nu} = M_{0\nu}^{GT} - \frac{g^2}{g_A^2} M_{0\nu}^{F} + \cdots
\]

with

\[
M_{0\nu}^{GT} = \langle F | \sum_{i,j} H(r_{ij}) \sigma_i \cdot \sigma_j \tau_i^+ \tau_j^+ | I \rangle + \cdots
\]

\[
M_{0\nu}^{F} = \langle F | \sum_{i,j} H(r_{ij}) \tau_i^+ \tau_j^+ | I \rangle + \cdots
\]

\[
H(r) \approx \frac{2R}{\pi r} \int_0^\infty dq \frac{\sin qr}{q + E - (E_i + E_f)/2} \quad \text{roughly } \propto \frac{1}{r}
\]

Contribution to integral peaks at \( q \approx 100 \text{ MeV} \) inside nucleus.

Corrections are from “forbidden” terms, weak nucleon form factors, many-body currents …
NME Current Status

For light neutrino exchange

Significant spread. And all the models could be missing important physics. Uncertainty hard to quantify.

One must do different calculations if other mechanisms are in play.
Signal and Background

An experimental challenge of rare events

Most measured half-lives of $2\nu\beta\beta$ are $O(10^{21})$ years
- Compare to lifetime of Universe: $10^{10}$ years
- Compare to Avogadro’s number $6 \times 10^{23}$
- Mole of isotope will produce $\sim 1$ decay/day

If it exists, half-lives of $0\nu\beta\beta$ would be longer
(Current limits $> \text{few } 10^{25}$ years)

<table>
<thead>
<tr>
<th>Half life (years)</th>
<th>Signal (cts/tonne-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{25}$</td>
<td>500</td>
</tr>
<tr>
<td>$5 \times 10^{26}$</td>
<td>10</td>
</tr>
<tr>
<td>$5 \times 10^{27}$</td>
<td>1</td>
</tr>
<tr>
<td>$5 \times 10^{28}$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Natural radioactivity: a nanogram produces more than 1 decay/day!
Cosmogenically induced radioactivity exacerbates technical challenge

$T_{1/2}^{0\nu} \propto \epsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \text{Source Mass} \cdot \text{Time}$

background free

$T_{1/2}^{0\nu} \propto \epsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \sqrt{\frac{\text{Source Mass} \cdot \text{Time}}{Bkg \cdot \Delta E}}$

background limited

backgrounds do not always scale with detector mass
Favorite Isotope?

For Ge, Te, Xe, Nd

uncertainty on value of $g_A^4$

Signal of 1 cnt/t-y for corresponding values of NME and $g_A$

R.G.H. Robertson, MPL A 28 (2013) 1350021 (arXiv 1301.1323)
Clearly $^{130}\text{Te}$ has an advantage. For the others, isotopic enrichment ($s$) is needed.
The Experimental Challenge

0νββ source with high isotopic abundance

Detector with high detection efficiency, good energy resolution, low-background

Experiment long exposure time, large total mass of isotope

To reach IH region requires sensitivities of

\[ 0\nu\beta\beta \ T_{1/2} \sim 10^{27} - 10^{28} \text{ years} \]

\[ (2\nu\beta\beta \ T_{1/2} \sim 10^{19} - 10^{21} \text{ years}) \]
2nu Half-Life

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$ (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>0.44</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>15</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>0.92</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>0.29</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>9.1</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>21</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Longer 2νββ $T_{1/2}$ (better) ⇒ lower background rate
Irreducible background ⇒ minimize with good resolution
Effect of Resolution

Backgrounds

• Primordial, natural radioactivity in the detector and array components: U, Th, K

• Backgrounds from cosmogenic activation while material is above ground (ββ-isotope or shield specific, $^{60}$Co, $^3$H, $^{39}$Ar, $^{42}$Ar, … )

• Backgrounds from the surrounding environment: external γ, (α,n), (n,α), Rn plate-out, etc.

