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Update on The MAJORANA Neutrinoless Double Beta Decay Experiment

Reyco Henning on behalf of the
MAJORANA **Collaboration**

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Abstract The MAJORANA collaboration is actively pursuing research and development aimed at a tonne-scale ^{76}Ge neutrinoless double-beta decay ($\beta\beta(0\nu)$-decay) experiment. The current, primary focus is the construction of the MAJORANA DEMONSTRATOR, an R&D effort that will field 30 kg of ^{76}Ge enriched and 10 kg of unenriched $^{\mathrm{nat}}$Ge detectors. This article provides a status update on the construction of the DEMONSTRATOR and an overview of recent activities.

1 Introduction

The MAJORANA collaboration [1,2] is actively pursuing research and development aimed at a tonne-scale ^{76}Ge neutrinoless double-beta decay ($\beta\beta(0\nu)$-decay) [3]. The current, primary focus is the construction of the MAJORANA DEMONSTRATOR experiment, an R&D effort that will field 30 kg of ^{76}Ge enriched and 10 kg of unenriched $^{\mathrm{nat}}$Ge detectors. A technical goal of the collaboration is to demonstrate a background low enough to justify building a tonne-scale ^{76}Ge experiment, while testing the claim of the discovery of the $\beta\beta(0\nu)$-decay of ^{76}Ge [4,5]. MAJORANA is working collaboratively with the GERDA collaboration [6] to prepare for a single international tonne-scale ^{76}Ge experiment that combines the best technical features of the two experiments. GERDA is pursuing a novel liquid argon or nitrogen shield in which the germanium detectors are directly immersed, while MAJORANA is pursuing a more conservative compact shield consisting of high purity copper and lead.

As a reminder, $\beta\beta(0\nu)$-decay is a type of nuclear decay where two electrons and no neutrinos are emitted. The observation of this decay would have several important physics implications:

R. Henning
University of North Carolina at Chapel Hill
CB 3255, NC 27599, USA E-mail: rhenning@unc.edu

- The neutrino is a Majorana fermion or its own antiparticle [7].
- Total lepton number is not conserved.
- It can also provide a handle on the absolute neutrino mass scale, if the decay is mediated via the exchange of a massive Majorana neutrino.

MAJORANA and GERDA use High-Purity Germanium (HPGe) semiconductor diode detectors fabricated from ^{76}Ge enriched material. HPGe detectors have excellent energy resolution, which is crucial to reduce the backgrounds due to other types of radioactive decays in the detectors and surrounding materials. HPGe detectors are also intrinsically very clean and have negligible intrinsic radioactivity. [8,9].

2 The MAJORANA DEMONSTRATOR

The MAJORANA DEMONSTRATOR will consist of 40 kg of HPGe detectors. Of these, 30 kg will be enriched to 86% in ^{76}Ge. This is the minimum amount of material required to achieve the technical and scientific goals outlined in the Introduction. An important technical goal for the DEMONSTRATOR is to demonstrate a background of 3 counts per tonne-year exposure in the 4 keV region-of-interest (ROI) around the 2039 keV Q-value of the decay after analysis cuts have been applied. Such a rate would correspond to a rate of 1 count per tonne-year for a tonne-scale experiment. The additional background reduction is achieved with the improved granularity and self-shielding of a larger detector. Obtaining as low a background as possible is essential to maximize detector sensitivity, as shown in figure 1. The DEMONSTRATOR will require ionizing radiation backgrounds a factor of order 100 lower than what has been achieved with germanium detector technology to date [10,9]. There are multiple sources of backgrounds. Ubiquitous, primordial U and Th, and their decay chain daughters are a significant concern and can contribute in several different ways. Gamma-rays from radioactive decays with sufficient energy to affect the ROI typically Compton scatter inside germanium with a scattering length of $\sim 1\,\mathrm{cm}$. This is a very different topology than a $\beta\beta(0\nu)$-decay, which would deposit all the ionization energy from the two electrons in a $\sim 1\,\mathrm{mm}^3$ region in the crystal, making it highly localized. Most of MAJORANA's analysis-based background reduction techniques rely on the ability to separate these multi-site events (MSE) from single-site events (SSE).

For MAJORANA, cylindrical crystals of semiconducting HPGe are doped to make large ($\sim 500\,\mathrm{g}$) diodes. By applying a reverse biasing potential, typically a few kilovolts, to the diode, an electrical field is established inside the crystal. Ionizing radiation creates electron-hole pairs that drift under the influence of the internal electrical field and are collected at the electrodes of the crystal. Small current pulses are induced on the electrodes by these drifting charges, which can be detected using standard nuclear physics electronics.

