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THE ^{76}Ge DOUBLE-BETA DECAY EXPERIMENT GERDA AT LNGS*

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In the second generation ^{76}Ge double-beta decay experiment GERDA bare detectors made out of enriched ^{76}Ge will be operated in an cryogenic fluid shield. The goal of the approved GERDA project is to reduce the background around $Q = 2039$ keV below 10^{-3} counts/(kg keV y) and reach a sensitivity for neutrinoless $\beta\beta$ decay of $T_{1/2} > 2 \times 10^{26}$ years after an exposure of 100 kg years.

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1. Introduction

The GERDA Collaboration builds a new experiment at Gran Sasso in order to search with unprecedented sensitivity for $0\nu\beta\beta$ decay in the nucleus ^{76}Ge [1]. The observation of this decay mode would be the only known practical experiment to demonstrate that neutrinos are Majorana particles. In the case of positive result, $0\nu\beta\beta$ decay is by far the most sensitive way to determine the mass scale of neutrino mass eigenvalues.

The results of the solar neutrino and atmospheric neutrino experiments imply the mass square differences $\Delta m^2_{ij} = |m_i^2 - m_j^2|$ with an usual convention $\Delta m^2_{\rm solar} = \Delta m^2_{21} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\,{\rm eV}^2\,(1\sigma)$, $\Delta m^2_{\rm atm} = |\Delta m^2_{32}| = 2.0^{+0.6}_{-0.4} \times 10^{-3}\,{\rm eV}^2\,(1\sigma)$. However, one cannot distinguish between three mass patterns: the so called "normal" hierarchy (NH), in which $m_1 \approx m_2 \ll m_3$, the "inverted" hierarchy (IH), where $m_1 \approx m_2 \gg m_3$ and the so called "quasi-degenerate" pattern (QD) in which $m_1 \approx m_2 \approx m_3 \gg 0$.

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If the $0\nu\beta\beta$ decay is observed and the $T^{0\nu}_{1/2}$ is determined, and the nuclear matrix elements are known, one will be able to calculate the effective Majorana mass $\langle m_{\beta\beta}\rangle$. The determination of the $\langle m_{\beta\beta}\rangle$ value would allow, in general, to distinguish between these patterns, and to determine a range of the mass of the lightest neutrino $m_{\rm min}$.

If one can experimentally establish that $\langle m_{\beta\beta}\rangle \geq 50$ meV, one can conclude that the QD pattern is the correct one and one can calculate allowed range of the $m_{\rm min}$. On the other hand, if $\langle m_{\beta\beta}\rangle \approx 20$–$50$ meV, only an upper limit for $m_{\rm min}$ can be established and the pattern is likely IH, even though exceptions exist. Finally, if one could determine that $\langle m_{\beta\beta}\rangle \leq 10$ meV but nonvanishing (which is unlikely in a foreseeable future), one could conclude that the NH pattern is the correct one [2].

Thus, observation of the $0\nu\beta\beta$ decay, and accurate determination of the $\langle m_{\beta\beta}\rangle$ value would not only establish that neutrinos are massive Majorana particles, but would contribute considerably to the determination of the absolute neutrino mass scale.

2. Sensitivity of a $0\nu\beta\beta$ experiment

$\beta\beta$-decay experiments are usually designed to measure the energy or summed energy of the emitted electrons in order to identify the decay channel. Good energy resolution is thus a key in suppressing $0\nu\beta\beta$-background. An important component of such background is due to $2\nu\beta\beta$-events scattered into the $0\nu\beta\beta$-analysis energy interval. The energy spectrum of the outgoing electrons is registered and the number of events in the window $Q \pm \Delta_E$ is evaluated, where $Q = T_{e1} + T_{e2}$ is the electron sum energy and Δ_E is proportional to the energy resolution of the detector.

The parameters determining the sensitivity of a neutrinoless $\beta\beta$ decay experiment are the measuring time, t, the mass of the relevant isotope, M, and the background level, B, expressed usually in counts/(keV kg y) in the studied Q energy range. In the case where no background events are found, the effective Majorana mass limit scales as $(M\,t)^{-1/2}$. If not negligible background is observed, then the $\langle m_{\beta\beta}\rangle$ limit varies as $(\varepsilon\, a)^{-1/2}[(B\,\Delta_E)/(M\,t)]^{1/4}$, with ε being the registration efficiency, a the fraction of enriched isotope. A high sensitivity experiment will need large detector mass as well as very low background.

