Recent results from the MAJORANA DEMONSTRATOR

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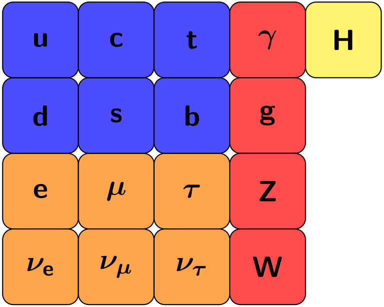
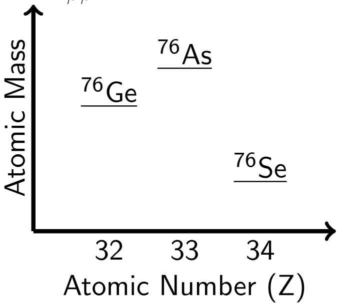
How do you solve a problem like neutrino mass?

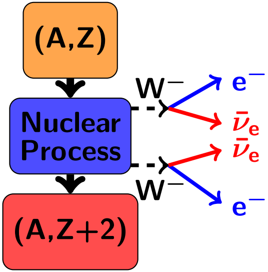
- Neutrinos are massless in the Standard Model.
  - Neutrino oscillation measurements show that neutrinos do in fact have mass.
- To generate neutrino masses, require some Beyond the Standard Model physics.
- In his 1937 publication, Ettore Majorana laid the theoretical groundwork for massive fermions to be their own antiparticles.
  - Majorana mass term mixes ν and $\bar{\nu}$.
  - Violates lepton number conservation.



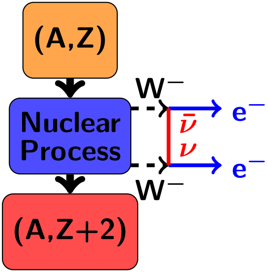
- Theoretically appealing, and has observable consequences that can be probed.

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





- $2\nu\beta\beta$-decay.



- $0\nu\beta\beta$-decay, "vanilla model".

- For some nuclei, beta decay is energetically forbidden.
- Instead, decay from nucleus of Z to one of Z+2 (with lower mass).
- $2\nu\beta\beta$-decay: SM allowed, observed to occur. (e.g. ^{76}Ge, ^{130}Te, ^{136}Xe)

$$^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^- + 2\bar{\nu}_e$$

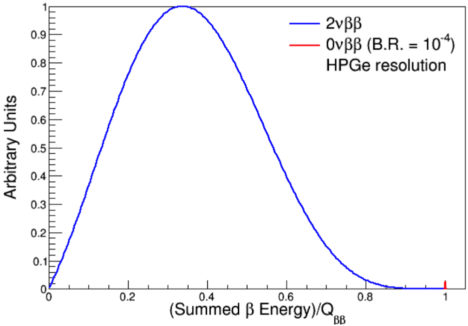
L: 0 0 2 -2

- $0\nu\beta\beta$-decay: If it occurs, does not conserve lepton number.

$$^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-$$

L: 0 0 2

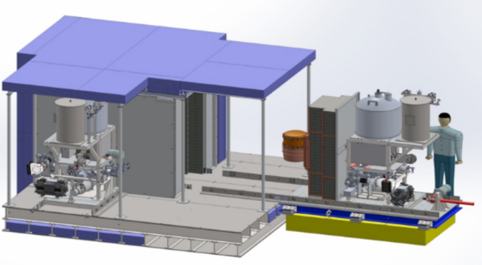
- $2\nu\beta\beta$-decay: Continuum of the sum of the electron energies. **Irreducible background.**
- $0\nu\beta\beta$-decay: Electron energies sum to Q-value of decay.
- Requires good energy resolution to separate them.



