Results from the **MAJORANA DEMONSTRATOR**

$^{76}\text{Ge}$ detector array

J.F. Wilkerson

on behalf of the **MAJORANA Collaboration**
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Sensitivity vs. Exposure vs. Signal

<table>
<thead>
<tr>
<th>Half life (years)</th>
<th>~Signal (cnts/ton-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>
<tr>
<td>$&gt;10^{29}$</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure.

$^{76}$Ge (87% enr.)

J. Detwiler
Advantages of Ge

- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: approaching 0.1% at 2039 keV (~3 keV ROI)
- Demonstrated ability to enrich from 7.44% to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape discrimination

**MAJORANA**
Compact configuration: Vacuum cryostats in a passive graded shield with ultra-clean materials

**GERDA**
Direct immersion in active LAr shield
**The 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 ≤ 3.5
  scales to 1 count/(ROI t y) for a tonne experiment
- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched $^{76}$Ge crystals
  - 14.4 kg of $^{\text{nat}}$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

DEMOnSTRATOR Background Budget

Based on assays of materials; When upper limit, use upper limit value as contribution

(NIMA 828 (2016) 22)

Background Rate (c/ROI-t-γ)

- Electroformed Cu
- OFHC Cu Shielding
- Pb shielding
- Cables / Connectors
- Front Ends
- Ge (U/Th)
- Plastics + other
- Ge-68, Co-60 (enrGe)
- Co-60 (Cu)
- External γ, (α,n)
- Rn, surface α
- Ge, Cu, Pb (n, n'γ)
- Ge(n,n)
- Ge(n,γ)
- direct μ + other
- ν backgrounds

Total: <3.5 c/ROI-t-γ
MAJORANA Electroformed Copper

- MAJORANA operated 10 baths at the 4850’ level of Sanford Underground Research Facility (SURF) and 6 baths at a shallow UG site at PNNL. All copper was machined at the SURF Davis campus.
- The electroforming of copper completed in May 2015.
  - 2474 kg of electroformed copper on the mandrels,
  - 2104 kg after initial machining,
  - 1196 kg that will be installed in the DEMONSTRATOR.

- Th decay chain (ave) $\leq 0.1 \mu$Bq/kg
- U decay chain (ave) $\leq 0.1 \mu$Bq/kg
AMETEK (ORTEC) fabricated enriched detectors.
35 Enriched detectors at SURF 29.7 kg, 88% $^{76}$Ge.
20 kg of modified natural-Ge BEGe (Canberra)
detectors in hand (33 detectors UG).

All detector assembly performed in $N_2$ purged gloveboxes.
All detectors’ dimensions recorded by optical reader.
**MAJORANA DEMONSTRATOR Implementation**

Module 1: 16.9 kg (20) $^{enr}\text{Ge}$  
5.6 kg (9) $^{nat}\text{Ge}$

Module 2: 12.9 kg (14) $^{enr}\text{Ge}$  
8.8 kg (15) $^{nat}\text{Ge}$

In-shield Running  
05/2015 – 10/2015  
Module Improvements  
01/2016 – ongoing  
07/2016 – ongoing
Data Sets and Duty Cycles

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-0</td>
<td>M1 Commissioning, No inner shield</td>
</tr>
<tr>
<td>DS-1</td>
<td>M1 Commissioning, inner shield</td>
</tr>
<tr>
<td>DS-2</td>
<td>M1 Multi-sampling</td>
</tr>
<tr>
<td>DS-3</td>
<td>Modules 1 and 2 Together in-shield</td>
</tr>
<tr>
<td>DS-4</td>
<td>Module 1 &amp; 2 Integrated DAQ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Module 1</th>
<th>Module 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-2</td>
<td>May 24 - July 14, 2016</td>
<td></td>
</tr>
<tr>
<td>DS-3</td>
<td>Aug. 25 - Sep. 27, 2016</td>
<td></td>
</tr>
<tr>
<td>DS-4</td>
<td>Aug. 25 - Sep. 27, 2016</td>
<td>Oct. 13, 2016 - ongoing*</td>
</tr>
</tbody>
</table>

| Total (days) | 103.15 | 144.50 | 50.97 | 32.37 | 32.36 | 97.7 |
| Total acquired | 87.93 | 136.98 | 50.47 | 31.73 | 25.80 | 90.41 |
| Physics | 47.70 | 61.34 + 20.41* + 9.82 + 30.56* | 29.97 | 23.84 | 82.52 |
| High radon | 11.76 | 7.32 | - | - | - |
| Calibration | 15.44 | 7.32 | 0.65 | 1.18 | 1.17 | 1.39 |
| Down time | 15.21 | 7.51 | 0.50 | 0.64 | 6.56 | 7.29 |
| Disruptive/Commissioning | 13.10 | 34.43 + 5.92* + 2.41 + 7.03* | 0.57 | 0.78 | 6.51 |

