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The MAJORANA Project

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Abstract. Building a $0\nu\beta\beta$ experiment with the ability to probe neutrino mass in the inverted hierarchy region requires the combination of a large detector mass sensitive to $0\nu\beta\beta$, on the order of 1-tonne, and unprecedented background levels, on the order of or less than 1 count per year in the $0\nu\beta\beta$ signal region. The MAJORANA Collaboration proposes a design based on using high-purity enriched ^{76}Ge crystals deployed in ultra-low background electroformed Cu cryostats and using modern analysis techniques that should be capable of reaching the required sensitivity while also being scalable to a 1-tonne size. To demonstrate feasibility, the collaboration plans to construct a prototype system, the MAJORANA DEMONSTRATOR, consisting of 30 kg of 86% enriched ^{76}Ge detectors and 30 kg of natural or isotope-76-depleted Ge detectors. We plan to deploy and evaluate two different Ge detector technologies, one based on a p-type configuration and the other on n-type.

1. Introduction

This is an exciting time in our quest to understand neutrinos — fundamental particles that play key roles in the early universe, in cosmology and astrophysics, and in nuclear and particle physics. Recent results from atmospheric, solar, and reactor-based neutrino oscillation experiments (Super-Kamiokande, SNO, and KamLAND)[1, 2, 3] have provided compelling evidence that neutrinos have mass and give the first indication after nearly forty years of study that the Standard Model (SM) of nuclear and particle physics is incomplete.

With the realization that neutrinos are massive, there is an increased interest in investigating their intrinsic properties. Understanding the neutrino nature (Majorana or Dirac), the neutrino mass generation mechanism, the absolute neutrino mass scale and the neutrino mass spectrum are some of the main focii of future neutrino experiments.

Lepton number, L, is conserved in the Standard Model because neutrinos are assumed to be massless and there is no chirally right-handed neutrino field. The guiding principles for extending the Standard Model are the conservation of electroweak isospin and renormalizability, which do not preclude each neutrino mass eigenstate ν_i to be identical to its anti-particle $\bar{\nu}_i$, or a "Majorana" particle. However, L is no longer conserved if $\nu = \bar{\nu}$. Theoretical models, such as the seesaw mechanism that can explain the smallness of neutrino mass, favor this scenario. Therefore, the discovery of Majorana neutrinos would have profound theoretical implications in the formation of a new Standard Model while possibly yielding insights into the origin of mass itself. If neutrinos are Majorana particles, they may fit into the leptogenesis scenario for creating the baryon asymmetry, and hence ordinary matter, of the universe. As of yet, there is no firm experimental evidence to confirm or refute this theoretical prejudice.

Many even-even nuclei are forbidden to undergo β decay, but are unstable with respect to the second order weak process of two-neutrino double beta decay ($2\nu\beta\beta$). In this process, the nucleus emits 2 β particles and 2 $\bar{\nu}$. This is an allowed process and has been observed. A similar process, neutrinoless double-beta decay ($0\nu\beta\beta$) can occur if a neutrino is exchanged between two neutrons and no neutrinos are emitted. In this case, the only leptons in the final state are the two electrons and hence the decay violates L by two units. This exchange of the neutrino however, will only occur if the neutrino is a massive Majorana particle and therefore experimental evidence of $0\nu\beta\beta$ would establish the Majorana nature of neutrinos. The science of $\beta\beta$ has been described in detail in many recent reviews [4, 5, 6, 7, 8, 9].

The most-restrictive upper limits on the $0\nu\beta\beta$ half-life come from Ge detector experiments [10, 11]. The half-life is $>1.9\times10^{25}$ y and this corresponds to an effective Majorana mass limit from $0\nu\beta\beta$ greater than about 400 meV depending on the choice of nuclear matrix element. The oscillation experiments, however, indicate that at least one of the neutrino mass eigenvalues is greater than about 45 meV. In the inverted hierarchy, this would imply an effective Majorana neutrino mass 45 meV or greater. The predicted half-life for $0\nu\beta\beta$ with an effective mass in this region is greater than 10^{27} years. An experiment will require approximately 1 tonne of isotope to be sensitive to such a long half-life, and it will require a background level of 1 count/tonne-year or better.

