ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА 2011 Т. 12 № 2 С. 124 - 128

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УДК 539.165

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FIRST RESULTS OF THE EXPERIMENT TO SEARCH FOR 2β DECAY OF ^{106}Cd WITH THE HELP OF $^{106}CdWO_4$ CRYSTAL SCINTILLATORS

An experiment to search for 2β processes in ^{106}Cd with the help of $^{106}CdWO_4$ crystal scintillator (mass of 215 g), enriched in ^{106}Cd up to 66 %, is in progress at the Gran Sasso National Laboratories of the INFN (Italy). After 1320 h of data taking, limits on double beta processes in ^{106}Cd have been established on the level of $10^{19} – 10^{20}$ yr, in particular (all the results at 90 % C.L.): $T_{1/2}(0\nu 2\varepsilon) > 3.6 \cdot 10^{20}$ yr, $T_{1/2}(2\nu\varepsilon\beta^+) > 7.2 \cdot 10^{19}$ yr, and $T_{1/2}(2\nu 2\beta^+) > 2.5 \cdot 10^{20}$ yr. Resonant 0ν2ε processes have been restricted as $T_{1/2}(0\nu 2K) > 1.4 \cdot 10^{20}$ yr and $T_{1/2}(0\nu LK) > 3.2 \cdot 10^{20}$ yr. A possible resonant enhancement of the 0ν2ε processes is estimated in the framework of the QRPA approach.

Keywords: double beta decay, ^{106}Cd, $CdWO_4$ crystal scintillator.

Introduction

Neutrinoless double beta decay (0ν2β) is a powerful tool to investigate properties of neutrino and weak interaction. Study of this extremely rare effect could determine an absolute neutrino mass and its hierarchy, establish nature of neutrino (Majorana or Dirac particle), check the lepton number conservation, possible contribution of right-handed admixture to weak interaction, existence of Nambu-Goldstone bosons (majorons).

The isotope ^{106}Cd is one of the most promising objects for 2β experiments thanks to large energy release ($Q_{2\beta} = 2770 \pm 7$ keV [1]) and comparatively high natural abundance (δ = 1.25 ± 0.06 % [2]). The decay scheme of the triplet ^{106}Cd – ^{106}Ag – ^{106}Pd is presented in Fig. 1. Experiments fulfilled to-date give only $T_{1/2}$ limits on 2β processes in ^{106}Cd on the level of 10^{18} - 10^{20} yr [3 - 7]. Taking into account theoretical calculations [8 - 14], double beta decay of ^{106}Cd could be detected at the level of sensitivity of 10^{21} - 10^{22} yr.

Cadmium tungstate ($CdWO_4$) crystal scintillators were successfully applied in experiments to search for double β decay [3, 6, 16], investigations of rare α [17] and β [18, 19] decays of cadmium and tungsten isotopes. A cadmium tungstate crystal scintillator enriched in ^{106}Cd to 66 % ($^{106}CdWO_4$) was developed with the aim to realize a high sensitivity experiment to search for 2β processes in ^{106}Cd [20]. First results of the experiment are presented here.

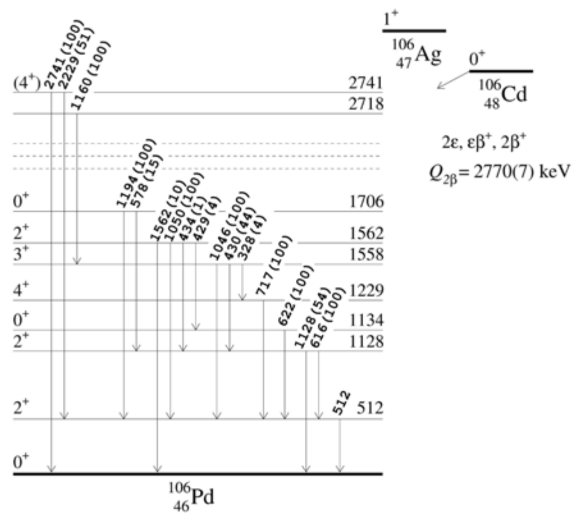

Fig. 1. Decay scheme of ^{106}Cd [15]. Energies of excited levels and emitted γ quanta are in keV (relative intensities of γ quanta are given in parentheses). $Q_{2\beta}$ is the double beta decay energy.