*Blind data

*Values up to Jan. 19, 2017

~93% live (phys+cal)
$0\nu\beta\beta$ with Point Contact Detectors

Results from the MAJORANA DEMONSTRATOR

Summed $^{228}$Th Calibration Spectrum (DS3&DS4)

- Enriched detectors in Modules 1 and 2
- $^{228}$Th calibration source
- FWHM = 2.4 keV at $Q_{\beta\beta}$ (2039 keV)

Calibration paper
arXiv:1702.02466

Energy (keV)

Counts

FWHM 2.8 keV

blue - data
red - fits to selected peaks
Summed $^{228}$Th Calibration (DS1) & Simulation

Calibration paper
arXiv:1702.02466
PSD cuts are optimized to keep 90% single-site and <10% multi-site events

- $0\nu\beta\beta$ is a single site event
- $^{208}\text{TI}$ 2614 keV $\gamma$ can pair produce with annihilation $\gamma$’s escaping detection
Cut for $\alpha$’s, Delayed Charge Recovery

- Alpha background with degraded energies observed in DS0
- Charge of these events drifts along the detector surface, not bulk
- Produces a distinctive waveform allowing a high efficiency cut

![Graphs showing examples of pole-zero corrected waveforms with slow drift of charges along passivated surface resulting in very slow signal component.]
Background Spectrum (DS3 & DS4)

Lowest background configuration, with both modules in shield.
(Previous data presented at Neutrino 16 was from Module 1, DS 0/1)

Enriched detectors in Modules 1 & 2, before and after PSD cuts

No PSD cuts
AvsE cut
AvsE & DCR cuts

Spectrum is dominated by $2\nu\beta\beta$
Estimated $0\nu\beta\beta$-decay ROI background (DS3 & DS4)

- Exposure: 1.39 kg $y$
- After cuts, 1 count in 400 keV window centered at 2039 keV ($0\nu\beta\beta$ peak)
- Projected background rate is $5.1^{+8.9}_{-3.2}$ c/(ROI $t$ $y$) for a 2.9 keV ROI, (68% CL).
- Background index of $1.8 \times 10^{-3}$ c/(keV kg $y$)
- Analysis cuts are still being optimized.
Detector Low-energy Thresholds and Noise (DS5)

$\text{FWHM}_{\text{Avg}} \approx 250 \text{ eV}$

$\text{Threshold}_{\text{Avg}} \approx 700 \text{ eV}$

Run 23450

Detector ID

FWHM or Threshold [keV]

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

0 10 20 30 40 50 60

Detector ID
DS0: Low-energy spectrum

Controlled surface exposure of enriched material.

For the DEMONSTRATOR, the enriched detector $^{68}\text{Ge}$ rate is low enough that an X-ray delayed coincidence cut will not be necessary.

Significant reduction of cosmogenics in the low-energy region. Factor of a few better in DS1. Tritium is obvious and dominates in natural detectors below 20 keV. Efficiency below 5 keV is under study.

DS0 Natural 4.1 kg Enriched 10.06 kg

Low-Energy Searches for Physics Beyond SM

- Pseudoscalar dark matter
- Vector dark matter
- 14.4-keV solar axion
- $e^- \rightarrow 3\nu$
- Pauli Exclusion Principle
Results from the Majorana Demonstrator

DS0: Low-energy spectrum

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Pseudoscalar axion-like particle dark matter coupling
**Majorana Demonstrator Summary**

- The $^{76}$Ge enriched point contact detectors developed by Majorana have attained the best energy resolution (2.4 keV FWHM at 2039 keV) of any $\beta\beta$-decay experiment.
  - They provide excellent pulse shape discrimination reduction of backgrounds.
  - At low energies have sub-keV energy thresholds and excellent resolution allowing the Demonstrator to perform sensitive test in this region for physics beyond the standard model.

- The Demonstrator’s initial backgrounds are amongst the lowest backgrounds in the ROI achieved to date (approaching to GERDA’s recent best value). Attained by development and selection of ultra-low activity materials and low mass designs.

