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Search for double β decay of ^{106}Cd by using isotopically enriched $^{106}CdWO_4$ crystal scintillator

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Abstract. A search for double β processes in ^{106}Cd was carried out at the Gran Sasso National Laboratories of the INFN (Italy) by using a $CdWO_4$ crystal scintillator (mass of 215 g) enriched in ^{106}Cd up to 66%. After 6590 h of data taking, half-life limits on double beta processes in ^{106}Cd were set at level of $10^{19}-10^{21}$ yr. A possible resonant enhancement of the $0\nu2\varepsilon$ processes has also been estimated in the framework of the QRPA approach.

1. Introduction

The double beta decay (2β) is a powerful tool to investigate the properties of the neutrino and of the weak interactions. The study of the neutrinoless mode (0ν) of the decay allows to determine an absolute scale of the neutrino mass and its hierarchy, to establish the nature of the neutrino (Majorana or Dirac particle), to check the lepton number conservation, possible contribution of right-handed admixture to weak interaction and the existence of Nambu-Goldstone bosons (majorons).

The experimental efforts during almost seventy years were concentrated mainly on the decays with emission of two electrons. As a result, the two neutrino mode (2ν) of 2β decay was detected for eleven nuclei with the half-lives in the range of $10^{19}-10^{24}$ yr, while the half-life limits at level of $10^{23}-10^{25}$ yr were set for the neutrinoless process in the most sensitive experiments. The results of the most sensitive searches for double electron capture (2ε), electron capture with positron emission ($\varepsilon\beta^+$) and emission of two positrons ($2\beta^+$) are at much modest level: $10^{18}-10^{21}$ yr. At the same time, a possibility to clarify a contribution of right-handed admixtures in weak interactions [1] gives strong motivation to search for neutrinoless 2ε and $\varepsilon\beta^+$ decays. Another important issue is a resonant enhancement of double electron capture in a case when the mother and (excited) daughter atoms are nearly degenerate in mass [2, 3].

The ^{106}Cd isotope is one of the most promising candidates to search for $2\beta^+$ processes thanks to the large energy release ($Q_{2\beta} = 2775.39 \pm 0.10$ keV [4]), the comparatively high natural abundance ($1.25 \pm 0.06\%$ [5]), and the possibility of a resonant enhancement of the $0\nu2\varepsilon$ decay of ^{106}Cd [3, 6].

Here we present results of the first stage of the experiment to search for 2β processes in ^{106}Cd with the help of especially developed [7] cadmium tungstate (^{106}CdWO$_4$) crystal scintillator enriched in ^{106}Cd to 66%.

2. Experiment

The ^{106}CdWO$_4$ crystal (mass 215 g) was fixed inside a cavity $\oslash 47 \times 59$ mm (filled with high purity silicon oil) in the central part of a polystyrene light-guide, 66 mm in diameter by 312 mm in length. Two high purity quartz light-guides 66 mm in diameter by 100 mm in length were optically connected on the opposite sides of the polystyrene light-guide. The assembling was viewed by two low radioactive EMI9265–B53/FL, 3" photomultipliers (PMT). The detector was installed in the low background DAMA/R&D set-up at the Gran Sasso National Laboratories of the INFN (Italy). It was surrounded by Cu bricks and sealed in a low radioactive air-tight Cu box continuously flushed with high purity nitrogen gas to avoid presence of residual environmental radon. The Cu box was surrounded by a passive shield made of high purity Cu, 10 cm of thickness, 15 cm of low radioactive lead, 1.5 mm of cadmium and 4 to 10 cm of polyethylene/paraffin to reduce the external background. The shield was contained inside a Plexiglas box, also continuously flushed with high purity nitrogen gas. An event-by-event data acquisition system recorded amplitude, arrival time, and pulse shape of the events over a time window of 100 μs. The energy resolution of the detector, measured with ^{22}Na, ^{133}Ba, ^{137}Cs, ^{228}Th, and ^{241}Am γ sources, above 0.5 MeV can be fitted by the function: $\mathrm{FWHM}_\gamma = \sqrt{-4900 + 21 \times E_\gamma}$, where FWHM$_\gamma$ and E_γ are in keV.

3. Results and discussion

The energy spectrum of the $\beta(\gamma)$ events (selected by pulse-shape analysis) accumulated with the ^{106}CdWO$_4$ detector over 6590 h is presented in Fig. 1. The decay of the β active ^{113m}Cd with activity 116(4) Bq/kg dominates at the energy < 0.65 MeV, while the pollution of the crystal surface by ^{207}Bi at level of 3 mBq/kg is the main source of the background up to ≈ 2.5 MeV. The activities of U/Th daughters in the scintillator, estimated by using the time-amplitude and the pulse-shape analyses, are rather low: 0.04 mBq/kg of ^{228}Th and 0.01 mBq/kg of ^{226}Ra. The total α activity of U/Th is at level of 2 mBq/kg.

