New results of ^{116}Cd double beta decay search

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The experiment was performed at the Solotvina Underground Laboratory with $CdWO_4$ crystal scintillators enriched in ^{116}Cd to 83%. For the total data collection time about 12000 hours the limit of half-life $T_{1/2}^{0\nu} \geq 3.2 \cdot 10^{22}$ y (90% CL) was obtained for $0\nu\beta\beta$ decay of ^{116}Cd which corresponds to the restriction of the neutrino mass less than 3.9 eV.

1. DETECTORS, INSTALLATION AND BACKGROUND

The energy released in the transition $^{116}Cd \rightarrow {}^{116}Sn$ is equal to 2804 keV [1] and the abundance of ^{116}Cd is 7.49(12)% [2]. Theoretical half-life estimate for ^{116}Cd is equal to $T_{1/2}^{0\nu} \cdot \langle m_n \rangle^2 = 4.87 \cdot 10^{23}$ y·eV^2 which is nearly four times lower than the predicted values for ^{76}Ge and ^{136}Xe [3].

The $CdWO_4$ crystal scintillators enriched in ^{116}Cd to 83% were grown [4, 5] for our 2β decay study of ^{116}Cd since 1987. Three crystals with initial volume of 19.0, 14.0 and 12.5 cm^3 were used separately in the different runs of the present experiment. The number of ^{116}Cd nuclei in these samples is $2.09 \cdot 10^{23}$, $1.54 \cdot 10^{23}$ and $1.37 \cdot 10^{23}$, respectively. The energy resolution of the crystals with the XP2412 (Philips) photomultiplier is about 12-13% for the energy of 662 keV.

Except the pilot experiment in Kiev [4] all measurements were carried out in the Solotvina Underground Laboratory of INR [6] built in a salt mine at a depth of more than 1000 m w.e., where the cosmic muon flux is suppressed by a factor of greater than 10^4.

The detector background in the energy interval 2.7-2.9 MeV was reduced successively by more than two orders of magnitude with different installations [4, 5, 7, 8]. In the best one the both active and passive shielding was applied. The passive shielding of OFHC copper (5 cm) and lead (23 cm) surrounds the large plastic scintillator which was used as active shielding. The cadmium tungstate crystal is viewed by PMT (FEU-110) through a light-guide 51 cm long. The energy resolution of the detector with $^{116}CdWO_4$ crystals is equal to 14.1, 8.2 and 7.1% at energy 662, 1770 and 2615 keV, respectively. The active shielding polystyrene scintillator is viewed by two low-background PMT (FEU-125). In case of a coincidence between $CdWO_4$ and plastic, a short (2.5 μs) signal is generated vetoing the $CdWO_4$ events. If the energy released in the plastic is above 2 MeV (that may be associated with cosmic ray muons), the duration of veto signal is 1.5 ms. It is enough to thermalize and capture most of the neutrons produced by the muons.

The data acquisition system consists of a microcomputer, a magnetic tape recorder and a CAMAC crate with electronic units which allow to record the amplitude and arrival time of each event. Since the decay time of $CdWO_4$ scintillators is 25 - 30 μs, a special electronic unit was used which integrates the PMT output signal during ≈40 μs and forms the short output pulses required by the ADC. Shifts in the gain were corrected by the hardware and software. As a result, the resolution for the background γ peak of ^{137}Cs (662 keV) measured during more than nine thousand hours (14.5%) does not differ from the resolution in the calibration run for half an hour (14.1%). The energy calibration was carried out with ^{207}Bi weekly and with ^{232}Th once in two weeks. The dead time of the acquisition system was periodically monitored by means of pulses from the light emitting diodes. Its value was within 3-5%.

The last improvement of the background was made in 1993 [8], when the $^{116}CdWO_4$ crystal (19.0 cm^3) was ground twice on 0.8-1.5 mm (its volume was decreased to 16.2 cm^3 and then to 15.2 cm^3). It removed the very weak contamination of the crystal by the ^{238}U. The spectrum of this crystal for 9048 h is shown in fig. 1. The distribution in low energy region is the spectrum of the fourth-forbidden β decay of ^{113}Cd ($T_{1/2}=9.3 \cdot 10^{15}$ y, $Q_\beta=316$ keV [9]) which is present in the enriched crystal (2.15%). The weak peak with the energy 661(9) keV can be explained by the presence of ^{137}Cs with an activity of $1.5(2) \cdot 10^{-3}$ Bk/kg. Analysis of the background in the energy region 0.8 -1.2 MeV gives the limit of residual activity of ^{238}U less than $3 \cdot 10^{-5}$ Bk/kg. For ^{40}K, ^{226}Ra and ^{232}Th the following upper limits of the