Half life (years)	~Signal (cnts/ton-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1
$>10^{29}$	0.05

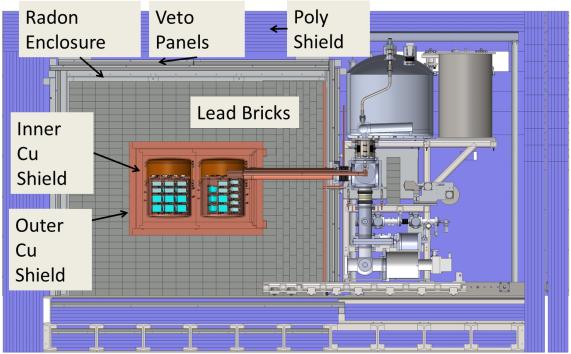
- Search in "Region of Interest" (ROI) around Q, defined by energy resolution.
- For ^{76}Ge ($Q = 2039$ keV):
  - $T^{2\nu}_{1/2} \sim 10^{20}$ y $\rightarrow$ Rare process.
  - $T^{0\nu}_{1/2} > 10^{26}$ y $\rightarrow$ Need low background and large mass, counting time.

- The main physics purpose is the search for lepton number violation via neutrinoless double-beta decay.
- The MAJORANA DEMONSTRATOR has 3 design goals:
  - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
  - Establish feasibility to construct and field modular arrays of Ge detectors.
  - Search for additional physics beyond the Standard Model.
- Background goal in the $0\nu\beta\beta$ peak ROI (4 keV at 2039 keV) 3 counts/ROI/t/y. (Upper limit from assays currently $\leq$ 3.5).



Majorana Demonstrator Overview

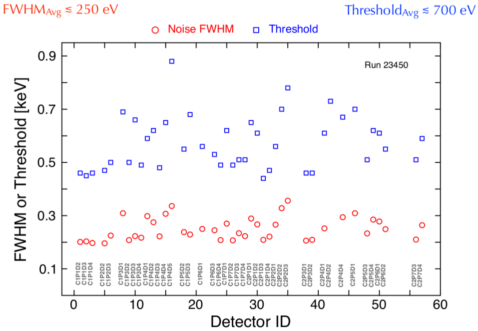
- Operating on the 4850' level (4300 mwe) of the Sanford Underground Research Facility in Lead, South Dakota.



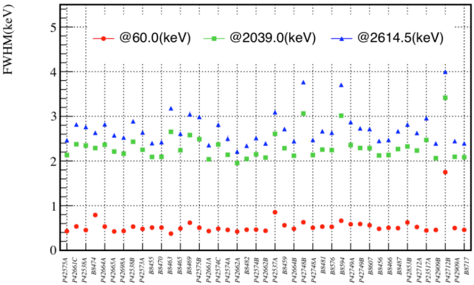
- Polyethylene shield against neutrons.
- Active muon veto.
- Sealed and N_2 purged against radon.
- Outer Pb shield and Cu shields (inner electroformed, outer OFHC) against γ.
- 2 cryostat modules, each containing 7 strings of 3 to 5 p-type Point Contact (PPC) High Purity Germanium (HPGe) crystal detectors.
- 29.7 kg of 88% enriched ^{76}Ge crystals, 14.4 kg natural Ge crystals (44.1 kg total).

Detector Performance

- Low noise.
- Sub-keV energy thresholds.

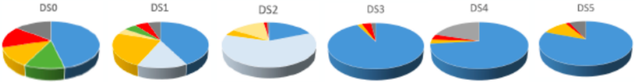


- Best energy resolution of any operating $0\nu\beta\beta$ experiment (2.4 keV FWHM at 2039 keV).



- Low thresholds, low noise, and excellent energy resolution enable a rich physics program, both for double-beta decay and Beyond the Standard Model searches at low energies.

