Spectral analysis for the MAJORANA DEMONSTRATOR 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.

- Operating 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) Assay U.L. currently ≤ 3.5

- 44.1-kg of Ge detectors
  - 29.7 kg of 87% enriched $^{76}$Ge crystals
  - 14.4 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 data sets

<table>
<thead>
<tr>
<th></th>
<th>DS0 (days)</th>
<th>DS1 (days)</th>
<th>DS2 (days)</th>
<th>DS3 (days)</th>
<th>DS4 (days)</th>
<th>DS5 (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Module 1</td>
<td>Module 1</td>
<td>Module 1</td>
<td>Module 1</td>
<td>Module 2</td>
<td>Module 1 &amp; 2</td>
</tr>
<tr>
<td>Total</td>
<td>103.15</td>
<td>144.50</td>
<td>50.97</td>
<td>32.37</td>
<td>32.36</td>
<td>147.68</td>
</tr>
<tr>
<td>Total acquired</td>
<td>87.93</td>
<td>136.98</td>
<td>50.47</td>
<td>31.73</td>
<td>25.80</td>
<td>137.42</td>
</tr>
<tr>
<td>Physics</td>
<td>47.70</td>
<td>61.34 + 20.41*</td>
<td>9.82 + 30.56*</td>
<td>29.91</td>
<td>23.69</td>
<td>119.38</td>
</tr>
<tr>
<td>High radon</td>
<td>11.76</td>
<td>7.32</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Disruptive Activities</td>
<td>13.10</td>
<td>34.43 + 5.92*</td>
<td>2.41 + 7.03*</td>
<td>0.63</td>
<td>0.93</td>
<td>15.68</td>
</tr>
<tr>
<td>Calibration</td>
<td>15.44</td>
<td>7.32</td>
<td>0.65</td>
<td>1.18</td>
<td>1.17</td>
<td>2.36</td>
</tr>
<tr>
<td>Down time</td>
<td>15.21</td>
<td>7.51</td>
<td>0.50</td>
<td>0.64</td>
<td>6.56</td>
<td>10.25</td>
</tr>
</tbody>
</table>

*Values thru 03/10/17

Currently taking blind data in DS6 with multi-sampling
Physics searches with (enriched) Ge-detectors

around 2039 keV

Data Set 3 + 4
1.39 kg-y

after Delayed Charge Recovery α-cut:
1 event in 400 keV window
→ BI = 1.8 \times 10^{-3} \text{ cnts / (keV\cdot kg\cdot y)}
Statistical methods for $0\nu\beta\beta$-search

variety of statistical methods used to search for a signal:

**Frequentist**

- **Feldman-Cousins** \textit{MJD, Neutrino 2016}
  
eliminates flip-flop problem (exclusion vs. discovery)
  
possible significant over-coverage

- **profile likelihood**
  
systematic uncertainties & constraints taken into account
  
simultaneous treatment of multiple datasets
  
large-sample case: Wilks’ theorem \textit{EXO200, Nature 2014}
  
small sample case (~10 events): Monte Carlo toy data \textit{GERDA, Nature 2017}
  
also as modified (“CLs”) method against down-fluctuations of background \textit{NEMO-3, PRD 2016}

**Bayesian**

different definition of probability \textit{CUORE0, PRL 2015}

needs prior for unknown parameters
Minimal signal + background likelihood model

- likelihood function for each dataset (based on GERDA, Nature 2017)

\[
\mathcal{L}(D|S, BI, \theta) = \prod_{n=1}^{N_{\text{obs}}} \frac{1}{\mu^S_n + \mu^B_n} \cdot \left[ \mu^S_n \cdot \frac{1}{\sqrt{2\pi}\sigma} \exp \left( \frac{-(E_n - Q_{\beta\beta} - \delta)^2}{2\sigma^2} \right) + \mu^B_n \cdot \frac{1}{\Delta E} \right]
\]

- Gaussian signal
- flat background

signal rate: \( \mu^S = \ln 2 \cdot (N_A/m_a) \cdot \epsilon \cdot \mathcal{E} \cdot S \) where \( S = (T_{1/2})^{-1} \)

bkg-rate: \( \mu^B = \mathcal{E} \cdot BI \cdot \Delta E \)

constrained nuisance parameter: \( \theta = \{\epsilon, \sigma, \delta\} \)

- simultaneous fit of multiple datasets \( i \)

\[
\mathcal{L}(D|S, BI, \theta_i) = \prod_i \left[ \frac{e^{-(\mu^S_i + \mu^B_i)} \cdot (\mu^S_i + \mu^B_i)^{N_{\text{obs}}^i}}{N_{\text{obs}}^i!} \cdot \mathcal{L}_i(D_i|S, BI_i, \theta_i) \right]
\]
Validation of analysis code with GERDA data

