A large-scale search for Neutrinoless Double-beta Decay of Germanium-76


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The MAJORANA[1] and GERDA[2] collaborations are searching for neutrinoless double beta decay using 76Ge, which has previously been shown to have a number of advantages in terms of sensitivity and background. The observation of neutrinoless double-beta decay would show that lepton number is violated, demonstrate neutrinos are Majorana particles, and provide information on neutrino mass. Attaining sensitivity for effective Majorana neutrino masses in the inverted hierarchy region, 15 – 50 meV, requires large, tonne-scale detectors with extremely low backgrounds, at the level of ~1 count t^-1 y^-1 or lower in the signal region. The MAJORANA collaboration is constructing the DEMONSTRATOR, an array consisting of 40 kg of p-type point-contact high-purity germanium (HPGe) detectors, of which ~30 kg will be enriched to 87% in 76Ge. The DEMONSTRATOR is being constructed in a clean-room laboratory at the 4850’ level (4260 m.w.e.) of the Sanford Underground Research Facility in Lead, SD. It utilizes a conventional graded shield approach with the inner portion consisting of ultra-clean electroformed Cu that is being grown and machined underground. The primary aim of the DEMONSTRATOR is to show the feasibility for a future large-scale measurement in terms of backgrounds and scalability. The GERDA collaboration is pursuing a similar set of measurements using a novel large liquid-argon-based shield. GERDA Phase I has recently presented results[2] using 18 kg of enriched Ge detectors at the Laboratori Nazionali del Gran Sasso in Italy (3100 m.w.e.). They have achieved the lowest background in the region of interest of any previous or operating double beta decay experiment in the world. They are in the process of constructing Phase II of GERDA, which will consist of up to ~40 kg of enriched detectors. In phase II, they aim to reduce their current backgrounds by over a factor of 10, with essentially the same background goal as for the MAJORANA DEMONSTRATOR.

If MAJORANA and/or GERDA are able to demonstrate backgrounds that would project for a large-scale experiment to ~1 count t^-1 y^-1 in the region of the signal, then the members of the
collaborations plan to jointly pursue building a large-scale $^{76}$Ge based array, selecting the best features and capabilities of the two current experiments.

I. SCIENTIFIC MOTIVATION

Neutrinoless double-beta decay ($0\nu\beta\beta$) is the only viable method to search for lepton number violation and correspondingly to determine the Dirac-Majorana nature of the neutrino\cite{3, 4}. Reaching the neutrino mass scale associated with the inverted mass hierarchy, 15 – 50 meV, will require a half-life sensitivity on the order of $10^{27}$ y, corresponding to a signal of a few counts or less per tonne-year in the $0\nu\beta\beta$ peak. To observe such a small signal, one will need to construct large-scale detectors with backgrounds in the region of interest at or below $\sim 1$ count $t^{-1} y^{-1}$. HPGe detectors have the best demonstrated energy resolution of any currently operating or proposed $0\nu\beta\beta$ experiments, $\sim 0.2\%$ at $Q_{\beta\beta}$ of 2039 keV, which for a 4 keV region of interest would correspond to a required background of $2.5 \times 10^{-1}$ counts keV$^{-1} t^{-1} y^{-1}$. This excellent energy resolution also ensures that backgrounds from the irreducible $2\nu\beta\beta$ decay ($T_{1/2} = 1.4 \times 10^{21}$ y) are negligible even at the sensitivity to $0\nu\beta\beta$ of $10^{27}$ y. We note that a convincing discovery that neutrinos are Majorana particles and that lepton number is violated will require the observation of $0\nu\beta\beta$ in multiple experiments using different $0\nu\beta\beta$ isotopes.

The discovery level of a $0\nu\beta\beta$ search increases with the exposure of the experiment, but ultimately depends on the achieved background level. This relationship is illustrated in Figure 1. Although this figure is drawn using experimental parameters and theoretical nuclear matrix elements relevant for $0\nu\beta\beta$ searches using $^{76}$Ge, the situation for other isotopes is not qualitatively different\cite{5}. It may be concluded that achieving sensitivity to the entire parameter space for inverted-hierarchical Majorana neutrinos would require, using optimistic values of matrix elements and $g_A$,

![Figure 1](image_url)

**FIG. 1.** The 3-$\sigma$ discovery level as a function exposure for $0\nu\beta\beta$-decay searches in $^{76}$Ge under different background scenarios. The different curves for for the various matrix element calculations as indicated in the legend.

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about $\sim 10$ tonne-years of exposure with a background rate of less than one count $t^{-1} y^{-1}$. Higher background levels would require significantly more mass to achieve the same sensitivity within a similar counting time.

II. THE MAJORANA DEMONSTRATOR

The MAJORANA collaboration is searching for $0\nu\beta\beta$ using $^{76}$Ge, which utilizes the demonstrated benefits of enriched high-purity germanium (HPGe) detectors such as intrinsically low-background source material, understood enrichment chemistry, excellent energy resolution, and the ability to apply sophisticated event reconstruction. The primary technical challenge is the reduction of environmental ionizing radiation backgrounds by about a factor 100 below what has been previously achieved. Specific goals of the MAJORANA DEMONSTRATOR are:

- Demonstrate a path forward to achieving a background rate at or below one count $t^{-1} y^{-1}$ in the 4 keV region of interest (ROI) around the 2039 keV Q-value of the $^{76}$Ge $0\nu\beta\beta$.
- Show technical and engineering scalability toward a large-scale instrument.