[†] Deceased.

Experiment

The $^{106}CdWO_4$ scintillator (∅27 · 50 mm, mass of 215.4 g) is fixed inside a cavity ∅47 · 59 mm (filled with high-purity silicon oil) in the polystyrene light-guide ∅66 · 312 mm. Two high purity quartz light-guides ∅66 · 100 mm are optically connected on opposite sides of the light-guide. The assembling is viewed by two 3" low radioactive EMI9265 photomultipliers (PMT). The detector is installed in the low background DAMA R&D set-up at the Gran Sasso National Laboratories of the INFN. It is sealed in a low radioactive Cu box flushed with high purity nitrogen gas to avoid presence of radon. The Cu box is surrounded by Cu (10 cm of thickness), 15 cm of lead, 1.5 mm of cadmium and 4 to 10 cm of polyethylene/paraffin. The shield is contained inside a Plexiglas box, also flushed by high purity nitrogen. An event-by-event data acquisition system records amplitude, arrival time, and pulse shape of events by a 1 GS/s 8 bit DC270 Transient Digitizer by Acqiris (adjusted to a sampling frequency of 20 MS/s) over a time window of 100 μs. Energy dependence of the detector energy resolution was measured with ^{22}Na, ^{133}Ba, ^{137}Cs, ^{228}Th and ^{241}Am sources as $FWHM_\gamma = \sqrt{11.2 \cdot E_\gamma}$, where E_γ is the energy of γ quanta; $FWHM_\gamma$ and E_γ are in keV.

Results and discussion

The energy spectrum of γ(β) events accumulated with the $^{106}CdWO_4$ detector over 1320 h is presented in Fig. 2. The γ(β) events were selected by pulse-

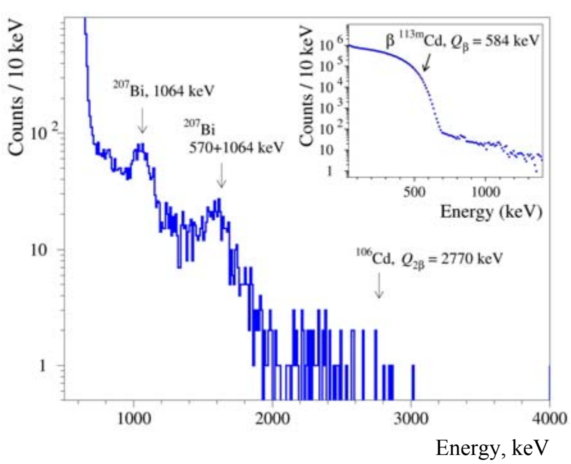

Fig. 2. Energy spectrum of γ(β) events measured with $^{106}CdWO_4$ scintillator over 1320 h in the low-background set-up. (Inset) Beta decay of ^{113m}Cd dominates at low energy (the data obtained over 268 h).

shape discrimination described in [21, 17, 22]. The counting rate ≈ 24 counts/s below the energy of ≈ 0.6 MeV is mainly due to the beta decay of ^{113m}Cd (Q_β = 584 keV, $T_{1/2}$ = 14.1 yr [15]) with the activity 112 ± 10 Bq/kg. The contamination of the enriched ^{106}Cd by ^{113m}Cd has been detected in the low-background TGV experiment [23]. Contributions to the background above the energy 0.6 MeV were analyzed by the time-amplitude (see, e.g. [24, 25]) and the pulse-shape discrimination techniques, as well by fit of the energy spectrum (the procedure is described in [6, 16, 19]) by models of background (internal ^{40}K, ^{207}Bi, U/Th, external γ rays from the set-up) simulated with the help of the EGS4 code [26]. Two peaks at ≈ 1.06 and ≈ 1.63 MeV can be explained by contamination of the crystal by ^{207}Bi. The data on radioactive contamination of $^{106}CdWO_4$ crystal are presented in Table 1.

