Search for $\beta\beta$ decay of $^{76}$Ge to the excited states in $^{76}$Se

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Abstract. Lower limits on the half-life of the $\beta\beta(2\nu + 0\nu)$ decay of $^{76}$Ge to the excited states in $^{76}$Se have been obtained using the results of low-background measurements with a HPGe detector surrounded by passive germanium shielding: $T_{1/2}(0^+ \rightarrow 2^+_1) > 1.1 \cdot 10^{21}$ y, $T_{1/2}(0^+ \rightarrow 0^+_1) > 1.7 \cdot 10^{21}$ y, $T_{1/2}(0^+ \rightarrow 2^+_2) > 1.4 \cdot 10^{21}$ y.

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1 Introduction

Research in double-beta decay is currently very attractive given the potential to study the physics beyond the standard model. Progress in low-background techniques and steadily increasing supply of $\beta\beta$ decay candidates compliment this research. Advances in terms of new constraints for particle physics, such as those on the effective Majorana neutrino mass and the right-handed current contributions to the weak interactions, carry much of the appeal in the field of double-beta decay while $\beta\beta(2\nu)$ decay research provides a continuing probe of the standard model. The $\beta\beta(2\nu)$ decay helps to improve the understanding nuclear physics aspect of $\beta\beta$ decay and to check the validity of theoretical schemes to calculate nuclear matrix elements.

The increased interest in $\beta\beta$ decay of atomic nuclei applies not only to transitions to the ground state but also to the excited states in daughter nuclei. Right-handed currents for instance can be probed with the $\beta\beta(0\nu)$ decay to the $2^+$ state of the daughter nucleus, while the $\beta\beta(0^+ \rightarrow 0^+_1)$ channel provides another mode to obtain the same information as from explorations of transitions to the ground state.

Probabilities of $\beta\beta$ transitions to the excited states are substantially smaller than those to the ground state principally due to smaller phase space considerations. To the first approximation the probability of the $\beta\beta(2\nu)$ decay is proportional to the $11^{th}$ power of the transition energy, Q. For the $\beta\beta(0\nu)$ decay it is proportional to the $5^{th}$ power of Q (massive neutrino) and to the $7^{th}$ power of Q (right handed currents and majoron emission). Because of this, the search for $\beta\beta$ decay to the excited states did not find any enthusiastic response among experimentalists. However, recently it was shown [1] that using modern low-background facilities utilizing high purity germanium (HPGe) detectors the $\beta\beta(2\nu)$ decay of $^{100}$Mo, $^{96}$Zr, and $^{150}$Nd to the $0^+_1$ level could be observed. These nuclei are particularly attractive candidates because of the large energies involved in the $\beta\beta$ transition to the $0^+_1$ level for these nuclei (1903, 2202 and 2627 keV respectively) coupled with modest half-lives of the order of $10^{20} - 10^{21}$ y. To date an experiment with approximately 1 kg of $^{100}$Mo and a 100 cm$^3$ HPGe detector has measured a $\beta\beta(2\nu; 0^+ \rightarrow 0^+_1)$ decay half-life of $T_{1/2} \approx 10^{21}$ y [2].

Additionally, the $\beta\beta(2\nu)$ decays to the $2^+$ excited states, as indicated in papers [3-4], were considered to be strongly suppressed with respect to the transition to the ground state, but recently [5] it has been shown that the suppression factor is smaller and it is possible to detect this decay mode by modern low background experiments. Therefore the study of $\beta\beta$ transitions to the excited states has become important and interesting.

In $^{76}$Ge the $\beta\beta$ decay to the ground state releases 2038.6 keV and transitions to excited states give much less decay energy. For instance the transition to the $0^+_1$ level yields 917.3 keV. If nuclear matrix elements are considered the same for $\beta\beta(2\nu)$ transitions as to the ground state as to the $0^+_1$ level then the half-life of the last process can be expected to be $(6 - 9) \cdot 10^{23}$ y, which addresses the range of results of the $\beta\beta$ decay to the ground state in $^{76}$Ge ($0.9 \cdot 10^{21}$ y [6-7] and $1.42 \cdot 10^{21}$ y [8]).

