Searching for Neutrinoless Double-Beta Decay with the MAJORANA DEMONSTRATOR

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on behalf of the MAJORANA collaboration
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Outline

• Introduction to neutrinoless double beta in $^{76}\text{Ge}$
• Experimental setup of the MAJORANA DEMONSTRATOR
• Background Modeling
• Implications for LEGEND
• Beyond the Standard Model searches
Neutrinoless Double Beta Decay (0νββ)

The signature of 0νββ is a model-independent probe of physics beyond the Standard Model.

Majorana neutrinos violate lepton conservation.

Credit: APS/Alan Stonebraker
Assuming $0\nu\beta\beta$ occurs via light neutrino exchange, the decay half life depends on the neutrino mass scale:

$$\left[ T_{1/2}^{0\nu} \right]^{-1} \propto m_{\beta\beta}^2$$

$$\langle m_{\beta\beta} \rangle = \left| \sum_k m_k U_{e,k}^2 \right|$$

Bayesian posterior distributions of $0\nu\beta\beta$ parameter space (assuming absence of mechanisms driving $m_{\beta\beta}$ or $m_l$ to 0)

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0νββ with Germanium Detectors

- **Intrinsic high-purity Ge** as both the source and detector
- Demonstrated ability to enrich from 7.4% $^{76}\text{Ge}$ to 88% (and beyond)
- Best energy resolution at the Q-value of all 0νββ experiments
- Powerful background rejection, leading to lowest achieved background index in the ROI of all 0νββ isotopes

If not background free,

\[
T^{0\nu}_{1/2} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}
\]
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
Mitigating Backgrounds

Potential sources of background include:

- Long-lived cosmogenics
- Naturally occurring radiation (alphas and gammas from $^{238}\text{U}$ and $^{232}\text{Th}$ decay chains)
- Neutrons
- $2\nu\beta\beta$

MAJORANA Background Reduction Techniques

- Underground lab space
- Passive shielding and active muon veto
- Radiopure near-detector components
- Analysis cuts due to PPC detector properties
Detector Modules and Shield

- 2 modules with independent electronics and cryogenics
- Active muon veto
- $N_2$ purged radon exclusion box
- Compact, graded shield
  - 30 cm polyethylene
  - 45 cm high-purity Pb
  - 5 cm commercial Cu
  - 5 cm underground electroformed copper (UGEFCu)
Radiopure Components

- Ultra-pure materials
  - Low mass design
  - Underground electroformed Cu
    - Th decay chain $\leq 0.1 \, \mu$Bq/kg
    - U decay chain $\leq 0.1 \, \mu$Bq/kg
  - Custom connectors and front-end electronics
  - Carefully selected plastics and pico-Coax cables
- Machining and cleaning in underground clean room
- Assembly and parts storage in $N_2$ purged environment
P-type Point Contact (PPC) Detectors

Benefit of PPCs for background rejection:

Pulse shape is highly dependent on position of energy deposit due to:

- **Slow drift time** of the ionization charge cloud
- Localized weighting potential—most of signal induced when charge carriers are very close to p⁺ contact
Multi-site Event Rejection

AvsE Cut: Amplitude of current pulse (A) is reduced for a multi-site event compared to a single-site event of the same event energy (E).

$^{228}$Th calibration data is used to tune AvsE cut and evaluate its efficiency.

PRC 99 065501 (2019)
Surface Alpha Rejection

Alpha background with degraded energies observed; charge trapped at passivated surface, slowly released into bulk

Implemented delayed charge recovery (DCR) cut based on slope of waveform tail
Energy Resolution

- **2.53 keV FWHM** at $0\nu\beta\beta$ Q-value—best of any $0\nu\beta\beta$ experiment
  - PPC design and location of first stage electronics near readout contact
  - Charge trapping and adc-nonlinearity corrections applied to filtered, pole-zero corrected waveforms

- **Weekly calibrations using $^{228}$Th line source**
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) $^{enr}$Ge
5.6 kg (9) $^{nat}$Ge

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

2017 Release
9.95 kg-yr open data
PRL 120 132502 (2018)

2018 Release
26 kg-yr open+blind
PRC 100 025501(2019)

*As of July 24, 2019
2018 $0\nu\beta\beta$ 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

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 $\pm$5 keV around $Q_{\beta\beta}$ and prominent $\gamma$ lines

Use counts in this window to estimate background level at $Q_{\beta\beta}$

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
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 $Q_{\beta\beta}$.

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

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
Background Model Development

Observed background of 11.9 +/- 2.0 c/(FWHM t y) based on the 1950-2350 keV window

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Developing a background model to fit the observed energy spectra
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- ~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,

Also consistent with the low rate of detector coincidences observed.

One observed coincidence between 583 and 2615 keV $^{208}$Tl-decay gammas.

Factor of 5-10 more expected for sources near detectors.

Identifying missing spectral components

Using coincidence studies to constrain spectral fits

No multisite cut, activities fit to background spectrum.
Significance for LEGEND

Next Generation $^{76}$Ge: LEGEND
Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay
(52 institutions, ~250 members)

The collaboration aims to develop a phased, $^{76}$Ge based double-beta decay experimental program with **discovery potential at a half-life beyond $10^{28}$ years.**

First phase:
- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c/(FWHM t y)
- start by 2021

Subsequent stages:
- 1000 kg (staged)
- BG: goal (x30 lower) <0.1 c/(FWHM t y)
- Location and start date: TBD

Select best technologies from existing experiments, such as MAJORANA and GERDA

- **GERDA**
  - Liquid argon veto
  - Water shield (no Pb)
  - Existing infrastructure

- **LEGEND**
  - Clean fabrication techniques
  - Controlled surface exposure
  - Development of new detectors

- **MAJORANA**
  - Radiopure components
  - Low noise electronics
  - Low energy thresholds
Beyond the Standard Model Searches

The DEMONSTRATOR’s low backgrounds and high resolution enable competitive BSM searches. For processes that require coincident events, backgrounds are even lower.