• μ-induced backgrounds generated at depth: Cu, Pb(n,n’γ), ββ-decay specific(n,n),(n,γ), direct μ

• 2 neutrino double beta decay (for ton-scale, impact depends on resolution)

• neutrino backgrounds (for ton-scale, can be a contribution)
Attacking Backgrounds

• Directly reduce intrinsic, extrinsic, & cosmogenic activities
  – Select and use ultra-pure materials
  – Minimize all non “source” materials
  – Clean (low-activity) shielding
  – Fabricate ultra-clean materials (underground fab in some cases)
  – Go deep — reduced μ’s & related induced activities

• Utilize background measurement & discrimination techniques

$^{0}\nu\beta\beta$ is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions
  – Energy resolution
  – Active veto detector
  – Tracking (topology)
  – Particle ID, angular, spatial, & time correlations
  – Fiducial self-consistent fits
  – Single site / multi site fitting
  – Granularity [multiple detectors]
  – Pulse shape discrimination (PSD)
  – Ion Identification

Best: $^{76}\text{Ge}, ^{130}\text{Te}, ^{136}\text{Xe}$
Sensitivity vs Exposure

$T_{1/2}^{0\nu}$ (background free) $\propto MT$

$T_{1/2}^{0\nu}$ (backgrounds) $\propto \sqrt{\frac{MT}{b\Delta E}}$

$10^{30}$

$10^{29}$

$10^{28}$

$10^{27}$

$10^{26}$

$10^{25}$

$10^{24}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$1$  $10$  $10^2$  $10^3$

Exposure [ton-years]

$76\text{Ge}$ $T_{1/2}$ 90% Sensitivity [years]

IH minimum $m_{\beta\beta}$

QRPA

SM

IBM-2

EDF

Background free

0.1 counts/ROI/t/y

1.0 count/ROI/t/y

10.0 counts/ROI/t/y

J. Detwiler

Neutrinoless Double-Beta Decay: Lecture 2

Krishna Kumar, NNPSS 2017
Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}-10^{26}$ y
(~100 meV)
30 - 200 kg
~8 expts
International Program

Previous Expts.  
$T_{1/2} \sim 10^{24}$ y  
($\sim 1$ eV)  
$\sim$kg scale

Quasi-degenerate  
$T_{1/2} \sim 10^{25}$-$10^{26}$ y  
($\sim 100$ meV)  
30 - 200 kg  
$\sim$8 expts

If $0\nu\beta\beta$ Observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques  
200-500 kg scale
Neutrinoless Double-Beta Decay: Lecture 2

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
($\sim 1$ eV)
$\sim$kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}-10^{26}$ y
($\sim 100$ meV)
30 - 200 kg
$\sim$8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}-10^{28}$ y
($\sim 15$ meV)
tonne (phased)
$\sim$3 experiments
All international in scope
U.S. involvement in $\sim$2

1980 - 2007
2007 - 2018
2016 - 2025
International Program

Previous Expts.  
$T_{1/2} \sim 10^{24}\text{ y}$  
$(\sim 1\text{ eV})$  
$\sim$kg scale

Quasi-degenerate  
$T_{1/2} \sim 10^{25}-10^{26}\text{ y}$  
$(\sim 100\text{ meV})$  
30 - 200 kg  
$\sim$8 expts

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques  
$\sim$tonne scale

If $0\nu\beta\beta$ Observed

Inverted hierarchy  
$T_{1/2} \sim 10^{27}-10^{28}\text{ y}$  
$(\sim 15\text{ meV})$  
tonne (phased)  
$\sim$3 experiments  
All international in scope  
U.S. involvement in $\sim$2

1980 - 2007  
2007 - 2018  
2016 - 2025


**International Program**

- **Previous Expts.**
  - $T_{1/2} \sim 10^{24}$ y
  - ($\sim 1$ eV)
  - ~kg scale

- **Quasi-degenerate**
  - $T_{1/2} \sim 10^{25}-10^{26}$ y
  - ($\sim 100$ meV)
  - 30 - 200 kg
  - ~8 expts

- **Inverted hierarchy**
  - $T_{1/2} \sim 10^{27}-10^{28}$ y
  - ($\sim 15$ meV)
  - tonne (phased)
  - ~3 experiments
  - All international in scope
  - U.S. involvement in ~2

- **Normal hierarchy**
  - $\sim 5$ meV
  - $\geq 10$’s ton scale

Timeline:
- 1980 - 2007
- 2007 - 2018
- 2016 - 2025
**Discovery Strategy**

- **Evidence**: a combination of
  - Correct peak energy
  - Single-site or localized energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Good signal to background (3\(\sigma\) discovery)
  - Full energy spectrum (backgrounds) understood.

