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# SEARCH FOR $^{76}$Ge AND $^{150}$Nd DOUBLE BETA DECAY TO EXCITED STATES

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New results of an experimental search for two neutrino double beta decay ($2\nu\beta\beta$) of $^{76}$Ge and $^{150}$Nd to excited states of the daughter nuclei are presented. Data from 228 days of measurements performed with four HPGe detectors in the low background laboratory of the Baksan neutrino observatory yield new lower limits $T_{1/2}(0^+ \to 0^+_1) \geq 6.2 \cdot 10^{21}$ y at 90 % C.L. for transition of $^{76}$Ge to $0^+_1$ level of $^{76}$Se and $T_{1/2}(0^+ \to 0^+_1) \geq 1.5 \cdot 10^{20}$ y at 90 % C.L. for transition of $^{150}$Nd to $0^+_1$ level of $^{150}$Sm.

Приводятся результаты экспериментального поиска двухнейтринного двойного бета-распада $^{76}$Ge и $^{150}$Nd на возбужденные уровни дочерних ядер. Анализ данных, набранных за 228 дней измерений с четырьмя HPGe-детекторами в подземной низкофоновой лаборатории БНО ИЯИ РАН, позволил установить новые пределы на периоды полураспада $T_{1/2}(0^+ \to 0^+_1) \geq 6{,}2 \cdot 10^{21}$ лет при 90 % C.L. для $(2\nu\beta\beta)$-перехода $^{76}$Ge на $0^+_1$-уровень дочернего ядра $^{76}$Se и $T_{1/2}(0^+ \to 0^+_1) \geq 1{,}5 \cdot 10^{20}$ лет при 90 % C.L. для $(2\nu\beta\beta)$-перехода $^{150}$Nd на $0^+_1$-уровень дочернего ядра $^{150}$Sm.

## INTRODUCTION

Recent interest in double beta decay ($\beta\beta$ decay) is mostly connected with the neutrinoless mode, because the neutrinoless $\beta\beta$ decay ($0\nu\beta\beta$) is the only practical way to determine the neutrino mass if neutrinos are Majorana particles [1]. This and some other features make the search for neutrinoless $\beta\beta$ decay invaluable for exploring nonstandard model physics. Nevertheless, new results of experimental search for the two neutrino double beta decay ($2\nu\beta\beta$) (transitions to the ground and excited states) yield a better understanding of the nuclear part of double beta decay, and allows one to check theoretical schemes of nuclear matrix element calculations [2, 3].

## 1. EXPERIMENT

The experiment to search for $2\beta$ decay of $^{76}$Ge and $^{150}$Nd with the use of four HPGe detectors is carried out in the framework of the IGEX collaboration in the Baksan underground low-background laboratory of the Institute for Nuclear Research of Russian Academy of Sciences. The laboratory is placed at a depth of 660 m (w.e.). The walls of the low-background chamber are composed from 50 cm low-radioactive concrete, 50 cm dunite and 8 mm steel [4]. Thus, gamma background inside the chamber is reduced by a factor of 100 in comparison with the surrounding rocks. All detectors are placed in a common passive shield which consists of 12 cm of copper, 6 cm of lead sheets, 15 cm of lead bricks, and 8 cm of borated polyethylene. The cosmic ray muon flux at this depth is reduced by a factor of 2000, nevertheless, liquid scintillator active shield is used for additional background reduction. The active shield efficiency was defined as $\approx 93\,\%$. Detailed description of the set-up is given in [4–6].

Conventional NIM electronic devices controlled by PC permit one to have complete information about each event in the detection system, namely, amplitude of a signal from each Ge detector; time of event and active shield trigger signal came in 20 $\mu$s time window.

