Feasibility study of the observation of the neutrino accompanied double beta-decay of $^{76}\text{Ge}$ to the $0^+_1$-excited state of $^{76}\text{Se}$ using segmented germanium detectors

K. Kröninger\textsuperscript{a}, L. Pandola\textsuperscript{b,\*}, V. I. Tretyak\textsuperscript{c}

\textsuperscript{a}Max-Planck-Institut für Physik, München, Germany
\textsuperscript{b}INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
\textsuperscript{c}Institute for Nuclear Research, Kiev, Ukraine

Abstract

Neutrino accompanied double beta-decay of $^{76}\text{Ge}$ can populate the ground state and the excited states of $^{76}\text{Se}$. While the decay to the ground state has been observed with a half-life of $1.74^{+0.18}_{-0.16} \times 10^{21}$ years, decays to the excited states have not yet been observed.

Nuclear matrix elements depend on details of the nuclear transitions. A measurement of the half-life of the transition considered here would help to reduce the uncertainties of the calculations of the nuclear matrix element for the neutrinoless double beta-decay of $^{76}\text{Ge}$. This parameter relates the half-life of the process to the effective Majorana neutrino mass.

The results of a feasibility study to detect the neutrino accompanied double beta-decay of $^{76}\text{Ge}$ to the excited states of $^{76}\text{Se}$ are presented in this paper. Segmented germanium detectors were assumed in this study. Such detectors, enriched in $^{76}\text{Ge}$ to a level of about 86\%, will be deployed in the GERDA experiment located at the INFN Gran Sasso National Laboratory, Italy. It is shown that the decay of $^{76}\text{Ge}$ to the 1122 keV $0^+_1$-level of $^{76}\text{Se}$ can be observed in GERDA provided that the half-life of the process is in the range favoured by the present calculations which is $7.5 \times 10^{21}$ y to $3.1 \times 10^{23}$ y.

Key words: Segmented germanium detectors, double beta-decay, nuclear matrix elements

PACS: 23.20.Lv, 23.40.-s, 27.60.+j

* INFN, Laboratori Nazionali del Gran Sasso, S.S. 17 bis km 18+910, I-67100 L'Aquila, Italy. Telephone number: +39 0862 437532, Fax number: +39 0862 437570

Email address: pandola@lns.infn.it (L. Pandola).
1 Introduction

The recent observation of flavor oscillations in experiments with atmospheric, solar, reactor and accelerator neutrinos has revealed a non-zero neutrino mass. Being sensitive only to the differences of the neutrino masses, oscillation experiments yield no information about the absolute neutrino mass scale or about the nature of the neutrino, namely if it is a Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$) particle. Both aspects can be probed by neutrinoless double beta-decay ($0\nu\beta\beta$), a process in which a nucleus of mass $A$ and charge $Z$ transforms into a nucleus with the same mass and charge $Z + 2$ under the simultaneous emission of two electrons only. This process violates lepton number conservation by two units and is only possible if the neutrino is a massive Majorana particle. While $0\nu\beta\beta$-decay is not part of the Standard Model (SM), it is predicted in many SM extensions, in particular in grand unified theories (GUTs) and supersymmetric (SUSY) models (see the latest reviews on double beta decay \cite{1} and references therein). Consequently, $0\nu\beta\beta$-decay is sensitive to different theoretical parameters such as the neutrino mass, lepton violation constants, right-handed admixtures in the weak currents, the mass of a right-handed $W_R$ boson and/or other theoretical parameters, depending on the assumed model. Even the non-observation of $0\nu\beta\beta$-decay constrains the parameters of various SM extensions and narrows the variety of theoretical models. The nuclear matrix element (NME) which describes the nuclear transition of the decay is also relevant. If $0\nu\beta\beta$-decay is observed, the accuracy of the derived theoretical parameters (e.g. the effective Majorana neutrino mass) also depends on the accuracy of the NME calculation. The spread between the calculations of NMEs performed with different methods is still large, and a massive effort is being devoted to this issue. The current theoretical status and the evidence of non-vanishing neutrino masses from neutrino oscillation experiments give a strong motivation for the experimental search for $0\nu\beta\beta$-decay.

Since the first double beta-decay experiment in 1948 \cite{2} the $0\nu\beta\beta$-decay process is still undetected. The current claim of discovery of $0\nu\beta\beta$-decay of $^{76}$Ge with a half-life of $T_{1/2} = 1.2^{+3.0}_{-0.5} \cdot 10^{25}$ y \cite{3} (3 $\sigma$-range) has been widely discussed and still has to be confirmed by other experiments. Today’s best limits on the half-life are of the order of $10^{24}$ y for $^{130}$Te \cite{4} and $^{136}$Xe \cite{5}, and $10^{25}$ y for $^{76}$Ge \cite{6,7}. For about ten other nuclei today’s best limits on the half-life are of the order of $10^{21} - 10^{23}$ y (see compilations \cite{8,9,10}).