In addition, the low thresholds and controlled surface exposure of enriched Ge material to minimize cosmogenic backgrounds make a low energy program possible.

Publications

Bosonic dark matter and other keV-scale exotic physics

PRL 118 161801 (2017)

Lightly Ionizing Particles

PRL 120 211804 (2018)

Tri-Nucleon Decay

PRD 99 072004 (2019)
Search for anomalous peaks in the low energy spectrum allows limits to be set for keV-scale BSM physical processes, including

- pseudoscalar and vector dark matter couplings
- 14.4-keV solar axion coupling
- Pauli exclusion principle violating decay ($\text{e}^- \rightarrow 3\nu$)

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

Low energy spectra during commissioning (blue) and first low-background physics running (red)
Candidate LIPs include noninteger-charged bound quarks, unbound quarks, and/or new leptons.

Charge reduction factor: \( f = \frac{e}{q} \)

**Event Signature:**
- a high multiplicity, non-muon event, background-free with a good muon veto

Sensitivity to e/1000 achieved via long path length through detectors and low thresholds.
Observation of three-nucleon decays in $^{76}$Ge would be evidence of baryon number violation

**Event Signature:**
Time-delayed, single-detector events

Energy and time-coincidence cuts reduce the DEMONSTRATOR’s already low backgrounds

**Multiple decay modes considered, including:**

$^{76}$Ge(ppn) → $^{73}$Zn e+ $\pi^+$

$T_{1/2} > 4.9 \times 10^{25}$ yr (90% UL)

$^{76}$Ge(ppp) → $^{73}$Cu e+ $\pi^+\pi^+$

$T_{1/2} > 4.7 \times 10^{25}$ yr

“Invisible” $^{76}$Ge(ppp)

$T_{1/2} > 7.5 \times 10^{24}$ yr
**Summary and Outlook**

**MAJORANA Demonstrator** began taking data with first module in 2015 and has been operating with both modules since 2016

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 being investigated and refined

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

Improved analysis and additional data will yield new results

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

Planning an upgrade to cables and connectors as a part of LEGEND R&D

Expect to reach ~65 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**
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<thead>
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The MAJORANA Collaboration
Backup Slides
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
Background Model Development: An example

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.

Nearby $\approx$ Within of the Ge-detector array.
Blindness Implementation

Data is split for statistical blindness, analysis cuts developed on open data.
Each 31 hours of open data is followed by 93 hours of completely blind data.

Unblinding in phases to perform data quality and consistency checks.
(<100 keV and multiple-detector events remain blind for other studies)

Open up outside the 1950-2350 keV background integration region.

Open the background integration window and measure background index.

Open the $Q_{\beta\beta}$ region to set the $0\nu\beta\beta$ half-life limit.

Counts/(2.5 keV kg yr)

Energy [keV]

26 kg-yr
AvsE Acceptance
An interacting particle produces an energy deposition, generating a cloud of charge which is collected in the point of contact.

- **The ADC non-linearity** associated to the electronics can modify the energy value.
- They have to be corrected sample by sample.
- An external pulser is used to determine this correction.

**Low gain channel** (amplif: ~ 3 times)

**High gain channel** (amplif: ~ 10 times)

14 bit 100 MS/s digitizers

**A non-linearity** associated with this process appears.

![Diagram of Germanium Detector Waveforms](image)

- **Rising edge**
- **Falling edge**
- **Amplitude of waveform**: proportional to the charge
- **Integral Nonlinearity (ADC Count)**
- **Slope due to the decay constant of the capacitance of the system**
Energy Estimation

**DECAY CONSTANT DETERMINATION**

The energy is determined from the waveform using a trapezoidal filter

\[
\frac{1}{\tau} = \frac{1}{\tau_{PZ}} + \frac{1}{\tau_{CT}}
\]

- **PZ (Pole Zero):** Intrinsic correction due to the pre-amp (70 µs)
- **CT (Charge Trapping):** The detector impurities capture part of the charge before it is collected
- **τ** is varied to find the value which minimizes the FWHM in calibration data

**t₀ determination**
- Small trapezoidal filter
  - 1 µs rise time
  - 1.5 µs flat time

**Decay constant determination**
- Pole zero correction
- Charge trapping correction

**Baseline subtraction**

**Filtered waveform**
- Trapezoidal filter
  - 4 µs rise time
  - 2.5 µs flat time
- **Energy (ADC counts)**

Schemes of the two events with the same energy and different rise times after pole-zero correction

Schemes of the two events with the same energy and different rise times after pole-zero correction and charge trapping correction
Energy Calibration

- Periodic energy calibrations ($^{228}$Th)

- Initial calibration: zero energy & 2614 keV

- Flat background + Peak (gaussian, tail and step function)

- Second step: simultaneous fit and combined statistics (by dataset)

Simultaneous fit to eight peaks in the calibration spectrum

| Peaks (keV) | 238.6 | 241.0 | 277.4 | 300.1 | 583.2 | 727.3 | 860.6 | 2614 |

$FWHM(Q_{\beta\beta}) = 2.53 \pm 0.08\text{keV}$

$FWHM(E) = \sqrt{(\Gamma_n^2 + \Gamma_F^2 E + \Gamma_q^2 E^2)}$
After data cleaning (>99.9% eff.), multiplicity cut and muon veto

1950-2350 keV background integration window

Shaded region: Accepted events