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Search for 2β processes in ^{106}Cd with ^{106}CdWO$_4$ crystal scintillator

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An experiment to search for double beta (2β) decay of ^{106}Cd with the help of a low-background cadmium tungstate crystal scintillator developed from cadmium enriched in ^{106}Cd to 66 % (^{106}CdWO$_4$, 215 g) is in progress at the STELLA facility of the Gran Sasso underground laboratory (INFN, Italy). The ^{106}CdWO$_4$ scintillator is viewed by low-background photomultiplier through a PbWO$_4$ crystal light-guide produced from deeply purified archaeological lead. The detector operates in coincidence with the four low-background HPGe detectors to search for 2β processes with the emission of gamma quanta. Sensitivity of the experiment after 10678 h of data taking to different channels of 2β decay of ^{106}Cd is on the level of $\lim T_{1/2} \sim 10^{19}$–$10^{21}$ years. In particular, the limit $T_{1/2}{}^{2\nu\varepsilon\beta+} \geq 1.3 \times 10^{21}$ yr at 90 % C.L. reached the region of theoretical predictions.

Keywords: crystal scintillator, cadmium tungstate, isotope ^{106}Cd, double-beta decay.

Исследования двойного бета-распада (2β) ядер ^{106}Cd ведутся в подземной лаборатории Гран-Сассо (Италия) с помощью низкофонового сцинтилляционного кристалла вольфрамата кадмия из кадмия, изотопно обогащенного ^{106}Cd (^{106}CdWO$_4$, обогащение 66 %, масса кристалла 215 г). Сцинтиллятор ^{106}CdWO$_4$ просматривается низкофоновым фотоумножителем через световод из кристалла PbWO$_4$, изготовленного из глубоко очищенного археологического свинца. Детектор работает в совпадениях с четырьмя низкофоновыми полупроводниковыми детекторами из сверхчистого германия для поиска 2β-процессов с испусканием гамма-квантов. Чувствительность эксперимента для разных каналов 2β-распада ^{106}Cd составляет $\lim T_{1/2} \sim 10^{19}$–$10^{21}$ лет. В частности, предел $T_{1/2}{}^{2\nu\varepsilon\beta+} \geq 1.3 \times 10^{21}$ достиг области значений теоретических предсказаний.

Пошук 2β процесів в ^{106}Cd за допомогою сцинтилляційного кристала $^{106}CdWO_4$. *О.Г.Поліщук, П.Беллі, Р.Бернабей, В.Б.Бруданін, Ф.А.Даневич, С.Д'Анжело, А.Інчікітті, Ф.Капелла, В.Карачіолло, М.Лаубенштейн, В.М.Мокіна, Д.В.Пода, В.І.Третяк, І.А.Тупіцина, Д.Н.Черняк, Р.Черуллі.*

Дослідження подвійного бета-розпаду (2β) ядер ^{106}Cd ведуться у підземній лабораторії Гран-Сассо (Італія) за допомогою низькофонового сцинтиляційного кристала вольфрамату кадмію з кадмію, ізотопно збагаченого ^{106}Cd ($^{106}CdWO_4$, збагачення 66 %, маса кристала 215 г). Сцинтилятор $^{106}CdWO_4$ проглядається низькофоновим фотопомножувачем через світловод з кристала $PbWO_4$, виготовленого з глибоко очищеного археологічного свинцю. Детектор працює у збігах з чотирма низькофоновими напівпровідниковими детекторами з надчистого германію для пошуку 2β процесів з випусканням гамма-квантів. Чутливість експерименту для різних каналів 2β розпаду ^{106}Cd становить $\lim T_{1/2} \sim 10^{19}–10^{21}$ років. Зокрема, межа $T_{1/2}^{2\nu\varepsilon\beta+} \geq 1.3 \cdot 10^{21}$ досягає області значень теоретичних передбачень.

1. Introduction

The investigations of the double-beta (2β) decay are considered as a unique possibility to test the Standard Model of particles (SM) [1–5]. While the two neutrino 2β decay is allowed in the SM and is observed for several nuclei, the neutrinoless double beta decay (0ν2β) is forbidden in the SM since it violates the lepton number by two units, and can exist only if the neutrino is a massive Majorana particle. However, massive Majorana neutrino is predicted by many SM extensions.