The neutrino accompanied double beta-decay ($2\nu\beta\beta$) is a nuclear transition $(A, Z) \rightarrow (A, Z + 2)$ which is accompanied by two electrons and two anti-neutrinos. Such a decay conserves lepton number and is predicted by the SM.
As it is a second-order weak process it has an extremely long half-life. The measurement of $2\nu\beta\beta$-decay plays an important role in helping to fix the nuclear model parameters, in particular the particle-particle strength parameter, $g_{pp}$, in quasi-particle random phase approximation (QRPA)-models [11]. Complementary information can be extracted from the measurement of the rate of $2\nu\beta\beta$-decay to the excited states of the daughter nucleus. The probabilities of these transitions have a different dependence on $g_{pp}$ than the transition to the ground state [12,13]. Thus, different aspects of the nuclear models can be investigated. The observation of transitions to the excited states can help to constrain the parameter space in the calculation of NMEs and could hence improve the accuracy of the calculation of the NME for the $0\nu\beta\beta$-decay process. Such an improvement is particularly interesting for $^{76}$Ge because of the recent claim of discovery of $0\nu\beta\beta$-decay [3].

The refinement of experimental methods over the last twenty years resulted in the observation of $2\nu\beta\beta$-decay. Nowadays, $2\nu\beta\beta$-decay has been observed in ten isotopes: $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, $^{128}$Te, $^{130}$Te, $^{150}$Nd, and $^{238}$U, with half-lives in the range of $10^{18} \sim 10^{21}\text{ y}$ [8,9,10].

$2\nu\beta\beta$-decay to excited states is phase-space suppressed. In only two cases the $2\nu\beta\beta$-decay to the first excited $0^+\text{I}$-state of the daughter nuclei has been observed, i.e. $^{100}$Mo with a half-life in the range of $T_{1/2} = (5.7 - 9.3) \cdot 10^{20}\text{ y}$ [14] and $^{150}$Nd with a half-life of $T_{1/2} = (1.4^{+0.4}_{-0.3}\text{ (stat.)} \pm 0.3\text{ (syst.)}) \cdot 10^{20}\text{ y}$ [15].

In this paper a study of the feasibility to detect the $2\nu\beta\beta$-decay of $^{76}$Ge to the $0^+_1$-excited state of $^{76}$Se is presented. The study is performed in the context of the GERDA experiment which will use segmented germanium detectors in the second phase of the experiment. The segmentation is the key to the identification of $2\nu\beta\beta$-events. In section 2 the GERDA experiment and the design of the segmented germanium detectors are introduced. Section 3 describes the double-beta decay of $^{76}$Ge. The signature and event selection are discussed in section 4. A Monte Carlo simulation developed in the context of GERDA is used to determine the efficiency of the signal identification as well as the residual background contributions for different segmentation schemes and is described in section 5. In section 6 the sensitivity of the GERDA experiment to this decay process is presented and discussed. It is shown that the theoretical predictions of the half-life are within the experimental reach. Conclusions are drawn in section 7.
2 GERDA and segmented germanium detectors

The GERmanium Detector Array, GERDA [16], is a new experiment which will search for $0\nu\beta\beta$-decay of $^{76}$Ge. It is currently being installed in the Hall A of the INFN Gran Sasso National Laboratory (LNGS), Italy. Its main design feature is to operate germanium detectors directly immersed in liquid argon which serves as cooling medium and as a shield against external $\gamma$-radiation simultaneously. With this setup a background index of $10^{-3}$ counts/(kg·keV·y) in the region of the $Q_{\beta\beta}$-value of 2039 keV is aimed at.

Several background reduction techniques have been developed in the context of GERDA. For the first time in double beta-decay experiments segmented germanium detectors will be deployed. Their potential for the identification of photons has been studied [17,18]. The considered segmentation scheme of the detectors comprises a 3-fold segmentation in the height $z$ and a 6-fold segmentation in the azimuthal angle $\phi$. This scheme is denoted $3_z \times 6_\phi$. Each segment and the core are read out separately. The detectors will be $n$-type true coaxial germanium diodes. They are still under design but expected to have a mass of about 1.6 kg and to be 70 mm high and 75 mm in diameter. This is slightly smaller than the detectors previously operated by the Heidelberg-Moscow [6] and IGEX [7] collaborations. The enrichment in $^{76}$Ge is about 86%. A non-enriched 18-fold segmented prototype detector has been successfully operated and characterized [18,19].