The DEMONSTRATOR is using P-type Point-Contact (PPC) detectors. PPC detectors have a very small p-type contact, which has two benefits for MAJORANA. The first is that the capacitance of the detector is minimized, sig-

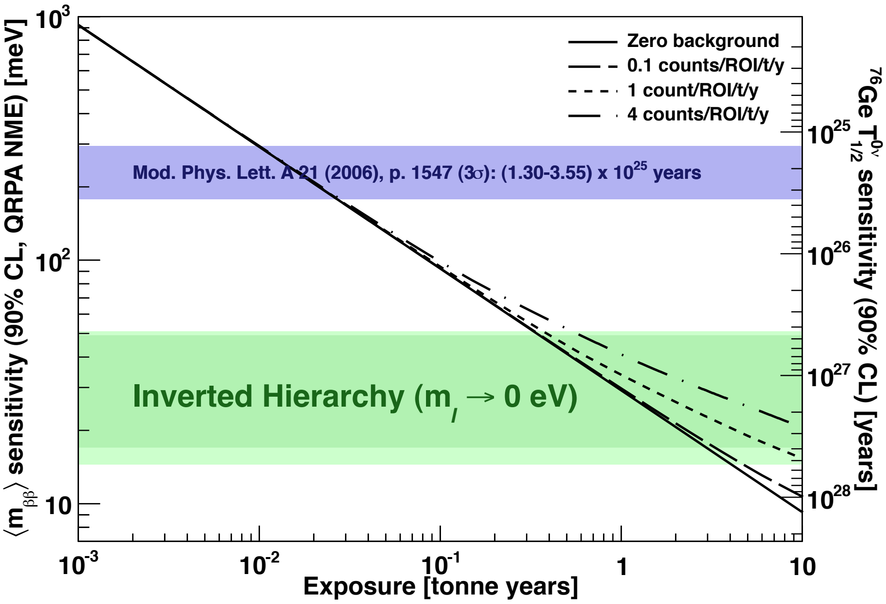

Fig. 1 Sensitivity of a germanium-based $\beta\beta(0\nu)$ search with different background rates.

nificantly reducing the series noise of the system compared to other HPGe detector designs. The second benefit is the sharp rise in the weighting fields very near the p-type contact, causing most of the induced signal to be generated only as the charge cloud approaches near the point-contact. This renders the detector's output pulse shape sensitive to the radial distribution of the initial charge deposits inside the crystal, since radially separated deposits will induce signals at different times. This is important for rejection of MSE vs. SSE in MAJORANA.

^{76}Ge has a natural abundance of 7.44% and detector germanium for MAJORANA must be enriched to 86% or better. ISOFLEX USA is the vendor of the enriched material, and the enrichment is being performed at the Electro-Chemical Plant (ECP) in Zelonogorsk, Russia. The enriched germanium oxide is transported from ECP inside a massive, steel-shielded container via ground transport and cargo ship to Oak Ridge, TN, where a commercial company processes the oxide into electronic grade material. The detector manufacturer will use standard zone-refining and Czochralski crystal growing techniques to further purify the material into detector grade material. So far 42.5 kg of enriched material has arrived in Oak Ridge, TN for conversion into crystals.

One of the dominant backgrounds in the $\beta\beta(0\nu)$ decay ROI is the Compton continuum of the 2.6 MeV gamma ray from ^{208}Tl decay in the ^{232}Th chain. It is mitigated primarily using electroformed copper as structural and shielding material, which has been demonstrated to have extremely low activity [11]. An-other significant background is cosmogenic activation products in copper and germanium, specifically ^{68}Ge in germanium and ^{60}Co in copper and germanium. These cosmogenic backgrounds are mitigated with analysis cuts and by minimizing surface exposure times using underground machining and fabrication processes. Backgrounds from radon and prompt cosmic-rays are mitigated with liquid nitrogen boil-off and by running deep underground with a cosmic-ray veto, respectively. As stated, HPGe detectors have excellent energy resolution and the $\beta\beta(2\nu)$-decay mode does not contribute a background. Other backgrounds, such as external gamma-rays and fission neutrons, are mitigated with shielding.

The detectors are arranged in seven three-crystal strings. Each string has the mounting fixtures for the crystals and front-end electronics. Seven strings are mounted electronically and mechanically to an e-formed copper cold-plate, and the entire cold-plate and string assembly is mounted inside an e-formed copper cryostat and IR shield. A liquid nitrogen thermosyphon [12] provides the cooling to maintain the crystals at about 80 K. Outside the shield the cryostat arm is connected to a vacuum system and the dewar for the thermosyphon, as well as a break-out box that connects cabling from the front-end electronics to pre-amplifiers.