Data Collected



M1 Commissioning, no inner shield	*M1 inner shield*	*M1 Multi-sampling*	*Modules 1 and 2 Together in-shield*	*Module 1 & 2 Integrated DAQ*

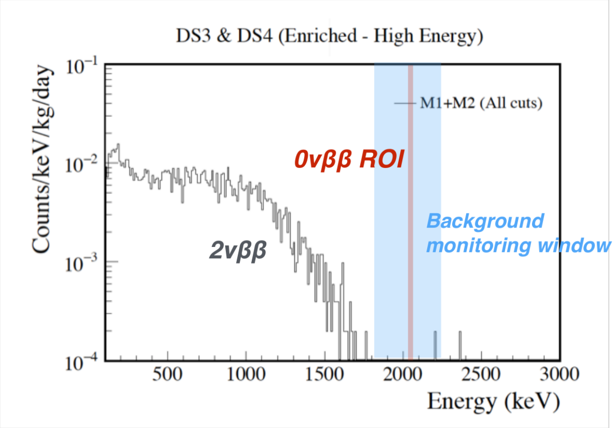
	DS0 (days) Module 1 June 26, – Oct. 7, 2015	DS1 (days) Module 1 Dec. 31, 2015 – May 24, 2016	DS2 (days) Module 1 May 24 – July 14, 2016	DS3 (days) Module 1 Aug. 25, – Sept. 27, 2016	DS4 (days) Module 2 Aug. 25, – Sept. 27, 2016	DS5 (days) Module 1 & 2 Oct. 13, 2016 – May 11, 2017*
Total	103.15	144.50	50.97	32.37	32.36	147.68
Total acquired	87.93	136.98	50.47	31.73	25.80	137.42
Physics *	47.70	61.34 + 20.41*	9.82 + 30.56*	29.91	23.69	119.38
High radon	11.76	7.32	-	-	-	-
Disruptive Activities *	13.10	34.43+ 5.92*	2.41 + 7.03*	0.63	0.93	15.68
Calibration	15.44	7.32	0.65	1.18	1.17	2.36
Down time	15.21	7.51	0.50	0.64	6.56	10.25

*Values thru 03/10/17

- DS3 and DS4 released in March 2017. $0\nu\beta\beta$-decay analysis of DS0-5 ($\sim$ 7 times the open exposure) currently underway.
- Currently taking blind data in DS6, with multi-sampling.

Backgrounds near ROI (DS3 and DS4)

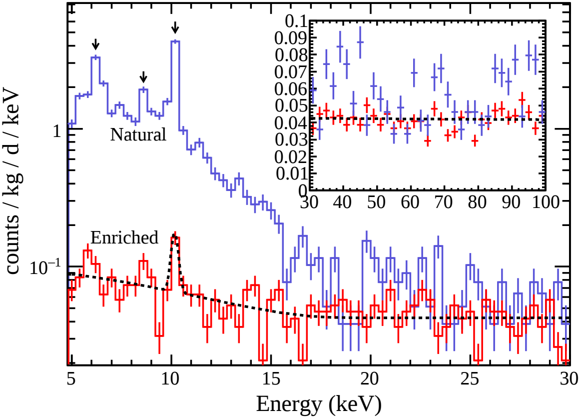
- M1 and M2 running simultaneously in shield, so realistic representation of final background.
- 1.39 kg·y exposure of enriched detectors.
- 1 background event in 400 keV window.
- DS3 (M1) ROI: 2.9 keV
- DS4 (M2) ROI: 2.6 keV



- **Background rate:** $5.1^{+8.9}_{-3.2}$ counts/(ROI·t·y) (68% CL).
- **Background index:** $1.8^{+3.1}_{-1.1} \times 10^{-3}$ counts/(keV·kg·y).
  - Better than all other currently-running $0\nu\beta\beta$-decay experiments, except GERDA-II (also ^{76}Ge) (but consistent with them and goal).

Measured Low Energy Spectrum (DS0)

- **Natural:** 195 kg·d.
- **Enriched:** 478 kg·d.
- Extreme care taken to limit cosmic ray exposure for enriched detectors.
- Resulting very low backgrounds at low energies opens up low energy Beyond the Standard Model physics searches.
- DS0 enriched low energy spectrum analyzed in the following searches.



- ^{3}H spectrum ($Q = 18.6$ keV), ^{68}Ge: 10.36 keV, ^{65}Zn: 8.9 keV, ^{55}Fe: 6.5 keV.

