The MAJORANA DEMONSTRATOR search for neutrinoless double beta decay

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The MAJORANA Collaboration is constructing the MAJORANA DEMONSTRATOR, an ultra-low background, modular, HPGe detector array with a mass of 44.8-kg (29.7 kg enriched $\geq$88% in ^{76}Ge) to search for neutrinoless double beta decay in ^{76}Ge. The next generation of tonne-scale Ge-based neutrinoless double beta decay searches will probe the neutrino mass scale in the inverted-hierarchy region. The MAJORANA DEMONSTRATOR is envisioned to demonstrate a path forward to achieve a background rate at or below 1 count/tonne/year in the 4 keV region of interest around the Q-value of 2039 keV. The MAJORANA DEMONSTRATOR follows a modular implementation to be easily scalable to the next generation experiment. First data taken with the DEMONSTRATOR are introduced here.

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1. Introduction

In a number of even-even nuclei, β decay is energetically forbidden, but the second order weak process of 2ν double beta decay is allowed, as first proposed by Goeppert-Mayer in 1935 [1]. If the neutrino is a Majorana particle, neutrinoless double beta ($0\nu\beta\beta$) decay could also occur via the exchange of a light Majorana neutrino, or by other mechanisms [2, 3]. This decay violates lepton number and provides a model-independent test of the nature of the neutrino. The rate of $0\nu\beta\beta$-decay via light Majorana neutrino exchange is given by

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2 \tag{1.1}$$

where $G^{0\nu}$ is a phase space factor, $M_{0\nu}$ is a nuclear matrix element, and m_e is the electron mass. $\langle m_{\beta\beta}\rangle$ is the effective Majorana neutrino mass of the exchanged neutrino. The latter is given by $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$, where U_{ei} specifies the admixture of neutrino mass eigenstate i in the electron neutrino. Because $\langle m_{\beta\beta}\rangle$ depends on the oscillation parameters, both the overall neutrino mass and the mass hierarchy can impact the observed rate. Provided the nuclear matrix elements are well evaluated, $0\nu\beta\beta$-decay experiments could establish an absolute scale for the neutrino mass.

Experimentally, $0\nu\beta\beta$-decay can be detected by searching the spectrum of the summed energy of the emitted betas for a monoenergetic line at the Q-value of the decay ($Q_{\beta\beta}$). Recent sensitive searches for $0\nu\beta\beta$ carried out in ^{76}Ge (GERDA [4, 5]), ^{136}Xe (KamLAND-Zen [6, 7] and EXO-200 [8, 9]), ^{130}Te (CUORE-0 [10]), among others, set limits on the decay half-life.

2. Overview of the MAJORANA DEMONSTRATOR

The MAJORANA DEMONSTRATOR [11] is an array of enriched and natural germanium detectors that will search for the $0\nu\beta\beta$-decay of ^{76}Ge. The specific goals of the MAJORANA DEMONSTRATOR are several: to demonstrate a path forward to achieving a background rate at or below 1 count/(ROI-t-y) in the 4 keV region of interest (ROI) around the 2039 keV $Q_{\beta\beta}$ of the ^{76}Ge $00\nu\beta\beta$-decay when scaled up to a tonne scale experiment; show technical and engineering scalability toward a tonne-scale instrument; and perform searches for other physics beyond the Standard Model, such as dark matter and axions.

The experiment is composed of 44.8 kg of high-purity Ge (HPGe) detectors which also act as the source of ^{76}Ge $0\nu\beta\beta$-decay. The benefits of HPGe detectors are that Ge is an intrinsically low-background source material, with understood enrichment chemistry, excellent energy resolution, and event reconstruction capabilities. P-type point contact detectors [12, 13] were chosen after extensive R&D by the collaboration for their powerful background rejection capabilities. The DEMONSTRATOR consists of a mixture of HPGe detectors including, 29.7 kg built from Ge material that is enriched to $\geq 88\%$ in ^{76}Ge and 15.1 kg fabricated from natural Ge (7.8% ^{76}Ge). The average mass of the enriched detectors is $\sim$850 g.

A modular instrument composed of two cryostats built from ultra-pure electroformed copper is being constructed. Each module hosts 7 strings of 3-5 detectors. The modules are operated in a passive shield that is surrounded by a 4π active muon veto. To mitigate the effect of cosmic rays and prevent cosmogenic activation of detectors and materials, the experiment is being deployed at