At present the $0\nu2\beta^-$ experiments provide the most sensitive test of the properties of neutrino and weak interactions. Nevertheless, investigations of double beta "plus" processes are also requested since they allow to refine mechanism of the 0ν2β decay (neutrino mass or right-handed admixture in weak interaction [6]).

Isotope ^{106}Cd (natural abundance is 1.25(6) % [7]) is among of the most widely studied $2\beta^+$ nuclides. Thanks to the large energy release ($Q_{2\beta}$ = 2775.39(10) keV [8]), theoretical calculations give favourable estimations on probability of the 2β decay of ^{106}Cd [6, 9–12]. Moreover, ^{106}Cd is interesting due to possible resonant 0ν double electron capture to excited levels of ^{106}Pd [9].

Cadmium tungstate crystal scintillator was produced from cadmium enriched in ^{106}Cd to 66 % ($^{106}CdWO_4$) by using the low-thermal-gradient Czochralski method from the deeply purified enriched cadmium and tungsten. The scintillator shows excellent optical and scintillation properties, low radioactive contamination [13, 14].

2. Experimental

The $^{106}CdWO_4$ scintillator is viewed through a lead tungstate ($PbWO_4$) crystal light-guide (∅40 × 83 mm), developed from the deeply purified low-radioactive archaeological lead [15, 16], by 3 inches low radioactive photomultiplier tube (PMT) Hamamatsu R6233MOD. The detector is installed inside an ultra-low background set-up GeMulti with four HPGe detectors (≈225 cm^3 each) in a well between the HPGe detectors. The schema of the set-up is presented in Fig. 1.

An event-by-event data acquisition system (DaQ) accumulates the pulse profiles of events in the $^{106}CdWO_4$ and HPGe detectors. The software of the DaQ calculates and records the energy of HPGe events, while the energy of $^{106}CdWO_4$ events and coincidence between the $^{106}CdWO_4$ and

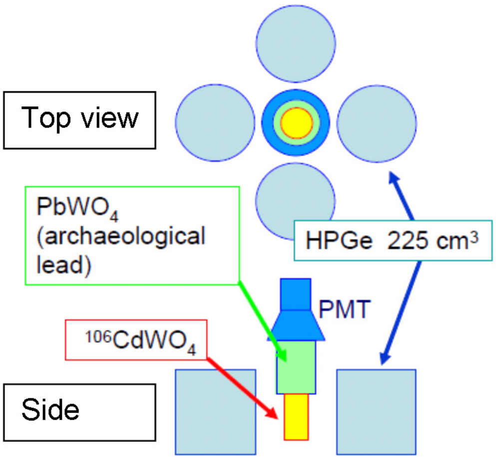

Fig. 1. Schema of the low-background set-up with the $^{106}CdWO_4$ crystal scintillator viewed by PMT through $PbWO_4$ light-guide. The scintillator is installed between four HPGe detectors.

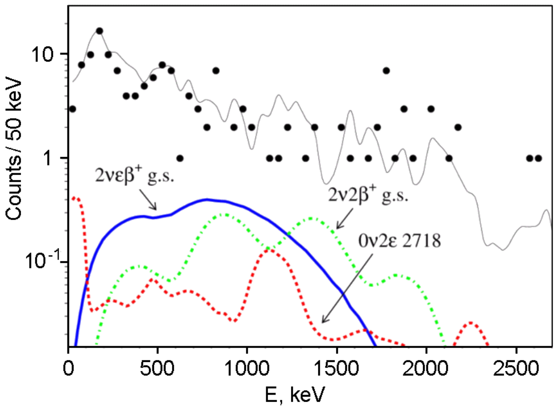

Fig. 2. The energy spectrum of the $\gamma(\beta)$ events accumulated over 10678 h in the low background set-up with the $^{106}CdWO_4$ crystal scintillator in anticoincidence with the HPGe detectors (points) together with the background model (solid line). The main components of the background are shown: the distributions of internal and external ^{40}K, internal ^{228}Th and ^{238}U with daughters, and the contribution the external γ quanta from U and Th contamination of the set-up in these experimental conditions.