2. The Majorana Demonstrator

The objective of the first experimental phase of Majorana is to build a 60-kg module of high-purity Ge, of which 30 kg will be enriched to 86% in ^{76}Ge, to search $0\nu\beta\beta$. This module is referred to by the collaboration as the Demonstrator. The physics goals for this first phase are to:

(i) Probe the neutrino mass region above 100 meV

(ii) Demonstrate that backgrounds at or below 1 count/tonne-year in the $0\nu\beta\beta$-decay region of interest can be achieved that would justify scaling up to a 1 tonne or larger mass detector.

(iii) Definitively test the recent claim[12] of an observation of $0\nu\beta\beta$ decay in ^{76}Ge in the mass region around 400 meV.

The half live of $0\nu\beta\beta$ is at least 10^{25} years, making it an extremely difficult process to observe and therefore a very sensitive experiment is required. The Majorana Demonstrator will consist of ^{76}Ge detectors, deployed in multi-crystal modules, located deep underground within a low-background shielding environment. The technique will be augmented with recent improvements in signal processing and detector design, and advances in controlling intrinsic and external backgrounds. The justification for a detector mass size of 60 kg is directly linked to all three of the above-stated science goals. The enriched Ge is handled differently than natural Ge and the isotopic makeups are different. Since both these issues lead to background differences, enriched material must also be used to validate the background model.

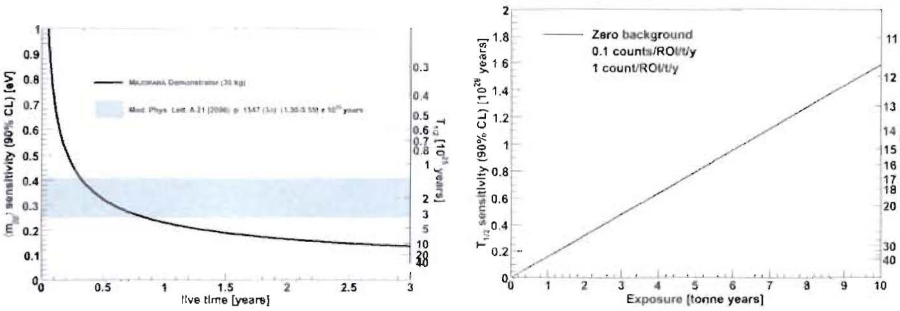

Figure 1. The left figure shows the sensitivity of the MAJORANA DEMONSTRATOR module as a function of time and indicates the range of values indicated by a recent controversial claim[12]. The right figure shows the sensitivity of a 1-ton experiment as a function of exposure for 3 different background levels. Note the factor of 1000 difference in the scales of the two panels. The matrix elements used are from Ref. [13]

The goal of the proposed MAJORANA DEMONSTRATOR is the construction of an instrument that provides sufficient sensitivity to test the recent claim, that allows a path forward to achieving a background level below 1 count/tonne-year in the 4-keV region of interest, and is scalable towards a large-scale instrument. We plan a module consisting of three cryostats each containing about 20 kg of HPGe detectors. One module will consist of 14 n-type segmented-contact (N-SC) HPGe detectors, while the other two modules will each consist of 28 smaller p-type point-contact (P-PC) HPGe detectors without segmentation. Approximately 40 of the P-PC detectors will be built of ~30 kg of enriched ^{76}Ge material. Employing these two complementary detector configurations allows us to evaluate and compare the two most promising implementations under the realistic conditions of an ultra-low background experiment. The multi-cryostat approach allows us to optimize each individual implementation, providing a fast deployment with minimum interference with already operational detectors. In addition, it allows us to separate both configurations in the data analysis. The proposed configuration is illustrated in Figure 2. Our initial emphasis will be on the first cryostat assembled with natural-Ge P-PC detectors.