- Combining the strengths of GERDA and the Majorana Demonstrator, the LEGEND Collaboration is moving forward with a ton-scale $^{76}$Ge based experiment. Based on the successes to date, LEGEND should be able to reach the backgrounds (~0.1 c/(ROI t y)) and energy resolution necessary for discovery level sensitivities in the inverted ordering region.
3σ Discovery: Exposure vs. Background

\[ \text{IO min. 3σ DL Req. Exposure [ton-years]} \]

- \(^{76}\text{Ge} (87\% \text{ enr.})\)
- \(^{136}\text{Xe} (90\% \text{ enr.})\)
- \(^{130}\text{Te} (\text{nat.})\)

Background [c/ROI-t-y]

- \(10^{-4}\)
- \(10^{-3}\)
- \(10^{-2}\)
- \(10^{-1}\)
- \(1\)
- \(10\)
- \(10^2\)
- \(10^3\)

DL Req. Exposure [ton-years]

- \(10\)
- \(10^2\)

- \(10^3\)

\(\sigma\)

Experiments:
- GERDA-II (PRL 2013)
- CUORE-0 (PRL 2015)
- NEMO-3 (\(^{100}\text{Mo, PRD 2015}\))
- CUORE-I (PRL 2013)
- NEXT 100 goal
- GERDA-I (Nu16)
- MAJORANA DEMONSTRATOR (CD-4)

J. Detwiler

Results from the MAJORANA DEMONSTRATOR

XVII Int. Workshop on Neutrino Telescopes

March 15, 2017

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Module and Shield Details

- Calibration System
- Thermosyphon
- Upper Veto
- Poly Shield
- Cryostat
- Keyed Pb Stacks
- Air Bearing Transport
- Preamps/HV Distribution
- Vacuum System

Results from the MAJORANA DEMONSTRATOR
4850’ level, SURF, Lead SD
Clean room conditions
Muon flux: $5 \times 10^{-9} \mu/cm^2 s$

(arXiv:1602.07742)
Cosmic ray exposure minimized throughout all processes
Typical sea-level equivalent exposure is about 35 d for the enriched detectors.
**DEMONSTRATOR** Electroforming Cu

Insertion of mandrel into EF bath

Electroforming Baths in TCR

Inspection of EF copper on mandrels

“Good” Mandrel

“Poor” Mandrel with large nodule growth
DEMONSTRATOR Cables and Connectors

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Biased</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DS3+DS4</td>
<td>Det (kg)</td>
<td>Active (kg)</td>
</tr>
<tr>
<td>Total</td>
<td>44.1</td>
<td>40.3 ± 0.7</td>
<td>58</td>
</tr>
<tr>
<td>Enriched</td>
<td>29.7</td>
<td>27.4 ± 0.4</td>
<td>35</td>
</tr>
<tr>
<td>Natural</td>
<td>14.4</td>
<td>12.9 ± 0.3</td>
<td>23</td>
</tr>
</tbody>
</table>

- 44 of the 58 installed detectors are operating
- Problems with non-operating detectors
  - 7 associated with the signal connectors that are located on the cryostat cold plate or with damaged low mass front end boards.
  - 7 detectors cannot be biased either because of problems with the HV cables, connections, or in one instance a likely detector problem.
- Upgrade underway
  - “Fuzz buttons” for signal connectors.
  - HV cable study in progress
Ge Processing and Recovery

- **Reduction & Zone refining**: 98.7% yield of > 47 Ohm-cm Ge from 42.5 kg of \(\text{enrGe}\) (61.7 kg of \(\text{GeO}_2\))

- **ORTEC manufactured**: 30 \(\text{enrGe}\) detectors, 25.3 kg of mass.
  - 64.4% yield of detectors, 3.22 kg of > 47 Ohm-cm Ge material not used,

- **Recovered Ge**: from processing det. manufacturing waste (NSF suppl. funding)
  - Reprocessed 8.4-kg of “scrap”
    - effluent, kurf, and 2.87 kg of metal from detector manufacturer reject.
  - Recovered 5.87 kg of Ge with >47 Ohm-cm.

- The 5.87 kg was combined with 3.22 kg of Ge material to provide 9.1 kg of Ge > 47 Ohm-cm. ORTEC manufactured 5 additional detectors with 4.4 kg mass.

- **Final yield of detectors**: 74.5%
  - unused \(\text{enrGe}\) inventory: 1.49 kg (crystal) and 1.15 kg (zone refined).
MJD Materials Assay

- Assay of samples from all materials used in the DEMONSTRATOR.
  - Radiometric, NAA, & ICP-MS techniques.
- By necessity have developed world’s most sensitive ICP-MS based assay techniques for U and Th in Cu (Original MJD Goal: <0.3 µBq/kg for U & Th)
  - Current MDL (method detection limits) with iridium anode improvements
    - U decay chain 0.1 µBq $^{238}$U/kg
    - Th decay chain 0.1 µBq $^{232}$Th/kg
  - Sensitivities with ion exchange copper sample preparation (MDL study)
    - U decay chain <0.13 µBq $^{238}$U/kg
    - Th decay chain <0.034 µBq $^{232}$Th/kg

Evaluation of iridium electrodes following copper sample preparation

NIM A 775 (2015) 93-98
DEMONSTRATOR Detector Strings

$^{\text{Nat}}$Ge BEGe PPC detector in MJD mount

String with 5 $^{\text{Nat}}$Ge BEGe PPC detectors

Cable Management System

Loading string into string test cryostat in Glove Box

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