A fit of the spectrum in the energy region $0.66 - 4.0$ MeV by the model built from Monte Carlo simulated distributions (internal contamination of the ^{106}CdWO$_4$ crystal by ^{113m}Cd, ^{40}K, ^{90}Sr-^{90}Y, ^{238}U/^{232}Th with their daughters, surface ^{207}Bi, contamination of the set-up by ^{40}K, ^{232}Th and ^{238}U), and the main components of the background are shown in Fig. 1. The energy distributions of the possible background components were simulated with the help of the EGS4 code [8]. The initial kinematics of the particles emitted in the nuclear decays was given by the event generator DECAY0 [9].

There are no peculiarities in the data accumulated with the ^{106}CdWO$_4$ detector which could be ascribed to double β decay of ^{106}Cd. Therefore only lower half-life limits were set by fit of the experimental data by the model constructed from the components of the background and the effect searched for (response functions of the ^{106}CdWO$_4$ detector to the 2β processes in ^{106}Cd were simulated with the help of the EGS4 [8] and the DECAY0 [9] packages). As an example, the excluded energy distributions expected for the $\varepsilon\beta^+$ decay of ^{106}Cd are shown in Fig. 2. The

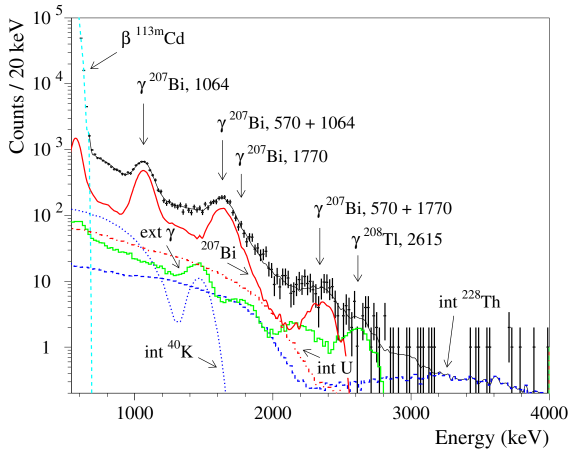

Figure 1. The energy spectrum of $\beta(\gamma)$ events accumulated over 6590 h in the low background set-up with the $^{106}CdWO_4$ crystal scintillator together with the model of the background. The main components of the background are shown: β spectrum of internal ^{113m}Cd, distributions of ^{40}K, ^{228}Th, ^{238}U, ^{207}Bi (deposited on the crystal surface), and the contribution from the external γ quanta from PMTs and copper box ("ext γ") in these experimental conditions.

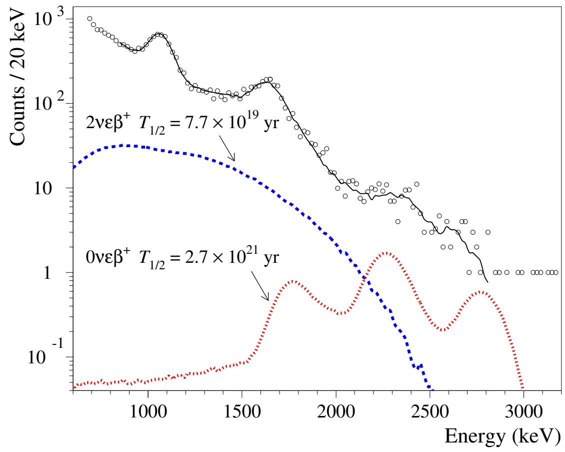

Figure 2. Part of the energy spectrum of $\beta(\gamma)$ events accumulated with the $^{106}CdWO_4$ detector over 6590 h (circles) and its fit in the energy interval $840-2800$ keV (solid line) together with the excluded distributions of $2\nu\varepsilon\beta^+$ and $0\nu\varepsilon\beta^+$ decay of ^{106}Cd.

half-life limits on 2β decay of ^{106}Cd obtained in the present work are summarized in Table 1 where results of the most sensitive previous studies are given for comparison.

