The Status and Initial Results of the MAJORANA DEMONSTRATOR Neutrinoless Double-Beta Decay Experiment

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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 0νββ 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

44.8-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
MAJORANA DEMONSTRATOR Implementation

Three Steps

Prototype cryostat: 7.0 kg (10) $^{\text{nat}}$Ge

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

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

In shield Operation

June 2014-June 2015

May–Oct. 2015, Final Installation, Dec 2015 - present

August 2016
**Demonstrator Background Model**

**Background Rate (c/ROI-t-y)**

- **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-y

**Background based on assay of materials:**


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ICHEP - Aug. 2016
Majorana Approach to Backgrounds

The detector: P-type point contact
- $^{enr}\text{Ge}$ metal zone refined and pulled into a crystal that provides purification
- Limit above-ground exposure to prevent cosmic activation
- Slow drift velocity and localized weighting potential: separation of multi-site events

Rejection of backgrounds
- Granularity: multiple detectors hit
- Pulse shape discrimination: multiple hits in a detector
- Alpha events near surface: based on response

Single-site event

Multiple scatters
Majorana Approach to Backgrounds

Ultra-pure materials
- Low mass design
- Custom cable connectors and front-end boards
- Carefully selected plastics & fine Cu coax cables
- **Underground Electro-formed Cu**
  - 10 baths at SURF, 6 baths at PNNL
  - 2654 kg of electroformed copper produced.
  - Th decay chain (ave) $\leq 0.1 \mu\text{Bq/kg}$
  - U decay chain (ave) $\leq 0.1 \mu\text{Bq/kg}$

Machining and Cleaning
- Cu machining in an underground clean room
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts
Assembled Detector Unit and String

Electroformed Copper

PFA + fine Cu coaxial cable

PTFE

Front-End Elec.

String Assembly
Detector Readout Components

Custom low mass front-end boards
Clean Au+Ti traces on fused silica
Amorphous Ge resistor
FET mounted with silver epoxy
EFCu + low-BG Sn contact pin

Connectors reside on top of cold plate.
In-house machined from Vespel.
Axon’ pico co-ax cable.
Low background solder and flux.

Fine Cu coaxial cable and clean connectors

Shipping Restraint
Epoxy
Feedback Resistor
FET

Epoxy
Connectors reside on top of cold plate.
In-house machined from Vespel.
Axon’ pico co-ax cable.
Low background solder and flux.
Detector Units and Strings

Detector units and strings built inside a glovebox with a radon-reduced, dry $N_2$ environment
Detector Module

- A self contained vacuum and cryogenic vessel
- Contains a portion of the shielding
- Can be transported for assembly and deployment

Cryostat mated to the glovebox for string installation
Loading of $^{enr}\text{Ge}$ in Cryostat 1

Loading of $^{enr}\text{Ge}$ in Cryostat 2
Passive Shielding and Muon Veto

Pb and outer Cu shield

Muon Veto Panels
Poly Shield
Pb Bricks
Radon Enclosure
Inner Cu Shield
Outer Cu Shield

Module deployment

Muon panels
Module 1 Data Set Duty Cycles

Break for Module 1 planned improvements

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<th>DS0 (days)</th>
<th>DS1 (days)</th>
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<tr>
<td></td>
<td>No inner shield</td>
<td>with inner shield</td>
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<table>
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<tr>
<th>Category</th>
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<th>DS1</th>
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<td>Calibration</td>
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<td>Down time</td>
<td>15.21</td>
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*Data taking ongoing
Delayed Charge Recovery and Alphas

- 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
  - Enables a powerful PSA rejection of alpha events
  - “Delayed Charge Recovery” parameter related to slope of tail

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 $\sim$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.
DS1: 500-2000 keV, $\beta\beta(2\nu)$

Data Set 1 spectrum after all cuts. Above ~1200 keV the spectrum is dominated by $\beta\beta(2\nu)$. Simulated rate using previously measured half-life (Eur. Phys. J. C 75 (2015) 416).
The Region of Interest 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.
Low Energy Spectrum in DS0

Controlled surface exposure of enriched material to minimize cosmogenics
Significant reduction of cosmogenics in the low-energy region.
- Factor of a few better in DS1.
- Enriched Detectors: ~0.04 cts/(kg-keV-d) near 20 keV
Efficiency below 5 keV is under study.

Permits Low-Energy physics

- Pseudoscalar dark matter
- Vector dark matter
- 14.4-keV solar axion
e- 3\nu
- Pauli Exclusion Principle
**MAJORANA DEMONSTRATOR Summary**

- Produced 35 (29.66 kg) of 88% enriched $^{76}\text{Ge}$ p-type point contact detectors.
- Attained highest yield to date (74.5%) of enriched $^{76}\text{Ge}$ 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. In-shield background measurements in 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 $^{76}\text{Ge}$ $0\nu\beta\beta$ 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.
- The low energy spectrum in DS0 is producing physics results.
- Predict $T_{1/2} = 1.2 \times 10^{26}$ y (90% Sensitivity) and $T_{1/2} = 1.2 \times 10^{26}$ y (3$\sigma$ Discovery)
  
  MJD 100 kg-year at 3.5 counts/ROI-t-y
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