3 $2\nu\beta\beta$-decay of $^{76}$Ge

The $2\nu\beta\beta$-decay of $^{76}$Ge to the ground state of $^{76}$Se was observed in several experiments with a measured half-life in the range of $(0.8 - 1.8) \cdot 10^{21}$ y (see [9] for references). The most precise determination of the half-life was achieved in the Heidelberg-Moscow experiment which yielded a half-life of $T_{1/2} = 1.74^{+0.18}_{-0.16} \cdot 10^{21}$ y [20]. The excited states of $^{76}$Se can also be populated. The level scheme of the double beta-decay of $^{76}$Ge with the lowest energy levels of $^{76}$Se is shown in Fig. [1].

A summary of the calculated half-lives of the $2\nu\beta\beta$-decay of $^{76}$Ge to the excited states of $^{76}$Se is given in Table [1]. The present experimental limits on the half-lives of these transitions are also listed. The limits cannot test the calculations so far. Experimentally, the transition to the $0^+\text{-level}$ is interesting due to the predicted half-life between $7.5 \cdot 10^{21}$ y and $3.1 \cdot 10^{23}$ y. Transitions to the
Fig. 1. Lowest energy levels of $^{76}\text{Se}$ which can be populated in the double beta-decay of $^{76}\text{Ge}$. The energies of the excited states and of the de-excitation $\gamma$-rays are given in keV [21].

$2^+$-levels are suppressed by several orders of magnitude due to the additional change in spin by two units.
Table 1
Calculated half-lives and current experimental limits (90% C.L.) for the $2\nu\beta\beta$-decay of $^{76}$Ge to the $2^+_1$, $0^+_1$- and $2^+_2$-excited states of $^{76}$Se. Four different models were used for the calculation, namely the Hartree-Fock-Bogoliubov model (HFB), the multiple commutator model (MCM), the quasi-particle random phase approximation (QRPA) and the shell model (SM).

| Populated $^{76}$Se level | Calculated half-life [y] and model | Experimental limit half-life [y] |
|---------------------------|-----------------------------------|--------------------------------|
| $2^+_1$ 559.1 keV        | $1.2 \cdot 10^{30}$ SM           | $> 1.1 \cdot 10^{21}$ [23]     |
|                           | $5.8 \cdot 10^{23}$ HFB          | [24]                           |
|                           | $5.0 \cdot 10^{26}$ QRPA         | [25]                           |
|                           | $2.4 \cdot 10^{24}$ QRPA         | [26]                           |
|                           | $7.8 \cdot 10^{25}$ MCM          | [27]                           |
|                           | $1.0 \cdot 10^{26}$ MCM          | [28]                           |
|                           | $(2.4 - 4.3) \cdot 10^{26}$ QRPA | [29]                           |
| $0^+_1$ 1122.3 keV        | $4.0 \cdot 10^{22}$ QRPA         | $> 6.2 \cdot 10^{21}$ [30]     |
|                           | $7.5 \cdot 10^{21}$ MCM          | [27]                           |
|                           | $4.5 \cdot 10^{22}$ QRPA         | [26]                           |
|                           | $(1.0 - 3.1) \cdot 10^{23}$ MCM  | [28]                           |
| $2^+_2$ 1216.1 keV        | $1.0 \cdot 10^{20}$ QRPA         | $> 1.4 \cdot 10^{21}$ [23]     |
|                           | $1.3 \cdot 10^{20}$ MCM          | [27]                           |
|                           | $(0.7 - 2.2) \cdot 10^{28}$ MCM  | [28]                           |
4 Signatures and event selection

4.1 Signatures

The $2\nu\beta\beta$-decay of $^{76}\text{Ge}$ to the $0^+_1$-excited state of $^{76}\text{Se}$ at $E^* = 1122.3$ keV is accompanied by a cascade of $\gamma$-rays. The final state contains two antineutrinos, two electrons and two $\gamma$-rays. Events of this kind are referred to as $2\nu\beta\beta - 0^+_1$-events. The sum energy spectrum of the electrons is continuous with an end-point at $Q_{\beta\beta} - E^* = 917$ keV. The two $\gamma$-rays $\gamma_1$ and $\gamma_2$ are monochromatic with energies of $E_1 = 559.1$ keV and $E_2 = 563.2$ keV, respectively. The directions of the emitted $\gamma$-rays are correlated. This correlation can be described as

$$W(\theta) = \frac{5}{8} \cdot (1 - 3\cos^2\theta + 4\cos^4\theta),$$

where $\theta$ is the angle between $\gamma_1$ and $\gamma_2$ and $W(\theta)$ is the probability density for $\theta$ [31].

