The Majorana Project: ^{76}Ge $0\nu\ \beta\beta$-Decay Neutrino Mass Measurement

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Interest in, and the relevance of, next-generation $0\nu\ \beta\beta$-decay experiments is increasing. Even with nonzero neutrino mass strongly suggested by SNO, Super Kamiokande, and similar experiments sensitive to δm^2, $0\nu\ \beta\beta$-decay experiments are still the only way to establish the Dirac or Majorana nature of neutrinos by measuring effective electron neutrino mass, $\langle m_\nu \rangle$. Various theorists have recently argued in favor of a neutrino mass between 0.01 and 1 eV. The Majorana Project aims to probe this effective neutrino mass range, reaching a sensitivity of 0.02–0.07 eV. The experiment relies entirely on proven technology and has been devised based upon the materials, technology, and data analysis demonstrated to produce the lowest background per kilogram of fiducial germanium. The project plan includes 500 kg of germanium detector material enriched to 85% in ^{76}Ge, specialized pulse-acquisition electronics and detector segmentation for background rejection, and electroformed copper support hardware.

1. Introduction

The analysis of recent results in solar neutrino and atmospheric neutrino experiments suggests that next-generation double-beta decay experiments sensitive to effective electron neutrino masses on the order of 0.05 eV could result in the direct observation of $0\nu\ \beta\beta$-decay. The task of scaling up previous experiments to achieve the desired sensitivity must be driven by practicality and, because of the magnitude of the time and resources needed, risk minimization. The sensitivity of next-generation ^{76}Ge $0\nu\ \beta\beta$-decay experiments can be greatly enhanced by the application of pulse-shape discrimination (PSD) and detector segmentation. Further, this can be a very cost-effective element of experiment design, as compared to an equivalent increase in fiducial mass.

A method has been envisioned for scaling up the results obtained in decades of ^{76}Ge and ^{100}Mo experiments. The solution is a mixture of larger fiducial detector mass, electronic signal processing techniques for background rejection, minimized support structure mass, and long counting time. Risk is minimized by

- using materials and processes proven in earlier double-beta decay experiments
- proving new methods, especially signal processing for background rejection, in above-ground experiments
- conducting a phased series of underground prototype experiments which will validate materials-related background goals and help optimize the cryogenic and electronic design.

The Majorana experimental apparatus has several key features. It will be

- compact, only about 4 meters by 3 meters footprint
- modular, with 1–2 modules built per year of construction (a total of 10 modules are planned)
- relocatable, if necessary, into a series of increasingly optimized active and passive shields
- realizable, with few engineering risks

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Alternative shielding and germanium detector cooling/housing methods have been discussed in recent underground physics conferences. While these techniques are quite speculative today, they may prove to be useful or superior methods in the future. No details of the design of the Majorana detector crystals are contingent on the selection of shielding material or cooling/housing method, and the copper support structures are relatively inexpensive, thus future decisions about cooling are not precluded by the conventional baseline approach.

2. Innovations in background suppression

At the level of 0.05 eV mass sensitivity, only a handful of counts of background can be tolerated in a 500-kg detector during a ten-year counting period. Accordingly, a series of chemical process improvements have been made which greatly improve the mechanical properties and radiopurity of the electroformed copper components used in detector construction[1, 3]. As an example, after the identification of ^{226}Ra and daughters in electroformed copper, a barium scavenge was developed to immobilize radium in the electroplating bath. This reduced ^{226}Ra measured in a 9-kg sample to less than 25 μBq/kg, or less than 1 part in 7×10^{19}(g/g). Progress such as this in reducing primordial radioactivity has been complemented by storing copper parts underground to minimize cosmogenic activation. It is planed that most or all parts of the Majorana apparatus could be electroformed underground, thereby essentially eliminating what has been a minor source of background.

Cosmogenic activation of the germanium has been documented as a serious concern since the construction of the first International Germananium Experiment (IGEX) detectors[2]. While no manufacturer has yet committed to such a plan, investigations are moving forward into the possibility of manufacturing the detectors in their entirety underground. This would limit the cosmogenic activity in the detectors to only the activation of ^{68}Ge that occurred between the enrichment facility and the introduction underground, a time period determined by the residence time in the centrifuge, subsequent batch storage at the enrichment facility, and transit time to the underground facility. All of these parameters are being examined to determine the possible levels of activation expected.

3. Baseline sensitivity calculation

To predict the sensitivity of the Majorana experiment, we begin with the rather conservative historical example of an IGEX detector, newly deployed in an underground location. This germanium had been recently zone refined, such that cosmogenic activation of ^{60}Co was suppressed along with other chemical impurities. However, the ^{68}Ge in the crystal was certainly at surface activation equilibrium since the material had not been recently enriched in ^{76}Ge. This crystal, in a high-quality lead shield with radon suppression, obtained a count rate of 0.2 counts/keV/kg/year in the decay Q-value region, 2038 keV. This was shown to arise mostly from ^{68}Ge (271d) with a substantial component from ^{60}Co (5.2y).

Several background reduction factors can be applied to this starting example. The first comes from the decay of the ^{68}Ge and ^{60}Co during the construction and running time of the experiment, effectively giving a reduction factor of $\sim$ 20 overall. This neglects other advantageous effects such as intra-crystal self-shielding. Thus the background count rate would be around 0.01 counts/keV/kg/yr. This count rate, taken with the proposed mass, counting time, and an optimal 1.2-FWHM-wide analysis region, yields about 178 expected background counts. Thus the critical level for detection (L_C) would be about 23 counts (90% CL). This limit corresponds to a $T_{1/2}$ of about 1×10^{27} years. It should be noted this assumes all the germanium is introduced into the underground facility on the same day. In reality, the average underground decay time of the germanium will be about three years before the complete instrument is commissioned, a factor of $\sim$ 16 in ^{68}Ge decay not included in this calculation.

It is possible invoke new methods of signal analysis and detector instrumentation to reject remaining multi-site background events such as those created by internal ^{60}Co and ^{68}Ge. Against internal, multi-site events, pulse-shape discrimination has been shown in above-ground laboratory tests to give a factor of 1.56 improvement in $T_{1/2}$ sensitivity. Monte Carlo simulations of a 6×2-segment crystal (azimuthal $\times$ axial contacts) were analyzed with a simple multi-segment versus single-segment cut, giving an additional factor of 2.4 increase in $T_{1/2}$ sensitivity. These two techniques are orthogonal, literally, as the pulse-shape analysis is sensitive essentially to radial seperation while the segmentation works on the azimuthal and axial seperations. Thus these factors are multiplicative, forming a total $T_{1/2}$ sensitivity improvement factor of 3.8. This corresponds to a total background rejection factor of 27 and total $0\nu\ \beta\beta$-decay efficiency after all cuts of 73%. The resulting half-life for neutrinoless double-beta decay is about 4×10^{27} years. Using a commonly-accepted range of nuclear matrix element calculations, sensitivity values of 0.02 eV to 0.068 eV for $\langle m_\nu \rangle$ can be obtained, thus reaching the desired mass sensitivity.

References

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