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Nuclear Physics B (Proc. Suppl.) 110 (2002) 389–391

NUCLEAR PHYSICS B
PROCEEDINGS
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New results of ^{116}Cd $\beta\beta$ decay experiment

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The measurements with 0.33 kg low background ^{116}CdWO$_4$ scintillators are in progress in the Solotvina Underground Laboratory. After 13254 h of data taking the new half-life limits for different modes of neutrinoless 2β decay of ^{116}Cd are presented, in particular for $0\nu2\beta$ decay of ^{116}Cd to the ground state of ^{116}Sn: $T_{1/2}(0\nu2\beta) \geq 1.3(1.8) \times 10^{23}$ yr at 90%(68%) C.L.

1. INTRODUCTION

The ^{116}Cd double β decay studies are performed with the help of cadmium tungstate crystal scintillators (enriched in ^{116}Cd to 83%) in the Solotvina Underground Laboratory [1] since 1989 [2]. The new set-up with four crystals has been mounted in October 1998. For 4629 h of the exposition the half-life of $2\nu2\beta$ decay of ^{116}Cd was measured as $T_{1/2} = 2.6\pm0.1(\mathrm{stat})^{+0.7}_{-0.4}(\mathrm{syst})\times10^{19}$ yr and $T_{1/2}$ limits for various 0ν channels were set [3]. In August 1999 the energy resolution and pulse shape discrimination ability of the detector were improved due to annealing of one of the crystals and by using of the photomultiplier (PMT) with the RbCs photocathode, whose spectral response better fits the CdWO$_4$ scintillation light. In the present paper new and advanced results of $\beta\beta$ decay search obtained after 13254 h of data taking are presented.

2. SET-UP AND MEASUREMENTS

The main detector consists of four enriched ^{116}CdWO$_4$ crystals (total mass 330 g) which are viewed by the low radioactive PMT (EMI D724KFL) through the light-guide 10 cm in diameter and 55 cm long. The ^{116}CdWO$_4$ crystals are surrounded by an active shield made of 15 natural CdWO$_4$ scintillators with total mass of 20.6 kg. The veto crystals are viewed by the low radioactive PMT (FEU-125nf, ⌀17 cm) through an active plastic light-guide 49 cm long. The whole array of CdWO$_4$ counters is placed inside an additional active shield made of plastic scintillator 40×40×95 cm. The outer passive shield consists of HP copper (thickness 3–6 cm), lead (22.5–30 cm) and polyethylene (16 cm). Two plastic scintillators (120×130×3 cm) are installed above the passive shield to provide a cosmic muons veto. For each event the amplitude of a signal, arrival time and the pulse shape (2048 channels with 50 ns channel's width) of the ^{116}CdWO$_4$ scintillators are recorded.

The energy scale and resolution of the main detector were measured with γ sources in the energy range $60-2615$ keV as $FWHM_\gamma(\mathrm{keV})=-44(6)+\sqrt{2800(700)+23.4(13)E_\gamma}$, where energy E_γ is in keV (for example, $FWHM_\gamma$=8.0% at the energy 2615 keV). The α/β ratio and energy resolution for α particles were determined in energy range of $2.1-8.8$ MeV[1]. The routine calibration is carried out with a ^{207}Bi and ^{232}Th γ sources. The dead time of the detector was measured with a light emitting diode as $\approx 4.9\%$.

3. DATA ANALYSIS

The energy and arrival time of each event can be used for analysis and selection of some de-

[1] $\alpha/\beta = 0.073+1.9\times10^{-5}E_\alpha$, $FWHM_\alpha(\mathrm{keV}) = 33+0.247\cdot(\alpha/\beta)\cdot E_\alpha$, where E_α is energy of α particles (keV).

