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Double β decay of ^{116}Cd. Final results of the Solotvina experiment and CAMEO project.

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Final results of the 2β decay experiment, performed in the Solotvina Underground Laboratory with the help of low-background ^{116}CdWO$_4$ crystal scintillators, are presented. The revised half-life value of the two-neutrino 2β decay of ^{116}Cd has been measured as $T_{1/2}^{2\nu} = 2.9^{+0.4}_{-0.3} \times 10^{19}$ yr, and the new half-life limit on the neutrinoless 2β decay of ^{116}Cd has been established as $T_{1/2}^{0\nu} \geq 1.7\ (2.6) \times 10^{23}$ yr at 90% (68%) C.L. The latter corresponds to a restriction on the Majorana neutrino mass: $m_\nu \leq 1.7\ (1.4)$ eV at 90% (68%) C.L. The CAMEO project could further advance sensitivity of the ^{116}Cd experiment to $m_\nu \leq 0.05$ eV.

Observations of neutrino oscillations manifest the non-zero neutrino mass and provide important motivation for highly sensitive experiments on neutrinoless double beta ($0\nu2\beta$) decay. However, this process still remains unobserved, and only half-life limits for $0\nu2\beta$ mode were obtained (see, e.g., reviews [1–3]). One of the most sensitive 2β experiments has been performed in the Solotvina Underground Laboratory [4] by the Kiev-Firenze collaboration with the help of the enriched cadmium tungstate (^{116}CdWO$_4$) crystal scintillators [5,6]. Here, we briefly describe the main results of this experiment and discuss the further advancement of its sensitivity.

The description of the set-up and its performance have been already published [5,6]. Four cadmium tungstate ^{116}CdWO$_4$ scintillators (enriched in ^{116}Cd to 83%) with a total mass of 330 g were used. They were surrounded by an active shield made of 15 CdWO$_4$ crystals of large volume with a total mass of 20.6 kg. The whole CdWO$_4$ array was situated within an additional active shield made of plastic scintillator 40×40×95 cm, thus, a complete 4π active shield of the main (^{116}CdWO$_4$) detector was provided. The outer passive shield consists of high-purity copper (3 – 6 cm), lead (22.5 – 30 cm) and polyethylene (16 cm). For each event in the ^{116}CdWO$_4$ detector, the amplitude of a signal, its arrival time and pulse-shape (2048 channels with 50 ns width) were recorded. The energy resolution of the detector was FWHM = 8.0% at 2615 keV. Due to active and passive shields, and as a result of the time-amplitude [7,8] and pulse-shape analysis [9,10] of the data, the background rate of the ^{116}CdWO$_4$ detector in the energy region $2.5 - 3.2$ MeV ($Q_{\beta\beta}$ of ^{116}Cd is 2.8 MeV) was reduced down to 0.037(10) counts/(yr·kg·keV) [5,6]. It is the lowest background rate which has ever been reached with crystal scintillators.

The background spectrum measured during 12649 h after set-up upgrading in 1999 (the energy resolution and pulse-shape discrimination ability of the detector were improved) is shown in Fig. 1. Fit of the data gives the half-life value of the $2\nu2\beta$ decay of ^{116}Cd:

$$T_{1/2}^{2\nu} = 2.9 \pm 0.06(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst}) \times 10^{19}\ \mathrm{yr}.$$

The main origins of the systematical uncertainties are possibly traces of the β active nuclides ^{234m}Pa and ^{90}Y (daughter of ^{90}Sr) in the ^{116}CdWO$_4$ crystals [6].

