Towards a background-free $\beta\beta$-decay experiment using the EDELWEISS cryogenic Ge detectors

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Abstract. The present generation of double-beta experiments is limited by two main backgrounds : surface alpha interactions and Compton interactions from high-energy gamma-ray lines. Using the detector developments realized for the EDELWEISS Dark Matter experiment, we propose a strategy to eliminate completely the alpha radioactivity background and to reduce by nearly two orders of magnitude the Compton background. This would lead to a nearly background-free experiment, and an effective neutrino mass sensitivity of 15 meV achieved in three years with a one-ton array of ionisation-heat ^{76}Ge detectors. In a first stage, the existence of the double-beta 0-ν Heidelberg candidate could be tested in a few years in the EDELWEISS-II cryostat.

1 Introduction

Over the last few years, the Superkamiokande, the SNO and the Kamland experiments have allowed to establish with good confidence that neutrinos are massive. Although cosmological constraints imply that neutrinos are unable to represent the solution to the Dark Matter enigma [1], understanding the neutrino mass hierarchy appears as one of the key problems of contemporary physics. In this respect, the observation of neutrinoless double-beta decay would provide a unique tool to access an effective electron neutrino mass below 100 meV [2], inaccessible to direct measurements.

Here, we want to show that a large-scale (several hundred kilograms) cryogenic germanium experiment, using developments realized for the EDELWEISS Dark Matter search, could lead to a nearly background-free double-beta decay experiment, able to reach a sensitivity on the effective neutrino mass of $\sim$ 15 meV for a measurement time of three years. The zero-neutrino double beta decay of a ^{76}Ge nucleus is detected by the observation of two electrons, usually indistinguishable in solid state detectors due to their limited range (a fraction of a millimeter), at a total energy of approximately 2039 keV. For present generation germanium double beta decay experiments, until now the best competitors for double-beta decay [3,4], the limitations originate from alpha tails associated with surface alpha contamination, and from Compton interactions associated with the high energy gamma-ray background, both populating rather uniformly the high-energy region around 2 MeV. The allowed 2-ν double-beta decay also represents a background, and an excellent energy resolution is necessary to limit the contribution of this process to the signal searched.

In the following, we discuss the strategies followed by the main present $\beta\beta$-decay experiments together with the novel features brought by a dedicated enriched ^{76}Ge cryogenic experiment.

2 Strategies for tonne-scale $\beta\beta$-decay experiments

Beyond the present generation of experiments, with GENIUS-TF [5], NEMO-III [6] and CUORICINO [7] as the main contenders, several strategies have been proposed for third generation experiments with a total mass of source material in the 100 kg to 1 tonne range.

The GENIUS project [8], proposing two stages with 1 ton and 10 tons of enriched ^{76}Ge detectors, has based its approach on the excellent germanium purity. The analysis of data accumulated over several years in the Heidelberg-Moscow experiment indicated that the most prominent contributions to the background originated from the copper structure surrounding the detectors. Therefore, GENIUS intends to reduce the surrounding materials to a minimum, and the proposed shielding is made by a 13 m diameter tank of ultrapure liquid nitrogen. Prototype detectors have been operated successfully in liquid nitrogen with FETs deported at distances of up to several meters, with energy resolutions comparable or even better than those obtained with conventional detectors. However, to be able to measure an effective neutrino mass of $\sim$ 20 meV or below, the radioactive background of a 0-ν double-beta decay experiment must be reduced, by reference to the best existing detectors, by three orders of magnitude. Similarly to the Heidelberg-Moscow experiment [4], pulse shape discrimination (PSD) techniques will be applied and will be used to identify a significant fraction of the alpha and multisite events.

According to the GENIUS proponents, the main limiting factors are therefore the radioactivity of all other materials than the germanium target. The internal radioactivity of germanium itself, resulting from cosmogenic activation, and most notably ^{68}Ge, is then the second most prominent background. The success of GENIUS requires that all materials other than liquid nitrogen and germanium are of limited mass and radioactively ultrapure. These additional components (wiring, charge collection electrodes, etc.) must contribute for less than typically 0.1% of the present contribution to the background of the Heidelberg-Moscow experiment. This level of extrapolation requires an intermediate test, which is presently attempted with the GENIUS-TF facility, using a total of 14 HPGe-detectors with a total active mass of $\sim$ 40 kg. Underground crystal fabrication is explored, as this would reduce the ^{68}Ge activation by one to two orders of magnitude (depending on the fabrication site and transport duration to the Gran Sasso deep-underground laboratory).

