Experimental search for double beta decay of ^{96}Zr to excited levels of ^{96}Mo

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The possibility of detecting double beta decay of ^{96}Zr to excited levels of the daughter nucleus ^{96}Mo has been studied with the help of a two-crystal gamma spectrometer in combination with proportional chambers. The following limits have been established on the decay half-life of ^{96}Zr for the specified transitions to excited levels over 2540 h of measurements: $T_{1/2}(0\nu+2\nu)>2.3\times 10^{19}$ yr for $0^+-0_1^+$; $T_{1/2}(0\nu+2\nu)>2.2\times 10^{19}$ yr for $0^+-2_2^+$. © *1995 American Institute of Physics.*

A substantial lowering of the background in experimental searches for the double beta (2β) decay of various nuclei makes it possible to study this process not only in the transition to the ground state but also in transitions to excited levels of daughter nuclei. In particular, we now have a positive result for 2β decay of the isotope ^{100}Mo to the 0_1^+ excited level of ^{100}Ru (Ref. 1). The probabilities for such transitions make it possible to calculate the nuclear matrix elements for both two-neutrino (2ν) and neutronless (0ν) 2β decays more accurately.

To study the decay of the ^{96}Zr nuclei to excited levels of the ^{96}Mo nucleus (Fig. 1 shows a level scheme of the nuclear triplet[2] ^{96}Zr–^{96}Nb–^{96}Mo),[2] we used an apparatus consisting of two NaI(Tl) detectors 15 cm in diameter and 15 cm thick in combination with two thin proportional chambers. The apparatus was installed in the low-background underground laboratory of the Baksan Neutrino Observatory, Institute of Nuclear Research, Russian Academy of Sciences, at a depth of 660 meters of water equivalent.[3] Passive shielding consisting of 15 cm of lead, 6 cm of oxygen-free electrolytic copper, and 3 cm of tungsten was assembled to suppress the background from external γ rays. To suppress the background to an extent greater than in a previous search[4] for e^-e^+ conversion of ^{58}Ni, we used thin proportional chambers with a working volume of $18\times 18\times 1$ cm, filled with propane at atmospheric pressure. The test sample, in the form of compound ZrO_2, contained 5.5 g of the isotope ^{96}Zr, in a Mylar-like stack with dimensions of 12×12 cm. The total thickness of the test sample was ~ 100 μg/cm^2. The ^{96}Zr sample was positioned between two proportional chambers, which were in turn between two NaI(Tl) detectors. The NaI(Tl) detectors were used to detect cascade γ rays with $E_{1\gamma}=370$ keV and $E_{2\gamma}=778$ keV (for the $0^+-0_1^+$ transition) and γ rays with $E_{2\gamma}=778$ keV and $E_{3\gamma}=720$ keV (for the $0^+-2_2^+$ transition). The proportional chambers were used to detect electrons emitted from the sample. They were connected in a coincidence circuit with the two NaI(Tl) detectors. The composite detection system made it possible to significantly reduce the background (by a factor of several hundred) in comparison with that of Ref. 4, since the proportional chambers are essentially insensitive to external γ rays.

For an energy calibration of the detection system and a calculation of the detection

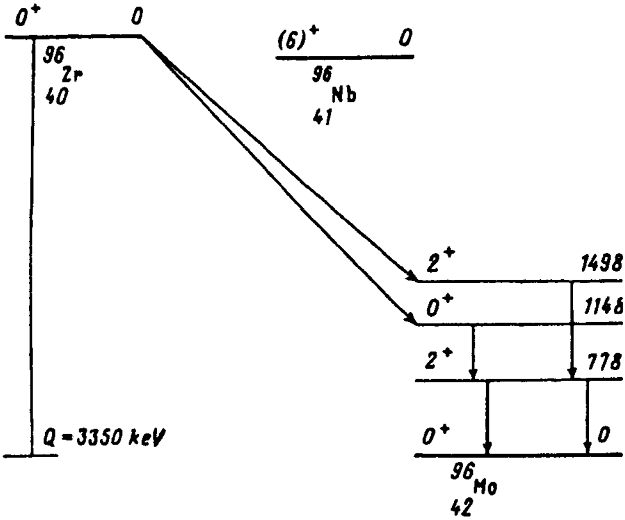

FIG. 1. Energy level diagram of the nuclear triplet ^{96}Zr$-^{96}$Nb $-^{96}$Mo and possible schemes for 2β decay of ^{96}Zr to the 0_1^+ and 2_2^+ levels of the ^{96}Mo daughter nucleus. The energy levels of the ^{96}Mo nucleus are in keV; Q is the total energy of the 2β transition.