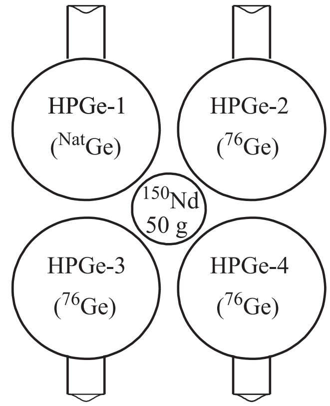



Fig. 1. Top view of the HPGe detector assembly with the $^{150}$Nd sample

Four low-background germanium detectors with masses about 1 kg each are used in the experiment [6]. Three of them have an active mass $\approx$ 0.7 kg and are made of a material isotopically enriched in $^{76}$Ge to 87 %. Detector manufactured from natural germanium has an active mass $\approx 0.99$ kg. All detectors are placed in common passive and active shields. Such a composition of detectors allows us to search for gamma quanta from cascade of $(0^+_1 \to 2^+ \to 0^+)$ transition simultaneously from $^{76}$Ge (escaped from one of the detectors) and $^{150}$Nd (escaped from a sample). A sample of $^{150}$Nd with effective mass 50 g ($\approx$ 60 mm long and $\approx$ 25 mm in diameter) is placed between Ge detectors along the vertical axis of symmetry of the detector assembly. Distances between centres of Ge detectors are 100 mm. Copper cup of each detector has diameter $\approx$ 90 mm and hight $\approx$ 120 mm. Top view of the detector assembly with the $^{150}$Nd sample is shown in Fig. 1. The described composition of detectors has obvious advantages for detecting gamma quanta from cascade of $(0^+_1 \to 2^+ \to 0^+)$ transition in comparison with detector assemblies used in the other long-term experiments of $^{76}$Ge $\beta\beta$-decay searching for. For example, Ge detectors placed inside a common shield have additional individual lead shield for each detector in the experiment [8]. Such screening reduces an efficiency of the multidetector set-up in detecting $\beta\beta$-decay modes with transition to the excited states. Double-beta and gamma-decay schemes of $^{76}$Ge and $^{150}$Nd are presented in Fig. 2, *a, b* respectively. One can see a fine signature of events due to both decay of $^{76}$Ge to $0^+_1$ level of $^{76}$Se and decay of $^{150}$Nd to $0^+_1$ level of $^{150}$Sm.

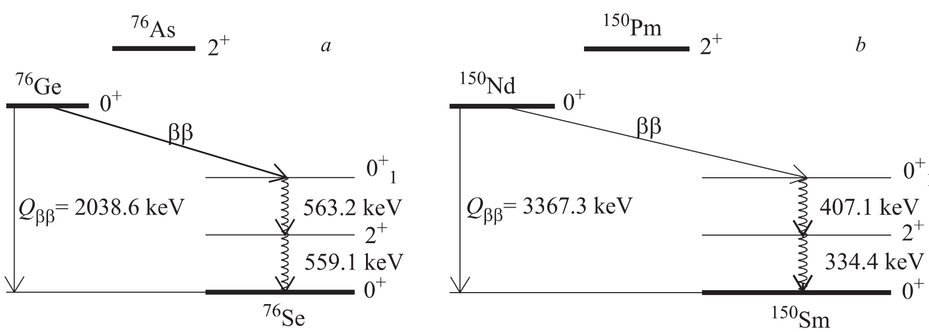
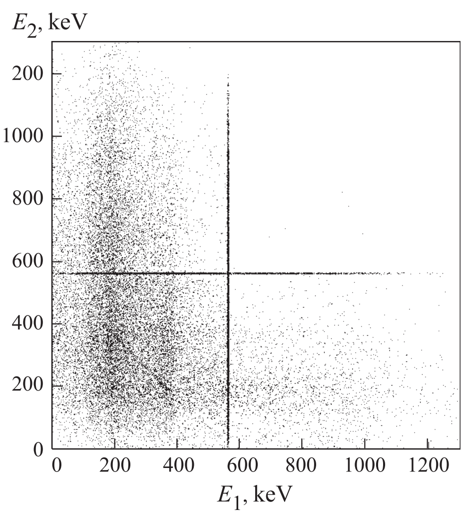