4.2 Event selection

In the following, three different event selections are introduced for the identification of $2\nu\beta\beta - 0^+_1$-events. Common to all three selections is the requirement of a triple-coincidence of three detector segments. For the 18-fold segmented detectors under study the two emitted electrons are expected to mostly deposit their energy in the same segment in which the decay took place. The $\gamma$-rays emitted in the decay are expected to interact in different segments due to the longer mean-free path (the interaction length for a 560-keV $\gamma$-ray in germanium is about 2.5 cm). The event selections are listed below in increasing restrictiveness:

- Selection 1: exactly three segments are hit. It is not required that the segments belong to the same crystal;
- Selection 2: exactly three segments are hit. At least one segment must show an energy compatible with $\gamma_1$ or $\gamma_2$;
- Selection 3: exactly three segments are hit. Two segments must show energies compatible with $\gamma_1$ and $\gamma_2$. In this case, the event topology is completely known and it is possible to derive the sum energy spectrum of the two electrons.
5 Monte Carlo simulation

The simulation is performed using the GeANT4-based \textit{MaGe} package which is jointly developed and maintained by the GERDA and Majorana Monte Carlo groups. Details on the experimental setup and the considered physics processes are given in \cite{17}. The simulated GERDA setup includes an array of 21 18-fold segmented germanium detectors. The number of segments in $\phi$ and $z$ is varied.

The energy resolution of each detector segment and the core are assumed to be 5 keV full width at half maximum (FWHM). The energy threshold of each detector segment and the core is assumed to be 50 keV. The assumptions on the energy resolution and the threshold are conservative with respect to the experimental results achieved with an 18-fold segmented germanium prototype detector \cite{18,19}. Given the energy resolution it is not possible to distinguish between $\gamma_1$ and $\gamma_2$. The energy range in the event selections 2 and 3 used for the identification of $\gamma_1$- and $\gamma_2$-candidates is $[E_1 - \text{FWHM}, E_2 + \text{FWHM}]$.

For the simulation of the final state of the $2\nu\beta\beta$-decay the \textit{decay0} code was used. The code takes the angular correlation between the two $\gamma$-rays into account according to Eq. (1). The sum energy spectrum of the two electrons is shown in Fig. 2 (left) as is the angular distribution between the two $\gamma$-rays (right). The distributions are derived from the \textit{decay0} generator.

The $2\nu\beta\beta$-events are uniformly distributed inside the crystals. For each segmentation scheme $10^5$ signal events were generated and the decay products were propagated through the geometry. Background sources were also simulated.

5.1 Signal detection efficiency

The detection efficiency is defined as the fraction of events which pass the event selection. The detection efficiency for the $2\nu\beta\beta - 0^+_1$-process, the signal detection efficiency, depends on the segmentation scheme of the detectors and on the geometry of the detector array (e.g. on the number and positions of the detectors, their distance-of-closest approach and the intermediate material). Table 2 summarizes the signal detection efficiency for a single, segmented \textit{n}-type detector with different segmentation schemes. For the event selection 2 the detection efficiency is shown in Fig. 3 (left) as a function of the number
Fig. 2. Left: Sum energy spectrum of the two electrons emitted in the $2\nu\beta\beta$-decay of $^{76}\text{Ge}$ to the $0^+_{1}$-level of $^{76}\text{Se}$. The expected end-point energy is 917 keV. Right: Distribution of the angular correlation between the two emitted photons. Shown are the values derived from the DECAY0 code (solid histogram) and the theoretical expectation from Eq. 11 (dashed curve).

The efficiency increases with the number of segments until a saturation at around 18 segments is reached.

Table 3 shows the signal detection efficiency for the array of 21 segmented detectors immersed in liquid argon and different segmentation schemes. The efficiencies are larger than those for a single detector because segments of different detectors may be hit. Fig. 3 (right) shows the detection efficiency for this setup as a function of the number of segments per detector for event selection 2. The $2\nu\beta\beta - 0^+_{1}$ selection criteria can also be met in an array of unsegmented detectors by requiring a three-fold detector coincidence. In this case, the detection efficiency is a factor of three smaller than for the reference $3_z \times 6_\phi$ segmentation scheme foreseen for the GERDA detectors. The detection efficiency initially increases with the number of segments per detector and forms a plateau between 8 and 18 segments. For a larger number of segments the probability that more than three segments fire is not negligible and the detection efficiency decreases. Hence, the reference $3_z \times 6_\phi$ segmentation scheme turns out to be well suited for the identification of $2\nu\beta\beta - 0^+_{1}$-events.
Fig. 3. Signal detection efficiency for a single, segmented detector (left) and for an array of 21 segmented detectors (right) as a function of the number of segments for event selection 2.