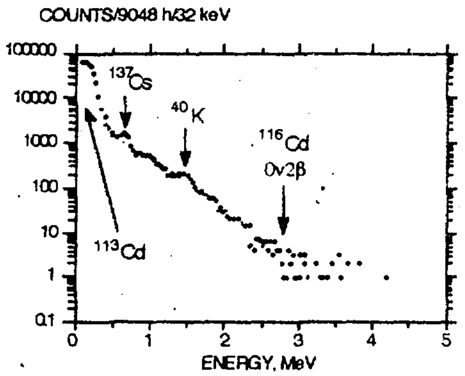

Figure 1. Background spectrum of $^{116}CdWO_4$ crystal (15.2 cm^3) measured during 9048 h.

activities are determined: $<3.8\cdot10^{-3}$, $<5.0\cdot10^{-5}$ and $<4.0\cdot10^{-5}$ Bk/kg, respectively.

As a result of all improvements, the background rate of $^{116}CdWO_4$ detector in the region of 2.7 - 2.9 MeV was reduced to ≈0.6 counts/y·kg·keV. For further decreasing of the background from intrinsic contamination of the crystal the off-line analysis of the time distribution of the measured events was developed and fulfilled. The sequence of two α decays belonging to the ^{232}Th family was searched for: ^{220}Rn ($E_\alpha=6.29$ MeV, $T_{1/2}=55.6$ s) → ^{216}Po ($E_\alpha=6.78$ MeV, $T_{1/2}=0.15$ s) → ^{212}Pb. These couples of α-events were found firmly and the ^{232}Th content was established to be equal to $1.8(2)\cdot10^{-5}$ Bk/kg. Even such a super-low ^{232}Th contamination can produce the background events in the region of 0νββ decay of ^{116}Cd due to β decay of ^{212}Bi plus α decay of its daughter ^{212}Po. ^{212}Pb ($Q_\beta=0.57$ MeV, $T_{1/2}=10.64$ h) → ^{212}Bi (64.1%: $Q_\beta=2.25$ MeV, $T_{1/2}=60.55$ m) → ^{212}Po ($E_\alpha=8.78$ MeV or ≈ 1.8 MeV in β scale, $T_{1/2}=0.3$ μs) → ^{208}Pb. Because of the short half-life of ^{212}Po its α-line and the ^{212}Bi β-continuum can not be time resolved in the $^{116}CdWO_4$ and will result in the broad distribution till the energy of 4.2 MeV. This delayed chain ^{212}Bi → ^{212}Po → ^{208}Pb occurs with probability of ≈55% within 2-16 h after the fast chain ^{220}Rn → ^{216}Po → ^{212}Pb. Therefore, rejecting about 14 h of measuring time after each couple of α-particle from ^{220}Rn and ^{216}Po, it is possible to eliminate the part of background in the energy region of 0νββ decay of ^{116}Cd. This technique was applied to the 10228 h spectrum (9048 h with 15.2 cm^3 crystal plus 1180 h with 16.2 cm^3 crystal) and results are shown in the Fig. 2 (a - initial spectrum, b - final spectrum). In the energy interval 2.3 - 4.0 MeV the number of background events was reduced on 20% (from 162 to 129) while the measuring time - only on 8.7% (from 10228 to 9342 h).

2. NEUTRINOLESS ββ DECAY OF ^{116}Cd

For 0νββ decay half-life estimate the total data were used which include the spectrum in Fig. 2b (or Fig. 2a) and previous 1660 h run with the smaller $^{116}CdWO_4$ crystal (12.5 cm^3). The total measuring time is 11002 h (11888 h), the product of the number of ^{116}Cd nuclei with time - $2.06\cdot10^{23}$ nuclei·y ($2.23\cdot10^{23}$ nuclei·y), the mean background rate in the interval 2.7 - 2.9 MeV - 0.55 (or 0.66) counts/y·kg·keV. A part of the total spectrum in the energy range 2.3 - 4.2 MeV is shown in fig. 3. Since the peak of the 0νββ decay is evidently absent, the data were used to obtain a lower limit of the half-life of this process with the known expression:

$$\lim T_{1/2} = \ln2\cdot\varepsilon\cdot t\cdot N_n/\lim S_e,$$

where N_n is the number of ^{116}Cd nuclei, ε - detection efficiency, t - measuring time, lim S_e - the number of 0νββ decay events which can be excluded with a given confidence level.

