The MAJORANA Experiment

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for the
MAJORANA Collaboration

NOW 2010
Outline

• Double-Beta Decay
• The MAJORANA Experiment
• The Initial MAJORANA Module
• Detectors
• Backgrounds and Background Rejections
• Recent Progress and Plans
Neutrinoless Double-Beta Decay

- No neutrinos emitted
- Discovery provides:
  - Neutrino is its own antiparticle (Majorana)
  - Lepton number violation
  - A measure of the effective neutrino mass

\[ ^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- \]

\[ n \rightarrow p + e^- + \bar{\nu}_e \quad (RH \bar{\nu}_e) \]
\[ (LH \nu_e) \quad \nu_e + n \rightarrow p + e^- \]

Exchange of a virtual neutrino
How $\beta\beta$ relates to the Neutrino

Observe double-beta decay by collecting the energy of the 2 e$^-$ in a detector

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \langle m^2_\nu \rangle$$

Measure decay rate of to get neutrino absolute mass scale

- $G$ are calculable phase space factors
- $M$ are nuclear physics matrix elements
- $m_\nu$ is the effective Majorana mass

Energy $Q = 2.039$ MeV
The MAJORANA Approach to $\beta\beta$ Detection

Ge crystal

Array inside cryostat

Low mass mount

Shield
MAJORANA Favors $^{76}\text{Ge}$

$^{76}\text{Ge}$ offers an excellent combination of capabilities & sensitivities.

- **Ge is the source & detector**
  - maximizes source to total mass ratio
  - Well-understood technologies
  - Excellent energy resolution: 0.16% at 2.039 MeV, 4-keV ROI
    - Advantage for improving signal to background
  - Existing, well-characterized large Ge arrays
- **Demonstrated ability to enrich 7.44% to 86%**
- **Favorable nuclear matrix element**
  - e.g. $<M_{0\nu}> = 3.9$ [Rodin et al. 2005, erratum], 2.6 [Caurier et al. 2007]
- **Slow 2$\nu\beta\beta$ rate ($T_{1/2} = 1.4 \times 10^{21}$ y)**
- **Powerful background rejection technologies**
  - Segmentation, granularity, timing, pulse shape discrimination
- **Best current limit on 0$\nu\beta\beta$ used Ge**
  - IGEX & Heidelberg-Moscow $T_{1/2} > 1.9 \times 10^{25}$ y
MAJORANA Collaboration Goals

Actively pursuing R&D aimed at a ~1 tonne scale $^{76}$Ge $0\nu\beta\beta$-decay experiment

- **Technical Goal**: Demonstrate background low enough to justify building a ton-scale experiment

- **Science Goal**: Build a prototype module to test the recent claim of an observation of $0\nu\beta\beta$

- Work cooperatively with the GERDA Collaboration to prepare for a single international ton-scale Ge experiment that combines the best technical features of MAJORANA and GERDA

- Pursue longer term R&D to minimize costs and optimize the schedule for a ton-scale experiment
Goal is to achieve ultra-low backgrounds of less than 1 count per ton of material per year in the Region of Interest (ROI) about the $\beta\beta(0\nu)$ Q-value energy.
Evaluate MAJORANA Design with Initial Module

The MAJORANA DEMONSTRATOR

- Up to 40 kg of Ge crystals
  - Up to 30 kg of 86% enriched $^{76}\text{Ge}$ crystals
  - Detector Technology: P-type, point contact
- 2 independent cryostat
  - Ultra-clean, electro-formed Cu cryostats
  - 20 kg of detectors per cryostat
  - Naturally scalable
- Compact Shield
  - Low-background passive Cu and Pb shield with active muon veto
- Located underground at 4850’ level (4200 m.w.e) at Sanford Lab/DUSEL
- Background goal in the 0νββ peak region of interest (4 keV at 2039 keV) is ~ 1 count/ROI/t-y after analysis cuts and scaled to a 1-tonne experiment.
Prototype Module Probes to 200 meV

- **Expected Sensitivity to 0νββ**
  - for 30 kg enriched material, running 3 years, or 0.09 t-yr of $^{76}$Ge exposure
  - $T_{1/2} \geq 1.0 \times 10^{26}$ y (90% CL) Sensitivity to $\langle m_\nu \rangle < 140$ meV (90% CL) [Rod06 erratum] RQRPA NME

