Recent Results from the MAJORANA DEMONSTRATOR Neutrinoless Double-Beta Decay Experiment

Christopher Haufe
on behalf of the MAJORANA collaboration
30 July 2019
MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of $^{76}$Ge in HPGe detectors and additional physics beyond the standard model

**Source & Detector:** Array of p-type, point contact detectors
29.7 kg of 88% enriched $^{76}$Ge crystals, and 14.4 kg of 7.8% (natural) $^{76}$Ge crystals.

**Excellent Energy resolution:** 2.5 keV FWHM @ 2039 keV

**Low Background:** 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Operating underground at the 4850’ level of the Sanford Underground Research Facility

See “Search for neutrinoless double-beta decays in Ge-76 in the LEGEND Experiment”
Francesco Salamida - Thursday, 1 August @ 14:35 in room M4
Benefit of P-type Point-Contact (PPC) style detectors for background rejection:

- Slow drift time of the ionization charge cloud
- Localized weighting potential gives excellent multi-site rejection

Amplitude of current pulse is reduced for a multi-site event compared to a single-site event of the same event energy ($E_{\text{av}}$).
Runtime and Exposure

Open data: Jun. 2015 - Mar. 2017
9.95 kg-yr

All blind data: Jan. 2016 - Apr. 2018
New Open Data: Mar. 2017 - Apr. 2018
+16.1 kg-yr

April 2018 - Present*

Jun. 2015 - Module 1: 16.9 kg (20) $^{enr}\text{Ge}$
5.6 kg (9) $^{nat}\text{Ge}$

Aug. 2016 - Module 2: 12.9 kg (15) $^{enr}\text{Ge}$
8.8 kg (14) $^{nat}\text{Ge}$

2017 Release
9.95 kg-yr open data

2018 Release
26 kg-yr open+blind

PRL 120 132502 (2018)

Neutrino 2018
arXiv:1902.02299

*As of July 24, 2019
2018 0νββ Result

Operating in a low background regime and benefiting from excellent energy resolution

Initial Release:

PRL 120 132502 (2018)

Latest Release:

First unblinding of data
26 kg-yr of exposure

Neutrino 2018
arXiv:1902.02299

Median half-life sensitivity:

$4.8 \times 10^{25}$ yr

Full Exposure Limit:

$T_{1/2}^{0\nu} > 2.7 \times 10^{25}$ yr (90% CL)

Background index at 2039 keV in the lowest background configuration:

$11.9 \pm 2.0$ cts/(FWHM t yr)
360 keV Background Integration Window

Flat between 1950 keV and 2350 keV
Remove ±5 keV around $Q_{\beta\beta}$ and prominent $\gamma$ lines
Use counts in this window to estimate background level at $Q_{\beta\beta}$

<table>
<thead>
<tr>
<th>Hit Energy [keV]</th>
<th>1800</th>
<th>1900</th>
<th>2000</th>
<th>2100</th>
<th>2200</th>
<th>2300</th>
<th>2400</th>
<th>2500</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arb.</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Simulated Background near $Q_{\beta\beta}$ (no cuts)

Exclude:
- 2099 - 2109 keV
- 2113 - 2123 keV
- 2199 - 2209 keV
- 2034 - 2044 keV

$Q_{\beta\beta} = 2039$ keV

MAJORANA-1710.01
Background Model Development

Observed background of $11.9 \pm 2.0 \text{ c/(FWHM t y)}$ based on the 1950-2350 keV window

Initial assay measurements with early simulations predicted $<2.2 \text{ c/(FWHM t y)}$ at $Q_{\beta\beta}$

Reviewed available assay information and updating the assay-based model with as-built simulations, detector configurations, and updated physics lists

As-built simulations predict a value of $4.3 \text{ c/(FWHM t y)}$ at $Q_{\beta\beta}$ (spectrum below)

All cuts, components fixed to assay estimate

Developing a background model to fit the observed energy spectra
- MaGe/Geant4 simulations with the as-built geometry of experiment
- ~4000 parts, ~70 unique designs
- ~40 component groups of related parts
Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components. Based on the energy dependence of the peak intensities, a scaling of a distant component matches both the 239-keV and 2615-keV peak intensities from the $^{232}$Th chain. Distant $\approx$ Outside of the Ge-detector array.
Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components.