To calculate the efficiency of the detector its response function was simulated by a Monte Carlo code [10]. The energy and angular distributions of the electrons in various mechanisms of 0νββ decay of ^{116}Cd, the processes of interaction of the electrons with the crystal as well as the detector's resolution were taken into account. It was found that response function of the $^{116}CdWO_4$ detectors for potential 0νββ events is a Gaussian with its center at 2804 keV and a FWHM=214 keV (such a distribution is shown in fig. 3 with $T_{1/2}=2\cdot10^{22}$ y). The total detection efficiency is $\varepsilon=83.5\%$. The value of lim S_e was evaluated by standard least-squares method [11]. It was assumed that the experimental spectrum can be described in the region of 2300 - 4200 keV by a sum of three functions, one of which is the 0νββ decay peak, while the other two correspond to the γ-line of ^{208}Tl (Gaussian centered at

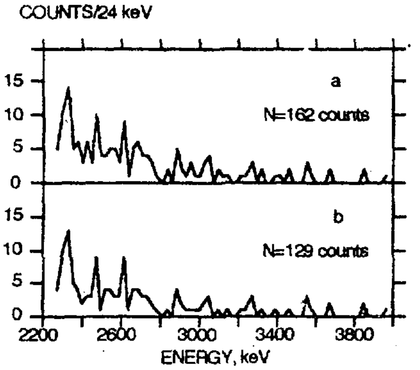

Figure 2. Background spectrum before (a) and after (b) elimination of the chain $^{212}Bi \rightarrow {}^{212}Po \rightarrow {}^{208}Pb$.

2614.5 keV with a FWHM = 204 keV) and linear background. The least-squares fit in the region of 2300 - 4200 keV gives a value of 3.2 counts for the area of the $0\nu\beta\beta$ peak excluded with a confidence level of 90%. It corresponds to the limit $T^{0\nu}_{1/2}\geq 3.8\cdot 10^{22}$ y.
In order to take in account the possible shift of energy scale and resolution the different fits were made with deviations of $0\nu\beta\beta$ and ^{208}Tl peak positions and their FWHM. The same procedure was carried out for 11888 h data. It leads to the set of the peak area estimates (excluded with a confidence level of 90%) from 2.8 to 3.8 counts $\{T^{0\nu}_{1/2}\geq (3.2 - 4.5)\cdot 10^{22}$ y$\}$.

Thus the final limit for the $0\nu\beta\beta$ decay of ^{116}Cd is:

$$T^{0\nu}_{1/2}\geq 3.2(5.4)\cdot 10^{22}\ \text{y} \quad 90\%(68\%)\ \text{CL.}$$

Comparing this limit with calculations [3] we have computed the restrictions on the neutrino mass and right-handed admixtures in the weak interaction: $<m_\nu>\leq 4.3$ eV, $<\eta>\leq 5.6\cdot 10^{-8}$, $<\lambda>\leq 5.1\cdot 10^{-6}$. If neglecting the right-handed contributions the limit on the neutrino mass can be obtained:

$$<m_\nu>\leq 3.9(3)\ \text{eV} \quad 90(68)\%\ \text{CL.}$$

To advance the obtained results the INR (Kiev) and MPI (Heidelberg) collaboration is working now under the big scale project for double beta decay study of ^{116}Cd and ^{160}Gd [12]. The low-background installation will consist approximately one thousand of pure GSO and $CdWO_4$ crystal scintillators with mass of each crystal about one - two kg. Recently several samples of such a $CdWO_4$ crystals were grown and pilot measurements were made successfully in the Solotvina and Gran Sasso Underground Laboratories [13]. With further improved

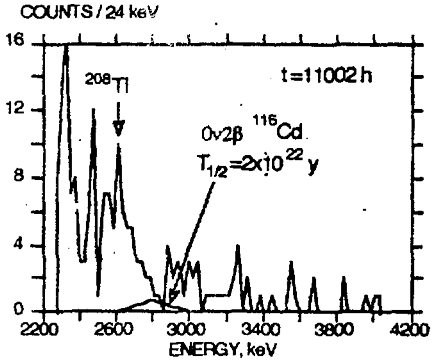

Figure 3. A part of the total spectrum with measuring time of 11002 h.

background of such a multi-detectors system the limit of $\approx 10^{25}$ y could be reached for the $0\nu\beta\beta$ decay of ^{116}Cd that corresponds the restriction of the Majorana neutrino mass less than 0.2 eV which is comparable with the sensitivity of the most advanced experiments with ^{76}Ge.

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