4850 ft depth (4260 m.w.e. overburden) at the Sanford Underground Research Facility in Lead, SD [14]. A picture of the MAJORANA DEMONSTRATOR is shown in Figure 1.
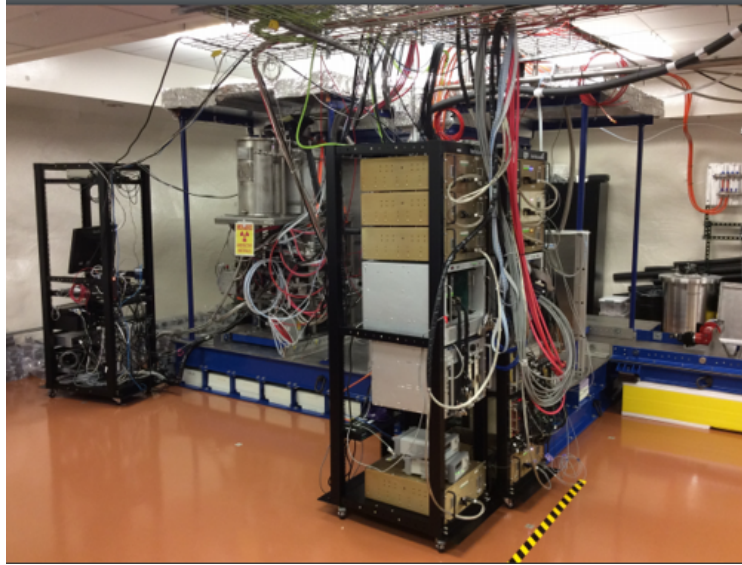

Figure 1: *Picture of the* MAJORANA DEMONSTRATOR.

The main technical challenge of the MAJORANA DEMONSTRATOR is to reach a background rate of 3 counts/(ROI-t-y) after analysis cuts, which projects to a background level of 1 count/(ROI-t-y) in a large scale experiment after accounting for additional improvements from thicker shielding, better self-shielding, and if necessary, increased depth. To achieve this goal, background sources must be reduced and offline background rejection must be maximized. The estimated ROI contributions based on achieved assays [15] of materials and simulations for cosmic muon interactions sum to <3.5 counts/(ROI-t-y) in the MAJORANA DEMONSTRATOR.

3. The MAJORANA DEMONSTRATOR implementation

The MAJORANA DEMONSTRATOR follows a modular implementation to scale easily to the next generation experiment. The modular approach allows the independent assembly and commissioning of each module, providing a fast deployment and minimizing interference with already-operational detectors.

As a first step, a prototype module was constructed using a commercial copper cryostat. It was loaded with three strings of natural-abundance germanium and placed into shielding. Data was collected with this module from June 2014 through July 2015. It served as a test bench for mechanical designs, fabrication methods, and assembly procedures for the construction of the electroformed-copper Modules 1 & 2. In addition, the prototype also tested DAQ, data building and analysis tools.

Following the prototype run, construction began on two modules with electroformed copper cryostats. The first, Module 1, was assembled in 2015. Module 1 houses 16.8 kg of enriched germanium detectors and 5.7 kg of natural germanium detectors. The strings were assembled and characterized in dedicated String Test Cryostats. Module 1 was moved into the shield, and data

taking began, during 2015. The final stage, Module 2 supports 12.8 kg of enriched and 9.4 kg of natural Ge detectors. Module 2 has been assembled and will start taking data soon. Figure 2 shows the installation of detectors into the cryostat of Module 2.

Figure 2: *Module 2 detectors being installed.*

4. Module 1 preliminary results

All open data from Module 1 are divided in two datasets: dataset 0 (DS0) and dataset 1 (DS1). DS0 was a set of commissioning runs used to test analysis and data production corresponding to data taken from June 2015 to October 2015. In fall 2015, we implemented planned improvements:

- Installed the electroformed inner copper shield. Built with the final pieces of electroformed copper, the inner shield was not yet ready for installation during the initial construction of Module 1.

- Added additional shielding within the vacuum of the cross arm.

- Replaced the cryostat Kalrez seal with PTFE which has much better radiopurity and much lower mass and entails a 3 orders of magnitude reduction in the ROI contribution.

- Repaired non-operating channels.

These changes define the difference between DS0 and DS1. Hence, DS1 is the dataset that is being used to determine the background. DS1 data described here are taken from December 2015 to April 2016. Data taking continues, but after that date data blinding began. Table 1 summarizes the distribution of the total time elapsed during DS0 and DS1. The exposure evolution, taking into account the total active mass is shown in Figure 3.

The state-of-the-art data analysis techniques that further enable the DEMONSTRATOR's physics reach are still being developed. Double beta decay events are characterized as single-site events because the range of the electron is small compared to that of a typical Compton-scattering background gamma. Using pulse shape discrimination methods [16], it is possible reject >90% of multi-site events while retaining 90% of single-site events and reducing the Compton continuum at $Q_{\beta\beta}$ by >50% in case of backgrounds from the ^{228}Th calibration source, as seen in Figure 4.