- **More direct confirmation**: very difficult
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay(s)

- **Convincing**
  - Observe 0\(\nu\)\(\beta\beta\) in several different isotopes, using a variety of experimental techniques that meet the above definition of evidence
Overview of Techniques
Multi-Prong Detection Strategy

Ionization

- Tracking & Cal:
  - SuperNEMO
  - PandaX-III

- Crystals:
  - GERDA
  - MAJORANA
  - COBRA

Ionization

TPC:
- EXO-200
- nEXO
- NEXT

Scintillation

- Liquid:
  - KamLAND-Zen
  - SNO+

Phonons

- CUPID (LUCIFER LUMINEU, ...), AMoRE

- Bolometer:
  - CUORE
## World Program

<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>CANDLES</td>
<td>Ca-48</td>
<td>305 kg CaF2 crystals - liq. scint</td>
<td>0.3 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>CARVEL</td>
<td>Ca-48</td>
<td>$^{48}$CaWO4 crystal scint.</td>
<td>~ ton</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 LAr</td>
<td>31</td>
<td>Operating</td>
</tr>
<tr>
<td>MAJORANA DEMONSTRATOR</td>
<td>Ge-76</td>
<td>Point contact Ge</td>
<td>25 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>LEGEND</td>
<td>Ge-76</td>
<td>Point contact</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<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></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>LUCIFER (CUPID)</td>
<td>Se-82</td>
<td>ZnSe scint. bolometer</td>
<td>18 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>AMoRE</td>
<td>Mo-100</td>
<td>CaMoO4 scint. bolometer</td>
<td>1.5 - 200 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>LUMINEU (CUPID)</td>
<td>Mo-100</td>
<td>ZnMoO4 / Li2MoO4 scint. bolometer</td>
<td>1.5 - 5 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>COBRA</td>
<td>Cd-114,116</td>
<td>CdZnTe detectors</td>
<td>10 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>CUORICINO, CUORE-0</td>
<td>Te-130</td>
<td>TeO2 Bolometer</td>
<td>10 kg, 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>Te-130</td>
<td>TeO2 Bolometer &amp; scint.</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>SNO+</td>
<td>Te-130</td>
<td>0.3% $^{nat}$Te suspended in Scint</td>
<td>160 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>EXO200</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>79 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>nEXO</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>KamLAND-Zen (I, II)</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>380 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>KamLAND2-Zen</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>750 kg</td>
<td>Upgrade</td>
</tr>
<tr>
<td>NEXT-NEW</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>5 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>NEXT</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>100 kg - ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>PandaX - 1k</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>DCBA</td>
<td>Nd-150</td>
<td>Nd foils &amp; tracking chambers</td>
<td>20 kg</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>
Ton Scale Experiments

• Active international collaborations building on current efforts.
  
  - $^{76}$Ge : LEGEND, HPGE crystals, ~ton (builds on GERDA & MAJORANA)
  - $^{82}$Se : SuperNEMO : Se foils, tracking and calorimeter, 100 kg scale
  - $^{100}$Mo : AMoRE : CaMoO$_4$ scint. bolometer, 200 kg scale
  - $^{136}$Xe : nEXO — Liquid TPC, 5 tons
    NEXT — High pressure gas TPC, ton scale
    PandaX - III — High pressure gas TPC, ton scale
    KamLAND-Zen — $^{136}$Xe in scintillator, 800 kg scale
    LZ — natXe liquid TPC, 7 tons, operating 2019
  - $^{130}$Te : CUPID (CUORE with Particle ID) — Bolometer - Scintillation
    SNO+ Phase I & II — $^{130}$Te in scintillator

• Experiments can be done in a staged (phased) approach. Most are considering stepwise increments.

• Isotope enrichment ($^{76}$Ge, $^{82}$Se, $^{136}$Xe) requires time and $s$.

