Search for 2β decay of ^{116}Cd with the help of a ^{116}CdWO$_4$ scintillator

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A ^{116}CdWO$_4$ scintillator with a volume of 19.24 cm^3 has been used in an underground experiment (1016.8 h) to search for the 2β decay of ^{116}Cd. At a confidence level of 68%, a lower limit of 1.3×10^{21} yr is found on $T_{1/2}$ for the neutrinoless decay channel.

The energy released in the 2β transition ^{116}Cd–^{116}Sn is 2802 ± 4 keV (Ref. 1; see Fig. 1 of the present paper). In a search for this process, a CdWO$_4$ scintillator,[2] enriched to 87% in ^{116} Cd, has been used. Samples of metallic ^{116}Cd were produced at the State Foundation of Stable Isotopes (with a total mass of 618.8 g with an average ^{116}Cd concentration of 91.2%). After purification by vacuum distillation, the ^{116}Cd was put in the form of the oxide ^{116}CdO. A cadium tungstenate single crystal with a mass of 510 g (112 mm long, maximum diameter of 35 mm) was grown at the Monokristall-Reaktiv Scientific-Industrial Alliance on an apparatus with induction heating (the Czochralski method) from a composite material prepared by sintering a mixture of the oxides WO$_3$ and ^{116}CdO. The crystal was then cleaved into five samples, the best of which (33.8 mm in diameter × 21.5 mm) was used in the experiments. The number of ^{116}Cd nuclei in the sample is 2.184×10^{23}.

The measurements were carried out at the Solotvina Underground Laboratory of the Institute of Nuclear Research, Academy of Sciences of the Ukrainian SSR,[3] at a depth of 100 meters water equivalent, at which the cosmic-ray muon flux was suppressed by a factor of 10^4. In addition, the detector was surrounded by shielding of mercury (8–10 cm thick), lead (22 cm), and polyethylene (32 cm). The scintillation detector consisted of an FÉU-93 photomultiplier, a quartz optical fiber (40–50 mm in diameter)×50 mm in size, and the ^{116} CdWO$_4$ crystal, which were mounted in a titanium box. The energy resolutions of the detector with respect to γ rays with energies of 661.7 and 2614.5 keV were 16% and 9%, respectively. The background spectra were built up in a multichannel pulse-height analyzer and then fed by cable to a computer for magnetic storage and subsequent processing. An energy calibration of the spectrometer was carried out daily with the help of ^{22}Na, ^{207}Bi, and ^{232}Th γ-ray sources, which were inserted within the shielding.

The spectra found in this experiment are shown in Fig. 2. The upper distribution was detected in the shielding by a detector without an optical fiber over 342.9 h; the lower spectrum was accumulated over 1016.8 h with the quartz optical fiber. The lowering of the background achieved through the use of the optical fiber demonstrates that the radioactive contamination of the photomultiplier makes a definite contribution to the detector background. The peaks present in the spectra are caused primarily by ^{40}K and radionuclides of the uranium and thorium families. Figure 3 shows, in

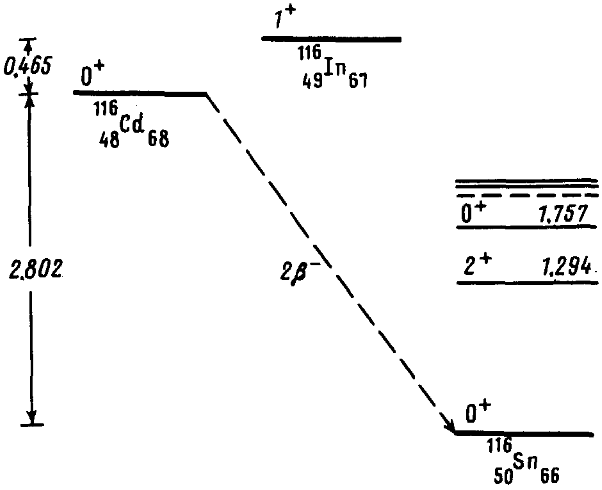

FIG. 1. ^{116}Cd–^{116}In–^{116}Sn level diagram.

