The MAJORANA $^{76}$Ge neutrino less double-beta decay project: A brief update

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Abstract. At present, MAJORANA is a research and development (R&D) project to investigate the feasibility and cost of constructing and operating a one ton $^{76}$Ge $0\nu\beta\beta$-decay experiment with ~1000 kg of Ge detectors fabricated from germanium enriched to 86% in $^{76}$Ge. The study will include three separate cryostats with various types of detectors: un-segmented, un-segmented point-contact, minimally segmented, and highly segmented. One cryostat will contain at least 30 kg of enriched (preferably point-contact) detectors. The performance of the cryostats and detectors as well as background levels will be investigated. The goal of the demonstrator project is to reach a 3σ discovery sensitivity of ~ $10^{26}$ y.

1. Introduction

The subject of double –beta decay has been well covered in several recent review articles [1-5]. It is well known from available experimental evidence from neutrino oscillation experiments [6], that at least one of the neutrino mass eigenvalues is approximately 0.05 eV. In the case of the inverted-mass hierarchy ($m_3 = m_2 >> m_1$), the solar oscillations involve ($m_3, m_2$), while atmospheric oscillations involve ($m_{3,2} \approx m_i$). An approximate expression of the theoretical rate can be written as:

$$ (T_{1/2}^{0\nu})^{-1} = G^{0\nu}(E_0, Z) \left| \frac{m_{\beta\beta}}{m_e} \right|^2 \left| M^{0\nu}_f - (g_A/g_V)^2 M^{0\nu}_{GT} \right|^2. $$

(1)

If the average oscillation parameters are used, one can write the following expression for the effective Majorana mass of the electron neutrino, in case of the inverted hierarchy:

$$ \left\langle m_{\beta\beta} \right\rangle = \left[ (0.70^{+0.02}_{-0.04}) m_3 + (0.30^{+0.04}_{-0.02}) m_2 e^{i\phi_2} + (\pm 0.05 m_1 e^{i(\phi_3 + \delta)}) \right]. $$

(2)

The atmospheric oscillation data [7] imply that $m_3 - m_1 \approx 0.05 eV$. With various nuclear structure calculations of the quantity: $\left| M^{0\nu}_f - (g_A/g_V)M^{0\nu}_{GT} \right|$, and of the phase-space factor, $G^{0\nu}(E_0, Z)$, one can predict the half-life corresponding to $\left\langle m_{\beta\beta} \right\rangle = 0.05 eV$, which is the case of the inverted hierarchy when the lightest eigenstate mass, $m_1$, is near zero.

Three very recent nuclear structure models were used to compute the half-lives corresponding to $\left\langle m_{\beta\beta} \right\rangle = 0.05 eV$. They yield the following values for the $0\nu\beta\beta$-decay of $^{76}$Ge: $3.2 \times 10^{27}$ y (Shell Model) [8], $(0.6 - 1.2) \times 10^{27}$ y (RQRPA) [9], and $1.5 \times 10^{27}$ y (QRPA) [10]. The longest of these should be the target sensitivity of a one-ton $^{76}$Ge $0\nu\beta\beta$-decay experiment.
2. The MAJORANA Demonstrator R&D project

The goal of the project is to design and build a “Demonstrator Module” containing about 60 kg of germanium, of which 30 kg will be enriched to 86% or more in $^{76}$Ge. The two most sensitive $0\nu\beta\beta$ decay results reported thus far are for $T_{1/2}^{0\nu}(^{76}\text{Ge})$, and are from the Heidelberg-Moscow experiment: $1.9 \times 10^{25}$ y [11], and the IGEX experiment: $1.6 \times 10^{25}$ y [12]. The one-ton experiment must increase the sensitivity by about a factor of 100. There is an unconfirmed claim of observation at $(1.30 - 3.55) \times 10^{25}$ y (3$\sigma$) [13]. Both the MAJORANA Demonstrator and the GERDA Phase-1 experiments are designed to be able to confirm or rule out that result.

Germanium-$^{76}$ 0νββ decay searches have several advantages: isotopic enrichment is well established; Ge detectors use a well-developed technology that can include pulse-shape discrimination and segmentation; they have the best energy resolution of any of the proposed techniques (−0.16% at 2039-keV) i.e., at the $\beta\beta$ decay end–point energy of $^{76}$Ge. They can also take advantage of the lessons learned from the Heidelberg-Moscow [11], and IGEX [12] experiments.

MAJORANA, in cooperation with the GERDA collaboration [14], is involved in R&D aimed at developing a one-ton scale 0νββ decay experiment. The specific MAJORANA goals are:

• To build a prototype module to test the claim of discovery of 0νββ decay [13],
• To demonstrate a background low enough to justify a 1-ton experiment,
• To prepare for a down-select between MAJORANA and GERDA techniques, and
• To pursue longer term R&D to minimize cost and to optimize the schedule for constructing the optimum one-ton scale $^{76}$Ge 0νββ decay experiment.

The reference-design parameters of the prototype Demonstrator Module that will demonstrate the efficacy of the design and will meet the science goals are as follows:

• Approximately 60-kg of ~1-kg crystals in a close-packed configuration.
• At least 30 kg of the Ge will be enriched to 86% or more in $^{76}$Ge,
• A likely mix of detector types (n-type, p-type, segmented, point contact etc.),
• A module design scalable to a one-ton scale experiment, with the cryostat constructed of ultra-low background electroformed copper as in IGEX, and
• Located deep underground (~4000 mwe) and enclosed in a low background passive shield surrounded by an active veto shield.

An experiment with 30-kg of Ge enriched to 86% in $^{76}$Ge, producing data for a live time of 3 years, or approximately 77-kg.y of $^{76}$Ge exposure, with a background of 1 count in the region of interest per ton-year, should have a sensitivity of approximately $T_{1/2}^{0\nu}(^{76}\text{Ge}) \geq 10^{26}$ y. This will probe the entire 3$\sigma$ range of the discovery claim $(1.30 - 3.55) \times 10^{25}$ y of reference [13]. See Figure 1.

The main questions that should be answered by the Demonstrator Module are as follows:

• Is the copper low enough in radioactive backgrounds; will it be necessary to electroform the copper parts underground?
• Can the small parts and cables be made pure enough to meet background requirements?
• Can large cryostats be operated with the detectors cooled by radiation?
• What will be the optimum detector configuration, point-contact detectors, modestly segmented, or highly segmented?
• How well does segmentation reject background?
The time evolution of the sensitivity of the 30-kg of enriched $^{76}\text{Ge}$, operating for a live time of three years, is shown in Figure 1. The darkened region represents the $3\sigma$ claimed discovery range $(1.30 - 3.55) \times 10^{25}$ y, corresponding to the most recent analysis of Klapdor-Kleingrothaus and Krivosheina [13].

![Figure 1](image_url)

**Figure 1.** The sensitivity achievable with 30 kg of enriched Ge in the MAJORANA Demonstrator Module in the configuration discussed in the text.

3. References

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