The half-life of the ^{106}Cd resonant 2ε process was estimated [6] by using the general formalism of [15] and by calculating the associated nuclear matrix element in a realistic single-particle space with a microscopic nucleon-nucleon interaction. We have used a higher-RPA (random-phase approximation) framework called the multiple-commutator model (MCM) [16, 17]. Using the UCOM short-range correlations [18], and taking into account the recent measurement of the $Q_{2\beta}$ value for ^{106}Cd [4], the half-life for the 0ν double electron capture in ^{106}Cd to the 2718 keV level of ^{106}Pd (assuming its spin-parity is 0^+) is estimated as $T_{1/2} = (2.1-5.7)\times 10^{30}$ yr (for the effective neutrino mass $\langle m_\nu\rangle = 1$ eV).

4. Conclusions

A search for 2β decay of ^{106}Cd has been realized using the 215 g cadmium tungstate crystal scintillator enriched in ^{106}Cd to 66%. After 6590 h of data taking new improved limits on 2β decay of ^{106}Cd were set at level of $10^{19}-10^{21}$ yr, in particular: $T_{1/2}^{2\nu 2\beta^+} \geq 3.9\times 10^{20}$ yr, and $T_{1/2}^{0\nu 2\varepsilon} \geq 2.4\times 10^{21}$ yr. Resonant $0\nu 2\varepsilon$ processes have been restricted as $T_{1/2}^{0\nu 2K} \geq 3.8\times 10^{20}$ yr and $T_{1/2}^{0\nu KL} \geq 9.6\times 10^{20}$ yr (all the limits at 90% C.L.). A possible resonant enhancement of $0\nu 2\varepsilon$ decay was estimated in the framework of QRPA approach. The half-life of the resonant decay depends on the difference between the value of $Q_{2\beta}$ and energies of the appropriate excited levels of ^{106}Pd minus the binding energies of two electrons on the shells of the daughter atom.

A next stage of the experiment with the $^{106}CdWO_4$ crystal in the GeMulti set-up with four 225 cm^3 HPGe detectors is in preparation. We estimate a sensitivity of the experiment, in particular

Table 1. Half-life limits on 2β processes in ^{106}Cd.

Decay channel	Decay mode	Level of ^{106}Pd (keV)	$T_{1/2}$ limit (yr) at 90% C.L. Present work	Best previous limits
2ε	2ν	2^+_2 1128	$\geq 5.1 \times 10^{20}$	$\geq 5.1 \times 10^{18}$ [11]
		0^+_1 1134	$\geq 3.2 \times 10^{20}$	$\geq 1.0 \times 10^{20}$ [12]
	0ν	g.s.	$\geq 2.4 \times 10^{21}$	$\geq 8.0 \times 10^{18}$ [13]
		2^+_1 512	$\geq 1.8 \times 10^{21}$	$\geq 3.5 \times 10^{18}$ [11]
		2^+_2 1128	$\geq 3.6 \times 10^{20}$	$\geq 4.9 \times 10^{19}$ [14]
		0^+_1 1134	$\geq 4.1 \times 10^{20}$	$\geq 7.3 \times 10^{19}$ [14]
Resonant $2K$	0ν	2718	$\geq 3.8 \times 10^{20}$	$\geq 1.6 \times 10^{20}$ [12]
Resonant KL	0ν	4^+ 2741	$\geq 9.6 \times 10^{20}$	$\geq 1.1 \times 10^{20}$ [10]
$\varepsilon\beta^+$	2ν	g.s.	$\geq 7.7 \times 10^{19}$	$\geq 4.1 \times 10^{20}$ [14]
		2^+_1 512	$\geq 8.8 \times 10^{19}$	$\geq 2.6 \times 10^{20}$ [14]
		2^+_2 1128	$\geq 1.8 \times 10^{20}$	$\geq 1.4 \times 10^{20}$ [14]
	0ν	g.s.	$\geq 2.7 \times 10^{21}$	$\geq 3.7 \times 10^{20}$ [14]
		2^+_1 512	$\geq 2.5 \times 10^{21}$	$\geq 2.6 \times 10^{20}$ [14]
		2^+_2 1128	$\geq 8.7 \times 10^{20}$	$\geq 1.4 \times 10^{20}$ [14]
$2\beta^+$	2ν	g.s.	$\geq 3.9 \times 10^{20}$	$\geq 2.4 \times 10^{20}$ [14]
		2^+_1 512	$\geq 9.6 \times 10^{20}$	$\geq 1.7 \times 10^{20}$ [12]
	0ν	g.s.	$\geq 1.6 \times 10^{21}$	$\geq 2.4 \times 10^{20}$ [14]
		2^+_1 512	$\geq 1.5 \times 10^{21}$	$\geq 1.7 \times 10^{20}$ [12]

to the $2\nu\varepsilon\beta^+$ decay of ^{106}Cd, to be at level of the theoretical predictions $T_{1/2} \sim 10^{20} - 10^{22}$ yr.

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