The efficient commercial production of Ge detectors depends strongly on the yields for producing high-purity single crystals of Ge and for producing p-n junction diodes from these crystals. Single-crystal boules naturally favor right circular cylindrical geometries, making coaxial detectors the natural choice to efficiently use the precious enriched Ge material. To minimize the passivated surface area and maximize the sensitive volume, coaxial detectors are typically fashioned in so-called closed-end geometries with a bore hole extending ~80% along the detector axis. This bore hole, with a central electrode, is necessary to produce sufficiently high electric fields to achieve not only depletion throughout the crystal but also high drift velocity of the charge carriers to minimize

Figure 2. Left: Setup of proposed MAJORANA DEMONSTRATOR. The cryostats will be built of ultrapure electroformed copper. The inner passive shield will also be constructed of electroformed copper surrounded by lead, which itself is surrounded by an active muon veto and neutron moderator. Middle: A conceptual design of a 3x19 detector arrangement of Ge detectors mounted in one cryostat, envisioned as a building block for a tonne-scale experiment. Right: A conceptual design of a two N-SC detector string.

charge trapping effects.

Previous-generation $0\nu\beta\beta$ decay searches in ^{76}Ge favored detectors made of p-type material primarily because p-type crystals can be grown more efficiently to larger dimensions than n-type crystals. In addition, with p-type detectors trapping effects are reduced, and generally slightly better energy resolution is obtained. P-type detectors are typically fabricated with a p+ B-implanted contact on the inner bore hole and an n+ Li-diffused contact on the outside electrode to obtain efficient and full depletion from the outside. While the inside B contact is very thin (typically <1 μm) the Li-diffused contact is typically more then 100 μm thick and can be up to 1 mm or more depending on the fabrication process and any subsequent annealing or prolonged storage at room temperatures. The thickness of the outside-Li contact provides an advantage since this dead layer absorbs alpha-particle radiation from surface contamination that may otherwise generate background for ^{76}Ge $0\nu\beta\beta$ decay.

While the pulse-shape obtained at the central contact in coaxial detectors[14] can provide radial separation of multiple interactions in any implementation, pulse-shapes obtained in segmented detectors[15, 16] provide improved sensitivity in the radial separation and, more importantly, in complementary directions as well. A high-degree of segmentation, such as a 6x6-fold segmentation, enables the full reconstruction of γ-ray interactions within the detectors. GRETINA in particular has provided very encouraging analyses that events can be reconstructed with a position uncertainty of $\sim$2 mm [17]. Even without absolute event vertex reconstruction, events with multiple energy depositions can be identified and rejected. Preliminary results from GRETINA and other highly-segmented HPGe arrays indicate that a minimum separation of 4 mm will be achievable. However, these advanced capabilities come at the price of a

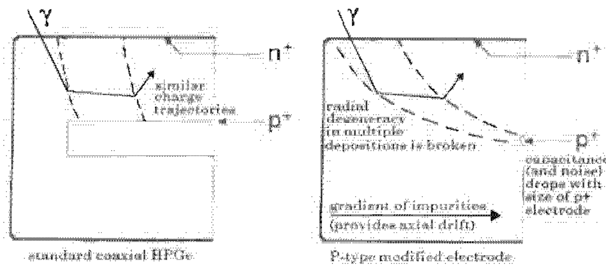

Figure 3. Closed-end coaxial p-type Ge detector (left) versus the p-type point contact Ge detector implementation (right). Figure is adapted from Ref. [19]

proportionally larger number of small parts such as cables near the detector, and their selection must be optimized against their ability to overcome added backgrounds.

An alternative right circular cylindrical detector design has been developed in which the bore hole is removed and in its place a point-contact, either B implanted or Li diffused, is formed at the center of the intrinsic (open end) detector surface [18]. The changes in the electrode structure result in a drop in capacitance to ~1 pF, reducing the electronics noise component and enabling sub-keV energy thresholds. This point-contact configuration also has lower electric fields throughout the bulk of the crystal and a weighting potential that is sharply peaked near the point contact. (Earlier attempts employing n-type material exhibited poor energy resolution at hight energies due to increased charge trapping.) This in turn results in an increased range of drift times and a distinct electric signal marking the arrival of the charge cloud at the central electrode. Figure 3 illustrates the p-type point-contact (P-PC) implementation in contrast to the conventional, closed-end coaxial detector approach. Instrumented with a modern FET, a P-PC detector was recently demonstrated by MAJORANA collaborators to provide low noise, resulting in a low energy trigger threshold and excellent energy resolution, as well as excellent pulse-shape capabilities to distinguish multiple interactions [19]. This detector was developed with the goal of detecting the very soft (sub-keV) recoils expected from coherent neutrino-nucleus scattering in a reactor experiment.