PII S0920-5632(02)01518-9

cay chains in ^{232}Th, ^{235}U and ^{238}U families. For example, the sequence of α decays from ^{232}Th family ^{224}Ra $\rightarrow$ ^{220}Rn $\rightarrow$ ^{216}Po $\rightarrow$ ^{212}Pb was selected with the help of the time-amplitude analysis. The obtained α peaks (α nature of events was confirmed by the pulse shape analysis) as well as the distributions of the time intervals between events are in good agreement with those expected for α particles of ^{224}Ra, ^{220}Rn and ^{216}Po. This analysis yields activity of ^{228}Th inside the $^{116}CdWO_4$ crystals equal to 39(2) μBq/kg. The same technique was applied to the sequence of decays from the ^{235}U and ^{238}U families. Activity of 5.5(14) μBq/kg for the ^{227}Ac (the ^{235}U family) and limit $\leq$ 5 μBq/kg for the ^{226}Ra (^{238}U family) in the $^{116}CdWO_4$ crystals were set. All correlated events found for ^{232}Th, ^{235}U and ^{238}U families were eliminated from the measured data.

The pulse shape discrimination of $CdWO_4$ scintillation signals was developed on the basis of the optimal digital filter, and clear discrimination between γ rays (electrons) and α particles was achieved [4]. The pulse shapes of enriched crystals were investigated in the energy range 2.1 – 6.8 MeV for α particles and 0.04 – 3.2 MeV for γ rays, which allows us to reject α decays and background events like double pulses, the plastic light-guide signal overlapping, noise, etc. For example, due to the front edge analysis of the signals, events caused by two fast decays in the chain ^{212}Bi $\rightarrow$ ^{212}Po $\rightarrow$ ^{208}Pb (which are not time-resolved by the slow $CdWO_4$ scintillator and can result in one background event with energy of 1.5 – 4.5 MeV) were discarded from the data.

4. RESULTS AND DISCUSSION

The part of the spectrum of the $^{116}CdWO_4$ crystals measured in anticoincidence with the shielding detectors and after the time-amplitude and pulse shape selection is shown in Fig. 1.

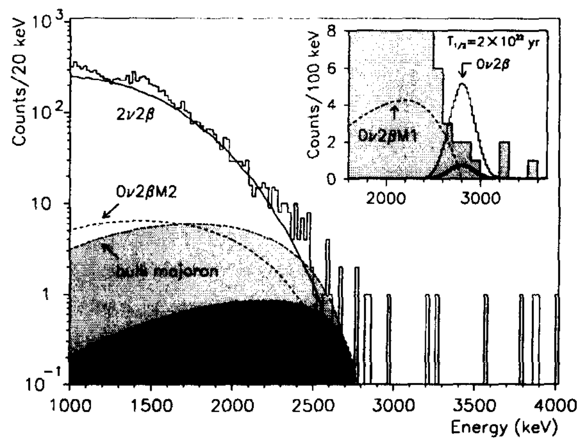

Figure 1. Part of experimental spectrum of the $^{116}CdWO_4$ detectors measured during 13254 h (histogram) together with the $2\nu 2\beta$ contribution ($T_{1/2} = 2.6 \times 10^{19}$ yr). The lower smooth curves are excluded with 90% C.L. distributions of 0νM1, 0νM2 decays and decay with bulk Majoron emission with $T_{1/2} = 6.8 \times 10^{21}$ yr, $T_{1/2} = 0.9 \times 10^{21}$ yr and $T_{1/2} = 0.9 \times 10^{21}$ yr, respectively. In the insert the expected peak from $0\nu 2\beta$ decay with $T_{1/2} = 2.0 \times 10^{22}$ yr is shown together with the excluded (90% C.L.) distribution (thick line) with $T_{1/2} = 1.3 \times 10^{23}$ yr.

The background rate in the energy interval 2.5 – 3.2 MeV is 0.04 counts/(yr·kg·keV). The peak of $0\nu 2\beta$ decay is absent, thus we obtain a lower limit of the half-life: $\lim T_{1/2} = \ln 2 \cdot N \cdot t \cdot \eta / \lim S$, where N is number of ^{116}Cd nuclei, t the measuring time ($N \cdot t = 6.27 \times 10^{23}$ nuclei·yr), η the total detection efficiency for $0\nu 2\beta$ decay, and $\lim S$ the number of events in the peak which can be excluded with a given confidence level. The value of the detection efficiency itself was calculated by the GEANT3.21 [5] and DECAY4 [6] codes as $\eta_{MC} = 0.83$. Taking into account the efficiency of the pulse shape analysis $\eta_{PS} = 0.95$ it yields the total efficiency $\eta = 0.79$. To estimate $\lim S$ the part of the spectrum in the 2.0 – 3.6 MeV energy interval was fitted by the sum of the simulated $0\nu 2\beta$ peak and three background functions: $2\nu 2\beta$ decay (81%), γ rays from PMTs (16%), and contribution from ^{228}Th intrinsic chain (3%). This fit gives the value of $S = 0.7 \pm 1.2$ counts, which corresponds – in accordance with Particle Data Group recommendation [7] – to a $\lim S = 2.6(1.9)$ counts with

