New techniques in $0\nu\beta\beta$ germanium experiments

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Abstract. This paper summarizes recent progress novel experimental concepts developed in the framework of the GERDA and MAJORANA projects using high-purity germanium detectors for the search of $0\nu\beta\beta$ decays.

1. Introduction

High-purity germanium (HP-Ge) detectors enriched in the isotope ^{76}Ge have been used for the search of neutrinoless double beta decay $0\nu\beta\beta$ in the Heidelberg-Moscow (HDM) [1] and IGEX [2] experiments. Both projects have been completed several years ago. Until today, the achieved sensitivities are the most stringent in the field. A part of the HDM collaboration claims evidence for a $0\nu\beta\beta$ signal after a reanalysis of the full data set [3].

Two new experimental projects are under preparation. The European Germanium Detector Array (GERDA) [4] and the US lead MAJORANA [5] experiment. Both projects pursue a phased approach with the ultimate goal of commonly operating a one ton experiment to explore the mass range predicted by neutrino oscillation experiments assuming an inverted mass hierarchy. Novel background techniques will be used to reduce or actively suppress backgrounds which could mimic $0\nu\beta\beta$ events.

2. Characteristics of ^{76}Ge

The isotope ^{76}Ge has several features which makes it a highly attractive element to be used for $0\nu\beta\beta$ search. Some of the features are listed below.

- Favorable nuclear matrix element $|M^{0\nu}| = 2.5$ [6]
- Reasonable slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.4 \cdot 10^{21}$ y) and high $Q_{\beta\beta}$ value (2039 keV).
- Germanium is both source and detector
- Elemental germanium maximizes the source-to-total mass ratio
- Intrinsic high-purity germanium diodes
- HP-Ge detector technologies are well established
- Industrial techniques and facilities available to enrich from 7% up to 90%
- Excellent energy resolution: FWHM 3.3 keV at 2039 keV (0.16%)
- Powerful background rejection possible: granularity (segmentation and close packing), timing, pulse shape discrimination, argon scintillation
- Best limits on $0\nu\beta\beta$ - decay used Ge $T_{1/2} > 1.9 \cdot 10^{25}$ y (90%CL)

3. Sensitivity and background considerations

Figure 1 displays the achievable half-life limit as a function of exposure given in kg·years under the assumption of background free operation. As long as no events occur in the energy analysis window, the sensitivity increases linearly with exposure. A background level of $\sim 10^{-3}$ counts/(kg·y·keV) must be reached for an exposure of 100 kg·years and $\sim 10^{-4}$ counts/(kg·y·keV) for 1000 kg·years. An energy resolution of approximately 3.3 keV FWHM at $Q_{\beta\beta}$ has been assumed. Novel background reduction and active suppression methods are required to improve the current state-of-the-art levels $\sim 10^{-1}$ counts/(kg·y·keV) by two to three orders of magnitudes. An exposure of 100 kg·years is required to explore the degenerate mass hierarchy, while the inverted mass hierarchy requires about $5 \cdot 10^3$ years to be fully covered.