Table 2
Signal detection efficiency for a single, segmented detector for different segmentation schemes and event selections. Quoted uncertainties are statistical only.

| Number of segments | Efficiency |
|--------------------|------------|
| along $z$ | along $\phi$ | total | Selection 1 [%] | Selection 2 [%] | Selection 3 [%] |
| 3       | 1          | 3   | 4.25 ± 0.07 | 0.64 ± 0.03 | 0.060 ± 0.008 |
| 1       | 3          | 3   | 4.21 ± 0.07 | 0.69 ± 0.03 | 0.08 ± 0.009 |
| 2       | 2          | 4   | 7.07 ± 0.08 | 1.19 ± 0.03 | 0.15 ± 0.01 |
| 3       | 2          | 6   | 11.8 ± 0.1  | 1.86 ± 0.04 | 0.21 ± 0.01 |
| 2       | 4          | 8   | 12.6 ± 0.1  | 2.07 ± 0.05 | 0.22 ± 0.01 |
| 3       | 4          | 12  | 16.2 ± 0.1  | 2.56 ± 0.05 | 0.32 ± 0.02 |
| 3       | 5          | 15  | 17.5 ± 0.1  | 2.67 ± 0.05 | 0.29 ± 0.02 |
| 3       | 6          | 18  | 18.8 ± 0.1  | 2.85 ± 0.05 | 0.32 ± 0.02 |
| 3       | 8          | 24  | 20.1 ± 0.1  | 2.91 ± 0.05 | 0.31 ± 0.02 |
| 4       | 8          | 32  | 21.4 ± 0.1  | 3.03 ± 0.06 | 0.34 ± 0.02 |
Table 3
Signal detection efficiency for an array of 21 segmented detectors for different segmentation schemes and events selections. Quoted uncertainties are statistical only.

| Number of segments | Efficiency |
|--------------------|------------|
|                    | along $z$ | along $\phi$ | total | Selection 1 [%] | Selection 2 [%] | Selection 3 [%] |
| 1                  | 1         | 1             | 1     | 10.4 ± 0.1       | 2.09 ± 0.05     | 0.23 ± 0.01     |
| 1                  | 3         | 3             | 3     | 22.0 ± 0.1       | 4.37 ± 0.07     | 0.56 ± 0.02     |
| 2                  | 2         | 4             | 4     | 23.3 ± 0.2       | 4.48 ± 0.07     | 0.56 ± 0.02     |
| 3                  | 2         | 6             | 6     | 25.7 ± 0.2       | 5.13 ± 0.07     | 0.66 ± 0.03     |
| 2                  | 4         | 8             | 8     | 26.8 ± 0.2       | 5.16 ± 0.07     | 0.64 ± 0.03     |
| 3                  | 4         | 12            | 12    | 27.6 ± 0.2       | 5.30 ± 0.07     | 0.65 ± 0.03     |
| 3                  | 5         | 15            | 15    | 27.9 ± 0.2       | 5.24 ± 0.07     | 0.63 ± 0.03     |
| 3                  | 6         | 18            | 18    | 28.1 ± 0.2       | 5.20 ± 0.07     | 0.61 ± 0.02     |
| 3                  | 8         | 24            | 24    | 28.1 ± 0.2       | 4.95 ± 0.07     | 0.55 ± 0.02     |
| 4                  | 8         | 32            | 32    | 27.6 ± 0.2       | 4.71 ± 0.07     | 0.53 ± 0.02     |
Table 4
Assumed activities for the materials close to the detectors in units of mBq/kg. Note that screening results for materials to be used in GERDA are still pending. The activity of cosmogenically produced $^{68}$Ge and $^{60}$Co are 90 events/(kg·y) and 5 events/(kg·y), respectively. The rate of $2\nu\beta\beta$-decay events is calculated to be less than 3 500 events/(kg·y).

| Isotope      | A(Copper) | A(Teflon) | A(Kapton) | A(Germanium) |
|--------------|-----------|-----------|-----------|---------------|
| $^{238}$U    | 0.016     | 0.160     | 9.0       | -             |
| $^{232}$Th   | 0.012     | 0.160     | 4.0       | -             |
| $^{137}$Cs   | -         | 0.070     | 3.0       | -             |
| $^{68}$Ge    | -         | -         | -         | $2 \cdot 10^{-3}$ (see caption) |
| $^{60}$Co    | 0.010     | 0.000     | 2.0       | $1.6 \cdot 10^{-4}$ (see caption) |
| $^{40}$K     | 0.088     | 15.000    | 130.0     | -             |
| $2\nu\beta\beta$ (g.s.) | -         | -         | -         | 0.111 (see caption) |

5.2 Background

Background to the $2\nu\beta\beta - 0^+_1$-process is produced by the decay of radioactive isotopes inside or in the vicinity of the detectors. These decays were previously simulated in context of the $0\nu\beta\beta$-process using the same simulation code. Considered here are the decays of cosmogenically produced $^{60}$Co and $^{68}$Ge in the crystals as well as the decays of the radioactive isotopes $^{238}$U, $^{232}$Th and $^{60}$Co in the suspension and the cabling. The Monte Carlo data sets are those used in [17] assuming detectors with an 18-fold segmentation. Additional data sets were produced for $^{40}$K and $^{137}$Cs in the corresponding parts close to the detectors. The unavoidable background due to the $2\nu\beta\beta$-process to the ground state of $^{76}$Se is also taken into account. The selection criteria 1–3 were applied to these data sets to estimate the background contribution.