The P-PC detector in [19] has a diameter of 5 cm and a length of 5 cm resulting in a total mass of 0.5 kg. While it may be possible to expand the radial dimension of these detectors, it will be more difficult to expand the axial dimension due to the requirement of a significant impurity gradient between the detector faces. Without an impurity concentration gradient, the electric fields can be sufficiently weak that the detector is susceptible to excessive charge trapping, even in the p-type configuration. It is interesting to note that increasing the voltage, *e.g.* beyond full depletion, will not significantly increase the electric field in the detector bulk away from the point contact. In contrast, the presence of space charge due to an appropriate impurity concentration and gradient is able to increase the electric field throughout the crystal. The first attempt to make a P-PC detector with a flat impurity concentration failed. The detector in [19] resulted from a second attempt with a factor two difference in impurity concentration between the detector faces. The collaboration has recently purchased and received several additional P-PC detectors from various vendors.

Although the detector mounts and feedthroughs require different designs, the overall dimensions of the cryostats can be similar, reducing the design effort and simplifying production. Fabricating multiple, similar cryostats will provide an opportunity to assess several risks associated with a large-scale modular deployment for a 1-tonne experiment. These risks include the reproducibility of the mechanical and thermal integrity of the cryostats, as well as the ability to consistently achieve and maintain radiopurity throughout the module production and assembly chain. Figure 2 shows the conceptual design of a larger, 57-detector cryostat currently envisioned for a tonne-scale modular deployment of ^{76}Ge detectors.

Following the selection of two different detector designs, *i.e.* the N-SC and P-PC configurations, the mechanical components within the cryostat will be optimized independently. However, the overall dimensions and wall thicknesses can be the same since each cryostat will contain about 20 kg of Ge detectors. Our reference design is a cylindrical vessel with a thick cold plate at the top from which the detectors hang. A thermal shroud mounted to the cold plate provides radiative cooling for the detector array. The cryostat, cold plate and thermal shroud will be fabricated using ultra-low-background, relatively-thick electroformed copper to eliminate any concern about collapse of the vacuum vessel. The coldplate shields the germanium detectors from backgrounds originating in the front-end electronics; thus, a thicker coldplate is favored. The cryostats themselves are situated within a thick layer of electroformed Cu comprising the innermost passive shielding layers, so extra cryostat wall and coldplate thickness is not a concern from the standpoint of backgrounds. However, thicker cryostat walls do reduce the potential for inter-cryostat granularity rejection. A combination of thermal, mechanical and background analyses will be used to determine the preferred thickness of these components for the cryostats in the DEMONSTRATOR with the upper limit being set by considerations of the copper electroforming process (time and material quality).

The detector mounts for each configuration will be different, as will the number of cables and feedthroughs. While the assembly and readout for the central channel in the N-SC configuration will be similar to the P-PC approach, all electronics components for the segment signals will be located outside the cryostat, at the maximum distance possible to minimize radioactive background in the detectors. This distance is constrained by the bandwidth and noise requirements for the pulse-shape analysis to achieve sufficent position sensitivity. Using warm FETs for the segments also reduces the heat load to the cryostat. Nevertheless, beyond the feedthroughs for high voltage, test input, feedback, ground, and signal for the central channel for each detector, N-SC detectors require an additional feedthrough for each outer segment of each crystal, resulting in an additional thermal burden to the cryostat and background burden to the detectors. Assuming, for comparison, 28 750-g P-PC detectors arranged in 4 layers of 7 detectors for each of the two cryostats, each P-PC cryostat will have 140 feedthroughs. In contrast, a cryostat with 14 1.5-kg N-SC 36-segment detectors arranged in 2 layers of 7 detectors will have 574 feedthroughs.