linear scale, a fragment of the background spectrum in the interval 2400–3200 keV. Since this spectrum has no clearly defined peak with an energy corresponding to the $0\nu2\beta$ decay of ^{116}Cd (2802 keV), the results of these measurements were used to estimate a limiting probability for the effect being sought. The response function of the spectrometer with respect to the events being sought was simulated by the Monte

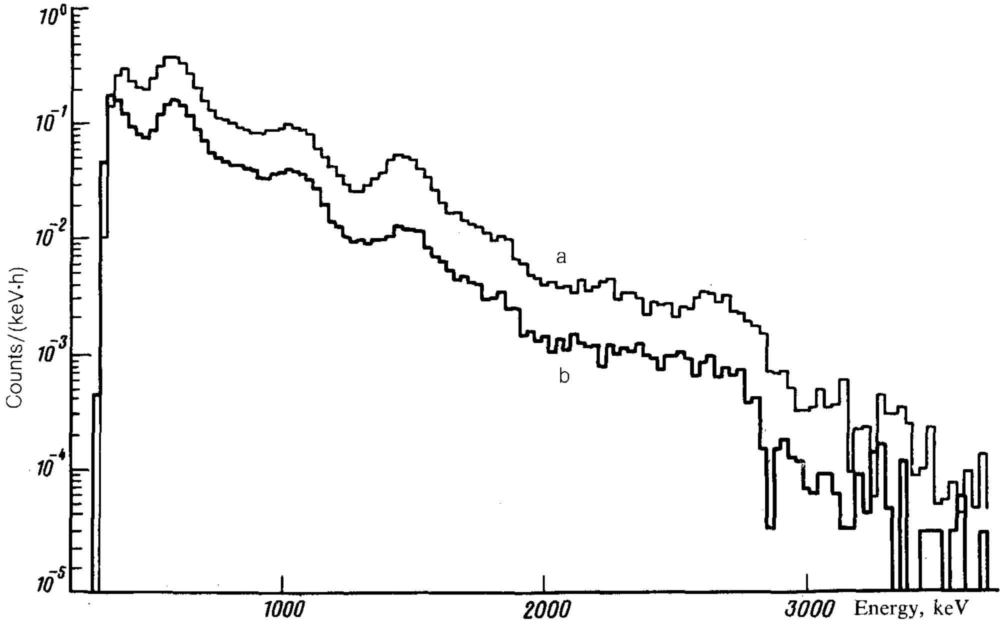

FIG. 2. Background spectra recorded in the experiment. a—Without an optical fiber, over 342.9 h; b—with an optical fiber, over 1016.8 h.

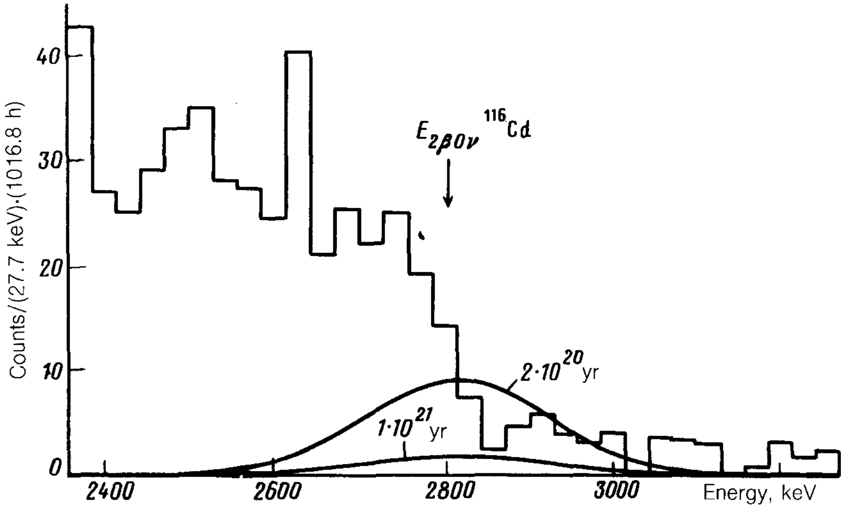

FIG. 3. Fragment of the background spectrum over 1016.8 h.