Table 1. **Radioactive contamination of $^{106}CdWO_4$ crystal. Data for $^{116}CdWO_4$ from [6, 17] and for $CdWO_4$ [19] are given for comparison**

Chain	Nuclide	Activity (mBq/kg) in crystals		
		$^{106}CdWO_4$	$^{116}CdWO_4$	$CdWO_4$
^{232}Th	^{232}Th	≤ 0.1	0.053(9)	≤ 0.026
	^{228}Th	0.053(5)	0.039(2)	≤ 0.014
^{238}U	^{238}U	≤ 0.3	≤ 0.6	≤ 0.045
	^{230}Th	≤ 0.8	≤ 0.5	≤ 0.18
	^{226}Ra	≤ 0.3	≤ 0.004	≤ 0.018
	^{210}Po	≤ 0.3		≤ 0.063
Total α activity (U/Th)		2.1(1)	1.40(10)	0.26(4)
	^{40}K	≤ 11	0.3(1)	≤ 5
	^{113}Cd	174*	91(5)	558(4)
	^{113m}Cd	112 000(5 000)	0.43(6)	≤ 3.4
	^{207}Bi	1.3(3)		

*Calculated taking into account the isotopic composition of ^{113}Cd in $^{106}CdWO_4$ and the half-life of ^{113}Cd [19].

There are no peculiarities in the spectrum which could be ascribed to the double β processes in ^{106}Cd. Therefore only lower half-life limits can be set according to formula: $\lim T_{1/2} = N\, \eta\, t \ln 2 / \lim S$, where N is the number of ^{106}Cd nuclei ($2.420 \cdot 10^{23}$), η is the detection efficiency, t is the measuring time, and $\lim S$ is the number of events of the effect searched for which can be excluded at a given confidence level (C.L.). To estimate values of $\lim S$, the experimental energy spectrum was fitted in different energy intervals by the sum of components representing the background (internal ^{40}K, ^{207}Bi, U/Th, external γ from the details of the set-up) and the expected models for 2β processes in ^{106}Cd simulated by using the EGS4 code. Some examples of the energy spectra of 2β processes in ^{106}Cd are presented in Fig. 3. The fits allow us to set limits on the processes of 2β decay in ^{106}Cd presented in Table 2.

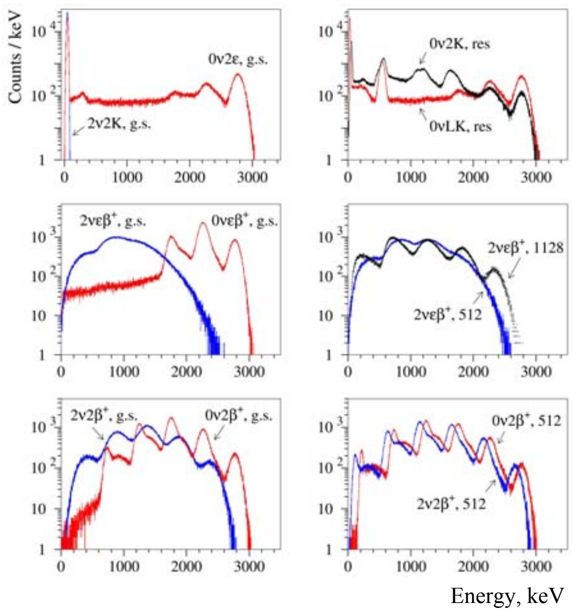

Fig. 3. Simulated response functions of the $^{106}CdWO_4$ scintillator to 2β processes in ^{106}Cd.