The same collaboration has tested in the Heidelberg Dark Matter Search (HDMS) experiment [9] the concept of anticompton detector. A small germanium crystal is almost completely surrounded by a well-type germanium detector. For single site energy deposition events, such as WIMP or double-beta decay, the Compton background can be suppressed using the anticoincidence between the internal and external crystals. Extensive tests of the HDMS detector have shown that the anticoincidence at high energies reached a factor $\sim$ 20, while at low energies the ancoincidence rejection factor was limited to $\sim$ 2-4 in the energy interval relevant for Dark Matter search. Although this strategy can hardly be extended to a tonne-scale experiment, the results of the HDMS experiment show that relatively large anticompton rejection factors can be obtained in a very compact geometry with individual detector mass in the few hundred gram range. This result will be relevant for the following discussion.

Based on the developments realized in the International Germanium Experiment (IGEX) collaboration [3], the Majorana project [10] has reached a different conclusion on the main limiting background for 0-ν double-beta decay. The cosmogenic activation of ^{68}Ge, with lifetime $T_{1/2}$ = 271 days, and ^{60}Co with a lifetime of 5.271 years, are considered as the main backgrounds, and radon contamination is also considered as a significant background in the high-energy signal region ($\sim$ 2.039 MeV).

The CUORICINO experiment [7], test stage of the CUORE experiment [11], is using an original and different approach. Using a compact structure of 44 $\times$ 760 g modules and 18 $\times$ 340 g TeO_2 bolometric detectors, operated at T $\sim$ 10 mK, this experiment presents a total target mass of $\sim$ 40 kg. The cosmogenic activation is not a problem here since radioactive isotopes of oxygen and tellurium are short-lived. The main problem encountered by the CUORICINO experiment appears to be related to the alpha contamination of the crystal surface and of the copper and teflon structures facing the detectors. Although the U/Th contamination can be kept at very low levels, surface implantation of heavy nuclear elements by radon disintegration appears as a major problem and is extremely difficult to control at the level required to reach the target sensitivity of the CUORE and GENIUS experiments. Although this might not be a problem for the GENIUS experiment due to the passivation of a large fraction of the crystal surface, these surface implantations lead in the CUORE experiment to a continuous background overlapping the 0-ν double-beta decay energy region.

Therefore, the techniques presently developed in the main double-beta decay experiments require an extropolation by several orders of magnitude in their background performances to be able to reach a negligible background level in the signal region of 0-ν double-beta decay for a tonne-scale experiment.

3 Cryogenic germanium detectors : experimental strategy

It may seem that the difficulty of operating cryogenic detectors at very low temperatures is an important drawback, only justified by their excellent discrimination properties between nuclear recoils and electron recoils. But double beta decay involves electron recoils, not nuclear recoils while, as noted previously, the two main backgrounds are represented by surface alpha interactions and Compton interactions from high-energy gamma-ray lines.

3.1 Alpha contamination

The cryogenic germanium charge-phonon detectors developed in the EDELWEISS Dark Matter experiment can get rid of the alpha background very efficiently through the simultaneous measurement of the charge and phonon signals [12]. Surface alpha particles have, compared to bulk electron recoils, a lower charge-to-phonon ratio which makes them easily identifiable. At MeV energies, this separation is nearly perfect. This important background, presently the main

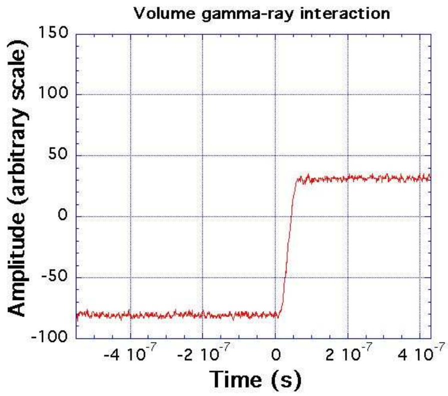

Fig. 1. Single 1.33 MeV ^{60}Co γ-ray event as recorded on the electrode of a prototype Ge detector, 20 mm diameter and 10 mm thick.

background for the MIDBD and CUORICINO experiments [13,7], would then be completely eliminated in our setup. More generally, all interactions occurring close to the surface are identified by their anomalous charge/phonon ratio (~ 0.5). Alpha contaminations in the bulk of germanium detectors and in the energy region of interest (approximately 2 MeV) are expected to be negligible and identified by their total energy. Even in this case, a pulse shape analysis of the fast risetime structure of the charge signal has shown that alphas can easily be discriminated from minimum ionizing tracks. Figs. 1 and 2 illustrate this discrimination on single γ-ray and alpha interactions.