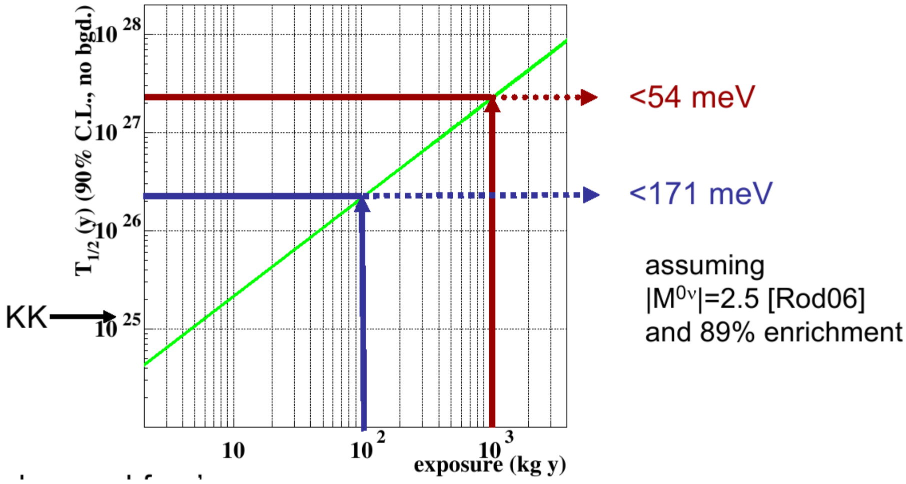

Figure 1. Achievable $T_{1/2}$ limit versus exposure in kg·years assuming background free operations. 'KK' indicates the half-life of the HdM claim. The corresponding limits on the effective neutrino mass are indicated and are based on the matrix elements of Ref.[6]. Isotope enrichment of 89% has been assumed.

4. Experimental implementations and background reduction strategies

The Majorana project plans to use arrays of enriched germanium detectors housed in electro-formed copper cryostat's. The shield against external radiation consists of electro-formed copper and lead and housed deep underground to be shielded against cosmic muon interactions. The proposal which is currently under review foresees a staged approach based on 60 kg arrays (60/120/180 kg). The Gerda experiment is located at the LNGS underground laboratory. Bare enriched detectors submerged in high-purity liquid argon serving simultaneously as cooling medium and as shield against external radiation. All 18 kg of enriched germanium crystals which have formerly been used in the HdM and Igex experiment will be used in phase I of Gerda. New detectors will be added in phase II and doubling the target mass to about 40 kg.

The physics goal of both experiments is to first explore the degenerate mass scale, study backgrounds and novel experimental techniques. A letter of intend has been worked out amongst the two collaborations to haven an open exchange of knowledge and technologies and at a later stage to consider to select the best technique and to explore the inverse hierarchy mass range in a joint experiment using about one ton of enriched crystals. Figure 2 displays schematically the two experimental setups.

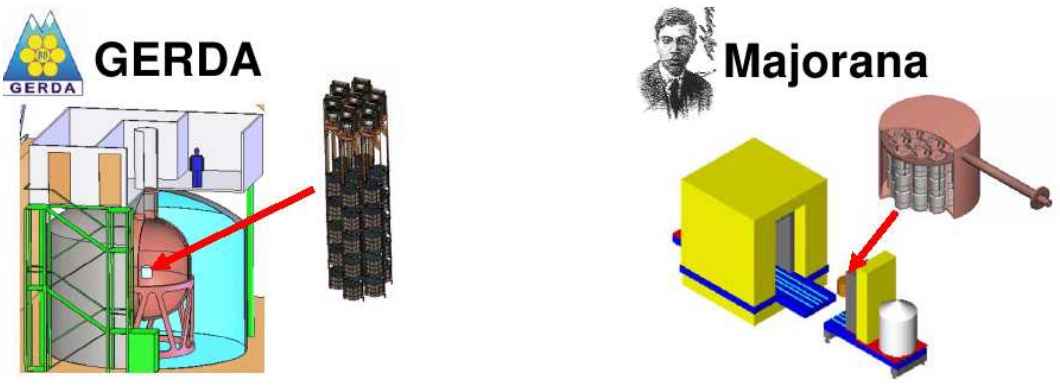

Figure 2. Schematic view of the GERDA and MAJORANAexperiment .

The main difference of the experimental concepts is the shielding against external radiation. While GERDA uses high-purity liquid argon (backup: nitrogen) enclosed in a large water tank, MAJORANA relies on high-purity electro-formed copper with an external lead shield. Given the Z-dependence of muon induced neutron production, MAJORANA requires a greater depth in comparison to GERDA in order to avoid backgrounds induced by neutron capture on ^{76}Ge. Figure 3 summarizes the main backgrounds and reduction strategies.