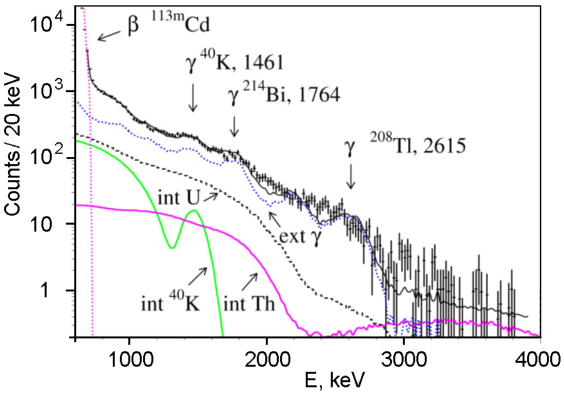

Fig. 3. The energy spectrum of the $^{106}CdWO_4$ detector accumulated over 10678 h in coincidence with 511 keV annihilation γ quanta in the HPGe detectors (circles). The model of background is shown by solid line. The Monte Carlo simulated distributions of the $2\nu\varepsilon\beta^+$ and $2\nu2\beta^+$ decays, and the $0\nu2\varepsilon$ transition of ^{106}Cd to the 2718 keV excited level of ^{106}Pd excluded at 90 % C.L. are shown.

HPGe detectors are calculated off-line. The energy resolution (FWHM) of the HPGe detectors is 2.0 keV for 1332 keV γ quanta of ^{60}Co. The $^{106}CdWO_4$ detector was calibrated with ^{22}Na, ^{60}Co, ^{137}Cs and ^{228}Th γ sources. The energy resolution of the detector can be described by the function: FWHM = $\sqrt{20.4 \times E_\gamma}$, where FWHM and $E\gamma$ are in keV. The experiment is running deep underground at the STELLA facility of the Gran Sasso National Laboratory (INFN, Italy) on the depth of 3600 m of water equivalent. The experiment is described in more detail in [17], where also preliminary results of the data taking over 3233 h are reported.

3. Results and discussion

The energy spectrum of $\gamma(\beta)$ events accumulated with the $^{106}CdWO_4$ detector in anticoincidence with the HPGe detectors over 10678 h is presented in Fig. 2. The α events were removed from the spectrum by using the pulse-shape discrimination technique. The spectrum was fitted by the model built from the energy distributions simulated by the EGS4 code [18].

The energy spectrum measured by the $^{106}CdWO_4$ detector in coincidence with 511 keV events at least in one of the HPGe detectors is presented in Fig. 3. A Monte Carlo simulated model of the background built by using the fit of the anticoincidence spectrum well reproduces the coincidence data. A measured counting rate in the coincidence spectrum (143 counts in the energy interval 50–3000 keV) is in agreement with the model of the background built using the anticoincidence data fit parameters (139 events).

There are no peculiarities in the coincidence data accumulated with the $^{106}CdWO_4$ detector that could be ascribed to the 2β processes in ^{106}Cd. The lower half-life limits can be estimated by using the following formula:

$$\lim T_{1/2} = N \cdot \varepsilon \cdot t \cdot \ln 2 / \lim S, \qquad (1)$$

where N is the number of ^{106}Cd nuclei in the $^{106}CdWO_4$ crystal ($2.42 \cdot 10^{23}$), ε is the detection efficiency, t is the time of measurements, 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 $\lim S$ values, the measured number of events in the coincidence data was compared with the supposed model of the background, built by using the fit of the anticoincidence spectrum. E.g. there are 33 counts in the energy interval 600–1200 keV, while the model contains 36.7 events. In accordance with the Feldman-Cousins procedure [19], it corresponds to $\lim S = 7.2$ counts at 90 % C.L. Taking into account the Monte Carlo calculated detection efficiency (7.59 %) for the $2\nu\varepsilon\beta^+$

