First Results of the Experiment to Search for 2β Decay of ^{106}Cd with the Help of $^{106}CdWO_4$ Crystal Scintillators

P. Belli [a], R. Bernabei [a,b], R. S. Boiko [c], V. B. Brudanin [d], F. Cappella [e,f], V. Caracciolo [g], R. Cerulli [g], D. M. Chernyak [c], F. A. Danevich [c], S. d'Angelo [a,b], A. E. Dossovitskiy [h], E. N. Galashov [i], A. Incicchitti [e,f], V. V. Kobychev [c], S. S. Nagorny [c], F. Nozzoli [a], B. N. Kropivyansky [c], V. M. Kudovbenko [c], A. L. Mikhlin [h], A. S. Nikolaiko [c], D. V. Poda [g,c], R. B. Podviyanuk [c], O. G. Polischuk [c], D. Prosperi [e,f,†], V. N. Shlegel [i], Yu. G. Stenin [i], J. Suhonen [j], V. I. Tretyak [c], Ya. V. Vasiliev [i]

[a] *INFN sezione Roma Tor Vergata, I-00133 Rome, Italy*

[b] *Dipartimento di Fisica, Università di Roma "Tor Vergata", I-00133 Rome, Italy*

[c] *Institute for Nuclear Research, MSP 03680 Kyiv, Ukraine*

[d] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*

[e] *INFN, sezione Roma "La Sapienza", I-00185 Rome, Italy*

[f] *Dipartimento di Fisica, Università di Roma La Sapienza, 00185 Rome, Italy*

[g] *INFN, Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy*

[h] *Joint Stock Company NeoChem, 117647 Moscow, Russia*

[i] *Nikolaev Institute of Inorganic Chemistry, 630090 Novosibirsk, Russia*

[j] *Department of Physics, University of Jyväskylä, FIN-40014 Jyväskylä, Finland*

Abstract. 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.): $T_{1/2}(0\nu 2\varepsilon) > 3.6 \times 10^{20}$ yr, $T_{1/2}(2\nu\varepsilon\beta^+) > 7.2 \times 10^{19}$ yr, and $T_{1/2}(2\nu 2\beta^+) > 2.5 \times 10^{20}$ yr. Resonant 0ν2ε processes have been restricted as $T_{1/2}(0\nu 2K) > 1.4 \times 10^{20}$ yr and $T_{1/2}(0\nu LK) > 3.2 \times 10^{20}$ yr. A possible resonant enhancement of the 0ν2ε processes is estimated in the framework of the QRPA approach.

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† Deceased.

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INTRODUCTION

Neutrinoless double beta ($0\nu2\beta$) decay 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 Majorons.

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 ($\delta = 1.25 \pm 0.06$ % [2]). 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, 4, 5, 6, 7]. Taking into account theoretical calculations [8, 9, 10, 11, 12, 13, 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 2β decay [3, 6, 15], investigations of rare α [16] and β [17, 18] decays of Cd and W isotopes. A $CdWO_4$ crystal scintillator enriched in ^{106}Cd to 66% ($^{106}CdWO_4$) was developed to realize a high sensitivity experiment to search for 2β processes in ^{106}Cd [19]. First results of the experiment are presented here.

EXPERIMENT

The $^{106}CdWO_4$ scintillator ($\varnothing 27 \times 50$ mm, mass of 215.4 g) is fixed inside a cavity $\varnothing 47 \times 59$ mm (filled with high-purity silicon oil) in the polystyrene light-guide $\varnothing 66 \times 312$ mm. Two high purity (HP) quartz light-guides $\varnothing 66 \times 100$ 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 HP 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 HP 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 $\mathrm{FWHM}_\gamma = \sqrt{11.2 \cdot E_\gamma}$, where E_γ is the energy of γ quanta; FWHM_γ and E_γ are in keV.

RESULTS and DISCUSSION

The energy spectrum of $\gamma(\beta)$ events accumulated with the $^{106}CdWO_4$ detector over 1320 h is presented in Fig. 1. The $\gamma(\beta)$ events were selected by pulse-shape discrimination described in [20, 16, 21]. The counting rate ≈ 24 counts/s below the energy of ≈ 0.6 MeV is mainly due to the β decay of ^{113m}Cd ($Q_\beta = 584$ keV, $T_{1/2} = 14.1$ yr [22]) with the activity 112 ± 5 Bq/kg. The contamination of the enriched ^{106}Cd by ^{113m}Cd was detected in the low-background TGV experiment [23].

