Initial Results from the MAJORANA DEMONSTRATOR

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Neutrinoless Double Beta Decay

This process could be possible due to: neutrino being Majorana particle, Majoron emission, RPV SYSY, Leptoquarks, color fermions, etc.

If neutrino is of Majorana nature ($\nu = \tilde{\nu}$) than the rate of this process is proportional to the effective neutrino mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) M^{0\nu} \approx \sqrt{m_\nu}$$

$$\langle m_\nu \rangle = \sum_{i=1}^{3} U_{ei}^2 \cdot m_i$$

$$\approx \left(0.87\right)^2 \cdot m_1 + \left(0.5\right)^2 \cdot \sqrt{m_1^2 + \Delta m_{21}^2} \cdot e^{2i\beta} + s_{13}^2 \cdot m_3 \cdot e^{-2i(\gamma-\delta)}$$
Sensitivity, Background and Exposure

Inverted Hierarchy ($m_\beta \rightarrow 0$ eV) (QRPA, $g_A = 1.25$)

$^{76}$Ge $T_{1/2}$ 3$\sigma$ DL [years]

$\beta$ sensitivity (90% CL) [meV]

Exposure [ton-years]

Background free

- 0.1 counts/ROI/t/y
- 1.0 count/ROI/t/y
- 10.0 counts/ROI/t/y

Yu.Efremenko
MJD Philosophy

To Reduce Region of Interest → Use Best Possible Energy Resolution.
Use detectors made out of enriched target material – $^{76}\text{Ge}$

To Reduce Intrinsic Background:
relay on underground-grown ultrapure copper
reduce mass of all other components other than detectors to absolute minimum
use pulse shape discrimination

Use Comprehensive External Shieling:
deep underground location
combination of gamma + neutron absorbers
two layers of $4\pi$ veto system

Use Modular Approach:
easy to scale up
use different type of detectors
ability to build/serve part of assembly while continue data taking

Goal of MJD is to demonstrate backgrounds low enough to justify building a tone-scale Ge experiment
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)

- 44.8-kg of Ge detectors
  - 29.7 kg of 88% enriched $^{76}$Ge crystals
  - 15.1 kg of $^{nat}$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

July 2016
AMETEK (ORTEC) fabricated enriched detectors. 35 Enriched detectors at SURF 29.7 kg, 88% $^{76}\text{Ge}$. 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.
Minimization of Exposure to the Cosmic Rays

$^{68}$Ge could be a problem

Typical sea-level equivalent exposure is about 35 d for the enriched detectors.
MAJORANA Electroformed Copper

- MAJORANA operated 10 baths at the Temporary Clean Room (TCR) facility at the 4850’ level and 6 baths at a shallow UG site at PNNL. All copper was machined at the Davis campus.
- The electroforming of copper for the DEMONSTRATOR successfully 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.
- Underground machining completed April 2016. (Machinist still available as needed.)
- TCR decommissioning is underway.

- Th decay chain (ave) \(\leq 0.1 \, \mu\text{Bq/kg}\)
- U decay chain (ave) \(\leq 0.1 \, \mu\text{Bq/kg}\)
Low Mass Front-End Board

Shipping Restraint

Epoxy

Feedback Resistor

Clean Au+Ti traces on fused silica, amorphous Ge resistor, FET mounted with silver epoxy, EFCu + low-BG Sn-coated-Cu contact pin

FET

Spring Clip

Mass is 0.08 g
Connectors reside on top of cold plate. In-house machined from vespel. Axon’ pico co-ax cable. Low background solder and flux. Axon’ Picoax HV and signal cables. All cables and connectors were HV tested (NIM A823 (2016) 83)
A Module is:
• Cryostat
• Calibration sys.
• Thermosyphon
• Vacuum
• Shield Section
• All resting on a movable bearing table
Module and Shield Details

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

July 2016
4850’ level, SURF, Lead SD
Clean room conditions
Muon flux: $5 \times 10^{-9} \, \mu/\text{cm}^2 \, \text{s}$
(arXiv:1602.07742)
Demonstrator Background Model

Background based on Assay Program (NIM A828 (2016) 22)
Poster P4.059 Clara Cuesta

Background Rate (c/ROI-t-γ)

- Electroformed Cu 0.23
- OFHC Cu Shielding 0.29
- Pb Shielding 0.63
- Cables / Connectors 0.38
- Front Ends 0.60
- Ge (U/Th) 0.07
- Plastics + other 0.39
- Ge-68, Co-60 (enrGe) 0.07
- Co-60 (Cu) 0.09
- External γ, (α,n) 0.10
- Rn, surface α 0.05
- Ge, Cu, Pb (n, n'γ) 0.21
- Ge(n,n) 0.17
- Ge(n,γ) 0.13
- Direct μ + other ν backgrounds <0.01
- Total: <3.5 c/ROI-t-γ

- Natural Radioactivity
- Cosmogenic Activation
- External, Environmental μ-induced
- Neutrinos

July 2016
MAJORANA DEMONSTRATOR Implementation

Three Steps

Prototype cryostat: 7.0 kg (10) \textsuperscript{nat}Ge
Same design as Modules 1 and 2, but fabricated using commercial Cu Components

Module 1: 16.8 kg (20) \textsuperscript{enr}Ge
5.7 kg (9) \textsuperscript{nat}Ge

Module 2: 12.8 kg (14) \textsuperscript{enr}Ge
9.4 kg (15) \textsuperscript{nat}Ge

June 2014-June 2015
Mid 2016
The inner Cu shield, and cross-arm shielding was added between DS0 & DS1. Also a temporary non low-background cryostat seal was replaced.