The experimental $2\nu2\beta$ Kurie plot (depicted in the inset of Fig. 1) is well described by the straight line in the $900 - 2500$ keV energy region,

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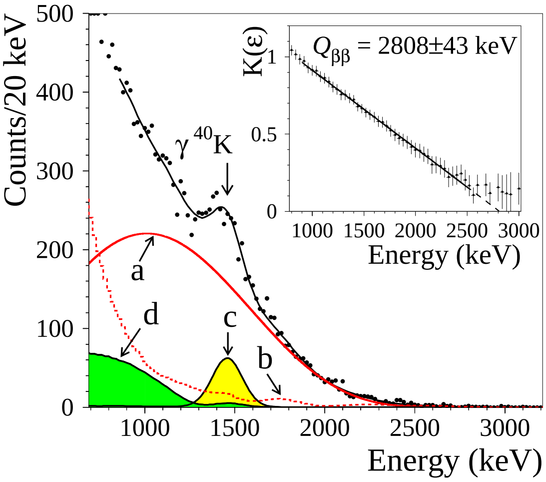

Figure 1. Spectrum of $\gamma(\beta)$ events measured with ^{116}CdWO$_4$ detector (12649 h). Also shown are the most important model components: (a) the $2\nu2\beta$ spectrum of ^{116}Cd; (b) external γ background caused by radioactive contamination of the PMTs; ^{40}K contamination of the (c) non-enriched and (d) enriched CdWO$_4$ scintillators. Solid line represents the fit of the data in the 860 – 2700 keV energy interval. (Inset) The $2\nu2\beta$ decay Kurie plot and its fit.

and derived $Q_{\beta\beta}$ energy (2808±43 keV) is in accordance with the table value 2805(4) keV. The obtained $T^{2\nu}_{1/2}$ is in agreement with our preliminary result [5] and with those measured earlier in other experiments [7,11,12].

The part of the spectrum measured with the ^{116}CdWO$_4$ detector during 14183 h $\{7.41 \times 10^{23}$ (nuclei of ^{116}Cd)$\times$yr$\}$ is presented in Fig. 2. Since any indications on the peak of $0\nu2\beta$ decay is absent in the experimental data, we set the bound on the half-life for $0\nu2\beta$ decay of ^{116}Cd:

$$T^{0\nu}_{1/2} \geq 1.7\ (2.6) \times 10^{23} \text{ yr at } 90\%\ (68\%) \text{ C.L.}$$

Using this limit and calculations [13], we derive restrictions on the Majorana neutrino mass and right-handed admixtures in the weak interaction: $m_\nu \leq 1.9$ eV, $\eta \leq 2.5 \times 10^{-8}$, $\lambda \leq 2.2 \times 10^{-6}$ at 90% C.L. Neglecting the right-handed contribution we get $m_\nu \leq 1.7$ (1.4) eV at 90% (68%) C.L., and on the basis of [12,14] the limit is $m_\nu \leq 1.5$ (1.2) eV. Besides, in accordance with ref. [15] the value of R-parity violating parameter of minimal SUSY standard model is restricted by our $T^{0\nu}_{1/2}$ bound to $\varepsilon \leq 7.0\ (6.3) \times 10^{-4}$ at 90% (68%) C.L.

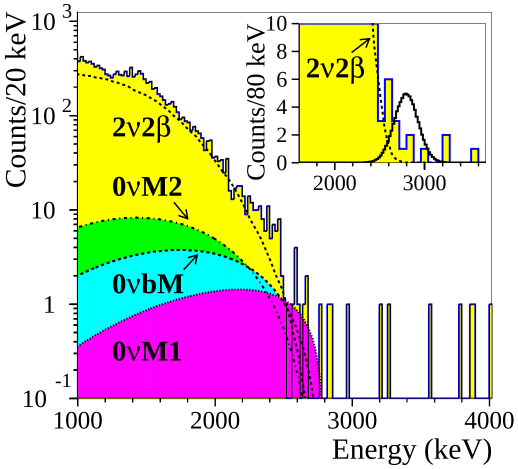

Figure 2. Part of experimental spectrum of the ^{116}CdWO$_4$, together with the $2\nu2\beta$ distribution of ^{116}Cd. Also are presented the excluded with 90% C.L. distributions of 0νM1, 0νM2 and 0ν decay with bulk Majoron emission with $T^{M1}_{1/2} = 8 \times 10^{21}$ yr, $T^{M2}_{1/2} = 8 \times 10^{20}$ yr, and $T^{bM}_{1/2} = 1.7 \times 10^{21}$ yr, respectively. In the inset the expected peak from $0\nu2\beta$ decay with $T_{1/2} = 2 \times 10^{22}$ yr is shown.