Fig. 2. $^{76}$Ge (*a*) and $^{150}$Nd (*b*) double-beta decay schemes

For $^{76}$Ge $\beta\beta$ decay a sum energy of two electrons is detected by one of the detectors and one or two emitted from the same detector $\gamma$ quanta can be simultaneously detected with a good resolution ($\approx$ 2 keV) in one (or more) of other three detectors. Monte Carlo simulation program based on GEANT code has been used for calculation of effective volumes of the detectors and overall detection efficiencies for different double beta decay modes, as well as for estimation of sensitivity of the experiment for different opportunities of data taking and treatment [7]. It was shown that the highest sensitivity in searching for $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ decay can be achieved in data analysis of a coincidence sum spectrum of any pair of detectors (coincidences between any two spectra from four Ge detectors) [8, 9]. Such two-dimensional coincident spectrum simulated for $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ decay is shown in Fig. 3. Corresponding two-dimensional spectrum accumulated for 228 days in anticoincidence with active shield is shown in Fig. 4. The optimal detection regions (ROIs) for events due to $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ decay are shown in this figure, too. They were obtained as a result of searching for maximum of signal to background ratio taking into account both experimental and calculated spectra. These ROIs correspond to energy regions (556–565) $\times$ (60–916) keV for axis of abscissae ($E1$) and axis of ordinates ($E2$). Total detection efficiency for $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ transition calculated for such data composition in the above determined ROIs was found as 1.7 %.



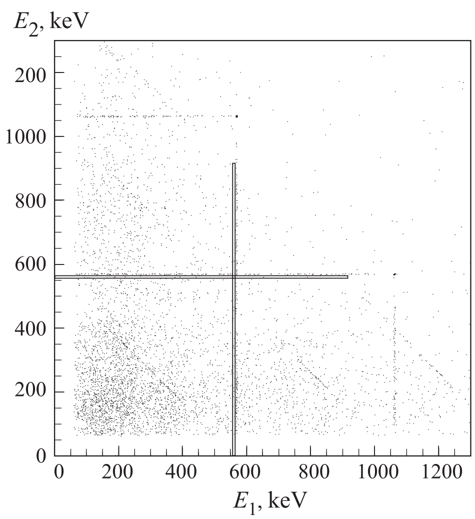




Fig. 3. MC simulated coincidence (of any two from four germanium) spectrum for $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ transition

Fig. 4. Experimental coincidence (of any two from four detectors) spectrum accumulated for 228 days. Boxes mark ROI for $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ transition

Some «event strips» located perpendicularly to axes have been observed in the two-dimensional experimental spectrum (Fig. 5). It was determined that they are due to cascade gamma quanta 570 and 1064 keV from a point-like impurity of $^{207}\mathrm{Bi}$ in the neodymium sample. There is also «diagonal of events» (Fig. 4) corresponding to interaction of gamma quanta with energy 1461 keV from the local impurity of $^{40}\mathrm{K}$ in an inner resistor located inside the cap of one of the detectors. It was possible to perform such localization of the impurities due to detailed analysis of ratio between corresponding gamma-peak areas in partial one-dimensional spectra accumulated from each of four detectors. Because such the ratios depend also on the detector active volumes, the special calibration measurements were performed with the point-like $^{40}$K, $^{60}$Co, $^{137}$Cs and $^{207}$Bi sources located in a lot of different points inside and outside the detector assembly.

The sensitivity optimization procedure performed for the $^{150}\mathrm{Nd}(2\beta, 2\nu + 0\nu)^{150}\mathrm{Sm}(0_1^+)$ transition shows that we can achieve higher sensitivity for this decay in the case of one-dimensional sum spectrum accumulated from all four detectors in comparison with two-dimensional coincidence spectrum. A fragment of the experimental one-dimensional sum energy spectrum of four detectors near the $^{150}\mathrm{Nd}(2\beta, 2\nu + 0\nu)^{150}\mathrm{Sm}(0_1^+)$ region of interest is shown in Fig. 5.