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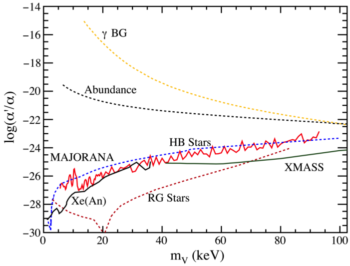
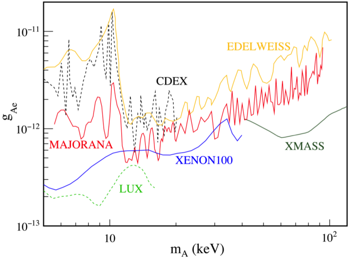
Low Energy Spectrum: Bosonic Dark Matter

- Compelling astronomical evidence for dark matter, but so far no direct observation.
- Focus of searches has been on WIMPs ($\mathcal{O}$(GeV)), but there are other models available, including larger densities of keV-scale bosonic dark matter.
- Both vector dark matter (top) and pseudoscalar (axion-like, bottom) dark matter interactions would produce a peak at their mass.
- **Future**: More exposure and more advanced analysis techniques improve sensitivity.





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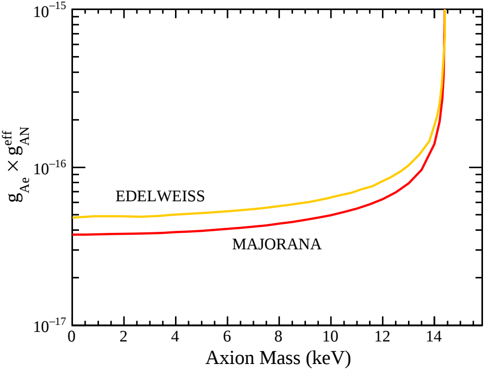
Low Energy Spectrum: Solar Axions

- The axion is a light dark matter candidate, introduced to explain the Strong CP Problem.
- In the sun, ^{57}Fe is abundant, and can be thermally excited into its first nuclear excited state (14.4 keV).
  - An axion can be emitted in the decay from this excited state.
  - Coupling to electrons in the detector would produce a 14.4 keV peak.



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- The flux (and therefore combined coupling) depends on the axion mass, ranging from 0 to 14.4 keV.
- **Future:** Search for other possible axion signals:
  - Characteristic solar axion spectrum below 15 keV.

    e.g. Javier Redondo JCAP12(2013)008
  - Primakoff conversion in Ge crystals (axion-photon coupling.)

    e.g. Phys.Lett. B427 (1998) 235-240

Next Generation ^{76}Ge: LEGEND

Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless $\beta\beta$ **D**ecay

Mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results."

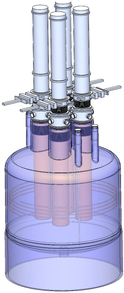
Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First phase:

- (Up to) 200 kg.
- Modification of existing GERDA infrastructure at LNGS.
- BG goal ($\times$5 lower) 0.6 c/(FWHM·t·y)
- Start by 2021.

Subsequent stages:

- 1000 kg (staged).
- Timeline connected to U.S. DOE down select process.
- BG goal ($\times$30 lower) 0.1 c/(FWHM·t·y)
- Location: TBD.
- Required depth (Ge-77m) under investigation.



Conclusions

- The lepton-number-violating process of neutrinoless double-beta decay is a topic of great theoretical and experimental interest.
- The MAJORANA DEMONSTRATOR seeks to probe this process, while demonstrating the backgrounds and feasibility necessary for a more sensitive tonne-scale experiment.
  - The MAJORANA DEMONSTRATOR has the best energy resolution of any operating $0\nu\beta\beta$ experiment (2.4 keV FWHM at 2039 keV).
- While accumulating data for this measurement, other beyond the Standard Model physics has also been probed.
- ^{76}Ge detector arrays have demonstrated the lowest backgrounds and best energy resolution of all the future tonne-scale experiment technologies. Planning for a tonne-scale experiment (LEGEND) is currently underway.
  - LEGEND would have $0\nu\beta\beta$-decay discovery potential at a half-life significantly longer than 10^{27} years.

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