![Graph showing expected sensitivity to 0νββ]
MAJORANA Backgrounds

- **Goal:** \( \leq 1 \) event / ton-year in 4 keV ROI
- **Backgrounds:**
  - Natural isotope chains: \(^{232}\text{Th}, \, ^{235}\text{U}, \, ^{238}\text{U}, \text{Rn}\)
  - Cosmic Rays:
    - Activation at surface creates \(^{68}\text{Ge}, \, ^{60}\text{Co}.\)
    - Hard neutrons from cosmic rays in rock and shield.
      - \((n,n'\gamma)\) in Pb, Ge, Cu
  - \(2\nu\beta\beta\)-decays.
- Need factor \(\sim100\) reduction over what has been demonstrated.
- Monte Carlo estimates of acceptable levels

Most backgrounds are multi-site. Signal is single-site.
# Background Model

<table>
<thead>
<tr>
<th>Component</th>
<th>Isotope</th>
<th>Gross Rate per Module, 1.9-3 MeV [c/month]</th>
<th>ROI Background (DEMONSTRATOR) [c/ROI/t/y]</th>
<th>ROI Background (tonne scale) [c/ROI/t/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Germanium Crystals (enriched)</strong></td>
<td>$^{68}\text{Ge}$</td>
<td>47 (7.6)</td>
<td>0.38</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$^{60}\text{Co}$</td>
<td>4.2</td>
<td>0.03</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>U/Th</td>
<td>-</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Cryostat, Inner Cu Shield (EFCu)</strong></td>
<td>$^{208}\text{Tl, 214Bi}$</td>
<td>2.1</td>
<td>0.91</td>
<td>0.48</td>
</tr>
<tr>
<td><strong>Outer Cu Shield</strong></td>
<td>$^{208}\text{Tl, 214Bi}$</td>
<td>0.8</td>
<td>0.40</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$^{60}\text{Co}$</td>
<td>2.0</td>
<td>0.02</td>
<td>$1\times10^{-3}$</td>
</tr>
<tr>
<td><strong>Pb Shield</strong></td>
<td>$^{208}\text{Tl, 214Bi}$</td>
<td>0.5</td>
<td>0.40</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Prompt Cosmogenics</strong></td>
<td>$(n,^8\text{B})$</td>
<td>-</td>
<td>$\sim1$</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>All Others</strong></td>
<td></td>
<td>1.2</td>
<td>0.38</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Totals:</strong></td>
<td></td>
<td>57.8 (18.5)</td>
<td>3.81</td>
<td>1.07</td>
</tr>
</tbody>
</table>
• A solid p-type detector: simpler to fabricate, easier handle, instrument, very low capacitance (~1pF).

• The longer drift distance in the PPC stretches the pulse leading to a clear indication of a multiple site event.

• Advantage of segmented detectors, without extra complexity and backgrounds.

• Low energy threshold permits additional physics applications: e.g. Dark Matter, Axions
P-type Point Contact Detectors

**Rising edge**
“stretched” in time
⇒ improved PSA

**PPC detectors have extremely low energy threshold**

Typical coaxial HPGe

**PPC**

- Cu K-shell BE ($^{65}$Zn EC)
  - 8.98 keV
  - (50% involve E = 1115 keV)

- Ga K-shell BE ($^{68,71}$Ge EC)
  - 10.36 keV

- Zn K-shell BE ($^{65,67,68}$Ga EC)
  - 9.66 keV

- Ge K-shell BE ($^{73}$As EC)
  - 11.10 keV

**Mostly Multiple Site Interaction**

**Single Site (DEP) Interaction**

- Raw Th spectrum
- After TFA peak count + width cut

- V. E. Guiseppe

Barbeau et al., JCAP 09 (2007) 009
arXiv:0807.0879v4 CoGeNT Collaboration

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Front End Electronics and Cables

- Requires materials very low in radioactive impurities
- Trace proximity of traces provides $\sim 1$ pF
- Silica or sapphire substrate provides thermal control
- Amorphous Ge resistor: deposit in H gives proper resistance at low temperature

Custom Parylene coated wires

1 mm
String and Detector Mount Testing

Single Detector Test with PPC

- Parylene Cable
- Front End Board

Thermal Testing
Pb excitations

- Specific Pb gamma rays are problematic backgrounds
  - $^{206}$Pb has a 2041-keV $\gamma$ ray
  - $^{207}$Pb has a 3062-keV $\gamma$ ray
  - $^{208}$Pb has a 3060-keV $\gamma$ ray