In both configurations, the detectors will be mounted in a string-like arrangment as shown in Figure 2 for the N-SC configuration. This reference design consists of a thick copper "lid", a copper support frame, and low-mass Teflon support trays or standoffs. Each individual detector is mounted in a separate frame built of electroformed Cu that eases handling of individual detectors during shipping, acceptance testing and string assembly. The assembled detector string is simply lowered through a hole in the cryostat cold plate until the string lid sits on the cold plate. This allows us to easily mount and dismount individual detector strings from the top. Cables are run vertically from the detector contacts through a slit in the string lid, above which low-background front-end electronics packages are mounted to read out the central contact. For N-SC detectors, HV blocking capacitors will also be mounted above the lid. The string lid provides some shielding between these components and the detectors, and allows the bandwidth to be maximized by placing the central contact FETs near the germanium detectors. The front-end and the outer contact leads are routed out of the detector along the cold finger.

The MAJORANA DEMONSTRATOR cryostats will be enclosed in a graded passive shield and an active muon veto to eliminate external backgrounds. Shielding reduces signals from γ rays originating in the experiment hall, cosmic-ray μ's penetrating the shielding, and cosmic-ray μ-induced neutrons. The strategy is to provide extremely low-activity material for the inner shield. Surrounding this will be an outer shield of bulk γ-ray shielding material with lower radiopurity. This high-Z shielding enclosure will be contained inside a gas-tight Rn exclusion box made of stainless-steel sheet. Outside this bulk high-Z shielding will be a layer of hydrogenous material, some of which will be doped with a neutron absorber such as boron, intended to reduce the neutron flux. Finally, active cosmic-ray anti-coincidence detectors will enclose the entire shield. The MAJORANA collaboration plans to site the DEMONSTRATOR deep underground in the Sanford Laboratory at the Homestake gold mine in Lead, South Dakota, USA.

The data acquisition software system will be constructed using the Object-oriented Real-time Control and Acquisition (ORCA) [20] application to achieve the goal of providing a general purpose, highly modular, object-oriented, acquisition and control system that is easy to develop, use, and maintain. The object-oriented nature of ORCA enables a user to configure it at run-time to represent different hardware configurations and data read-out schemes by dragging items from a catalog of objects into a configuration window.

Monte Carlo (MC) radiation transport simulation models have been developed for MAJORANA using MaGe [21], an object-oriented MC simulation package based on ROOT [22] and the Geant4 [23, 24] toolkit and optimized for simulations of low-background germanium detector arrays. MaGe is being jointly developed by the MAJORANA and GERDA [25] collaborations in consultation with collaborators from the National Energy Research Scientific Computing Center (NERSC) at LBNL. MaGe defines a set of physics processes, materials, constants, event generators, etc. that are common to these experiments, and provides a unified framework for geometrical definitions, database access, user interfaces, and simulation output schemes in an effort to reduce repetition of labor and increase code scrutiny.

3. Conclusion

The MAJORANA collaboration is carrying out R&D to develop a 1-tonne $0\nu\beta\beta$ experiment based on enriched ^{76}Ge. The Ge detectors will be housed in a classic cryostat design that is constructed from ultra low-radioactivity materials. The cryostats will be contained within a passive shield, and active veto system and operated deep underground. The project should demonstrate that this technology will be low enough in background to verify the feasibility of constructing a 1-tonne Ge-based $0\nu\beta\beta$ experiment.

Acknowledgments

This conference was organized to celebrate the 75^{th} birthdays of Frank Avignone, Etorre Fiorini and Peter Rosen. The entire field of $\beta\beta$ research has benefitted from the long and storied efforts of Frank and Etorre. I admire their scientific leadership at this time we celebrate their careers. The contributions to this field by Peter Rosen are also paramount. It is with fondness that we remember his legacy, but with sadness that we can't also share his 75^{th} birthday at this event.

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