Goal: testing of statistical analysis code (based on RooStats \textit{arXiv:1009.1003}) with well studied data from \textit{GERDA, Nature 2017}

\begin{itemize}
\item Published data
\item Published model parameters
\end{itemize}

\begin{table}
\caption{List of data sets, exposures (for total mass), energy resolutions in FWHM, efficiencies (including enrichment, active mass, reconstruction efficiencies and dead times) and background indices (BI) in the analysis window.}
\begin{tabular}{lllll}
\hline
\text{data set} & \text{exposure} & \text{FWHM} & \text{efficiency} & \text{BI} \\
& [kg\text{yr}] & [keV] & & $10^{-3}$cts/(keV kg yr) \\
\hline
PI golden & 17.9 & 4.3(1) & 0.57(3) & 11 \pm 2 \\
PI silver & 1.3 & 4.3(1) & 0.57(3) & 30 \pm 10 \\
PI BEGe & 2.4 & 2.7(2) & 0.66(2) & $5^{+4}_{-3}$ \\
PI extra & 1.9 & 4.2(2) & 0.58(4) & $5^{+4}_{-3}$ \\
PIIa coaxial & 5.0 & 4.0(2) & 0.53(5) & $3.5^{+2}_{-1.5}$ \\
PIIa BEGe & 5.8 & 3.0(2) & 0.60(2) & $0.7^{+1}_{-0.5}$ \\
\hline
\end{tabular}
\end{table}

→ reconstruction of 6 unbinned datasets

nearly full reconstruction of likelihood model
Deriving upper limits using hypothesis tests

- hypothesis tests performed for a assumed signal strength $S_j$
- two-sided test statistic $t_{sj}$ is based on Profile Likelihood Ratio
- generated MC toy datasets:
  100,000 $S_j$ + Background
  20,000 B-only
- p-value of test statistic observed data: $p_{S_j} = 0.10$
- p-value of B-only distribution median: $p_{B-only} = 0.34$

$S_j = 0.19 \left(T_{1/2} = 5.2 \cdot 10^{25} \text{ y}\right)$

\[
p_{S_j} = \int_{t_{obs}}^{\infty} f(t_S|S_j) \, dt_S
\]
Test: Reproduction of GERDA $0\nu\beta\beta$ exclusion limit

- hypothesis test performed for increasing values of $S_j$
- observed limit at 90% C.L. when:
  \[ p'_{S_j} \leq 0.1 \]

- w/ actual GERDA data
- but w/o all correlation terms:
  RooStats code reproduces official limits to ~ 2% accuracy ✔

<table>
<thead>
<tr>
<th>analysis</th>
<th>$\mu_S$ (counts)</th>
<th>$T_{1/2}$ ($10^{25}$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>official</td>
<td>2.0</td>
<td>5.3 (4.0)</td>
</tr>
<tr>
<td>reproduced</td>
<td>$2.10\pm0.01$ (2.77)</td>
<td>$5.19\pm0.03$ (3.94)</td>
</tr>
</tbody>
</table>

- test statistics in limit cases
  (e.g. test statistic of empty toy data sets?)
Application to MAJORANA toy data set

- efforts have been undertaken to optimize selection of physics data from DS0 to DS5 (improved cuts & data quality selection → poster J. Myslik)

- results based on this data: ongoing process of internal collaboration review
to demonstrate method:

single B-only toy data set with based on DS3+4 background index & typical parameter values

<table>
<thead>
<tr>
<th>model parameter</th>
<th>model value</th>
</tr>
</thead>
<tbody>
<tr>
<td>background index $BI$ (cnts/(kg·y·keV))</td>
<td>$1.8 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>exposure (kg·y)</td>
<td>$10 \pm 2%$</td>
</tr>
<tr>
<td>FWHM ($\rightarrow \sigma$)</td>
<td>$2.35 \pm 1%$</td>
</tr>
<tr>
<td>efficiency $\varepsilon$</td>
<td>$0.59 \pm 10%$</td>
</tr>
<tr>
<td>E-shift $\delta$ (keV)</td>
<td>$0 \pm 0.2$</td>
</tr>
</tbody>
</table>
Exclusion limit and sensitivity from toy data set

- **B-only** toy dataset
  - no fitted signal
  - all nuisance parameters at expected values
- Median sensitivity: \( T_{1/2} > 1.8 \cdot 10^{25} \) yr
- (standard) profile likelihood method: significantly stricter limits than Feldman-Cousins

<table>
<thead>
<tr>
<th>method</th>
<th>( \mu_S ) (counts)</th>
<th>( T_{1/2} ) (10^{25} yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>1.79 (1.8)</td>
<td>1.81 (1.8)</td>
</tr>
<tr>
<td>CLs</td>
<td>2.54 (2.5)</td>
<td>1.28 (1.3)</td>
</tr>
</tbody>
</table>
Conclusion & Outlook

● analysis of $0\nu\beta\beta$-search with non-blinded data from DS0–5 is nearing completion
● data taking with full shielding and both cryostat modules ongoing
● additional blinded data available and blinding scheme in effect for all new data