efficiencies we used ^{22}Na and ^{207}Bi point γ-ray sources. We also used distributed ^{232}Th and ^{238}U sources. In coincidences of signals from each of the two NaI(Tl) detectors and the signals from the proportional chambers, a 3D coincidence spectrum was formed. Data from an NTA-4096 multichannel pulse-height analyzer were recorded on magnetic tape; the spectra were subsequently processed off-line. In this case the use of the $(E_\gamma \times E_\gamma \times N_{\rm ev})$ multidimensional spectra has additional advantages in the detection of cascade γ rays, and it improves the sensitivity of the experiment.[3]

Figure 2 shows a 3D $(E_\gamma \times E_\gamma \times N_{\rm ev})$ experimental spectrum from the two NaI(Tl) detectors in coincidence with the proportional chambers, acquired over 2540 h with a ^{96}Zr sample. The energy evolution in the NaI(Tl) detectors is plotted along the X and Y axes; the number of events is plotted along the Z axis. The count rate in the energy interval 370×780 keV (780×370 keV) is $(1.34\pm0.23)\times 10^{-2}$ events/h. Since there are no statistically significant peaks in these regions, we can establish a limit on the decay-life with respect to $0\nu+2\nu$ and $0^+-0_1^+$ transitions. We calculate limits on the half-life from

$$\lim T_{1/2} = \ln 2 \times \epsilon N_0 t / N_b^{1/2}, \qquad (1)$$

where ϵ is the detection efficiency, N_0 is the number of ^{96}Zr nuclei, t is the measurement time, and N_b is the number of readings in the energy region under study. Using the total detection efficiency of 1.9% for this transition, calculated by the Monte Carlo method, we find the following limitation on the decay half-life:

$$T_{1/2}(0\nu+2\nu,\ 0^+-0_1^+) > 2.3\times 10^{19}\text{yr}.$$

In the energy region 720×780 keV (780×720 keV) the background rate is $(4.72 \pm 1.36)\times 10^{-3}$ events/h. Substituting the calculated value $\epsilon = 1.1\%$ into (1), we find the following limit on the half-life for 2β decay of ^{96}Zr for the $0^+-2_2^+$ transition:

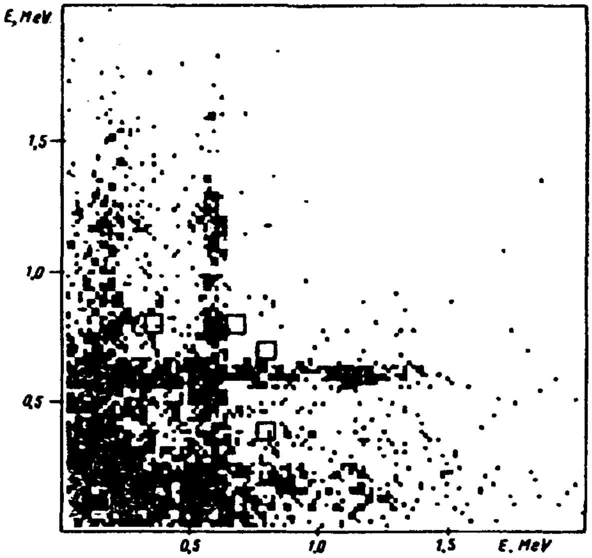

FIG. 2. Three-dimensional ($E_\gamma \times E_\gamma \times N_{ev}$) experimental spectrum from the two NaI(Tl) detectors in coincidence with the proportional chambers, acquired over 2540 h with a ^{96}Zr sample. The squares show the regions studied. Here E_γ is the energy of the γ ray, and N_{ev} is the number density of events.

$$T_{1/2}(0\nu+2\nu,\ 0^+-2_2^+)>2.2\times 10^{19}\text{yr}.$$

Each of these results is given at a confidence level of 68%.

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