Low Energy Rare Event Searches with the \textbf{MAJORANA DEMONSTRATOR}

Clint Wiseman
CENPA, University of Washington
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The **Majorana Demonstrator**

**Searching for neutrinoless double beta decay in $^{76}\text{Ge}$ and additional physics beyond the Standard Model**

- **Source == Detector:** 29.7 kg 88% enriched $^{76}\text{Ge}$ crystals
- **“PPC HPGe”:** P-type point contact high-purity germanium
- **Excellent energy resolution:** 2.5 keV FWHM @ 2039 keV
- **Low Backgrounds:** 2 modules, compact graded shield, active muon veto, and ultra-clean materials

- **Recent Publications:**
  - PRL 120 132502 (2018): 9.95 kg-yr exposure
  - PRC 100 025501 (2019): 26 kg-yr (unblinded)

**Operating at the Sanford Underground Research Facility**

![Image of the Majorana Demonstrator setup](image-url)

The **DEMONSTRATOR** has excellent energy resolution and extremely low backgrounds.

Many rare event searches are possible: bosonic dark matter, solar axions, etc!

Detectors are routinely operated at ~1 keV thresholds (using 5 keV threshold in this talk)

Background above tritium region (18 keV) is a factor ~4 lower after shield completion

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**The MAJORANA Low-Energy Program**

- **DS1–6A (open)**
  - Enriched: 11.17 kg-γ
  - Natural: 3.69 kg-γ
  - Background 20–40 keV:
    - ~0.01 cts/(kg-d)/keV

- **DS-0 (commissioning)**
  - Enriched: 478 kg-d, Natural: 195 kg-d
  - Background 20–40 keV:
    - ~0.04 cts / (kg-d keV)

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**Observations:**

- enrGe shows much lower tritium (limited surface exposure)
- 46 keV feature from $^{210}$Pb (not previously visible)
Fractionally charged particles \( f = \frac{e}{a} \) could transit the array and light up a whole string of detectors

**Event Signature:** a whole-string, non-muon event

With 1 keV trigger thresholds + multiplicity cuts, we reached limits of \( e/1000 \)

**Published:** PRL 120, 211804 (2018)
First results from MAJORANA used 478 kg-d of commissioning data (PRL 118, 161801 (2017))

Energy resolution:
0.4 keV FWHM at 10.4 keV

Rare event searches:
- Bosonic dark matter, solar axions,
- electron decay (e⁻ → 3ν)
- Pauli exclusion principle violation

Ongoing efforts:
- Data denoising, pulse shape analysis,
- Efficiency (acceptance) of analysis cuts

The current DS1—6A analysis is almost a factor 10 more enriched exposure (4080 kg-d, enrGe) and a factor 6.9 more natural exposure (1347 / 195). Unblinding will give ~20 kg-y more.
Energy-degraded events from near the n+ surface are a challenging background for low-energy rare event searches with PPC HPGe detectors (CoGeNT, MAJORANA, CDEX, TEXONO, MALBEK, …)

Charges slowly diffuse through the Ge/Li layer, and some make it to the bulk region after a delay, producing pulses with a measurably slower rise time

(Degradation at the passivated surface is also possible)
We need a slow pulse estimator that works at the lowest S/N regions in the data.

We choose a heuristic function (exponentially modified Gaussian) and fit to each waveform.

\( \mu \): center of rising edge, \( \tau \): exponential (RC) decay, 
\( \sigma \): slope of rising edge (slowness!)

\[
xG(t) = \frac{A}{2\tau} \exp\left(\frac{t-\mu}{\tau} + \frac{\sigma^2}{2\tau^2}\right) \operatorname{erfc}\left(\frac{1}{\sqrt{2}} \left( \frac{\sigma}{\tau} - \frac{t-\mu}{\sigma} \right) \right) + B
\]

Waveform fit “slowness” (\( \sigma \)):
Sensitive to fast, slow, and electronics noise. Distinction between fast and slow gets harder at lower energies … need a training set!

The fast pulse acceptance efficiency can be evaluated with high-multiplicity \(^{228}\text{Th}\) calibration data to 1 keV

Note: even for asymmetric signals, \( \sigma \) is still correlated with slowness of a pulse
Many hit patterns possible with the ~50 detectors in the DEMONSTRATOR

The 238 keV gamma from $^{212}$Pb is not emitted in coincidence with others.

Let’s look at $m=2$, sumE=238 keV events …
Isolating a Fast Event Population

Multiplicity-2, sum-energy 238 keV events:

- Must be **minimally energy degraded**
- 238 keV peak is well above the background
- Estimate slow fraction as entire bkg under peak: 1.85% events, 3.7% of the hits
- **Saving hits w/ sumET=238 isolates a mostly fast event population to train cuts on**

\[ E' = \frac{E}{1 + \frac{E}{m_ec^2} \left(1 - \cos\theta\right)} \]

Mean free path of a 238 keV gamma: **14.7 mm**
Avg. HPGe detector radius: **30 mm**
Typical n+ degraded region: **1-2 mm**

*Most 238 keV γ's deposit energy in bulk*
Determining the Slow Pulse Cut

Each detector has a different number of m2s238 events, relative to the calibration track. We need to combine ALL calibration data (> 600 hrs!) to obtain enough events.
Each detector contributes to the total efficiency proportional to its exposure $X_i$:

$$F(E) = \frac{1}{X_T} \sum_i^{N_D} \left( \sum_j^{N_B} X_{ij} \, \text{erf}(E, \mu_{ij}, \sigma_{ij}) \right) \frac{A_i}{B_i}$$

- Total Exposure
- Exposure $\times$
- Trigger eff.