In this paper results for $\beta\beta$ decay search of $^{76}$Ge to the excited states in $^{76}$Se are presented. The decay scheme for the triplet $^{76}$Ge - $^{76}$As - $^{76}$Se is shown in Fig. 1. The search for $(0^+ \rightarrow 0^+_1)$ and other transitions is accomplished by looking for gamma-ray spectral features corresponding to the decay scheme.

2 Experimental setup

Limits on $\beta\beta$ decay of $^{76}$Ge were obtained through studies of background measurements with HPGe detector installed in a low-background environment with a germanium shielding [10]. The intent of the experiment was to study very low backgrounds using the semiconductor germanium as a
passive shielding. The production of the semiconductor germanium is based on the zone refining technique which solves the high purity material problem with a well established technique.

The experimental configuration is shown in Fig. 2. The central part of the apparatus was a vacuum cryostat, in which there was a cavity 390 mm in diameter and 360 mm high. The cavity was surrounded by 80 mm thick mercury. The evacuated cryostat was cooled to liquid nitrogen temperature. The zone refined germanium was formed into trapezoidal blocks with a mass 1.25 kg each and they were used to fill the cavity in a close packing fashion. Before installing the every block surface was etched in the mixture of a fluoric and nitric acids and in a hydrogen peroxide. The total mass of germanium was 200 kg, and mass of $^{76}\text{Ge}$ was 16.1 kg ($1.29 \cdot 10^{26}$ atoms of $^{76}\text{Ge}$). When the HPGGe detector (116 cm$^3$) was transferred from a standard submersible cryostat to germanium cavity, the surface of the detector was also etched, and the central P-type contact was replaced by a special spring germanium contact with a fine gold film deposit. Accordingly the device is unique for measuring the germanium activity.

The shielding of the apparatus beyond the cryostat consisted of a 15 cm of copper, a 2 mm of cadmium, and 30 cm of polyethylene. Above the apparatus there was a scintillation detector with an area 2.5 m$^2$, which generated a cosmic-ray veto signal for the germanium detector. The measurements were carried out in the underground laboratory of the Institute of Nuclear Research (Ukraine), in the Solotvino salt mine at a depth of $\sim 1000$ m w.e.

3 Results and discussion

The total energy spectrum for 1004 hours of exposure was previously published [10]. The main contribution to the background (70%) was found to be due to the cosmogenic $^{68}\text{Ge}$ with a half-life of 280 days. The background in the energy range of $\beta\beta(0v)$ decay for $^{76}\text{Ge}$ (2038.6 keV) was $1.5 \pm 0.5$ counts/(keV-kg-year).

Figure 3 shows the spectrum of the energy range under investigation. The annihilation peak (511 keV) is clearly visible. The energy resolution is 5 keV (FWHM) at 511 keV. The marginal energy resolution is due to the microphonic effects which were only partially removed.

No peak signaling $\beta\beta$ decay of $^{76}\text{Ge}$ appeared at the energies corresponding to the $(0^+ \rightarrow 2^+_1), (0^+ \rightarrow 0^+_1)$ or $(0^+ \rightarrow 2^+_2)$ transitions to $^{76}\text{Se}$. Corresponding limits for the life-time were obtained with a likelihood function. In this technique every bin of the energy spectrum was considered to be Poisson distribution with a mean value equal to the sum of the background and the contributions of gamma-ray signal being investigated. The spectral feature for gamma-line was assumed to have a gaussian form. Backgrounds were taken as constant ($\sim 0.96$ counts/keV) in energy range 530 to 662 keV. For the $(0^+ \rightarrow 0^+_1)$ transition the limit was calculated using two spectral features with energy 559.1 keV and 563.2 keV, and for $(0^+ \rightarrow 2^+_2)$ transition the limit was calculated using the 559.1 and 657.0 keV lines.

Detection efficiencies were calculated by the computer code written to simulate the propagation of low energy electrons and photons through matter. The code was tested and compared to other codes (GEANT3.14 and EGS4). The code...