Observation of the excess of events in the experiment on the search for a two-neutrino double beta decay of ^{100}Mo

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An excess of events in the beta spectra of samples enriched with ^{100}Mo isotope compared with the spectra of samples with a natural concentration of a given isotope has been observed in the experiment on the search of the double beta decay of ^{100}Mo. This result may be interpreted as the observation of a two-neutrino $\beta\beta$ decay of ^{100}Mo with a half-life $T_{1/2} = (3.3^{+2.0}_{-1.0}) \times 10^{18}$ yr.

The new detector SYSTEM II was used to carry out the first measurements of the experimental program on the search for mechanisms of the double beta decay (the $\beta\beta$ decay) of various nuclei. The detector was placed in an underground low-background laboratory of the Baksan Neutrino Observatory of the Institute of Nuclear Research, Academy of Sciences of the USSR, at a depth of 660 meters water equivalent. This device is the most recent modification of the multilayer detector used for the search of the $\beta\beta$ decay based on a multidimensional analysis.[1]

SYSTEM II consists of four plastic scintillators and two proportional counters (PC), between which is placed a cassette with a thin powder sample (Fig. 1). Each scintillator $500 \times 250 \times 40$ mm in size is viewed by four photomultipliers PM-97 through lightguides. The energy resolution of a single scintillator is $\Delta E/E \approx 17\%$ for $E = 1$ MeV. The internal scintillators are used to detect the energy loss of electrons which have escaped from the sample and the two external scintillators are used as an active shield. The total working volume of each PC is $420 \times 220 \times 10$ mm. The chambers are used to monitor two-electron events and to record the ionization loss with $\approx 90\%$ total efficiency. The entrance windows of the chambers were made of thin (20 μm) mylar and the working gas C_3H_8 was held at a pressure of 1 atm. To eliminate systematic errors which stem from possible time fluctuations of the background level of the detector, the test sample (enriched sample) and the control (unenriched) sample were measured simultaneously. Each PC was therefore divided into two sections with independent signal outputs. The cassettes with the samples to be measured consisted of two halves: one for the enriched sample and the other for the unenriched sample, respectively. After each 200 h of measurements the two halves of the cassette switched places. To prepare a thin (~ 70 mg/cm^2) source, we used two layers of the mylar film (20 μm) which were stretched on a titanium frame. The powder was distributed uniformly among the films, the volume was pumped out, and the cassette was sealed.

The system used for recording and analyzing the events makes it possible to select and group into a correlation matrix ($E_{c1} \times E_{c2} \times N_{\text{events}}$) events which give readings in

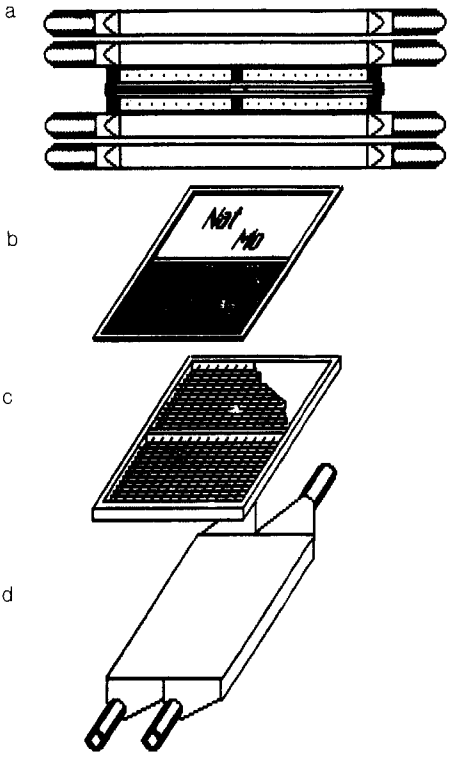

FIG. 1. Schematic diagram of the SYSTEM A-II detector. *a*—Overall view; *b*—cassette with ^{100}Mo and ^{nat}Mo samples; *c*—a two-section proportional counter; *d*—plastic scintillator viewed by four photomultipliers through the lightguides.

the upper and lower (internal) scintillators in coincidence with two simultaneously operating sections of the proportional counters, stacked one on top of the other, and which also give readings when there are no signals sent from the other half of the counters and from the external scintillators. A subsequent analysis of the multidimensional matrix makes it possible to identify one-dimensional spectra of the total energy and partial energy of the paired electrons. A triggering of only one internal scintillator, which is in coincidence with the corresponding sections of the proportional counters, builds up one-dimensional spectra of "single-electron" (unpaired) events. The spectra from each detector are recorded independently in the separate memory sectors. The triggering threshold of each scintillator is 125 keV and that of the PC is ≈ 1 keV.