To this end, the collaboration is building the DEMONSTRATOR, a modular instrument composed of two cryostats built from ultra-pure electroformed copper, each of which can house over 20 kg of HPGe detectors [1]. The individual p-type point-contact (PPC) detectors have masses in the range of 0.6-1.1 kg. These PPC style detectors were chosen after extensive R&D by the collaboration. The baseline plan calls for two thirds of the detectors to be grown from 87% enriched material, resulting in a $^{76}$Ge mass of 30 kg enriched detectors and 10 kg of natural detectors. This enriched material is sufficient to achieve the physics goal while still optimizing cost and providing a systematic check of enriched vs. natural Ge. The modular approach will allow us to assemble and optimize each cryostat independently, providing step-wise deployment with minimum interference on already operational detectors. The cryostats sit within a graded shield where the inner passive shield will be constructed of electroformed and commercial high-purity copper, surrounded by high-purity lead, which itself is surrounded by an active muon veto and neutron moderator (Figure 2).

Cryostat 1, fabricated using ultra-clean electroformed Cu, will contain seven strings of mostly enriched Ge detectors and is scheduled to be commissioned in late 2014 with data collection in 2015. Cyostat 2, which will contain a mixture of enriched and natural detectors, is scheduled to be completed in 2015. The full array should be in operation near the end of 2015 or early 2016.

In typical materials uranium (U) and thorium (Th) decay-chain contaminants are found at levels of $\mu$g/g to ng/g, which will produce unacceptable backgrounds in the DEMONSTRATOR. It has been shown that electroforming copper in a carefully-controlled and clean environment allows one to produce ultra-clean copper, with U and Th below the level of $10^{-12}$ g/g[8]. Copper has mechanical, thermal, and electrical properties that are suitable for the DEMONSTRATOR’s cryostats, detector mounts, and inner shield. Ultra-clean electroformed copper is being produced at an underground production facility at the Sanford Underground Research Facility (SURF) (Figure 3) and at a shallow facility at Pacific Northwest National Laboratory. The experiment is producing copper that has about ten times lower U and Th impurities than commercial electroformed copper, with an activity of $<0.1 \mu$Bq/kg for Th, which meets
the requirements for a large-scale experiment. The **Demonstrator** is currently being assembled in an underground cleanroom laboratory at the 4850’ level (1478 m) of SURF. This facility also includes a full machine shop for producing copper parts in an ultra-clean underground environment.

### III. GERDA PHASES I AND II

The GERDA Phase I experiment has collected 21.6 kg·y of data with 15 kg of conventional P-type coaxial HPGe detectors and 3 kg of P-type, point contact detectors\[2\]. As described in a recent GERDA paper\[9\], these enriched detectors were originally used in the Heidelberg-Moscow and IGEX experiments before being refurbished for GERDA. The detectors are mounted in strings with typically three diodes each. The detector array is surrounded by 64 m$^3$ of 99.999% liquid argon (LAr), contained in a vacuum-insulated cryostat made of stainless steel, lined on the inner side by a 3 to 6 cm thick layer of copper. The cryostat is placed at the center of a 580 m$^3$ tank of ultra-pure water equipped with 66 photomultiplier tubes used to veto cosmic ray muons. The water also serves as a shield to moderate and capture neutrons produced by natural radioactivity and in muon-induced hadronic showers.

GERDA reports a background index of 10 counts keV$^{-1}$ t$^{-1}$ y$^{-1}$ around the expected signal corresponding to 40 counts ROI$^{-1}$ t$^{-1}$ y$^{-1}$. Canberra fabricated of 30 enriched BEGe style detectors, with a combined mass of 20.8 kg. In 2013, GERDA stopped Phase I data collection and is implementing upgrades associated with Phase II. The upgrade to Phase II includes installation of a new air-lock system for detector insertion, the addition of a LAr scintillation light readout system, and a number of other upgrades aimed at reducing backgrounds. Data taking with Phase II should begin in late 2014 or early 2015.

### IV. TOWARDS A LARGE-SCALE EXPERIMENT - GERDA AND MAJORANA COOPERATION

The GERDA and **Majorana** collaborations have signed a formal cooperative agreement with the objective of combining in a joint future large-scale experiment. The collaborations currently share resources and knowledge where appropriate in their development of the two different array configurations. The simulations framework, MaGe \[10\], was developed jointly. The collaborations hold annual joint meetings to discuss technical issues. Students from each collaboration have had extended visits at institutions from the other collaboration. Both collaborations have benefited from the cooperative spirit that exists between them. Discussions have begun on the eventual path forward to form a collaboration to pursue a large-scale Ge experiment. The collaborations expect to “cherry pick” the best technologies and techniques developed as part of the **Majorana Demonstrator** and GERDA Phases I and II. Likewise, the
collaborations expect the respective agencies currently providing funding support would be sent proposals requesting the cost of constructing a large-scale array be shared amongst the participating countries and agencies.