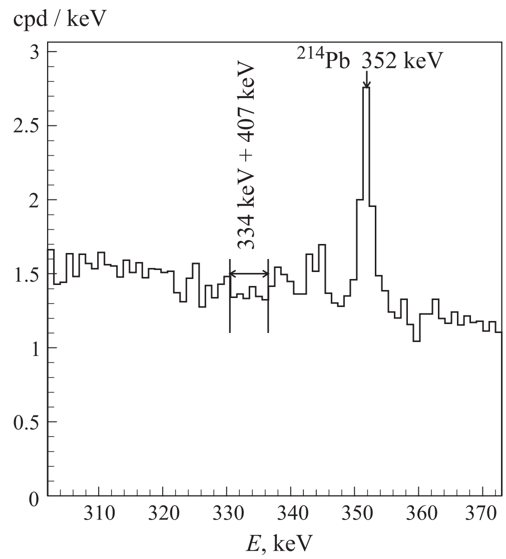



Fig. 5. A fragment of the experimental one-dimensional spectrum near the $^{150}\mathrm{Nd}(2\beta, 2\nu + 0\nu)^{150}\mathrm{Sm}(0_1^+)$ region of interest

## 2. RESULTS

Limits on half-life were obtained by using expression

$$\lim T_{1/2} = \frac{\ln(2) N_0 t \varepsilon}{\sqrt{N_b}},$$

where $N_0$ is the number of $^{76}$Ge ($^{150}$Nd) nuclei, $t$ is the measurement time; $\varepsilon$ is the detection efficiency of events in ROI; $N_b$ is the number of events in the region of interest.

For the case of the $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ transition a total count rate of events is $0.34 \pm 0.04$ cpd in the corresponding two-dimentional ROIs. Statistically significant excess of count rate was not observed in these ROIs in comparison with surrounding regions, and data from 228 day measurements yield a new lower limit: $T_{1/2}(0^+ \to 0_1^+) \geq 6.2 \cdot 10^{21}$ y at 90 % C.L. for the $^{76}\mathrm{Ge}(2\beta 2\nu)^{76}\mathrm{Se}(0_1^+)$ transition. The best previous result for this transition was obtained in work [10], and it is equal to $T_{1/2}(0^+ \to 0_1^+) \geq 1.7 \cdot 10^{21}$ y at 90 % C.L.

The result of a fit of the sum energy spectrum of four detectors in the regions corresponding to gamma lines for $^{150}\mathrm{Nd}(2\beta, 2\nu + 0\nu)^{150}\mathrm{Sm}(0_1^+)$ transition gives a negative value of counts. In such a case Bayes approach [11] gives $\mathbf{N} \leq 50.8$ events in ROI and it corresponds to $0.22 \pm 0.03$ cpd count rate. Applying the procedure recommended by PDG [12] gives 45.0 events in ROI and it corresponds to $0.20 \pm 0.029$ cpd.

Thus, for the $^{150}\mathrm{Nd}(2\beta, 2\nu + 0\nu)^{150}\mathrm{Sm}(0_1^+)$ transition a lower bound on half-life was obtained as: $T_{1/2}(0^+ \to 0_1^+) \geq 1.5 \cdot 10^{20}$ y at 90 % C.L.

For comparison, the best previous result for $^{150}\mathrm{Nd}(2\beta, 2\nu + 0\nu)^{150}\mathrm{Sm}(0_1^+)$ transition was obtained in [13], and it is equal to $T_{1/2}(0^+ \to 0_1^+) \geq 1.0 \cdot 10^{20}$ y at 90 % C.L.

## CONCLUSION

The measurements performed with four HPGe detectors assembly for 228 days of lifetime give us a possibility to obtain new limits for the $^{76}\mathrm{Ge}(2\beta, 2\nu)^{76}\mathrm{Se}(0_1^+)$ and $^{150}\mathrm{Nd}(2\beta, 2\nu + 0\nu)^{150}\mathrm{Sm}(0_1^+)$ transitions. It was found that the main background components are due to $^{40}$K and $^{207}$Bi isotopes located inside the detector cap and in the Nd sample, respectively. Analysis of relative intensity of $^{40}$K and $^{207}$Bi gamma-line peaks yielded the location of these isotopes with good accuracy.

We plan to reduce present level of background by removing the defined impurities with the well-known locations and to increase a sensitivity of the experiment for such decay modes at least by a factor of 3.

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