The choice of materials for GERDA is not yet final and material screening results are still pending. The assumed activities are listed in Table 4. Also listed are the activities of cosmogenically produced $^{60}$Co and $^{68}$Ge. The total rate of $2\nu\beta\beta$-decays to the ground state of $^{76}$Se is calculated to be less than 3 500 events/(kg·y) assuming a half-life of $T_{1/2} = 1.74 \cdot 10^{21}$ y.

Each detector is assumed to have a mass of 1.6 kg. A detector holder consists of 31 g copper and 7 g Teflon. The cables for one detector are assumed to be made out of 1.3 g copper and 0.8 g Kapton.

$^{60}$Co events have the highest probability to fake the process under study be-
Table 5
Detection efficiencies for the main background contributions obtained from the Monte Carlo simulation. The efficiencies for $^{238}\text{U}$, $^{232}\text{Th}$, $^{137}\text{Cs}$ and $^{60}\text{Co}$ are set to those of $^{60}\text{Co}$. The efficiency for $^{40}\text{K}$ is that of events from the cables.

| Source                | Selection 1 [%] | Selection 2 [%] | Selection 3 [%] |
|-----------------------|-----------------|-----------------|-----------------|
| Cosmogenic $^{68}\text{Ge}$ | 27.5            | 0.30            | $0.3 \cdot 10^{-3}$ |
| Cosmogenic $^{60}\text{Co}$ | 23.9            | 0.44            | $7.0 \cdot 10^{-3}$ |
| Radioactive $^{60}\text{Co}$ | 16.1            | 0.32            | $3.0 \cdot 10^{-3}$ |
| Radioactive $^{40}\text{K}$ | 0.6             | $7.0 \cdot 10^{-3}$ | $3.0 \cdot 10^{-3}$ |
| $2\nu\beta\beta$ (g.s.) | 0.1             | $2.0 \cdot 10^{-3}$ | $0.3 \cdot 10^{-3}$ |

cause two photons are emitted. As a conservative estimate the detection efficiencies for events from $^{238}\text{U}$, $^{232}\text{Th}$, $^{137}\text{Cs}$ and $^{60}\text{Co}$ are set to those of $^{60}\text{Co}$. The efficiency for $^{40}\text{K}$ is that of events from the cables. The detection efficiencies for all sources of background are summarized in Table 5 for the three event selection criteria. To be conservative the resulting number of background events are multiplied with a factor 1.5. This yields background levels of 170.2 events/(kg·y), 2.7 events/(kg·y) and 0.2 events/(kg·y) for the three event selections, respectively.

6 Sensitivity

The sensitivity is estimated using a statistical analysis method applied to Monte Carlo data from a simulation of the nominal GERDA setup equivalent to an exposure of 100 kg-years.

6.1 Statistical analysis

A Bayesian analysis is used (1) to judge whether the signal process contributes to the number of observed events and (2) to set a limit on the signal contribution in case the requirements for a discovery are not met. The analysis is adopted from that developed in [35] for $0\nu\beta\beta$-decay. Here, no spectral information is used, i.e. only the number of events is used to evaluate a possible signal contribution. In this formalism the prior probability for the signal contribution is chosen to be flat in the number of events up to the current experimental limit which corresponds to a half-life of $T_{1/2} > 6.2 \cdot 10^{21}$ y, and zero otherwise. The background is assumed to be known up to Poissonian fluctuations\footnote{Residual background for selections 2 and 3 can be precisely evaluated by slightly shifting the selection window in energy.}. The
prior probabilities for the hypotheses whether or not the signal process contributes to the data, \( H_2 \) and \( H_1 \), respectively, are assumed to be equal. The discovery criterion is defined as in \([35]\), namely as \( p(H_1) < 10^{-4} \), corresponding to approximately 3.9 \( \sigma \) evidence.

Ensembles of Monte Carlo data were created for fixed signal and background contributions. In case no discovery can be claimed the 90\% probability lower limit on the half-life is calculated. The discovery potential, defined as the half-life for which 50\% of the ensembles can claim a discovery, is calculated for different exposures.

