Pis'ma v ZhETF, vol. 79, iss. 1, pp. 12 – 15

Double beta decay of ^{150}Nd to the first 0^+ excited state of ^{150}Sm

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Submitted 3 November 2003

Two neutrino double beta decay of ^{150}Nd to the first 0^+ excited state in ^{150}Sm is investigated with the 400 cm^3 low-background HPGe detector. Data analysis for 11320.5 hours shows the excess of events at 333.9 keV and 406.5 keV. This allowsto estimate the half-life of the investigated process as $[1.4^{+0.4}_{-0.2}(\mathrm{stat}) \pm \pm 0.3(\mathrm{syst})] \cdot 10^{20}$ yr.

PACS: 23.40.–s

The neutrinoless double beta ($0\nu\beta\beta$) decay is allowed if neutrino mixing, involving the electron neutrino ν_e, is present in the weak charged lepton current and the neutrinos with definite mass are Majorana particles (see, e.g., [1]). Strong evidences for neutrino mixing, i.e., for oscillations of solar electron neutrinos ν_e driven by nonzero neutrino masses and neutrino mixing, have been obtained in the solar neutrino experiments (see review [2]): Davis et al. (Homestake) experiment and in Kamiokande, SAGE, GALLEX/GNO and Super-Kamiokande. These evidences have been spectacularly reinforced during the last two years by the data from the SNO solar neutrino [3 – 5] and KamLAND reactor antineutrino [6] experiments. This very exciting result has greatly renewed the interest in $0\nu\beta\beta$ decay. This process is the most sensitive to possible Majorana nature of the massive neutrinos. Their detection will give the information of the absolute scale of neutrino masses and their type of hierarchy (normal, inverted and quasi-generated), and under specific conditions of the CP violation in the lepton sector (see review [2]).

One of problems in the $0\nu\beta\beta$ decay physics is the reliable evaluation of nuclear matrix elements having the accuracy of a factor of 2–3 up to now. In connection with the $0\nu\beta\beta$ decay, the detection of double beta decay with the emission of two neutrinos ($2\nu\beta\beta$), which is an allowed process of second order in the Standard Model, enables the experimental determination of nuclear matrix elements involved in the double beta decay processes. Accumulation of experimental information for the $2\nu\beta\beta$ processes (transitions to the ground and excited states) promotes a better understanding of the nuclear part of double beta decay, and allows one to check theoretical schemes of nuclear matrix element calculations for the two neutrino mode as well as for the neutrinoless one.

The $\beta\beta$ decay can proceed through transitions to the ground state as well as to various excited states of the daughter nuclide. Studies of the latter transitions allow one to obtain supplementary information about $\beta\beta$ decay [7]. Because of smaller transition energies, the probabilities for $\beta\beta$-decay transitions to excited states are substantially suppressed in comparison with transitions to the ground state. But as it was shown [8], by using low-background HPGe detectors, the $2\nu\beta\beta$ decay to the 0^+_1 level in the daughter nucleus may be detected for such nuclei as ^{100}Mo, ^{96}Zr and ^{150}Nd. In this case the energies involved in the $\beta\beta$ transitions are large enough (1903, 2202 and 2627 keV, respectively), and the expected half-lives are of the order of $10^{20} - 10^{21}$ yr. The sensitivity required for detection was only reached for ^{100}Mo and the transition was detected in the three experiments [9 – 11] with half-life lying within $(6-9) \cdot 10^{20}$ yr. (the average value is $(6.8 \pm 1.2) \cdot 10^{20}$ y [12]. Recently additional isotopes, ^{82}Se, ^{130}Te, ^{116}Cd and ^{76}Ge, have become of interest to studies of the $2\nu\beta\beta$ decay to the 0^+_1 level too (see review [13]).

Theoretical estimates of the $2\nu\beta\beta$ decay to a 2^+ excited state have shown that for a few nuclei (^{82}Se, ^{96}Zr, ^{100}Mo, and ^{130}Te) the half-lives can be $\sim 10^{22} - 10^{23}$ yr. [7]. This would mean that the detection of such decays becomes possible using the present and new installations in the near future.

It is very important to note that in the framework of QRPA models the behaviour of nuclear matrix elements with g_{pp} parameter is completely different for transitions to the ground and excited (2^+ and 0^+) states [7, 14]. This is why the decay to excited states may probe different aspects of the calculational method than the decay

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to the ground states. So the search for $\beta\beta$ transitions to the excited states has its own special interest.

In this article, results of an experimental investigation of the $\beta\beta$ decay of ^{150}Nd to the first 0^+ excited state in ^{150}Sm are presented. The decay scheme is shown in Fig.1. A search for $\beta\beta$ transitions of ^{150}Nd to the first 0^+ excited state in ^{150}Sm has been carried out using a germanium detector to look for γ-ray lines corresponding to the decay scheme.