- The DEP of the $\sim$3062 keV $\gamma$ ray is a single site energy deposit at $\beta\beta$ Q-value

- Neutron interactions in Pb can excite these levels

- Cross sections unknown
Measured gamma-ray production cross sections from a Pb target in a neutron beam at LANSCE

\[ \text{natPb}(n,\gamma)\text{Pb}^{206} \text{Pb} \text{ 2041 keV} \]

\[ \text{natPb}(n,\gamma)\text{Pb}^{207,208} \text{Pb} \text{ 3062 keV} \]

Other cross sections in Cu and Ge being measured

V.E. Guisepppe et al. (2009) PRC 79, 054604
Cosmic Activation of $^{76}$Ge

Activation rate measured by placing a $^{76}$Ge sample and a HPGe detector in a high-intensity neutron beam (LANSCE)

S. R. Elliott et al, arXiv:0912.3748
Electroforming Cu
MAJORANA Lab Space

Design of underground space at Sanford Lab 4850’ level Davis Campus

Clean Machine Shop

Electroforming

Detector Hall
MAJORANA Status

Funded by DOE Nuclear Physics & NSF Particle and Nuclear Astrophysics

- **Progress towards DEMONSTRATOR Module**
  - 20-kg of $^{\text{nat}}$Ge modified BEGe p-type, point contact (10 kg in-hand and remaining on order and arriving)
  - Variety of PPC prototypes underground
  - Detector string prototypes being tested
  - Assay and selection of materials
  - Interim electro-forming facility at 4850’ level of Sanford Lab and underground facility at PNNL
  - DEMONSTRATOR Lab excavated
  - Ge refinement laboratory being established in Oak Ridge, TN
The MAJORANA Collaboration

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Note: Red text indicates students
P-PCs can study additional physics

• Low energy threshold of \(\sim 100\) eV provides sensitivity to:
  - DM (light/slow WIMPs, Q-balls), CvNS (Reactor, SN \(\nu\ldots\)), axions, e-decay

arXiv:0807.0879v4  CoGeNT Collaboration
Neutrino Hierarchy
Majorana Mass

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- No mixing

\[\left\langle m_{\beta\beta} \right\rangle = m_{\nu_e} = m_1\]

- With mixing

\[\left\langle m_{\beta\beta} \right\rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i\]

- Beta decay

\[\left\langle m_\beta \right\rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}\]

- Cosmology

\[\sum m_i = \sum m_i\]
Heidelberg-Moscow

47.7 kg y: $T_{1/2}^{2ν} = [1.55 \pm 0.01 \text{(stat)}^{+0.19}_{-0.15} \text{(syst)}] \times 10^{21}$ y


Slide from: J. Detwiler
SORMA West 2008
Heidelberg-Moscow

$35.5 \, \text{kg y}: \quad T_{1/2}^{0\nu} > 1.9 \times 10^{25} \, \text{y} \, (90\% \, \text{CL})$

Slide from:
J. Detwiler
SORMA West 2008

IGEX

116.75 mole year - 8.87 kg·year in $^{76}$Ge

Complete data set: $T_{1/2}(0\nu) > 1.13 \times 10^{25}$ yr (90% CL)

Reduced data set: $T_{1/2}(0\nu) > 1.57 \times 10^{25}$ yr (90% CL)


Slide from:
J. Detwiler
SORMA West
2008
71.7 kg y
71.7 kg y

\[ T_{1/2}^{0\nu} = 1.2 \pm 0.3 \times 10^{25} \text{ y} \]

\[ <m_{\nu}> = 0.44 \pm 0.14 \text{ eV} \]

significance: 4.2\sigma


Slide from:
J. Detwiler
SORMA West
2008
Future Data Requirements

• Why wasn’t this claim sufficient to avoid controversy?

• Low statistics of claimed signal - hard to repeat measurement

• Background model uncertainty

• Unidentified lines

• Insufficient auxiliary handles

• Result needs confirmation or repudiation
**Background modeling**
- Simulated major background sources for detector components using MaGe
- Calculated total backgrounds individually for each detector technology under consideration
- Cu purity of ~0.3 Bq/kg is required; sizeable contribution from $^{208}$Tl in the cryostat and shield.
- Higher rejection of segmented designs is roughly balanced by extra readout components.
- P-PC appears to achieve the best backgrounds with minimal readout complexity.