• Potential underground lab sites
  
  - SNOLAB, JingPing, Gran Sasso, SURF, CanFranc, Frejus, Kamioka, ANDES, Y2L
Germanium-76
Advantages of Germanium

- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: approaching 0.1% at 2039 keV (~2.4 keV ROI)
- Demonstrated ability to enrich from 7.44% to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape discrimination
Majorana and GERDA

**MAJORANA**
“Traditional” configuration: Vacuum cryostats in a passive graded shield with ultraclean materials

**GERDA**
“Novel” configuration: Direct immersion in active LAr shield
Majorana Demonstrator

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

- Located underground at 4850’ Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently $\leq 3.5$

- 44.1-kg of Ge detectors
  - 29.7 kg of 87% enriched $^{76}\text{Ge}$ crystals
  - 14.4 kg of $^{\text{nat}}\text{Ge}$
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto
Majorana Underground Laboratory

4850’ level, SURF, Lead SD
Clean room conditions
Muon flux: $5 \times 10^{-9} \mu / \text{cm}^2 \text{s}$
(arXiv:1602.07742)
Initial Results

First results from Modules 1 and 2 in-shield

- Exposure: 1.39 kg y
- After cuts, 1 count in 400 keV window centered at 2039 keV (0νββ peak)
- Projected background rate is $5.1^{+8.9}_{-3.2}$ c/(ROI t y) for a 2.9 keV (Module 1- DS3) and 2.6 keV (Module 2 - DS4) ROI, (68% CL).
- Background index of $1.8 \times 10^{-3}$ c/(keV kg y)
- Analysis cuts are still being optimized.
- Through mid-May, have 10x more exposure in hand. Analysis is in progress.
GERDA Configuration

30 BEGe (20 kg) and 7 Coax (15.6 kg) (Phase II)
GERDA Results

- Phase I and II Exposure: 34.4 kg y
- Projected background from 1930 to 2190 keV window excludes 2104 ± 5 keV and 2119 ± 5 keV. Window of ±20 keV around $Q_{\beta\beta}$ blinded.
- For Phase II BEGes, have achieved “background free” measurement with background index of 1.8 c/(FWHM-t-y) or $(0.6^{+0.6}_{-0.4}) \times 10^{-3}$ c/kky)
- $T_{1/2} (0\nu\beta\beta) \geq 5.3 \times 10^{25}$ years (90% CL)
**Legend**

**Mission:** The collaboration aims to develop a phased, $^{76}$Ge-based double-beta decay experimental program with discovery potential at a half-life significantly longer than $10^{27}$ years, using existing resources as appropriate to expedite physics results.

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

**First Phase:**
- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c/(FWHM t y)
- start by 2021

**Subsequent Stages:**
- 1000 kg (staged)
- timeline connected to U.S. DOE down select process
- BG: goal (x30 lower) 0.1 c/(FWHM t y)
- Location: TBD
- Required depth ($^{77m}$Ge) under investigation
Tellurium-130
CUORE Bolometer

TeO₂ Bolometer: Source = Detector

Heat sink:
Cu structure (10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor (100 kΩ/μK)
Absorber:
TeO₂ crystal
(C ≈ 2 nJ/K ≈ 1 MeV / 0.1 mK)

main candidate isotope: $^{130}\text{Te}$

Q-value: $2526.515 \pm 0.013$ keV

Isotopic abundance: 34%

For $E = 1$ MeV: $\Delta T = E/C \approx 0.1$ mK

Signal size: 1 mV

Time constant: $\tau = C/G = 0.5$ s

Energy resolution: ~ 5-10 keV at 2.5 MeV
CUORE Overview

CUORE-0 (2013 – 2015)

$T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24} \text{ y (90\% C.L.)}$


$T_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24} \text{ y (90\% C.L.)}$

EPJC 74, 2956 (2014) arXiv:1504.0245

Projected

$T_{1/2}^{0\nu\beta\beta} \sim 9 \times 10^{25} \text{ yr (90\% C.L.)}$

CUORE (2017 – )

Cuoricino (2003 – 2008)

$T_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24} \text{ y (90\% C.L.)}$


Andrea Giachero (Andrea.Giachero@mib.infn.it) The status of the CUORE experiment NPA5 2011, April 5th, 2011 8 / 22
CUORE at LNGS

Gran Sasso National Laboratory

CUORE Hut

Average depth ~ 3600 m.w.e.