V. LARGE-SCALE DESIGN AND PERFORMANCE

The large-scale configuration will be chosen to maximize the physics reach and to balance tradeoffs between competing design aspects including cost, required shielding and technical complexity. Hybrid and alternative shielding configurations are being investigated; the two concepts presented here represent the maximum and minimum extremes in size, technical complexity, and cost. Both approaches allow for a phased implementation of adding and operating additional enriched Ge diodes. Thus one could start with for example 250 kg of detectors, and increment the amount in 250-kg steps (the optimum amount of material to use at each phase is still being studied.) Reducing cosmogenically-induced activities in materials requires underground facilities for electroforming and machining. For the same reason it may be beneficial to grow Ge crystals and fabricate detectors underground. All facilities for construction and operation of the array must be operated under clean room conditions (classes 100 to 2000) and in some areas will require radon mitigation.

Two baseline shielding configurations for a large-scale $^{76}$Ge $0\nu\beta\beta$ experiment are being considered:

- **Compact**: Close-packed arrays of enriched Ge diodes are housed inside ultra-pure electroformed copper vacuum cryostats, surrounded by graded, passive shielding of electroformed copper, lead, polyethylene, and a $4\pi$ active muon veto (See Figure 4). This configuration follows the current MJD $0\nu\beta\beta$ design.

- **Cryogenic Vessel**: Arrays of enriched Ge diodes are submerged in liquid cryogen (LN or LAr) contained by a 5-m diameter steel cryostat lined with clean copper. The cryostat is enclosed by a 10-15 m diameter water tank instrumented with PMTs that serves as a water Cherenkov muon veto (See Figure 4). This configuration is similar to the GERDA $0\nu\beta\beta$ experiment layout.

The performance of a large-scale $0\nu\beta\beta$ experiment with $^{76}$Ge is critically dependent on the background level. Simulations indicate that a large scale Ge experiment will likely face backgrounds approaching 1 count ROI$^{-1}$ t$^{-1}$ y$^{-1}$ from sources inside the shield (the detectors themselves, their mounts, and the shield materials). Therefore, mitigating cosmogenic backgrounds is key to obtaining sufficiently low backgrounds. Of particular concern are fast neutrons generated by muons that pass outside the detector veto. These neutrons may have significant veto inefficiency, and can scatter elastically or inelastically from active and inactive detector materials, resulting in backgrounds for $0\nu\beta\beta$. The highly penetrating nature of fast neutrons makes them difficult to shield, and interactions in the material surrounding the detector can generate additional neutrons, compounding the background problem. Minimizing high-Z shielding materials relaxes the overburden requirement. This can potentially be achieved using a liquid argon (or liquid nitrogen) cryostat and a water Cherenkov veto tank, similar to GERDA. This configuration requires a shield.
up to 15 m in diameter to adequately mitigate U/Th backgrounds from the cavern walls and prompt $\mu$-induced backgrounds. The limiting depth-dependent background in this configuration is in-situ production and subsequent decay of cosmogenic isotopes such as $^{77m}$Ge ($T_{1/2}=53s$) and $^{77}$Ge ($T_{1/2}=11.3h$), whose predominantly pure, high Q-value $\beta$-decays present a potential background difficult to suppress using pulse-shape discrimination. Again, we will learn more about this background based on the measurements of both MAJORANA and GERDA.

VI. SCHEDULE AND COST ESTIMATES

Assuming that MJD and/or GERDA can demonstrate the necessary backgrounds, the expectation is that construction start could occur as early as 2018, and that one would initiate long-lead time procurements also in 2018. Major construction would be carried out in a staged approach over a 5-8 year period, starting in 2019. Operations of the first 250-kg module could start by 2020.

Preliminary schedules and costs estimates have been reviewed by several committees, including the Committee to Evaluate DOE-SC Options for Underground Science (Marx/Reichanadter Committee) in the spring of 2011. Likewise, work towards the large-scale experiment was reviewed as part of the annual NSF “S4” review process in 2010 and 2011. The NSAC subcommittee on neutrinoless double beta decay has completed an initial review of the available technologies for a future large $0\nu\beta\beta$ experiment. Both the GERDA and MAJORANA DEMONSTRATOR projects are reviewed on an annual basis by their respective funding agencies.

VII. SUMMARY

Collectively the MAJORANA and GERDA collaborations have made substantial progress towards proving the feasibility of constructing a large-scale $^{76}$Ge based $0\nu\beta\beta$ experiment. Already in Phase I, GERDA has achieved the lowest backgrounds in the region of interest of any current experiment, while MAJORANA has developed the capability to produce ultra-clean materials in bulk. Likewise, the collaborations have already signed a letter of intent to join together in a future large-scale experiment and have been holding joint meetings for the past several years. By 2016 the experiments should be in position to determine if either can achieve backgrounds that would project for a large-scale experiment backgrounds of $\sim 1$ count t$^{-1}$ y$^{-1}$ in the region of the signal.