Table. Half-life limits on 2β processes in ^{106}Cd (at 90 % C.L.). Comparison with theory is given

Decay channel, level of ^{106}Pd (keV)	$T_{1/2}$ (yr)		
	Present work	Best previous limits	Theory
$2\nu2\varepsilon$, 0_1^+ 1134	$\geq 3.0\cdot10^{20}$	$\geq 1.7\cdot10^{20}$ [14]	$1.1\cdot10^{24}$ [12]
$0\nu2\varepsilon$, g.s.	$\geq 5.6\cdot10^{19}$	$\geq 1.0\cdot10^{21}$ [14]	
$2\nu\varepsilon\beta^+$, g.s.	$\geq 1.3\cdot10^{21}$	$\geq 8.4\cdot10^{20}$ [17]	$8.3\cdot10^{20}$ [20]
			$2.7\cdot10^{22}$ [12]
			$7.7\cdot10^{22}$ [11]
$2\nu\varepsilon\beta^+$, 0_1^+ 1134	$\geq 1.4\cdot10^{21}$	$\geq 9.4\cdot10^{20}$ [17]	$1.1\cdot10^{27}$ [12]
$0\nu\varepsilon\beta^+$, g.s.	$\geq 9.3\cdot10^{20}$	$\geq 2.2\cdot10^{21}$ [14]	$3.4\cdot10^{26}$ [6]
			$(1.3–2.3)\cdot10^{26}$ [9]
$2\nu2\beta^+$, g.s.	$\geq 4.2\cdot10^{21}$	$\geq 2.5\cdot10^{21}$ [17]	$2.4\cdot10^{27}$ [12]
			$3.1\cdot10^{27}$ [11]
$0\nu2\beta^+$, g.s.	$\geq 2.5\cdot10^{21}$	$\geq 1.2\cdot10^{21}$ [14]	$4.8\cdot10^{27}$ [6]
			$(1.9–3.2)\cdot10^{27}$ [9]
Res. $0\nu2\varepsilon$, 2718	$\geq 7.4\cdot10^{20}$	$4.3\cdot10^{20}$ [14]	
Res. $0\nu2\varepsilon$, 2741 4^+	$\geq 8.0\cdot10^{19}$	$\geq 9.5\cdot10^{20}$ [14]	
Res. $0\nu2\varepsilon$, 2748 $(2,3)^-$	$\geq 1.8\cdot10^{20}$	$\geq 4.3\cdot10^{20}$ [14]	

decay of ^{106}Cd to the ground state of ^{106}Pd, a part of the $2\nu\varepsilon\beta^+$ distribution in the energy interval (59.5 %), and the 99 % time efficiency of the coincidence of ^{106}CdWO$_4$ events with 511 keV events in the HPGe detectors (in total, $\varepsilon = 4.7$ %), we got the following half-life limit on the process searched for:

$$T_{1/2}^{2\nu\varepsilon\beta+} \geq 1.3\cdot10^{21} \text{ yr at } 90\%\text{C.L.}$$

The half-life limits on 2β processes in ^{106}Cd to the ground state (g.s.) and to the first 0^+ 1134 keV excited level of ^{106}Pd obtained in a similar way. Limits on possible resonant $0\nu2\varepsilon$ transitions to the excited levels 2718 keV, 2741 keV 4^+, and 2748 keV $(2,3)^-$ of ^{106}Pd have been also set. The limits are presented in Table.

4. Conclusions

An experiment to search for double beta decay of ^{106}Cd with enriched in ^{106}Cd (to 66 %) low background ^{106}CdWO$_4$ scintillation detector (215 g) in coincidence with the four crystals HPGe γ spectrometer GeMulti is in progress at the Gran Sasso underground laboratory (INFN, Italy). The sensitivity of the experiment after 10678 h of data taking is on the level of $\lim T_{1/2} \sim 10^{19}–10^{21}$ yr. In particular, the limit $T_{1/2}^{2\nu\varepsilon\beta+} \geq 1.3\cdot10^{21}$ yr reached the region of the theoretical predictions (see Table).

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