6.2 Results

Table 6 summarizes the discovery potential and the expected lower limit on the half-life which can be set in case no discovery can be claimed. A total exposure of 100 kg-years is assumed. For event selection 2 the sensitivity for the reference segmentation scheme and an array of unsegmented detectors are compared. Event selections 1 and 3 are only applied in the case of the reference segmentation scheme. The signal efficiencies and expected background levels are taken from section 5. The background level for the array of unsegmented detectors is expected to be smaller than that for the array of 18-fold segmented detectors. To be conservative, the background level for the unsegmented detectors is assumed to be the same as for the segmented detectors. For the reference segmentation scheme event selection 2 yields the best performance with a discovery potential of \( T_{1/2} = 1.9 \cdot 10^{23} \) y or a 90\% probability lower limit on the half-life of \( T_{1/2} > 5.6 \cdot 10^{23} \) y. These results are compatible with the range of theoretical predictions (7.5 \( \cdot 10^{21} \) y to 3.1 \( \cdot 10^{23} \) y) and about two orders of magnitude above the present experimental limit of \( T_{1/2} > 6.2 \cdot 10^{21} \) y. For an array of unsegmented detectors the discovery potential and the expected lower limit are lower by a factor of about 2.5.

Fig. 4 shows the expected lower limit on the half-life (left) and the discovery potential (right) for the double beta-decay under study for the GERDA experiment using event selection 2 as a function of the exposure.

7 Conclusions

The study presented indicates the possibility to observe the very interesting neutrino accompanied double beta-decay of \(^{76}\text{Ge}\) to the \( 0^+ \)-excited state of \(^{76}\text{Se}\). The 18-fold segmented germanium detectors to be deployed in the
Discovery potential and expected 90% probability lower limit on the half-life of the 2νββ-decay of 76Ge to the 0+ excited state of 76Se for the three event selections. Detection efficiencies and background levels are taken from section 5. The background for the array of unsegmented detectors is conservatively assumed to be the same as for the array of segmented detectors. A total exposure of 100 kg-years is assumed.

| Event selection | Background level [counts/(kg·year)] | T1/2 discovery potential [y] | T1/2 lower limit (90% prob.) [y] |
|-----------------|-------------------------------------|-----------------------------|---------------------------------|
| Sel. 1 (3z × 6φ) | 170.2                               | 1.3 · 10^{23}               | 3.9 · 10^{23}                   |
| Sel. 2 (3z × 6φ) | 2.7                                 | 1.9 · 10^{23}               | 5.6 · 10^{23}                   |
| Sel. 2 (no segmentation) | 2.7                               | 0.8 · 10^{23}               | 2.2 · 10^{23}                   |
| Sel. 3 (3z × 6φ) | 0.2                                 | 0.7 · 10^{23}               | 2.2 · 10^{23}                   |

GERDA experiment make it possible to tag single photons in an event and thus identify the specific decay. Several event selections and segmentation schemes were studied. The segmentation scheme considered for the GERDA detectors can improve the sensitivity by a factor of about 2.5 compared to unsegmented detectors yielding a best lower limit on the half-life of $T_{1/2} > 5.6 \cdot 10^{23}$ y (90% prob.). This is two orders of magnitude above the present experimental limit. A discovery with 50% probability or better is expected for half-lives up to $1.9 \cdot 10^{23}$ y. This is well within the range favoured by present calculations which is $7.5 \cdot 10^{21}$ y to $3.1 \cdot 10^{23}$ y.

Fig. 4. Expected lower limit on the half-life (left) and the discovery potential (right) for the 2νββ-decay of 76Ge to the 0+ excited state of 76Se for the GERDA experiment using event selection 2 as a function of the exposure. The sensitivity for an array of 18-fold segmented detectors is indicated by the solid line, the sensitivity for an array of unsegmented detectors is represented by the dashed line.
8 Acknowledgments

This work is dedicated to our friends and colleagues M. Altmann and N. Ferrari who prematurely passed away in July, 2006. We express our gratitude to Prof. E. Bellotti for having suggested the possibility to detect the $2\nu\beta\beta$-decay to excited states using the GERDA segmented detectors, and to Iris Abt and Bernhard Schwingenheuer for their helpful comments. We would like to thank R. Henning, J. Detwiler and the other colleagues of the Majorana Monte Carlo group with whom we fruitfully share the development of the MAGE framework. This work has been partially supported by the Ilias integrating activity (Contract RII3-CT-2004-506222) as a part of the EU FP6 program.

References

[1] A. Faessler, F. Simkovic, J. Phys. G 24 (1998) 2139. 
H.V. Klapdor-Kleingrothaus, Int. J. Mod. Phys. A 13 (1998) 3953. 
P. Vogel, in Current Aspects of Neutrino Physics, ed. by D. Caldwell (Springer-Verlag, 2000). 
S.R. Elliott, P. Vogel, Annu. Rev. Nucl. Part. Sci. 52 (2002) 115. 
J.D. Vergados, Phys. Rep. 361 (2002) 1. 
Yu.G. Zdesenko, Rev. Mod. Phys. 74 (2002) 663. 
E. Fiorini, Nucl. Phys. B (Proc. Suppl.) 110 (2002) 233. 
O. Cremonesi, Nucl. Phys. B (Proc. Suppl.) 118 (2003) 287. 
S.R. Elliott, J. Engel, J. Phys. G 30 (2004) R183. 
A.S. Barabash, Phys. At. Nucl. 67 (2004) 438. 
F.T. Avignone III, G.S. King, Yu.G. Zdesenko, New J. Phys. 7 (2005) 6. 
H. Ejiri, J. Phys. Soc. Japan 74 (2005) 2101. 
S. Jullian, C. R. Physique 6 (2005) 778. 
E. Fiorini, Phys. Scripta T 121 (2005) 86. 
S.T. Petcov, Phys. Scripta T 121 (2005) 94.

