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The MAJORANA DEMONSTRATOR: Progress towards showing the feasibility of a ^{76}Ge neutrinoless double-beta decay experiment

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Abstract. The MAJORANA DEMONSTRATOR will search for the neutrinoless double-beta decay ($0\nu\beta\beta$) of the ^{76}Ge isotope with a mixed array of enriched and natural germanium detectors. The observation of this rare decay would indicate the neutrino is its own anti-particle, demonstrate that lepton number is not conserved, and provide information on the absolute mass-scale of the neutrino. The DEMONSTRATOR is being assembled at the 4850 foot level of the Sanford Underground Research Facility in Lead, South Dakota. The array will be contained in a low-background environment and surrounded by passive and active shielding. The goals for the DEMONSTRATOR are: demonstrating a background rate less than 3 counts $\text{tonne}^{-1} \text{year}^{-1}$ in the 4 keV region of interest (ROI) surrounding the 2039 keV ^{76}Ge endpoint energy; establishing the technology required to build a tonne-scale germanium based double-beta decay experiment; testing the recent claim of observation of $0\nu\beta\beta$ [1]; and performing a direct search for light WIMPs (3-10 GeV/c^2).

1. Introduction

The MAJORANA collaboration [2, 3, 4] will search for the neutrinoless double-beta decay ($0\nu\beta\beta$) of ^{76}Ge . The observation of this rare decay would indicate the neutrino is its own anti-particle, demonstrate that lepton number is not conserved, and provide information on the absolute mass-scale of the neutrino. Reaching the neutrino mass scale associated with the inverted mass hierarchy, 25 – 50 meV, will require a half-life sensitivity on the order of 10^{27} y. This corresponds to a signal of a few counts or less per tonne-year in the $0\nu\beta\beta$ peak (2039 keV for ^{76}Ge). To observe such a small signal, one will need to construct tonne scale detectors with backgrounds in the region of interest at or below ~ 1 count $\text{tonne}^{-1} \text{year}^{-1}$. The MAJORANA collaboration is constructing the DEMONSTRATOR, an array of high-purity germanium (HPGe) detectors at the 4850 foot level of the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The DEMONSTRATOR will consist of a mixture of natural (10-15 kg) and $>86\%$ enriched ^{76}Ge (up to 30 kg) HPGe detectors in two low-background cryostats. Each cryostat will contain seven closely-packed stacks, called strings, and each string will have up to five crystals (see Figs. 1 and 2). The DEMONSTRATOR aims to:

- (i) demonstrate a background rate less than 3 counts $\text{tonne}^{-1} \text{year}^{-1}$ in the 4 keV region of interest (ROI) surrounding the 2039 keV ^{76}Ge endpoint energy;
- (ii) establish the technology required to build a tonne-scale germanium based $0\nu\beta\beta$ experiment;
- (iii) test the recent claim of observation of $0\nu\beta\beta$ [1];
- (iv) and perform a direct search for light WIMPs (3-10 GeV/c^2).

The MAJORANA and GERDA [5] collaborations are working together to prepare for a single tonne-scale ^{76}Ge experiment that will combine the best technical features of both experiments. There are two main differences between the experimental techniques employed by MAJORANA and GERDA. First, the DEMONSTRATOR array will be deployed in a custom vacuum cryostat, whereas GERDA is submerging theirs in liquid argon. Secondly, the DEMONSTRATOR will use a compact shield with lead, oxygen-free copper, electroformed copper, and scintillator paddles, whereas GERDA is using the liquid argon and high-purity water as a shield.