<table>
<thead>
<tr>
<th></th>
<th>DS0 (days)</th>
<th>DS1 (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No inner shield</td>
<td>with inner shield</td>
</tr>
<tr>
<td>Total</td>
<td>103.15</td>
<td>104.68</td>
</tr>
<tr>
<td>Total acquired</td>
<td>87.93</td>
<td>97.52</td>
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<tr>
<td>Physics</td>
<td>47.70</td>
<td>54.73</td>
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<tr>
<td>High radon</td>
<td>11.76</td>
<td>7.32</td>
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<tr>
<td>Disruptive tests</td>
<td>13.10</td>
<td>28.61</td>
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<tr>
<td>Calibration</td>
<td>15.44</td>
<td>6.86</td>
</tr>
<tr>
<td>Down time</td>
<td>15.21</td>
<td>7.16</td>
</tr>
</tbody>
</table>

*Data taking ongoing

July 2016
Point Contact Detectors (PPC)

- Ultra-low background requires PSA rejection of multi-site gamma events
- Initially considered coaxial n-type detectors with modest segmentation
- Chose P-type Point-Contact (PPC) detectors
  - No deep hole; small point-like central contact
  - Length is shorter than standard coaxial detector
  - Simple, cost-effective, low background
  - Localized weighting potential gives excellent multi-site rejection
  - Low capacitance (~ 1 pF) gives superb resolution at low energies

Ge Detector PSD Performance in Module 1 (DS1)

- **208\(^{\text{Tl}}\) DEP (single site events) fixed to 90%**
- **208\(^{\text{Tl}}\) SEP (Multiple site events) reduced to 6%**

Acceptance (%)

- **Tl DEP Mean**
- **Tl SEP Mean**
The Delayed Charge Recovery Cut for α’s

- Alpha background response observed in Module 1 commissioning (DS0)
- Identified as arising from alpha particles impinging on passivated surface.
- Results in prompt collection of some energy, plus very slow collection of remainder.
- Produces a distinctive waveform allowing a high efficiency cut.

Example pole-zero corrected waveforms

Slow drift of charges along passivated surface results in very slow signal component
DS1 DCR Cut and Bulk-Event Response

Removes most events above 2 MeV in the background spectrum, which are \( \alpha \) candidates. Cut is 90% efficient for retaining events within detector bulk. Only \(~5\%\) of \( \alpha \)'s survive cut.

During calibration runs, \( \gamma \) events survive cut.

During Background runs, \( \beta\beta(2\nu) \) events survive cut.

Candidate \( \alpha \) events from background runs are removed.
We perform some data cleaning cuts, granularity and PSD cuts to remove multiple site energy deposits, and the DCR cut to remove surface alphas. DCR cut events stop at about 5.3 MeV. Circumstantial evidence that its Po.
Data Set 1 spectrum after all cuts.
Above \(~1200\) keV the spectrum is dominated by $\beta\beta(2\nu)$.
The ROI and DCR in DS1

The enriched detectors in Data Set 1 are used to estimate the background. The lowest-background configuration. $Q_{\beta\beta} = 2039$ keV.

Most events near ROI are removed by the DCR cut. Only 5 survive in 400 keV window. Background rate is $23^{+13}_{-10}$ counts/(ROI t y) for a 3.1 keV ROI, (68% CL).

Background index is $(7.5^{+4.5}_{-3.4}) \times 10^{-3}$ counts/(keV kg y).

All analysis cuts are still being optimized.

![Graph showing counts per keV/kg/day vs. energy (keV)]
DS0 + DS1: $0\nu$ Sensitivity

- No ROI events in either data set.
- $T_{1/2} > 3.7 \times 10^{24}$ y (90% CL).
- DS0 & DS1 total exposure: 3.03 kg y.
  - DS0 1.37 kg-y, DS1 1.66 kg y
- Efficiency for $0\nu\beta\beta$ is $0.61 \pm 0.04$.
  
  
  $0.61 = (0.84)(0.9)(0.9)(0.9) = (\text{Resol.})(\text{Full Energy})(A/E)(\text{DCR})$

- Background very low. Sensitivity almost linear with exposure.
- We are exploring additional techniques for reducing background.
  - Fast rise-time cut.
- This analysis is on open data.
- Blind data taking began on April 14.
- We are studying the possibility of repairing cables/connectors. Could increase mass by 50%
Next Generation $^{76}\text{Ge}$ Experiment

Working cooperatively with GERDA and other interested groups toward the establishment of a next-generation $^{76}\text{Ge}$ $0\nu\beta\beta$-decay experimental collaboration to build an experiment to explore the inverted ordering region of the effective mass. Poster P4.075 SRE

Joint MAJORANA-GERDA Meeting
Nov. 2015 Kitty Hawk

Meeting of Interested Parties
April 2016 Munich

Next Meeting
End Oct. East Coast US

Produced and machined underground over 2100 kg of ultra clean electroformed Cu.

Produced 35 (29.66 kg) of 88% enriched $^{76}$Ge p-type point contact detectors.

Attained highest yield to date (74.5%) of enriched $^{76}$Ge detectors from initial material.

Module 1 in operation with improved shielding since January 2016, blind data collection mode since April 2016.

Module 2 undergoing commissioning. Aim for in-shield background measurements by August.

Final additions (neutron shielding) to main shield will be installed once Module 2 is in shield.

Independent work continues to improve cables and connectivity in terms of an optimized next generation ton scale $^{76}$Ge 0νββ experiment.

Collected 3.03 kg yr of exposure from DS0 & DS1 before going blind. $T_{1/2} > 3.7 \times 10^{24}$ y

Measured background level in DS1 at ROI is $23^{+13}_{-10}$ counts/(ROI t y).

The ROI is 3.1 keV.