Based on the energy dependence of the peak intensities, a scaling of a nearby component scaled to the 239-keV peak underestimates the 2615-keV peak intensity from the $^{232}$Th chain.
Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional searches

Controlled surface exposure of enriched material to minimize cosmogenics

Excellent energy resolution: 0.4 keV FWHM at 10.4 keV

Ongoing effort on:
- low energy data cleaning, de-noising
- low energy cut development & efficiencies

Permits low-energy physics

pseudoscalar dark matter, vector dark matter, 14.4-keV solar axion, $e^- \to 3\nu$, Pauli Exclusion Principle

Low energy spectra during commissioning (blue) and first low-background physics running (red)

The 90% UL on the pseudoscalar axionlike particle dark matter coupling

PRL 118 161801 (2017)
Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional searches

First Limit on the direct detection of Lightly Ionizing Particles for Electric Charge as Low as $e/1000$

Candidate LIPs include noninteger-charged bound quarks, unbound quarks, and/or new leptons.

Sensitivity to $e/1000$ achieved via long path length through detectors and low thresholds.

Improvement on existing limits between $e/6$ and $e/200$

$f = \text{factor by which the elementary charge (e) is divided}$

The 90% UL on the Lightly Ionizing Particle flux with 1σ uncertainty bands Calculated through the Feldman-Cousins technique.
Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional searches

**Search for Tri-Nucleon Decay:**
A test of baryon number violation

*Calculated via Feldman-Cousins

<table>
<thead>
<tr>
<th>Decays:</th>
<th>Total Efficiency</th>
<th>Candidate Signals</th>
<th>90% Signal UL* (Counts)</th>
<th>Half-Life (10^{24} years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) - Invisible</td>
<td>0.26</td>
<td>1</td>
<td>4.36</td>
<td>7.5</td>
</tr>
<tr>
<td>(D) - Decay-Specific</td>
<td>0.923</td>
<td>0</td>
<td>2.44</td>
<td>47.0</td>
</tr>
<tr>
<td>76Ge(ppp) -&gt; 73Cu (I)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76Ge(ppp) -&gt; 73Cu + e^+ + π^+ + π^+ (D)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76Ge(ppn) -&gt; 73Zn + e^+ + π^+ (D)</td>
<td>0.958</td>
<td>0</td>
<td>2.44</td>
<td>48.7</td>
</tr>
</tbody>
</table>

Used data from June 2015 to April 2018. Exposure of 26 kg-yrs (Ge enriched detectors). Analyzed E-spectrum from 100 keV to 11MeV.

Sensitive to certain Ge tri- an di-nucleon decays, as daughter decay signatures above the 2vββ irreducible background (>2 MeV)
Summary and Outlook

**MAJORANA DEMONSTRATOR** construction complete, continuing to take data in its final configuration since Spring 2017

- Latest limit from 26 kg-yr exposure: \(>2.7 \times 10^{25}\) yr (90% C.L.); sensitivity \(4.8 \times 10^{25}\) yr (90% C.L.)
- Excellent energy resolution of 2.5 keV FWHM @ 2039 keV

**Background Model under development**

- Initial background fits are informing possible distribution of background sources
- Goal of a full background model consistent with the data - inform design of next generation experiments

**Optimization of analysis cuts underway to improve background rejection**

- New results and improved analysis reported later this year - stay tuned

Low background + low threshold + energy resolution allows for broad physics program

**Planning an upgrade to improve channel reliability and background**

- Expect to reach 50-70 kg-yr exposure with sensitivity in the range of \(10^{26}\) yr half-life before a shutdown for LEGEND-200 in late 2020

- Next Generation \(^{76}\)Ge: LEGEND is selecting the best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR

---

**References**

- arXiv:1902.02299
- PRL 118 161801 (2017)
- PRL 120 211804 (2018)
- PRD 99 07200 (2019)