90%(68%) C.L., and subsequently to half-life limits for $0\nu2\beta$ decay of ^{116}Cd:

$$T_{1/2}(0\nu2\beta) \geq 1.3(1.8)\times10^{23} \text{ yr, } 90\%(68\%) \text{ C.L.}$$

Using these bounds and calculations [8], one can obtain restrictions on the neutrino mass and right-handed admixtures in the weak interaction: $m_\nu \leq 2.2$ eV, $\eta \leq 2.8\times10^{-8}$, $\lambda \leq 2.5\times10^{-6}$ at 90% C.L. Neglecting right-handed contribution we get $m_\nu \leq 1.9(1.6)$ eV at 90% (68%) C.L., and on the basis of [9] the limit is $m_\nu \leq 1.7(1.5)$ eV.

Excited levels of ^{116}Sn with $E_{lev} \leq Q_{2\beta}$ can be also populated in $0\nu2\beta$ decay of ^{116}Cd. The full absorption of all emitted particles should result in the peak with $E = Q_{2\beta}$. Calculated with the help of GEANT3.21 and DECAY4 codes full peak efficiencies for $0\nu2\beta$ decay to the first and second excited levels of ^{116}Sn (2^+_1 with $E_{lev} = 1294$ keV and 0^+_1 with $E_{lev} = 1757$ keV) are: $\eta_{MC}(2^+_1) = 0.14$ and $\eta_{MC}(0^+_1) = 0.07$. These numbers result in the following restrictions on half-lives of ^{116}Cd $0\nu2\beta$ decay to excited levels of ^{116}Sn:

$$T_{1/2}(\text{g.s.} \rightarrow 2^+_1) \geq 2.2(3.0)\times10^{22} \text{ yr,}$$
$$T_{1/2}(\text{g.s.} \rightarrow 0^+_1) \geq 1.1(1.5)\times10^{22} \text{ yr.}$$

To obtain the half-life limits for $0\nu2\beta$ decay with emission of one, two and bulk [10] Majoron(s), the measured spectrum was fitted in the energy region 1.6 – 2.8 MeV by using the same model of background as for the $0\nu2\beta$ decay fitting procedure. As a result, the number of events under a theoretical 0νM1 curve was determined as -48 ± 59, giving no statistical evidence for the effect. It leads to an upper limit of 55(21) events at 90%(68%) C.L., that together with an efficiency value $\eta_{MC} = 0.905$ corresponds to the half-life limit:

$$T_{1/2}(0\nu\text{M1}) \geq 0.68(1.8)\times10^{22} \text{ yr.}$$

A similar procedure for $0\nu2\beta$ decay with two and bulk Majorons emission gives the same results for both channels:

$$T_{1/2}(0\nu\text{M2}) \geq 0.9(1.5)\times10^{21} \text{ yr,}$$
$$T_{1/2}(0\nu \text{ with bulk Majoron}) \geq 0.9(1.5)\times10^{21} \text{ yr.}$$

Excluded with 90% C.L. distributions of 0νM1, 0νM2 and decay with bulk Majoron emission as well as the $0\nu2\beta$ decay peak of ^{116}Cd are shown in Fig. 1.

Using our bound on $0\nu2\beta$ decay with one Majoron emission and calculations [11] the effective Majoron-neutrino coupling constant can be restricted as $g_M \leq 8.8(5.4)\times10^{-5}$, and on the basis of calculation [9] as $g_M \leq 5.0(3.1)\times10^{-5}$, which are among the best constraints obtained up to date in the direct 2β decay experiments [12].

All half-life limits reported in present work are the most stringent for ^{116}Cd nucleus. We consider this study as a pilot step for the future large scale experiment (CAMEO project [13]), which sensitivity to the neutrino mass would be enhanced up to the level of $m_\nu \approx 0.02$ eV.

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