Table 2. **Half-life limits on 2β processes in ^{106}Cd**

Decay channel	Level of ^{106}Pd	Experimental limit on $T_{1/2}$ at 90 % C.L.	
		Present work	Best previous limits
0ν2ε	g.s.	≥ 3.6 · 10^{20}	≥ 8.0 · 10^{18} [6]
2νεβ$^+$	g.s.	≥ 7.2 · 10^{19}	≥ 4.1 · 10^{20} [5]
	2_1^+ 512 keV	≥ 9.0 · 10^{19}	≥ 2.6 · 10^{20} [5]
	2_1^+ 1128 keV	≥ 3.2 · 10^{20}	≥ 1.4 · 10^{20} [5]
	0_1^+ 1134 keV	≥ 3.5 · 10^{20}	≥ 1.6 · 10^{20} [7]
0νεβ$^+$	g.s.	≥ 2.1 · 10^{20}	≥ 3.7 · 10^{20} [5]
2ν2β$^+$	g.s.	≥ 2.5 · 10^{20}	≥ 2.4 · 10^{20} [5]
	2_1^+ 512 keV	≥ 3.2 · 10^{20}	≥ 1.7 · 10^{20} [7]
0ν2β$^+$	g.s.	≥ 2.1 · 10^{20}	≥ 2.4 · 10^{20} [5]
Resonant 0ν2*K*	2718 keV	≥ 1.4 · 10^{20}	–
Resonant 0ν*KL*	2741 keV	≥ 3.2 · 10^{20}	≥ 1.6 · 10^{20} [7]

In case of 0ν capture of two electrons from the *K* shell (or *L* and *K* shells) of cadmium atom, energy release of 2721 ± 7 keV (2742 ± 7 keV) is equal, within the errors, to the energy of the excited levels of ^{106}Pd with E_{exc} = 2718 keV and 2741 keV [15]. Such a coincidence could give a resonant enhancement of the 0ν2ε capture [27, 28]. The limits on the resonant 2ε processes obtained by fit of the experimental data are presented in Table 2.

The resonant 2β half-life of ^{106}Cd was estimated by using the general formalism of [27] and calculating the associated nuclear matrix element in a realistic single-particle space using a microscopic nucleon-nucleon interaction. We have used a higher-RPA (random-phase approximation) framework called the multiple-commutator model (MCM) [29, 30]. We have assumed that the spin-parity of the resonant levels is 0^+. The half-life can be written as:

$$T_{1/2} = 5.561 \cdot 10^{23} \frac{x^2 + 9.42 \text{ eV}^2}{\langle m_\nu \rangle^2} \text{ yr}, \quad (1)$$

where $x = |Q - E|$ and $\langle m_\nu \rangle$ (the effective Majorana neutrino mass) are in units of eV. Here *Q* is the difference in atomic masses between ^{106}Cd and ^{106}Pd and *E* contains the nuclear excitation energy and the hole energies in the atomic *s* orbitals. The dependence of the half-life on *x* (Fig. 4) gives a strong motivation for precise measurements of the atomic masses' difference between ^{106}Cd and ^{106}Pd, and properties (spin and parity) of the 2718 and 2741 keV excited levels of ^{106}Pd.

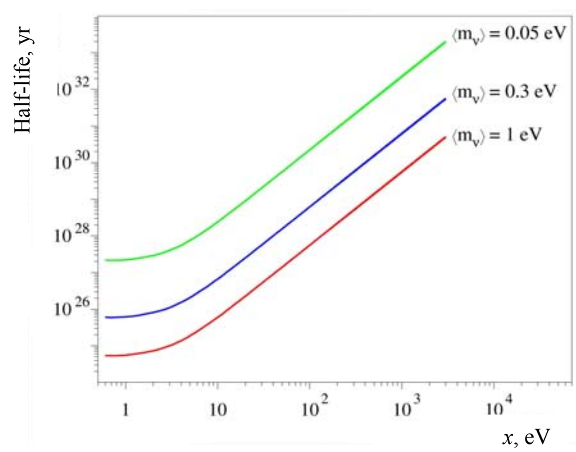

Fig. 4. Calculated dependence of the half-life of ^{106}Cd relatively to the resonant 0ν2ε capture to excited levels of ^{106}Pd on parameter *x* (see text) for different values of the effective neutrino mass.