Source	**Action GERDA**	**Action Majorana**
γ's external to crystals from ^{208}Tl (^{232}Th), ^{214}Bi (^{226}Ra), ^{60}Co,...	Shield: high-purity liquid argon (nitrogen) / water shield	Shield: Electroformed copper, lead
Front-end electronics	ASIC (77/85° K)	Discrete low-level design
μ induced prompt signals	Underground location LNGS (3400 mwe); Water Cherenkov μ-veto	Underground location >4500 mwe; plastic scintillator μ-veto
μ induced delayed signals (e.g. n+^{76}Ge$\rightarrow$^{77}Ge$\xrightarrow{53s}$ ^{77}As	Low-Z material shield (Ar/water)	high-Z shield: deep under-ground location >4500 mwe
Internal to crystal: cosm. ^{60}Co ($t_{1/2}$= 5.27 y)	Minimize time above ground after crystal growing (30d$\rightarrow$2.5$\cdot$10^{-3} cts/(keV kg y)	same
Internal to crystal: cosm. ^{68}Ge ($t_{1/2}$= 270 d)	Minimize time above ground after end of enrichment; shielded transp. container (180d$\rightarrow$12$\cdot$10^{-3} cts/(keV kg y)	same 6

Figure 3. Backgrounds and reduction strategies of GERDA and MAJORANA.

5. Novel background suppression methods

Despite careful selection of the material in close vicinity of the detectors, residual background events are expected. In particular isotopes induced by cosmic ray interactions during detector operations above ground are are of major concern. Novel background suppression techniques will be employed using the characteristic signature of $0\nu\beta\beta$ signal and background events. Interactions which lead to background events typically have an initial energy which is higher than $Q_\beta\beta$. Different to $0\nu\beta\beta$ events, which are point-like on the scale of the crystal dimension, background events have energy depositions at several sites inside as well as outside of the crystals. This signature can be used for background suppression by analyzing the pulse shape of the charge signal, by segmenting of the electrodes of the diode, by anti-coincidence amongst crystals in an array, or by detecting the energy deposition in the surrounding material in case of liquid argon [7]. Figure 4 shows results from prototype measurement of a bare crystal operated in liquid argon detecting the scintillation light with a photomultiplier tube.

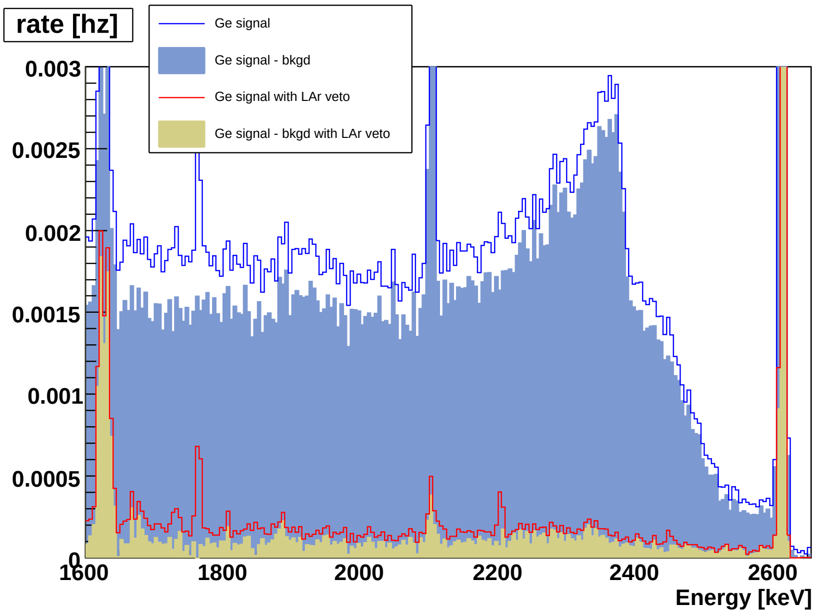

Figure 4. Background suppression of the 2.614 MeV Compton continuum from an ^{228}Th source external to the crystal using the liquid argon scintillation light as veto signal. The Compton spectrum at $Q_\beta\beta$ has been suppressed by a factor of 20 limited by the size of the setup [8].

6. Outlook

The GERDA experiment is under construction in Hall A of the LNGS. 18 kg of enriched crystals are prepared for operations in phase I of GERDA. Detector commissioning is planned for 2008. The DOE Office of Nuclear Physics has identified $0\nu\beta\beta$ as a mission need, and approved Majorana to pursue R&D and to prepare for a Conceptual Design Review (CDR). The site under consideration is SNOlab or DUSEL with a required depth larger than 4500 mwe.

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