	DS0	DS1
Total	103.15 d	104.68 d
Total acquired	87.93 d	97.52 d
Physics	47.70 d	54.73 d
High radon	11.76 d	7.32 d
Disruptive commissioning tests	13.10 d	28.61 d
Calibration	15.44 d	6.86 d
Down time	15.21 d	7.16 d

Table 1: *DS0 and DS1 duty cycles. The run time is distributed as follows: Total: total - time elapsed from the beginning until the end of the dataset; total acquired - total livetime of the dataset; physics - background runs to be used in the physics analysis; high radon - runs during which the radon purge for the shield was compromised, either intentionally or accidentally; disruptive commissioning tests - data corresponding to DAQ tests and electronics calibrations; calibration - calibration runs taken with a ^{228}Th or ^{60}Co source; down time - difference between the total and the acquired time, where the dominant period correspond to detectors being biased down to troubleshoot some detectors.*
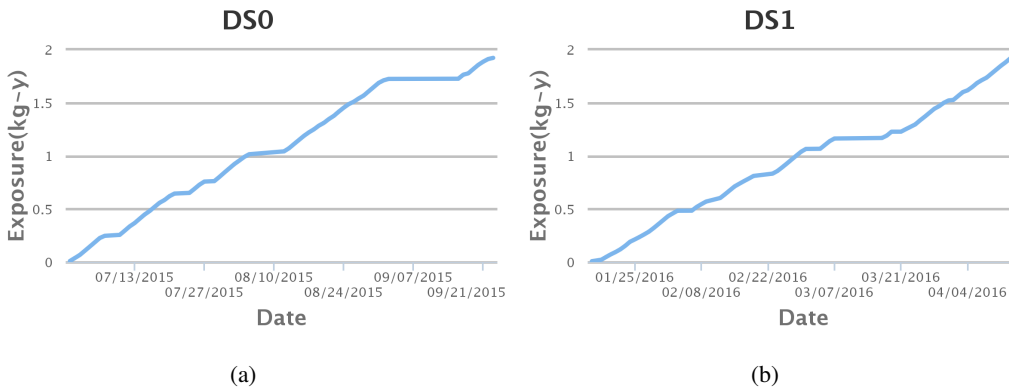

Figure 3: *DS0 and DS1 exposure plots of the physics data.*

5. Next generation ^{76}Ge experiment

The MAJORANA Collaboration is working cooperatively with GERDA and others towards the establishment of a single ^{76}Ge $0\nu\beta\beta$-decay collaboration to build a large experiment to explore the inverted hierarchy region. Periodic joint meetings take place with this purpose. Leading a tonne-scale $0\nu\beta\beta$ experiment is one of the highest priorities new activity for the US Nuclear Physics community as indicated in the latest Long Range Plan for nuclear science in the US recently released by the Nuclear Science Advisory Committee [17]. We anticipate down-select of best technologies, based on results of the two experiments. Moving forward is predicated on demonstration of projected backgrounds. There is on-going work to go from a conceptual design to a viable, competitive proposal including R&D on: robust signal and high voltage connectors, ultra-clean materials, alternative detector designs, detector signal readout, cryostat and detector mount designs, enrichment, cooling and shielding, and required depth.
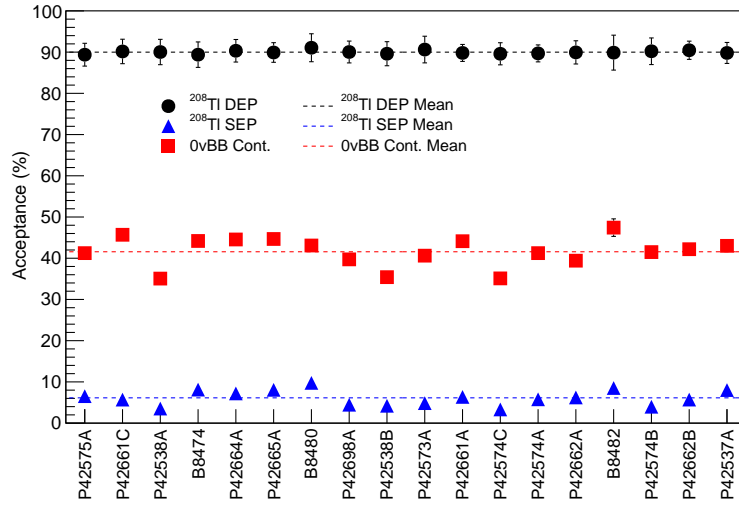
Figure 4: Acceptance efficiency of the pulse shape discrimination cuts at the double-escape peak (single-site events), the single-escape peak (multi-site events), and at $0\nu\beta\beta$ ROI (Compton scattering events) of the Module 1 detectors evaluated with ^{228}Th calibration data.

Summary

The MAJORANA DEMONSTRATOR will search for the $0\nu\beta\beta$-decay with an array of ^{76}Ge detectors. A modular instrument composed of two cryostats built from ultra-pure electroformed copper is being constructed. Module 1 has been taking data since June 2015, and before data blinding started in April 2016, 185 days of data were taken from which 102 days are used in the physics analysis. The data are divided in two datasets: DS0 and DS1. In Fall 2015, we implemented planned improvements: installed the inner copper shield, added additional shielding within the vacuum of the cross arm, exchanged the cryostat seal for one with a low background component, and repaired non-operating channels. These changes define the difference between DS0 and DS1, and DS1 is being used to determine the background. Data analysis is in progress and includes, for instance, pulse shape discrimination to reject multi-site events. The DEMONSTRATOR aims to reach a background rate of 3 counts/(ROI-t-y) after analysis cuts. This projects to a background level of 1 count/(ROI-t-y) in a large scale experiment that is already being planned.

Acknowledgments

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