Conclusions

An experiment using a cadmium tungstate crystal scintillator enriched in ^{106}Cd up to 66 % is in progress in the DAMA R&D set-up at the Laboratori Nazionali del Gran Sasso of INFN. After 1320 h of data taking we have estimated radioactive contamination of the $^{106}CdWO_4$ scintillator relatively to U/Th (total α activity) on the level of ≈ 2 mBq/kg. The main components of background of the detector are β active ^{113m}Cd (112 Bq/kg) and ^{207}Bi (1.3 mBq/kg). By analysis of the experimental data we have set limits on 2β processes in ^{106}Cd on the level of 10^{19} - 10^{20} yr. A possible resonant enhancement of 0ν2ε processes was estimated in the framework of QRPA approach. A sensitivity of the experiment to different 2β processes in ^{106}Cd after ≈ 3 yr of measurements is expected to be on the level of ~ 10^{21} yr.

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ПЕРШІ РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТУ ПО ПОШУКУ 2β-РОЗПАДУ ^{106}Cd ЗА ДОПОМОГОЮ КРИСТАЛІЧНИХ СЦИНТИЛЯТОРІВ $^{106}CdWO_4$

Експеримент по пошуку 2β-процесів у ^{106}Cd за допомогою кристалічних сцинтиляторів $^{106}CdWO_4$ (з масою 215 г), збагачених ^{106}Cd до 66 %, проходить у Національній лабораторії Гран Сассо Національного інституту ядерної фізики (Італія). Після накопичення даних протягом 1320 годин отримано обмеження на періоди напіврозпаду для подвійних бета-процесів у ^{106}Cd на рівні 10^{19} - 10^{20} років, зокрема (усі результати даються з 90 %-ною довірчою ймовірністю): $T_{1/2}(0\nu2\varepsilon) > 3{,}6 \cdot 10^{20}$ років, $T_{1/2}(2\nu\varepsilon\beta^+) > 7{,}2 \cdot 10^{19}$ років та $T_{1/2}(2\nu2\beta^+) > 2{,}5 \cdot 10^{20}$ років. Резонансні 0ν2ε процеси обмежені як $T_{1/2}(0\nu2K) > 1{,}4 \cdot 10^{20}$ років та $T_{1/2}(0\nu LK) > 3{,}2 \cdot 10^{20}$ років. Можливе резонансне підсилення 0ν2ε процесів розраховане в рамках моделі QRPA.

Ключові слова: подвійний бета-розпад, ^{106}Cd, кристалічний сцинтилятор $CdWO_4$.

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ПЕРВЫЕ РЕЗУЛЬТАТЫ ЭКСПЕРИМЕНТА ПО ПОИСКУ 2β-РАСПАДА ^{106}Cd С ПОМОЩЬЮ КРИСТАЛЛИЧЕСКИХ СЦИНТИЛЛЯТОРОВ $^{106}CdWO_4$

Эксперимент по поиску 2β-процессов в ^{106}Cd с помощью кристаллических сцинтилляторов $^{106}CdWO_4$ (с массой 215 г), обогащенных ^{106}Cd до 66 %, проходит в Национальной лаборатории Гран Сассо Национального института ядерной физики (Италия). После накопления данных на протяжении 1320 ч получены ограничения на период полураспада для двойных бета-процессов в ^{106}Cd на уровне 10^{19} - 10^{20} лет, в частности (все результаты даются с 90 %-ной доверительной вероятностью): $T_{1/2}(0\nu2\varepsilon) > 3{,}6 \cdot 10^{20}$ лет, $T_{1/2}(2\nu\varepsilon\beta^+) > 7{,}2 \cdot 10^{19}$ лет и $T_{1/2}(2\nu2\beta^+) > 2{,}5 \cdot 10^{20}$ лет. Резонансные 0ν2ε процессы ограничены как $T_{1/2}(0\nu2K) > 1{,}4 \cdot 10^{20}$ лет и $T_{1/2}(0\nu LK) > 3{,}2 \cdot 10^{20}$ лет. Возможное резонансное усиление 0ν2ε процессов оценено в рамках модели QRPA.

Ключевые слова: двойной бета-распад, ^{106}Cd, кристаллический сцинтиллятор $CdWO_4$.

Received 07.06.10,
revised - 14.03.11.