Carlo method. Here we used the program of Ref. 4, which incorporates the resolution of the detector, the energy and angular distributions of the electrons for the various channels and mechanisms for the 2β decay of ^{116}Cd (Refs. 5 and 6), and also the interactions of electrons with the crystal material. It was found that for the $0\nu 2\beta$ decay of ^{116}Cd ($m\nu \neq 0$, $\lambda = 0$) the spectrum of the detector is Gaussian, with a center of gravity which corresponds to an energy of 2802 keV and a half-width of 250 keV. Edge effects (one or two electrons escape from the crystal) take 5.5% of the events out of the peak. Shown for comparison in Fig. 3 are two such distributions, corresponding to decay half-lives of 10^{21} and 2×10^{20} yr.

There are various ways to estimate a limiting rate of the $0\nu 2\beta$ decay. The simplest is to equate this rate to the statistical error in the determination of the average background intensity over the energy range studied. This method is applicable only if the background distribution in the selected region can be described reliably by some simple and smooth function and if the background amplitude varies only slightly over the interval studied. In the experimental spectrum, these requirements were met in the region 2.8–3.2 meV, where the background is essentially linear. In the range 2802–3053 keV we find 49% of the area of the expected distribution from the $0\nu 2\beta$ decay of ^{116}Cd; 35 background counts were detected during the measurement time. At an overall efficiency of 46.3%, this result corresponds at a confidence level of 68% to a limiting decay half-life 1.35×10^{21} yr.

More-complex procedures for estimating this limit are based on an approximation of the experimental spectrum by a set of functions to represent the background and the effect. In those procedures, not only integral statistical characteristics but also differences in the shape of energy distributions can be used to distinguish the effect. We used two such procedures in the present study: the maximum likelihood method and a standard least-squares technique. We assumed that the experimental spectrum can be described in the region 2440–3200 keV by a sum of three functions, one of which corresponds to the effect, while the two others correspond to background. As the latter two functions we selected a first-degree polynominal and a Gaussian function with a center of gravity at an energy of 2614.5 keV and a half-width of 235 keV (the γ-ray line of ^{208}Tl). On the basis of these data and the assumption that the processes causing the background and the effect are Poisson processes, we constructed a likelihood function, whose parameters were the coefficients of a linear functional dependence and the areas under the two peaks. A maximization of the likelihood function yields a set of parameter values which corresponds to the maximum probability for observing the measured spectrum (with the model adopted). The use of this procedure in the region (2520 ± 80)–3200 keV yields a mean value of (-2.5 ± 10) readings for the $0\nu2\beta$ decay of ^{116}Cd. In this case the limit on the decay half-life is 6×10^{21} yr (1σ). We know, however, that estimates of the parameter values found by the maximum likelihood method can be biased.[7] We accordingly found a least-squares fit of the measure spectrum by the set of functions listed above. In this approach, we are guaranteed that there is no bias in the estimates; furthermore, we do not need information about the parameter distribution law. The mean value of the area under the peak from the expected effect was found by this approximation to be (7 ± 12) counts. Hence the decay half-life of ^{116}Cd with respect to $0\nu2\beta$ decay is, at a confidence level of 68%, 1.3×10^{21} yr. This value is 10^4 times the earlier result.[8]

For a comparison of experiment and theory we used the data of Ref. 9, where the product of $T_{1/2}(^{116}\mathrm{Cd})$ and the square of the neutrino mass was calculated: 1.7×10^{23} yr·eV^2. Working from this value, we find that the limit established on $T_{1/2}$ in the present study leads to the following limitation on the neutrino mass: $\langle m_\nu \rangle \leqslant 12$ eV.

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