\( \mu: 3 \times 10^{-8} \, \mu/s/cm^2 \)

\( n < 10 \text{ MeV}: 4 \times 10^{-6} \, n/s/cm^2 \)

\( \gamma < 3 \text{ MeV}: 0.73 \, \gamma/s/cm^2 \)
CUORE Cryostat

**Shielding**
- 2.1t modern lead @ 50 mK
- 4.6 t roman lead @ 4 K
- 35 cm external lead
- 18 cm PET + 2 cm H$_3$BO$_3$
CUORE/CUPID

CUORE detectors installed

• CUORE Milestones:
  • Tower installation: Jul-Aug 2016
  • Cryostat closeout: Nov 2016
  • Cooldown: Dec-Jan 2016
  • Commissioning and initial performance optimization: Jan-May 2017
  • First science run: May 2017
  • Cryostat performs very well: base T < 7 mK
  • >95% of detectors operational
  • First data to be reported in Summer 2017
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  • First data to be reported in Summer 2017

• Intense CUPID R&D effort in the next 2-3 years
  ❖ US focus: $^{130}\text{TeO}_2$ enrichment and purification, high-resolution sensors for Cherenkov light
  ❖ Complementary European efforts
  ❖ Background goal is 0.1 cts/ROI-t-yr; achieve sensitivity to the full Inverted Hierarchy
  ❖ Other important R&D: detailed background analysis, cosmogenic backgrounds @ LNGS — to be addressed before downselect
  ❖ Worldwide efforts: 8 countries, 32 institutions
  ❖ Data from CUORE and pilot detectors will drive technology and isotope choice

Neutrinoless Double-Beta Decay: Lecture 2

Krishna Kumar, NNPSS 2017
Xenon-136
Kamland-ZEN

- $^{136}\text{Xe}$ (90% enr) in liquid scintillator, balloon R=1.5 m
- $Q_{\beta\beta}=2457.8$ keV ; $\sigma \sim 114$ keV (4.6%)
- Phase II (PRL 117 082503 (2016))
  - 380 kg (2.96% by Xe wt.)
  - R=1 m fiducial cut
  - 534.5 days, with 126 kg y exposure
  - $^{110m}\text{Ag}$ contamination reduced by x10
  - $T_{1/2} > 1.07 \times 10^{26}$ y (90% CL)

Sensitivity $T_{1/2} > 5.6 \times 10^{25}$ y (90% CL)

Unsuccessful new larger mini balloon deployment - 2016

Construction and deployment of new mini balloon with improved welding procedure for 800 kg (750 kg$_{iso}$) phase - 2017
Kamland-ZEN Future

Higher energy resolution for reducing 2ν BG $\rightarrow$ KamLAND2-Zen

Winston cone
light collection $\times 1.8$

high q.e. PMT
$17''\phi \rightarrow 20''\phi \varepsilon = 22 \rightarrow 30 +\%$
light collection $\times 1.9$

New LAB LS
(better transparency)
light collection $\times 1.4$

expected $\sigma(2.6\text{MeV})= 4\% \rightarrow \sim 2\%$

target sensitivity: 20 meV

1000+ kg xenon

Far future:

Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV

Neutrinoless Double-Beta Decay: Lecture 2

Krishna Kumar, NNPSS 2017
Advantages of Xenon

Isotopic enrichment easier & known: Xe is a gas and $^{136}$Xe is the heaviest isotope.

Xenon is “reusable”: can be re-purified (noble gas: relatively easy) during measurement and easily recycled into a different detector (no crystal growth)

…. replace $^{136}$Xe with nat’l Xe if signal observed

Monolithic detector: LXe is self shielding, surface contamination minimized.

Minimal cosmogenic activation: no long lived radioactive isotopes of Xe.

Energy resolution in LXe improved: scintillation light + ionization anti-correlation.

Standard 2νββ is slow! (see later): get away with modest energy resolution

…. admits a novel coincidence technique: background reduction by Ba tagging

…. potentially access normal hierarchy
Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP

WIPP’s Low Background Characteristics
The salt formation surrounding WIPP contains extremely low levels of naturally occurring radioactive materials.
- U \sim 30 \text{ ppb}
- Th \sim 80 \text{ ppb}
- K-40 \sim 170 \text{ ppb}
- Rn < 78\text{Bq/m}^3

Older experimental cavities potentially useable for research
Areas made available for research
Rock overburden
Salt
Waste Disposal Area
EXO-200 at WIPP

- EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM
- 1600 mwe flat overburden (2150 feet, 650 m)
- Salt mine for low-level radioactive waste storage
- Salt “rock” low activity relative to hard-rock mine

\[
\Phi_\mu \sim 1.5 \times 10^5 \text{ yr}^{-1} \text{ m}^{-2} \text{ sr}^{-1}
\]