From the inside out the shield consists of 5 cm of e-formed copper, 5 cm of commercial OFHC-grade copper, 45 cm of commercial lead, 30 cm of polyethylene moderator, and an active plastic scintillator cosmic-ray veto. The entire inner lead and copper shield cavity is hermetically sealed and continuously purged with liquid nitrogen (LN) boil-off gas to reduce radon. Each cryostat is mounted with its vacuum system and thermosyphon to a part of the shield, called a monolith, which can be moved in and out of the entire shield, easing installation. Each cryostat is surrounded by an e-formed copper track for placing and removing encapsulated calibration sources near the detectors and inside the shield.

The collaboration has performed extensive Monte Carlo simulations of the DEMONSTRATOR to verify these analysis cuts and to determine purity requirements for materials. Over 50,000 combinations of radioactive isotopes and detector components have been simulated to date and are compiled into a background model. MAJORANA collaborators have also developed detailed simulations of pulse-generation and charge drift inside the PPC detectors to characterize the electronic response of the detectors and help diagnose pathologies in pulse-shapes arising from events near the detector surfaces.

During the last year the collaboration has made significant progress in commissioning an underground laboratory and the construction of the experiment. The DEMONSTRATOR is located at the Sanford Underground Research Facility (SURF) in Lead, SD, USA. The laboratory is at a depth of 4850 mwe and consists of a machine shop and detector assembly area. There is also a separate copper electroforming facility on the same level about 1 km away. Figure 2 shows some pictures from these facilities.

MAJORANA hopes to probe physics other than $\beta\beta(0\nu)$-decay. With a large target mass, low background and low thresholds, the DEMONSTRATOR should

Fig. 2 Various underground activities at SURF. At the top left we see the underground electroforming facility, top right shows the inside of the electroforming facility, bottom left the machine shop, and bottom right the space where the detector is to be assembled.

also be able to search for low mass WIMPS, as demonstrated by CoGeNT [13, 14]. The collaboration has deployed a low-background PPC detector at the Kimballton Underground Research Facility (KURF) in Virginia to study the low-energy backgrounds in PPC detectors. Because the Majorana detector technology does not distinguish between nuclear and electronic recoils, the Demonstrator will also be sensitive to keV scale dark matter (aka. Super-WIMPS) that scatter off electrons. The Demonstrator can also perform searches for solar axions and study low energy neutrino scattering from a neutrino source. Figure 3 shows the sensitivity of the Demonstrator to light WIMP dark matter.

A prototype module of the Demonstrator filled with natural germanium detectors will be deployed and operated at SURF by early 2013, with the first module of $10 - 12$ kg enriched detectors coming on-line underground at SURF in the fall of 2013 and the second module of $18 - 20$ kg enriched detectors online in 2014. The Demonstrator should test the Klapdor-Kleingrothaus discovery claim within a year or two of commissioning its first module.

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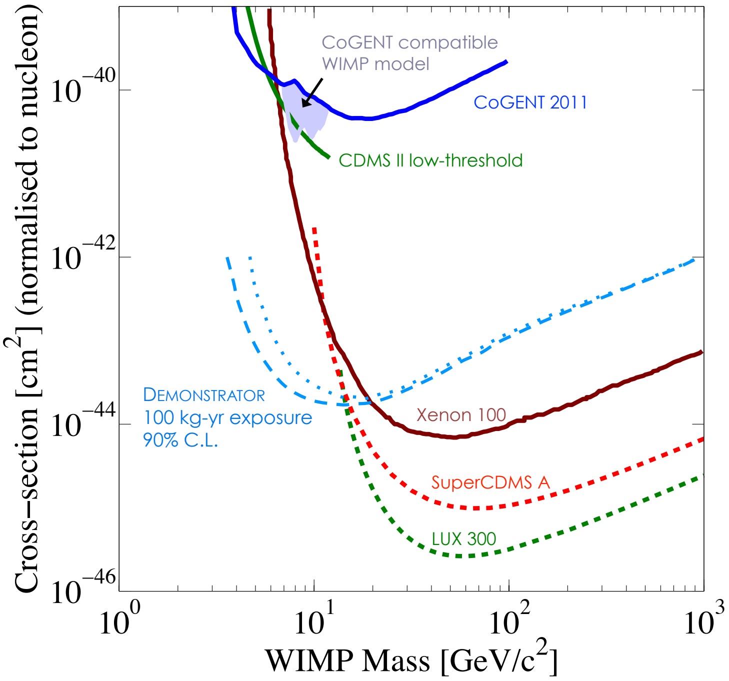

Fig. 3 Sensitivity of the Demonstrator to light WIMPS with different experimental energy thresholds.

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