3.2 Gamma-ray background

High-energy gamma-ray lines can, through multiple Compton energy deposits, populate rather uniformly the high-energy region around the double-beta decay Q value. The anti-Compton strategy, studied in recent years by the HDMS well-type germanium detector [9], can be further extended in a cryogenic germanium

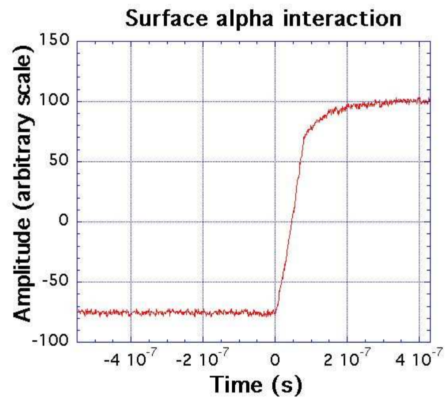

Fig. 2. Single 5.49 MeV alpha surface interaction from an ^{241}Am source. Time scale, amplitude scale and data taking conditions are identical to those of Fig 1. Note the larger collection time for the alpha surface interaction compared to the volume γ-ray interaction, and the rounded shape of the current signal for the alpha pulseshape. Also note that the alpha amplitude is quenched by a factor $\sim$ 2.5 due to the incomplete collection at the crystal surface. Collection voltage : -6.4 V, temperature 50 mK.

experiment. It is based here on three complementary aspects. Firstly, a very compact geometrical arrangement of the crystals, each of diameter approximately 100 mm, and 30 mm thick, shaped hexagonally, will be used, with the supporting copper beams of the detector structure only representing of the order of 10% of the total crystal mass. Although challenging, such a compact structure is presently realized in the CUORICINO experiment. Preliminary discussions with Canberra-Eurisys show that such 1-kg Ge crystals can be realized at a reasonable cost. Secondly, the charge signal of each crystal of cylindrical shape will be analyzed at a frequency of 500 Msamples/s. As was shown by Broniatowski et al. [14,15] in developments realized for EDELWEISS, the analysis of the time structure of the charge risetime, typically a few hundred ns for the electric fields used and a 3-cm thick Ge detector, allows a precise determination of the interaction position. The position resolution is presently $\sim$ 1 mm at 122 keV, under conditions where the charge signal develops over a time scale of approximately 250 ns/cm at collection voltages of a few volts/cm. The time structure of a single 122 keV gamma-ray event on both center and guard electrodes of a test Ge detector (real event and best fit from a collection of calculated templates) is shown in Fig. 3, illustrating the previous statement. Electronics developments realized for the CERN LHC have considerably lowered the cost and power consumption of digitizing means with precision $>$ 10 bits and $>$ 500 Msamples/s [16]. In addition, further improvements, by a factor $\sim$ 3, in the charge signal/noise ratio are expected through the use of specific ultra-low noise ($\sim$ 0.2 nV/$\sqrt{Hz}$ at frequencies $> 10^5$ Hz) GaAs HEMTs operating at 4 K and developed at the LPN Marcoussis [17,18]. Thirdly, the charge signal would be analysed on several

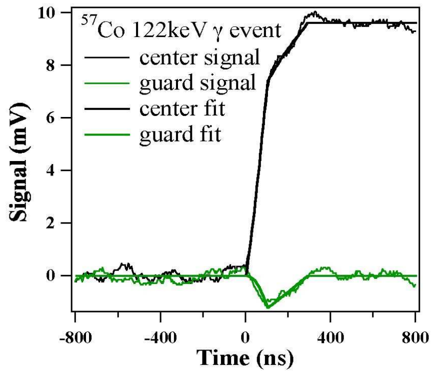

Fig. 3. Single 122 keV γ-ray event as recorded on the center and guard electrodes of a prototype Ge detector 10 mm thick. Best fits according to pulseshapes predicted by simulation superimposed. Collection voltage : 6.2 V, temperature 16 mK (from Ref. [14])
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(typically 5 to 10) electrodes, similarly to the Majorana project [10]. Based on the present performances of our prototypes, the combined time structure of the charge signals on these electrodes is expected to constrain the position of the interaction to 0.2 mm along the vertical axis and better than 1 mm in the radial coordinate. The position determination of the interaction in each detector will be used to reject events occurring with multiple energy deposits. For a detector thickness of 3 cm, the anti-Compton rejection factor for multiple interactions occurring in a single detector is then expected to be ~ 100.