The measurements were carried out in a low-background underground chamber which was protected from radioactive emission from rocks by 0.5-meter-thick slightly radioactive concrete and by dunite of the same thicknesses. The auxiliary shielding surrounding the detector consisted of tungsten (5 cm), plastic (10 cm), and OFHC copper (20 cm).[1]

The experiments were begun by measuring a metallic molybdenum sample (46 g) enriched to 90% with the isotope ^{100}Mo, which has a large $\beta\beta$ transition energy (3033 keV), and which must have, as the latest calculations have shown,[2,3] a relatively large value of the nuclear matrix element of the two-neutrino $\beta\beta$ decay. Along with this

sample we have measured molybdenum with a natural isotopic abundance (^{nat}Mo) (46 g, 9.6% ^{100}Mo). Analysis of the events collected during the 600 h of measurements showed that in the case of total energy spectra of the two-electron events and in the case of single-electron spectra, upon subtracting the corresponding ^{nat}Mo spectra from the ^{100}Mo spectra, we see a net positive number of events ΔN (^{100}Mo – ^{nat}Mo) $= (0.64 \pm 0.15_{stat} \pm 0.10_{syst})$ event/h when the effective mass of ^{100}Mo is $M_{eff} = 41.6$ g.

We have then carried out a control series of measurements with MoO_3 samples. After 400 h of measurements we have again obtained a surplus of events ΔN ($^{100}MoO_3 - {}^{nat}MoO_3$) $= 0.49 \pm 0.18_{stat} \pm 0.07_{syst}$) event/h ($M_{eff} = 27.6$ g).

Figure 2 shows the difference spectrum of the total energy of the two-electron events for 1000 h of measurements, which was obtained by subtracting the ^{nat}Mo spectra (600 h) and the $^{nat}MoO_3$ spectra (400 h) from the ^{100}Mo spectra (600 h) and the $^{100}MoO_3$ spectra (400 h), respectively. Also shown in this figure is the total energy spectrum of two electrons calculated by the Monte Carlo method for a two-neutrino (2ν) $\beta\beta$ decay of ^{100}Mo with a half-life $T_{1/2} = 3 \times 10^{18}$ yr. We see that the experimental difference spectrum is in agreement with the calculated spectrum for $\beta\beta$ (2ν) decay of ^{100}Mo within the theoretical and experimental errors. The same agreement between the experimental and theoretical spectra is also observed for "single-electron"

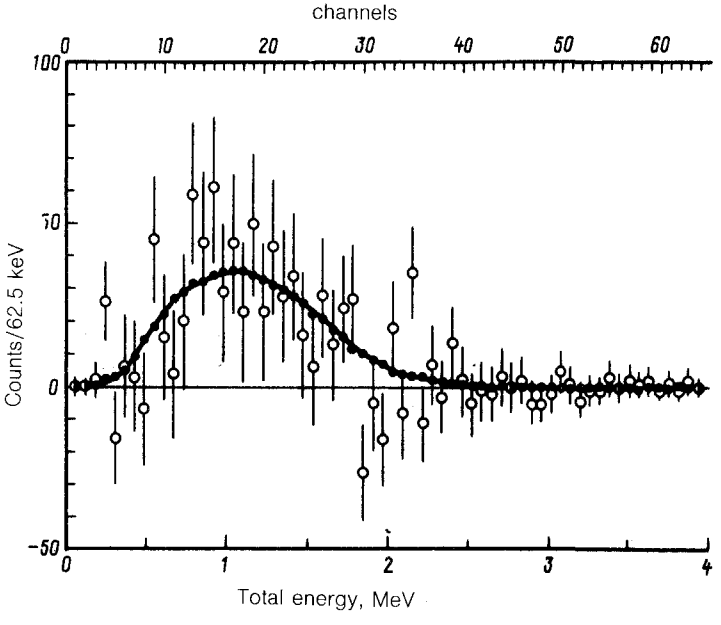

FIG. 2. Spectrum of the total energy of two-electron events, obtained by subtracting the ^{nat}Mo and $^{nat}MoO_3$ spectra from the ^{100}Mo and $^{100}MoO_3$ spectra, respectively (○). Collection time: 600 h with samples made from a metallic molybdenum powder and 400 h with samples made from molybdenum oxide. Shown is the spectrum of the total energy of two electrons calculated by the Monte Carlo method for $\beta\beta(2\nu)$ decay with $T_{1/2} = 3 \times 10^{18}$ yr (●).

events (in the case of the decay these are the events in which both electrons are emitted into one hemisphere by one of the oscillators).