To obtain limits for $0\nu2\beta$ decay with emission of one (M1), two (M2) and bulk [16] Majoron(s), the spectrum was analyzed in the energy region 1.6 – 2.8 MeV. Excluded with 90% C.L. distributions of $0\nu2\beta$ processes with Majoron emission are also shown in Fig. 2. In particular, $T^{M1}_{1/2} \geq 0.8\ (1.8) \times 10^{22}$ yr at 90% (68%) C.L. Using this bound and calculations [17], the effective Majoron-neutrino coupling constant is restricted as $g_M \leq 8.1\ (5.4) \times 10^{-5}$, and on the basis of calculation [12,14] as $g_M \leq 4.6\ (3.1) \times 10^{-5}$, which are among the strongest constraints reached in the direct 2β decay experiments [3]. It should be stressed that all these restrictions were obtained with small ^{116}CdWO$_4$ detectors ($\approx$ 0.3 kg), in contrast with those for ^{76}Ge studies ($\approx$10 kg of enriched HP ^{76}Ge detectors [18]).

Therefore, the Solotvina experiment demonstrates that CdWO$_4$ crystals possess several unique properties required for a 2β decay experiment: low level of intrinsic radioactivity, good scintillation characteristics and pulse-shape discrimination ability, which allow one to reduce background effectively. But, to enhance the sensitivity to the neutrino mass bound to $m_\nu \leq 0.05$ eV, we have to increase the mass of enriched ^{116}CdWO$_4$ detector and measuring time, to improve the energy resolution and to reduce the background of the detector further. Note that, for our ^{116}CdWO$_4$ detectors, the background in the 2.5–3.1 MeV energy interval is caused by the $2\nu2\beta$ decay of ^{116}Cd ($\approx$50%), internal ^{232}Th contamination ($\approx$30%), and by the external γ rays from the PMTs ($\approx$20%). Hence, the further purification of the ^{116}CdWO$_4$ scintillators and the improvement of their energy resolution could additionally reduce the background. Namely, the CAMEO project [19], which intends to use $\approx$100 kg of ^{116}CdWO$_4$ crystals placed in a large volume of high purity liquid, calls also for improvement of the energy resolution (FWHM) at 2.8 MeV to 4% and for background reduction by factor $\approx$100. The required radioactive contamination of ^{116}CdWO$_4$ crystals has to be less than $\approx$10 μBq/kg, both for ^{228}Th and ^{226}Ra [19]. Actually, even already existing CdWO$_4$ crystals satisfy these requirements for ^{226}Ra ($<$ 4 μBq/kg) [6], but ^{228}Th contamination varies in different crystals as $(3 - 39)$ μBq/kg [6,20]. At the same time, the required energy resolution FWHM = 4.3% at 2615 keV (^{232}Th) has been already measured with the CdWO$_4$ crystal $\oslash 4 \times 3$ cm placed in a liquid [19].

To conclude, fulfilment of the CAMEO experiment has practically no technical risk, and it seems to be very realistic because developed technique with the ^{116}CdWO$_4$ crystal scintillators is very simple and reliable. As the first step, the CAMEO project is foreseen to produce $\approx$10 kg of ^{116}CdWO$_4$ crystals with required improved characteristics (radiopurity, energy resolution, etc.), which have been already obtained for several samples of CdWO$_4$ scintillators. With such crystals, a half-life sensitivity $\approx$10^{25} yr (corresponding to neutrino mass $\approx$ 0.2 eV) could be reached during 5 yr of measurements.

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