Therefore, the essential differences between the classical germanium approach and our proposal relies on several complementary properties :

- firstly, the surface of cryogenic detectors need not be passivated since all surface alpha contaminations can be easily identified through their anomalous charge/phonon ratio ;
- secondly, this absence of passivation allows to use large surface electrodes and to keep the cylindrical symmetry of charge collection, making the fast time analysis of the charge signal much easier to interpret, unlike the classical approach where a large fraction of the surface is passivated ;
- thirdly, the collection field is low, a few volts, in order to reduce the Luke-Neganov dissipation in the detector. The time structure of the charge signal can be approximated to an excellent precision by the sum of two constant currents during the drift of both electrons and holes, and by one constant current after the arrival at the surface of one of the two carrier species. Electron and hole mobilities have been measured and have been shown to be close to each other [14].

In addition, we plan to design a dedicated set of electrodes to optimize the 3-D information of energy deposition inside the detector. Several approaches have been proposed for classical detectors [19–21] and position resolutions of the order of 1 mm have been obtained on prototype detectors (see, e.g., [19]).

4 Neutrino mass sensitivity

The present background rate obtained in the EDELWEISS-I experiment is $\sim$ 1.5 event/kg/keV/day at energies of a few keV, and is $\sim$ 2 event/kg/keV/year at 2 MeV. A one-ton $\beta\beta$-decay experiment would involve the fabrication of germanium crystals and ultrapure copper structure in an underground site, with much reduced U/Th content and cosmogenic activation of all surrounding materials. We make the rather conservative hypothesis that one order of magnitude improvement over the present EDELWEISS-I background performances can be obtained with these precautions. Such background performances are comparable to those of existing small-scale germanium experiments, such as the Heidelberg-Moscow experiment and do not require an important level of extrapolation. These background performances are expected to be met in the EDELWEISS-II experiment.

We also assume a 0.2 millimeter resolution in the determination in the axial coordinate of the interaction, which appears conservative for 30 mm crystals and 2 MeV interactions. Combined with the radial information on all electrodes, and complemented by the compact crystal structure, this results in a factor of the order of 50-100 in the anticompton efficiency. Although probably conservative, this number will have to be estimated more precisely using Monte-Carlo simulations. As a matter of comparison, the anticompton efficiency obtained by the HDMS experiment at MeV energies, with a much coarser resolution, is $\sim$ 20. The energy resolution of bolometers at high energies has been shown by the Milano group to be of the same order or even superior to the energy resolution of conventional germanium detectors at 2 MeV, i.e. approximately 3 keV [22]. At lower energies, EDELWEISS has obtained resolutions better than 0.6 keV on 320 g Ge detectors [23]. We make the assumption of a 3 keV resolution at 2 MeV, which leads to a negligible background from the allowed 2-ν double-beta decays of germanium.

Therefore, with a pessimistic anticompton efficiency of a factor 50, $\sim$ 6 background counts per year and per ton of germanium would remain within the resolution of the 2039 keV double-beta decay peak for an optimized (1.4 σ) peak-over-noise selection. A one-ton enriched ^{76}Ge cryogenic double-beta decay experiment (the mass of the first stage of the GENIUS project) would then be able to propose a nearly background-free double-beta decay measurement, reaching a ν_1 effective mass sensitivity of $\sim$ 15 meV with a 4-σ precision in three years.

As an intermediate stage, we can test our strategy by looking for the 0-ν double-beta decay candidate reported by Klapdor et al. [24]. The statistical significance of this 0-ν candidate has been criticized by Aalseth et al. [25], but a recent analysis [26] appears to confirm the initial claim, albeit at a $\sim$ 2.1 sigma level. This claim could be tested in the next few years using 21×1 kg dedicated ^{76}Ge detectors operated in the EDELWEISS-II cryostat.

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