- \(U \sim 0.048 \text{ ppm}\)
- \(Th \sim 0.25 \text{ ppm}\)
- \(K \sim 480 \text{ ppm}\)

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EXO-200 Concept

EXO R&D showed the way to improved energy resolution in LXe:
Use (anti)correlations between ionization and scintillation signals

- Two TPCs with common cathode in middle
- APD planes observe prompt scintillation for drift time measurement.
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.
EXO-200 at WIPP
Module 1

- HV FILTER AND FEEDTHROUGH
- VETO PANELS
- DOUBLE-WALLED CRYOSTAT
- LXe VESSEL 1.37 mm
- LEAD SHIELDING > 25 cm
- VETO PANELS
- JACK AND FOOT
- FRONT END ELECTRONICS
- VACUUM PUMPS

High purity Heat transfer fluid HFE7000 > 50 cm
Low Activity Copper

- Very light (~1.5mm thin, ~15kg) to minimize materials

- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done in cosmic-ray shielded building
TPC: The Innards

- Teflon reflectors
- Cathode plane
- APD plane
- Field shaping rings
- Wire “triplet” terminus
- Wire “triplet” detail
- Cable detail (back of APD plane)
TPC Entering the Cryostat
Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in $^{136}\text{Xe}$
Copper conduits (6) for:
• APD bias and readout cables
• U+V wires bias and readout
• LXe supply and return
Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Xenon Recirculation

- Gx pressure reduction & control
- Gx purity monitor
- Gx purification
- Gx purity monitor
- LXe condenser
- Compressors
- 200 kg Xe (bottle farm)
- Gx pump
- LXe heater
- Purification loop
- Liquid shielding and thermal bath
- HFE system pressure control
- TPC
- Cryostat
- LXe heater
Xenon Recirculation

complicating factors:
ultra-radiopurity, emergency recovery, electronic noise environment, thermal stability
Xenon Recirculation
EXO-200 Module 2

circa 2010

LXe boil-off heater

dual xenon compressors

EXO-200 goal:
0.1 ppb O$_2$ equivalent
($\sim 4$ ms electron lifetime)
Calibration System

Miniaturized sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Weak (kBq)</th>
<th>Strong (kBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-Co</td>
<td>3.0</td>
<td>15.0</td>
</tr>
<tr>
<td>137-Cs</td>
<td>0.5</td>
<td>7.2</td>
</tr>
<tr>
<td>228-Th</td>
<td>1.5</td>
<td>38.0</td>
</tr>
</tbody>
</table>

Stainless steel capsule

6m long, low friction cable

Provide 4 full energy deposition peaks in the energy range 662 keV – 2615 keV

new $^{226}$Ra source also added

weak $^{228}$Th
Event Multiplicity

Single Site (SS)  Multiple Site (MS)

Low Background Data

$^{228}$Th Calibration Source

$2\nu\beta\beta$
Single Site Event

Top display is charge readout (V are induction wires and U are collection wires).

Left display is light readout. APD map refers to the sample with max signal.

Scintillation light is seen from both sides, although more intense and localized on side 2, where the event occurred.

Small depositions produce induction signals on more than one V wires but are collected by a single U wire. V signal always comes before U.

Light signals precede in time the charge ones.
**Single Site Event**

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Two-Site Compton Event

All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

The scintillation light is brighter and more localized on Side 1 where the scattering occurs.
Two-Site Compton Event

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Rn Content in Liquid Xenon

$^{214}\text{Bi} - ^{214}\text{Po}$ correlation in the EXO-200 detector

Long-term study shows a constant source of $^{222}\text{Rn}$ dissolving in enr$\text{LXe}$: $360 \pm 65 \text{ µBq (Fid. vol.)}$

Total $^{222}\text{Rn}$ in LXe after initial fill
EXO-200 2014 Result

$T_{1/2}^{0
\nu\beta\beta}>1.1 \cdot 10^{25}\text{yr}$
(90\%CL)

$<m_\nu> < 190 – 450 \text{ meV}$

$T_{1/2}^{0\nu\beta\beta}$ sensitivity:

$1.9 \cdot 10^{25} \text{ yr}$

J.B. Albert et al.
(EXO-200)
Nature 510 (2014) 229

Neutrinoless Double-Beta Decay: Lecture 2
Phase-II Running

- EXO-200 Phase-II operation begins on 31 Jan 2016, after enriched liquid xenon fill.
- Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.