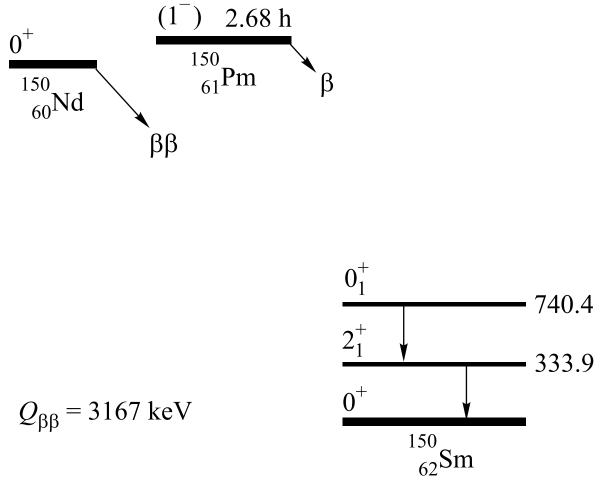

Fig.1. Decay scheme of ^{150}Nd. Energies of levels are in keV

The experimental work is performed in the Modane Underground Laboratory (depth of 4800 m w.e.). A 400 cm^3 low-background HPGe detector is being used for investigation of 3046 g Nd_2O_3 powder placed into a special Marinelli delrin box which has been put on the detector endcap. With taking into account the natural abundance (5.64%) 153 g of ^{150}Nd is exposed. The data collected for 11320.5 hours have been used to analyze.

The HPGe detector is surrounded by a passive shield consisting of 2 cm of archeological lead, 10 cm of OFHC copper and 15 cm of ordinary lead. To reduce the ^{222}Rn gas, which is one of the main sources of the background, special efforts were made to minimize the free space near the detector. In addition, the passive shield was enclosed in an aluminum box flushed with high-purity nitrogen. The cryostat, the endcap and the critical mechanical components of the HPGe detector are made of very pure Al-Si alloy. Finally, the cryostat has a J-type geometry to shield the crystal from possible radioactive impurities in the dewar.

The electronics consist of currently available spectrometric amplifiers and an 8192 channel ADC. The energy calibration was adjusted to cover the energy range from 50 keV to 3.5 MeV. The energy resolution was 1.9 keV for the 1332 keV line of ^{60}Co. The electronics were stable during the experiment due to the constant conditions in the laboratory (temperature of 23 °C, hygrometric degree of 50%). A daily check on the apparatus functioning is made.

The detection photopeak efficiencies are equal to 2.33% at 333.9 keV and 2.33% at 406.5 keV. The efficiencies have been computed with the CERN Monte Carlo code GEANT3.21. Special calibration measurements with radioactive sources and powders containing well-known ^{226}Ra activities confirmed that the accuracy of these efficiencies is about 10%.

The dominate detector backgrounds come from natural ^{40}K, radioactive chains of ^{232}Th and ^{235,238}U, man-made and/or cosmogenic activities of ^{137}Cs and ^{60}Co. The sample was found to have considerable activity of ^{40}K (46.3 mBq/kg). Additionally long-lived radioactive impurities were observed in the sample, but with much weaker activities. In our case the most important isotopes contributing to energy ranges of the investigated transition are ^{214}Bi (1.15 mBq/kg), ^{228}Ac (0.93 mBq/kg), ^{227}Ac (0.62 mBq/kg) and their daughters.

Fig.2 and Fig.3 show the energy spectrum in the ranges under interest. As one can see there is an excess of events above continuous background at the investigated energies. Isotopes of natural radioactivity (^{211}Pb, ^{214}Bi, ^{227}Th, and ^{228}Ac), found in the spectrum, have γ-lines near these energies. ^{214}Bi contributes

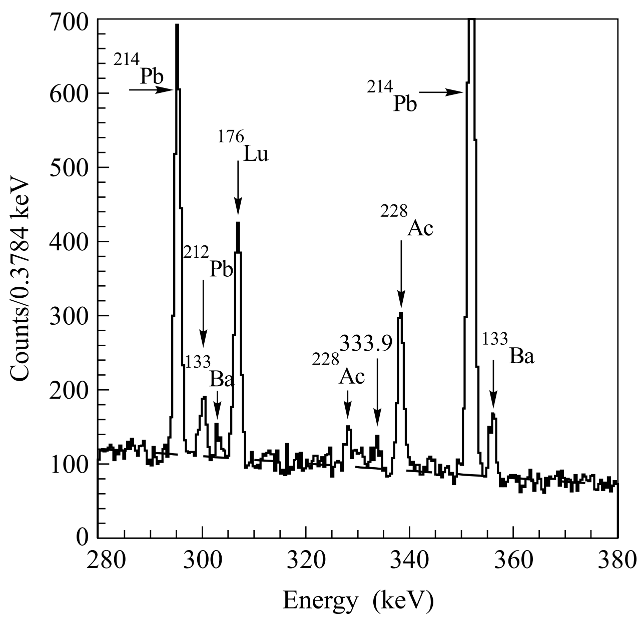

Fig.2. Energy spectrum in the range of 333.9 keV. Dashed line is continuous background used in the analysis