3. The experiment

The GERDA experiment has been proposed in 2004 as a new ^{76}Ge double-beta decay experiment at LNGS. A facility where germanium detectors made out of isotopically enriched material (^{76}Ge enriched at the level of 86 %) will be operated inside a cryogenic fluid shield and will be located in Hall A of LNGS. Germanium, both as source and detector with excellent energy resolution will be used. The baseline option of the facility uses about 2 m of liquid nitrogen (or argon) as a primary shield, contained in a vacuum-isolated copper (or stainless steel) cryostat, followed by about 3 m of highly purified water. The diameter of the cryostat is chosen such that the nitrogen (argon) absorbs the low residual radiation of the cryostat walls. The outer water shield reduces gamma flux emitted by the rock and concrete. It also serves as a neutron shield and equipped with photomultipliers — as a veto against cosmic muons [3].

Background sources can be classified as external and internal backgrounds. External backgrounds are those coming from the environment (natural radioactivity in the laboratory walls, air, cosmic radiation *etc.*), from containment, support and shielding materials, and from detector surface contamination. External background will be effectively reduced by the nitrogen (argon) shield and highly purified water layer. The water Čerenkov detector serves as a veto against cosmic muons. Internal background arises from radioactive isotopes within the detector itself (*e.g.* ^{60}Co, ^{68}Ge in the bulk material) which are of the cosmogenic origin or belong to the natural radioactive chains. For germanium those backgrounds are the result of observing only a fraction of the energy carried by the decay products. It is critical to distinguish these types of energy deposits from those resulting from $\beta\beta$ decay. R&D is currently under way in producing segmented Ge detectors which can resolve multi-site energy deposits. Another complementary approach is to discriminate multi-site deposits from the time structure of the signal (pulse shape analysis). Both techniques will likely be necessary in order to reach the desired background level. Furthermore, for the case of liquid argon as a cryogenic liquid shield, we study the possibility to suppress background by simultaneously measuring the scintillation of liquid argon [3].

A cleanroom and a sophisticated lock and a suspension system on top of the cryostat allow to insert and remove detectors without introducing contamination into the vessel. Gas purification and handling system make extensive use of the experience gained in the BOREXINO experiment [4].

4. Phases of the experiment

The experiment will be performed in three phases:
Phase I: Encompasses the installation of the cryostat and shields, the installation and operation of conventional Ge detectors to determine the background rejection and to screen materials and identify background components by classifying their spectra, and the operation of almost 20 kg of existing enriched ^{76}Ge detectors, used in the past in the Heidelberg–Moscow and IGEX experiments. Within one year of measurement, the sensitivity

of this setup should allow a statistically unambiguous statement concerning neutrinoless double beta decay with a lifetime around 1.2×10^{25} years as measured by [5].

Phase II: In parallel with the construction of the first phase of the experiment, techniques will be studied and implemented to provide improved enriched detectors to be used in the second phase. Particular emphasis is devoted to minimize cosmogenic activation of detectors by reducing the exposure. Detector geometry and segmentation will be optimized on the basis of detailed calculations and simulations. At the end of Phase II with an exposure > 100 kg y data, the sensitivity will be $T_{1/2} > 2 \times 10^{26}$ years at 90 % confidence level corresponding to a limit of the effective neutrino Majorana mass of $\langle m_{\beta\beta} \rangle < 0.09$–$0.29$ eV.

Phase III: The ultimate experiment capable of reaching the 10 meV scale requires ~ 0.5 t of enriched germanium and represents another huge step, which can only be afforded in the context of a worldwide collaboration. Options for detector shielding and detector arrangements will have to be re-evaluated on the basis of results achieved by the proposed experiment and by studies following other options, such as the copper shield foreseen in the Majorana proposal [6].

It is clear that such an ultimate ^{76}Ge experiment would be carried out in the framework of a world-wide collaboration, merging the different current efforts. Close contacts with the Majorana Collaboration have already been established (the MoU was signed) with the goal to provide a large degree of transparency between the collaborations and to work ultimately towards a merger of the collaborations [3].

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