New results to be released next week!
Towards the Ton Scale

Because one can take full advantage of:
1) Compton tag and rejection (if detector has double-hit recognition ability)
2) External background identification and rejection

The larger the detector the more useful this is.
→ Ton scale is where these features become dominant.
Shielding a detector from gammas is difficult!

**Gamma Shielding**

Gamma interaction cross section

Example:

\[ \gamma \text{ interaction length in Ge is } 4.6 \text{ cm, comparable to the size of a germanium detector.} \]

**Typical \( \beta \beta 0\nu \text{ Q values} \)**

**Shielding \( \beta \beta \) decay detectors is much harder than shielding Dark Matter ones**

We are entering the “golden era” of \( \beta \beta \) decay experiments as detector sizes exceed int lengths.
nEXO Concept

Preliminary artist view of nEXO in the SNOlab Cryopit
One essential point: nEXO IS NOT A PURE CALORIMETER

To think about nEXO exclusively in terms of energy resolution is misleading. nEXO uses optimally more than just the energy measurement.

The signal/background discrimination is based on four parameters:
1. Energy measurement
2. Event multiplicity (SS/MS in EXO-200)
3. Distance from the TPC surface
4. Particle ID (α-electron)

There is no rational reason to prefer the use of an “Energy ROI” over a “topology ROI” or a “topology ⊗ energy ROI”. In fact, more independent axes provide a more powerful constraint on the signal.
nEXO Strategy

Flexible program based on the initial nEXO investment

- **Procure 5 tons of $^{enr}\text{Xe}$**
- **Build nEXO**
- **Run nEXO for 5yrs**

**Comprehensively cover inverted hierarchy**

- **Discover $\beta\beta$ decay?**
  - **No**
    - **Upgrade with Ba tagging or buy more Xe**
    - **Higher sensitivity run**
    - **Attack normal hierarchy**
  - **Yes**
    - **Replace $^{natl}\text{Xe}$ or $^{depl}\text{Xe}$**
    - **Confirm discovery?**
      - **Yes**
        - **Build GXe TPC for same $^{enr}\text{Xe}$**
        - **Study electron correlations**
      - **No**
        - **Think!**
nEXO R&D

- High Voltage
- SiPMs: QE, radiopurity…
- Internal Electronics
- TPC Internals
- Calibration Concepts

Local R&D
- BNL Instrumentation Division: Internal Electronics
- SBU/BNL: Novel Calibration Concepts
Particularly in the larger nEXO, background identification and rejection fully use a fit that considers simultaneously energy, multiplicity and event position.

→ The power of the homogeneous detector, this is not just a calorimetric measurement!
nEXO Sensitivity Reach

![Graph showing nEXO sensitivity reach with normal and inverted hierarchies.]

Normal hierarchy:
- 9.5x10^{27} yr
- 6.2x10^{27} yr

Inverted hierarchy:
- 1.9x10^{25} yr


EXO-200 Sensitivity (90% C.L.)
Outlook for the Field
Discovery Sensitivity Comparison

*Discovery probability of next-generation neutrinoless double-beta decay experiments*

Matteo Agostini, Giovanni Benato, and Jason Detwiler

arXiv:1705.02996v1

---

Red : Achieved Backgrounds;  Black : Projected Backgrounds

**Width of bands based on range of NME values**
Discovery Probability

- LEGEND 1k
- LEGEND 200

- CUPID (Te)
- SNO+ Phase II
- SNO+ Phase I

- nEXO
- PANDAX 1k
- NEXT 1.5k
- KamLAND2-Zen
- KamLAND-Zen 800

Discovery probability for NO:

- discovery probability for NO
- live time [yr]

Discovery probability for IO:

- discovery probability for IO
- live time [yr]
Closing Thoughts

• Given the compelling theoretical motivation and discovery of neutrino mass, the search for neutrinoless double-beta decay has become one of the highest priorities for experimental nuclear physics research worldwide.

• The field of experimental searches for neutrinoless double beta decay is now maturing and coalescing into a handful of ton-scale discovery experiments.

In these lectures, I have tried to educate you on the above.

• With a little bit of luck, we may learn whether neutrinos are their own antiparticles within a decade.

• With a further bit of luck we might have a new paradigm for the origin of all matter in the universe.

• In any case, this research will have tremendous impact well beyond nuclear physics, touching particle physics, astrophysics and cosmology.