On the other hand, the resultant spectrum of the total electron energy does not fully correspond to either the separately chosen spectra of the possible radioactive impurities ^{40}K, ^{60}Co, ^{137}Cs, ^{232}Th, ^{238}U, etc. or their combinations. (The standard spectra were built up by using radioactive sources with a known activity, which were uniformly distributed in 46-g quantities of ^{nat}Mo and measured in the same cassettes as the principal samples.) The results of measurements of the ^{100}Mo and $^{100}MoO_3$ samples and of the corresponding standard sources using low-background NaI γ-ray spectrometers[4] show that the known radioactive impurities contribute no more than 15% to the observed effect if the given radioactive sources emit γ rays with energies $E_\gamma \gtrsim 200$ keV and have a relative γ-ray yield of $\gtrsim 10\%$.

If it is assumed that ^{100}Mo and $^{100}MoO_3$ samples which we have measured have no radioactive impurities and that the surplus of the events pertains to the two-neutrino $\beta\beta$ decay of ^{100}Mo, we obtain the following estimate for the half-life of ^{100}Mo (the rated measurement efficiency is $\epsilon_{2\nu} = 0.11$):

$$T_{1/2}(\beta\beta, 2\nu) = (3.3^{+2.0}_{-1.0}) \cdot 10^{18} \text{ yr}, \quad 90\% \text{ C.L.}$$

This result is in agreement with the most recent calculations of the probability of the two-neutrino $\beta\beta$ decay of ^{100}Mo, which estimate the half-life for the given mode on the order of several units per 10^{18} yr.[2,3]

For the two neutrino $\beta\beta$ decay $T_{1/2} = 1/C_{GT} \cdot |M^{2\nu}_{GT}/\mu_0|^2$, where $M^{2\nu}_{GT}$ is the nuclear matrix element, and the coefficients G_{GT} and μ_0 for ^{100}Mo are assumed to be 9.434×10^{-18} 1/yr and 20, respectively.[5] Working from the known value of $T_{1/2}$ ($\beta\beta$, 2ν), we accordingly estimate the nuclear matrix element of ^{100}Mo for the 2ν transition to be

$$|M^{2\nu}_{GT}| = (3{,}6^{+0.7}_{-0.8}) \quad 90\% \text{ C.L.}$$

The experimental ratio of the number of two-electron events to the number of one-electron events is found to be $\eta_{exp} = 5.9 \pm 1.8$. This ratio characterizes the integrated angular distribution of electrons. This parameter value is in good agreement with the theoretical prediction of the dominance of the $0^+ \to 0^+$ transition over the transition to the excited levels of the $\beta\beta(2\nu)$ decay, since the calculation based on the Monte Carlo method gives $\eta_{calc} = 6.5$ for the $0^+ \to 0^+$ transition, while $\eta_{calc} = 2.2$ for the $0^+ \to 2^+$ transition.

There is no surplus of events, within statistical deviations, in the energy region corresponding to the neutrinoless $\beta\beta$-decay mode. Working from the background counting rate of 3.5×10^{-6} event/g·keV·h in the energy interval 2.6–3.1 MeV and the measuring efficiency $\epsilon_{0\nu,m} = 0.19$, we found the limit on the lifetime of ^{100}Mo for the neutrinoless $\beta\beta$-decay mode for the mechanism with a nonzero mass of the Majorana neutrino: $T_{1/2}$ ($\beta\beta$,0ν) $> 7.1 \times 10^{20}$ yr, 68% C. L., which corresponds to the limit on the Majorana neutrino mass[2]: $m_\nu < 6.8$ eV.

To confirm the estimates of the parameters of the decay of ^{100}Mo we have obtained, we are planning to measure the isotopic composition of the samples using

highly sensitive mass spectrometers. This approach will make it possible to determine the exact contribution of all possible radioactive impurities to the events which have been observed.

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