[2] E. Fireman, Phys. Rev. 74 (1948) 1238.

[3] H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198.

[4] C. Arnaboldi et al., Phys. Rev. Lett. 95 (2005) 142501.

[5] R. Bernabei et al., Phys. Lett. B 546 (2002) 23.

[6] H.V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A 12 (2001) 147.

[7] C.E. Aalseth et al., Phys. Rev. D 65 (2002) 092007.

[8] V.I. Tretyak, Yu.G. Zdesenko, At. Data Nucl. Data Tables 61 (1995) 43.
[9] V.I. Tretyak, Yu.G. Zdesenko, At. Data Nucl. Data Tables 80 (2002) 83.
[10] A.S. Barabash, Czech. J. Phys. 56 (2006) 437.
[11] V.A. Rodin, A. Faessler, F. Simkovic, P. Vogel, Nucl. Phys. A 766 (2006) 107.
[12] J. Suhonen, O. Civitarese, Phys. Rep. 300 (1998) 123.
[13] J. Griffiths, P. Vogel, Phys. Rev. C 46 (1992) 181.
[14] A.S. Barabash et al., Phys. Lett. B 345 (1995) 408;
    A.S. Barabash et al., Phys. At. Nucl. 62 (1999) 2039;
    M.J. Hornish et al., Phys. Rev. C 74 (2006) 044314;
    R. Arnold et al. (NEMO Collaboration), Nucl. Phys. A 781 (2007) 209.
[15] A.S. Barabash, F. Hubert, P. Hubert and V. I. Umatov, Phys. Atom. Nucl. 67 (2004) 1216 [Yad. Fiz. 67 (2004) 1238].
[16] I. Abt et al., GERDA Proposal 2004, http://www.mpi-hd.mpg.de/ge76;
    S. Schönert et al., Nucl. Phys. B (Proc. Suppl.) 145 (2005) 242.
[17] I. Abt et al. (GERDA Collaboration), Nucl. Instr. Methods A 570 (2007) 479.
[18] I. Abt et al., arXiv:nucl-ex/0701005 submitted to Nucl. Instrum. Methods A.
[19] I. Abt et al., arXiv:nucl-ex/0701004 submitted to Nucl. Instrum. Methods A.
[20] C. Dörr, H.V. Klapdor-Kleingrothaus, Nucl. Instrum. Methods A 513 (2003) 596.
[21] R.B. Firestone et al., Table of isotopes, 8-th ed., John Wiley, New York, 1996 and CD update, 1998.
[22] W.C. Haxton, G.J. Stephenson, Jr., Prog. Part. Nucl. Phys. 12 (1984) 409.
[23] A.S. Barabash, A.V. Derbin, L.A. Popeko, V.I. Umatov, Z. Phys. A 352 (1995) 231.
[24] S.K. Dhiman, P.K. Raina, Phys. Rev. C 50 (1994) 2660.
[25] O. Civitarese, J. Suhonen, Nucl. Phys. A 575 (1994) 251.
[26] S. Stoica, I. Mihut, Nucl. Phys. A 602 (1996) 197.
[27] M. Aunola, J. Suhonen, Nucl. Phys. A 602 (1996) 133.
[28] J. Toivanen, J. Suhonen, Phys. Rev. C 55 (1997) 2314.
[29] J. Schwieger, F. Simkovic, A. Faessler, Phys. Rev. C 57 (1998) 1738.
[30] S.I. Vasil’ev, A.A. Klimenko, S.B. Osetrov, A.A. Smolnikov, JETP Lett. 72 (2000) 279.
[31] R.D. Evans, The atomic nucleus, McGraw-Hill (1955).
[32] Geant4 Collaboration, S. Agostinelli et al., Nucl. Instrum. Methods A 506 (2003) 250;
    Geant4 Collaboration, J. Allison et al., IEEE Trans. Nucl. Sci. 53 (2006) 270.
[33] M. Bauer et al., Journal of Physics, Conf. Series 39 (2006) 362.
[34] O.A. Ponkratenko et al., Phys. Atom. Nucl. 63 (2000) 1282 and
    arXiv:nucl-ex/0104018.
[35] A. Caldwell, K. Kröninger, Phys. Rev. D 74 (2006) 092003.