Analysis of events in the range of peaks under study

Peak	333.9 ± 1.12			406.5 ± 1.12	
Number of events	779			603	
Continuous background	656.6			484.5	
Isotopes E_γ, keV	^{214}Bi 333.1; 334.78	^{227}Th 334.37	^{228}Ac 332.37	^{214}Bi 405.74	^{211}Pb 404.853
Contributions from isotopes	8.8	22.6	5.4	9.7	8.7
Excess of events	86 ± 28			100 ± 25	

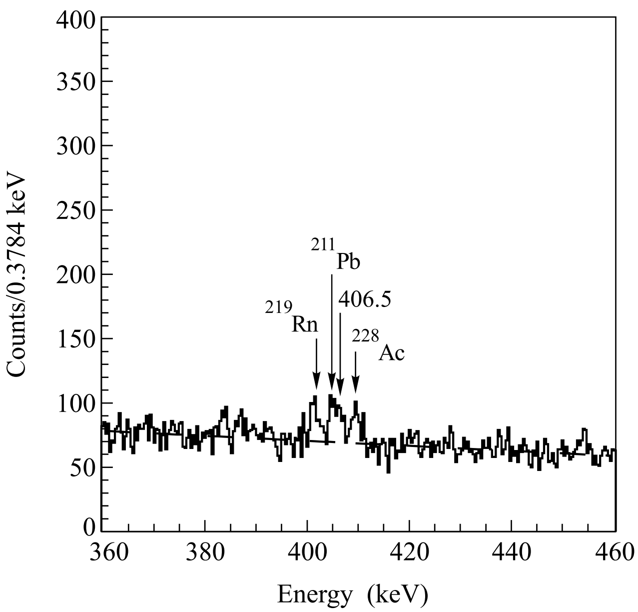

Fig.3. Energy spectrum in the range of 406.5 keV. Dashed line is continuous background used in the analysis

to both investigated ranges through γ-rays with energies of 333.31 keV (0.080%) and 334.78 keV (0.034%) for the 333.9 keV peak, and 405.74 keV (0.17%) for the 406.5 keV peak. ^{228}Ac touches the 333.9 keV peak range with its γ (332.37 keV, 0.40%). ^{227}Ac exhibits through its daughters, ^{227}Th (334.37 keV, 1.14%) and ^{211}Pb (404.853 keV, 3.78%). There is also the artificial isotope, ^{150}Eu ($T_{1/2}$ = 36.9 yr.), decaying to the same daughter, ^{150}Sm, with γ-rays of 333.9 keV (96%), 406.5 keV (0.14%), 439.4 keV (80%), 584.3 keV (52.6%). But its possible exhibition at 439.4 keV is within standard deviation of continuous background, therefore it can be taken into account as a systematic error.

Table presents the results of the analysis for the two peak energy ranges under study. A peak shape is described as a gaussian with a standard deviation of $\sim$ 0.56 keV at energies investigated. For the analysis a peak range is taken within four standard deviations (E$\pm 2\sigma$), i.e. 0.9545 of a peak area. As one can see there is an excess of events for each peak under study. Summing the two peaks give (186 ± 38) events, that corresponds to about the 5σ positive effect. Finally we can estimated the half-life of the $2\nu\beta\beta$ decay of ^{150}Nd to the first 0^+ excited state of ^{150}Sm as $T_{1/2} = [1.4^{+0.4}_{-0.2}(\mathrm{stat}) \pm 0.3(\mathrm{syst})] \cdot 10^{20}$ yr.

Previous experiments gave only limits on this transition, $> 1 \cdot 10^{20}$ yr [15] and $> 1.5 \cdot 10^{20}$ yr [16]. Taking into account all errors, our result is not in contradiction with the previous limits.

If to compare our result with the average experimental value of the half-life for the $2\nu\beta\beta$ transition of ^{150}Nd to the ground state, $T_{1/2} = (7.0 \pm 1.7) \cdot 10^{18}$ yr. [12], and to take into account phase space factors [7] then one can obtain for nuclear matrix elements the following ratio, $M^{2\nu}_{\mathrm{g.s.}} \approx 1.4 \cdot M^{2\nu}_{0^+_1}$. So, the nuclear matrix element for the transition to the first 0^+ excited level is less a little than one for the transition for the ground state.

The authors would like to thank the Modane Underground Laboratory staff for their technical assistance in running the experiment. The portions of this work were supported by grant INTAS # 00-00362.

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