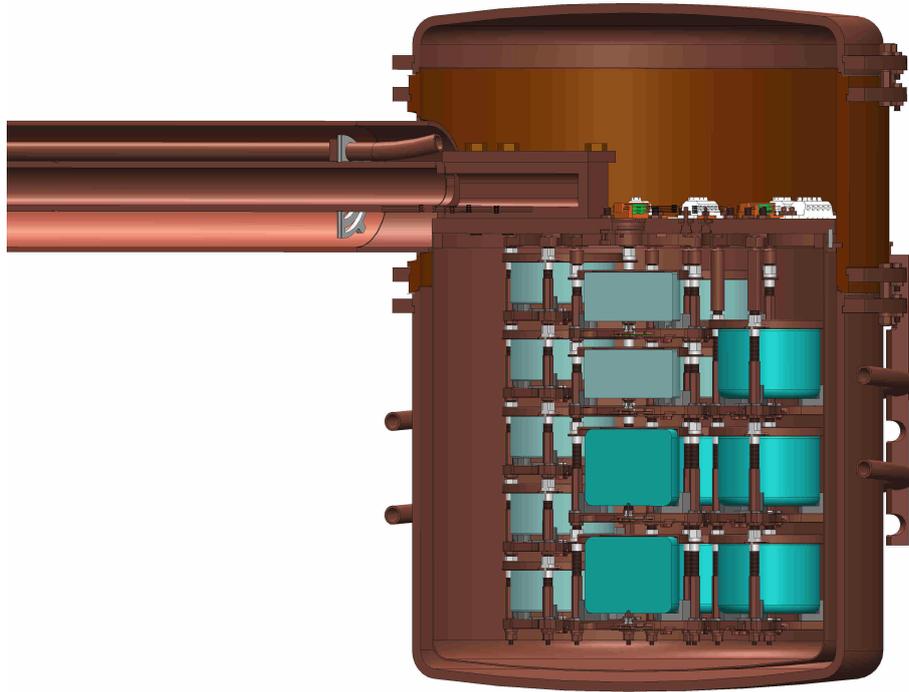


Figure 1. A cross sectional view of a MAJORANA DEMONSTRATOR cryostat. The strings within the cryostat hold a mixture of natural (smaller/light blue) and enriched (larger/dark blue) germanium detectors (Color online).

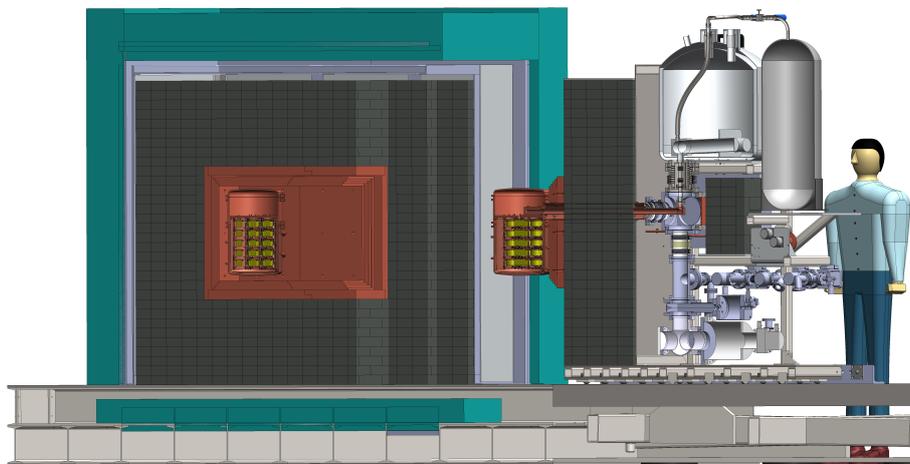


Figure 2. The MAJORANA DEMONSTRATOR is shown here with both active and passive shielding in place. One cryostat is in place inside the shield while the other is being positioned for insertion. For scale, the inner copper shield is 20" high and 30" in length (Color online).

2. Detector Technology

The MAJORANA collaboration will use p-type point contact (PPC) HPGe detectors. These detectors [6, 7] have been demonstrated to provide both exceptional energy resolution (<2.0 keV FWHM at 1332 keV) and low-energy thresholds (~ 500 eV) [7, 8], see e.g. Figure 1 in Ref. [8]. Several successful prototypes have been commercially produced and successfully operated in an underground environment [8, 9, 10, 11]. The PPC detectors used in the DEMONSTRATOR will each have a mass of 0.6-1.0 kg.

3. Background Mitigation Techniques

One of the technical goals of the DEMONSTRATOR is to show that a 1 count tonne⁻¹ year⁻¹ ROI⁻¹ background rate is achievable for a tonne-scale experiment; this translates into a 3 counts tonne⁻¹ year⁻¹ ROI⁻¹ background rate for the DEMONSTRATOR, which is ~ 100 times lower than previous Ge experiments. One of the primary methods for achieving this rate is to deploy the detectors inside two independent cryostats that minimize the amount of interstitial material (see Figs. 1 and 2). In addition, the materials used to fabricate the DEMONSTRATOR have been screened and selected based on strict radiopurity requirements. The main structural material closest to the detectors within the DEMONSTRATOR is electroformed copper due to its intrinsically low-background and excellent physical properties. Electroformed copper is made by electroplating from high-purity commercial oxygen-free copper nuggets onto stainless steel mandrels. The electroforming process greatly reduces the radioactivity due to U, Th and cosmogenically-produced ⁶⁰Co. Electroformed copper is being used to fabricate both of the cryostats for the DEMONSTRATOR. A prototype cryostat has been built from commercial oxygen-free copper and is currently being tested. The successful performance of the prototype cryostat will give the MAJORANA collaboration confidence in the future performance of both electroformed copper cryostats.

Further background reduction in the DEMONSTRATOR is achieved using the technological features of the PPC detectors. A $0\nu\beta\beta$ event will deposit all of its energy within a ~ 1 mm³ region inside the PPC detector. These are called single-site events (SSE). In contrast, gamma-rays from radioactive contaminants of sufficient energy to affect the 2039 keV ROI will typically Compton scatter several times with a scattering length of ~ 1 cm. These are called multi-site events (MSE). The DEMONSTRATOR will reduce Compton scattered gamma-ray backgrounds by implementing sophisticated pulse shape analysis (PSA) techniques to separate SSE from MSE within a single Ge crystal. In addition to signal PSA, background events that deposit energy in more than one detector can be removed with a coincidence cut on the order of several microseconds.