**Single-detector efficiency uncertainty**, calculated by Toy Monte Carlo (Poisson-varying each bin and re-fitting)

**Preliminary**

**Efficiency, (single) detector**
- m2s238 Hits
- Pass
- Fail
- 1.0 keV

**Efficiency, final for all detectors**
- Weighted eff.
- Weibull centroid
- Weibull upper
- Weibull lower
- 1 keV
- m2s238 eff, det 262

**Counts/1.0 keV**
Energy Spectrum Before & After Cuts

We reduce noise and slow pulse backgrounds by a factor $10^4$ at 5 keV, with known efficiency!

After threshold and basic cuts, slow pulses are the primary background. (blue curve)

Spectral lines are much more clear after application of the slow pulse cut. (red curve)

Shown here: $^{enr}$Ge + $^{nat}$Ge spectrum
Energy Spectrum and Background Model

We fit our spectrum to a background model: a combination of spectral lines (~Gaussian) and continuum shapes (tritium, linear term), using an unbinned max. likelihood fit (RooFit).

Peak widths are given by an exposure-weighted energy resolution (right).

Preliminary uncertainty in the resolution in the 5—100 keV region is about 30%

Rare event signals (e.g. bosonic dark matter) can now be included as a component of the model
With our factor ~10 increased exposure, known cut efficiencies, and resolution uncertainty, we include a Gaussian “rare event” signal peak, and compute the upper limit (90% CL):

\[
N_{\text{exp}} = M T \Phi \sigma
\]

\[
\Phi'_{\text{DM}}(E, m_a) = (7.8 \times 10^{-17}) \frac{\beta}{m_a}
\]

\[
|g_{ae}| \leq \left( \frac{N_{UL}}{MT \left( \frac{7.8 \times 10^{-17}}{m_a} \right) \sigma_{ae}(m_a)} \right)^{1/2}
\]
We can also update our 2017 limit on solar axions from nuclear transitions, by searching for a peak at 14.4 keV (the M1 transition energy of $^{57}$Fe)

$$\Phi_a(14.4 \text{ keV}) = \beta^3 (g_{an}^{\text{eff}})^2 \times 4.56 \times 10^{23}$$

$$|g_{ae} g_{aN}^{\text{eff}}| \leq \left( \frac{N_{UL}}{MT (4.56 \times 10^{23}) \beta^3 \sigma_{ae}(m_a)} \right)^{1/2}$$
Conclusions and Outlook

In this analysis, we have:

- Set competitive limits on bosonic dark matter and solar axions, with 11.17 kg-y exposure
- Nearly a factor 10 more enriched exposure than the 2017 MAJORANA analysis
- Implemented a new slow pulse parameter from a waveform fit (works to 1 keV)
- New slow pulse efficiency determination (works to 1 keV)

Next steps: improve $^{210}$Pb PDF (simulations) before unblinding
The MAJORANA Collaboration

Black Hills State University, Spearfish, SD:
Kara Keeter

Duke University, Durham, NC, and TUNL:
Matthew Busch

Joint Institute for Nuclear Research, Dubna, Russia:
Viktor Brudanin, M. Shirchenko, Sergey Vasilyev, E. Yakushev, I. Zhitnikov

Lawrence Berkeley National Laboratory, Berkeley, CA:
Yuen-Dat Chan, Alexey Drobizhev, Jordan Myslik, Alan Poon

Los Alamos National Laboratory, Los Alamos, NM:
Pinghan Chu, Steven Elliott, In Wook Kim, Ralph Massarczyk, Samuel J. Meijer, Keith Rielage, Brandon White, Brian Zhu

Massachusetts Institute of Technology, Cambridge, MA:
Julieta Gruszko

National Research Center ‘Kurchatov Institute’ Institute of Theoretical and Experimental Physics, Moscow, Russia:
Alexander Barabash, Sergey Konovalov, Vladimir Yumatov

North Carolina State University, Raleigh, NC and TUNL:
Matthew P. Green, Ethan Blalock, Rushabh Gala

Oak Ridge National Laboratory, Oak Ridge, TN:
Fred Bertrand, Vincente Giuseppe, Charlie Havenier, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan:
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, WA:
Isaac Arnquist, Eric Hoppe, Richard T. Kouzes

Princeton University, Princeton, NJ:
Graham K. Giovanetti

Queen's University, Kingston, Canada:
Ryan Martin, Alex Piliounis, Vasundhara

South Dakota School of Mines and Technology, Rapid City, SD:
Cabot-Ann Christoferson, Brandon DeVries, Abigail Otten, Tyler Ryther, Jared Thompson

Tennessee Tech University, Cookeville, TN:
Mary Kidd

Technische Universität München, and Max Planck Institute, Munich, Germany:
Tobias Bode, Susanne Mertens

University of North Carolina, Chapel Hill, NC, and TUNL:
Brady Bos, Thomas Caldwell, Morgan Clark, Aaron Engelhardt, Ian Guinn, Chris Haufe, Reyco Henning, David Hervas, Eric Martin, Gulden Othman, Anna Reine, John F. Wilkerson

University of South Carolina, Columbia, SC:
Frank Avignone, David Edwins, David Tedeschi

University of South Dakota, Vermillion, SD:
C. J. Barton, Jose Mariano Lopez-Castano, Tupendra Kumar Oli, Wenqin Xu

University of Tennessee, Knoxville, TN:
Yuri Efremenko, Andrew Lopez

University of Washington, Seattle, WA:
Clara Cuesta, Jason Detwiler, Alexandru Hostiuc, Walter Pettus, Nick Ruof, Clint Wiseman

*students