Cosmogenically-produced isotopes represent another source of background. Cosmic rays can create ⁶⁰Co in copper components as well as ⁶⁸Ge, ⁶⁰Co and tritium within the detectors themselves. In an effort to minimize these backgrounds, the surface exposure of detectors and copper components will be minimized. Reducing surface exposure is the only option for most cosmogenically-produced isotopes. However, the background due to ⁶⁸Ge is a special case. ⁶⁸Ge decays to ⁶⁸Ga which has a half-life of 67.71 minutes. The low-thresholds and excellent energy resolution of PPC detectors allow for a single-site time-correlation (SSTC) cut, which looks forward and backward in time from the current event in the ROI to search for signatures of parent or daughter isotopes [12, 13]. The DEMONSTRATOR will implement a SSTC cut for the ⁶⁸Ge-⁶⁸Ga coincident decay for five ⁶⁸Ga half-lives following the 10 keV K-shell de-excitations. The SSTC method can also be used to reduce backgrounds due to ²⁰⁸Tl ($T_{1/2} = 3.05$ min) and ²¹⁴Bi ($T_{1/2} = 19.9$ min) in the Ge crystals and the inner mount. The SSTC and SSE/MSE cuts will both be used in order to maximize background reduction.

4. Background Modeling Tools

The MAJORANA collaboration uses a Monte Carlo simulation framework, MaGe [14], which is co-developed by the MAJORANA and GERDA collaborations, to estimate background contributions to the ROI. MaGe is based on the GEANT4 [15, 16] and ROOT [17] packages and provides a common set of physics processes, event generators, and various management classes. MaGe also provides a user-interface for output classes and detector geometries. The radioactivities of all components within the DEMONSTRATOR have been measured. The results of these measurements are used with MaGe to develop a comprehensive background model for the DEMONSTRATOR.

5. Dark Matter

The low-energy performance of PPC detectors, due to their low-capacitance point-contact design, makes them suitable for dark matter (DM) searches. The direct detection of DM, which makes up $\sim 23\%$ of the Universe, remains an active area of research. Weakly interacting massive particles (WIMPs), a generic class of potential DM candidates, are widely regarded as the most promising candidate [18]. Recent direct searches for WIMPs have hinted towards a low-mass WIMP at $\sim 7 \text{ GeV}/c^2$ [8, 9, 10, 11, 19]. The favored $\sim 7 \text{ GeV}/c^2$ WIMP is also consistent with the theoretical model proposed by Hooper and Goodenough [20] to explain the excess flux of gamma-rays from the Galactic center. The DEMONSTRATOR will be able to probe the low-mass WIMP parameter space and test these claims [11, 21].

As a part of the research and development (R&D) efforts for the DEMONSTRATOR, the MAJORANA collaboration has deployed a custom PPC detector (MALBEK) in the Kimballton Underground Research Facility (KURF) in Ripplemead, Virginia, at a depth of 1450 meters water equivalent [22]. MALBEK is a 465 g natural Ge crystal housed in a low-background cryostat and shield. The data acquisition (DAQ) and slow-control system for MALBEK was built around ORCA, an object oriented data acquisition that provides an easy to use, graphical interface for manipulation of experimental hardware and data streams [23]. The goals for this R&D effort are to:

- (i) test a MAJORANA DEMONSTRATOR-like DAQ;
- (ii) validate the MAJORANA DEMONSTRATOR background model;
- (iii) systematically characterize the low-energy spectrum;
- (iv) and perform a light WIMP search.

6. DEMONSTRATOR Implementation

The MAJORANA DEMONSTRATOR prototype cryostat is expected to be completed by late 2012 and will contain two strings of natural Ge PPC crystals. The electroformed cryostats, Cryostat 1 and Cryostat 2, are being fabricated in a phased approach. Cryostat 1 will contain seven strings of Ge crystals, four holding natural Ge crystals and three containing Ge crystals enriched to greater than 86% ^{76}Ge . Cryostat 1 is expected to be completed towards the end of 2013. Cryostat 2 will contain seven strings of Ge crystals, all of which enriched to greater than 86% ^{76}Ge . Cryostat 2 is expected to be completed by the end of 2014. The MAJORANA DEMONSTRATOR will search for $0\nu\beta\beta$ and low-mass WIMPs once fabrication is completed at SURF. In addition, the MAJORANA DEMONSTRATOR should be able to verify or refute the recent observational claim of $0\nu\beta\beta$ [1] within 2-3 years of commissioning Cryostat 1.

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