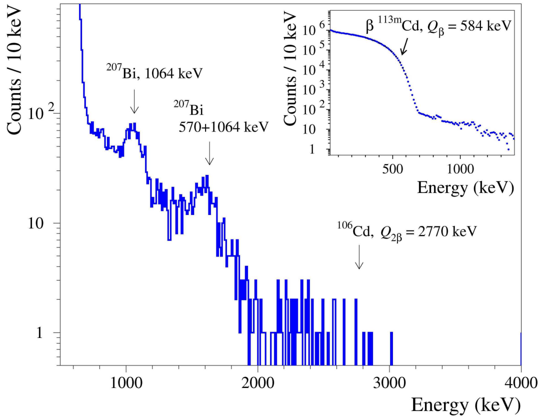

FIGURE 1. Energy spectrum of γ(β) events measured with $^{106}CdWO_4$ scintillator over 1320 h in the low-background set-up. (Inset) β decay of ^{113m}Cd dominates at low energy (the data over 268 h).

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 [20, 16, 21], as well by fit of the energy spectrum (the procedure is described in [6, 15, 18]) 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 summarized as (in mBq/kg): ^{232}Th ≤ 0.1, ^{228}Th = 0.045(6), ^{238}U ≤ 0.3, ^{230}Th ≤ 0.8, ^{226}Ra ≤ 0.3, ^{210}Po ≤ 0.3, total α activity (U/Th) = 2.1(1), ^{40}K ≤ 5, ^{113}Cd = 174, ^{113m}Cd = 112 000(5 000), ^{207}Bi = 2.3(5).

There are no peculiarities in the spectrum which could be ascribed to the 2β processes in ^{106}Cd. Therefore, lower half-life limits can be set according to formula: $\lim T_{1/2} = N \cdot \eta \cdot t \cdot \ln 2 / \lim S$, where N is the number of ^{106}Cd nuclei (2.420×10^{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's) and the expected models for 2β processes in ^{106}Cd simulated by using the EGS4 code (some examples of the simulated 2β spectra are presented in Fig. 2). The fits allow us to set limits on the 2β decays in ^{106}Cd given in Table 1.

In case of 0ν capture of two electrons from the K shell (or L and K shells) of Cd atom, energy release of 2721 ± 7 keV (2742 ± 7 keV) is equal, within errors, to energy of the excited levels of ^{106}Pd with E_{exc} = 2718 keV (2741 keV) [22]. Such a coincidence could give a resonant enhancement of the 0ν2ε capture [27, 28].

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^+.

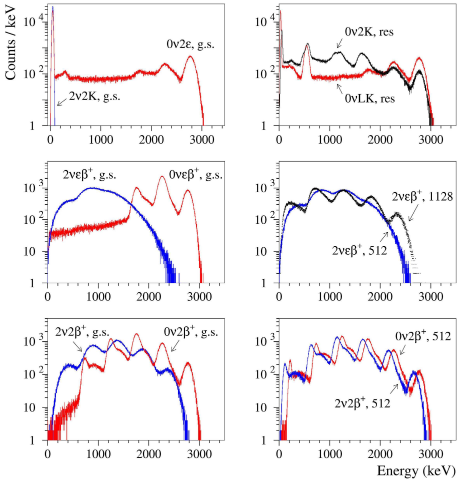

FIGURE 2. Simulated response functions of the $^{106}CdWO_4$ scintillator to 2β processes in ^{106}Cd.

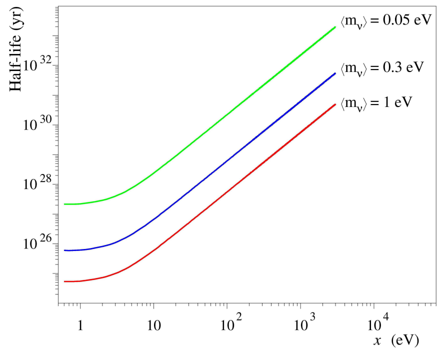

FIGURE 3. Calculated dependence of the half-life of ^{106}Cd relatively to the resonant 0ν2ε capture to excited levels of ^{106}Pd on parameter *x* (see text) for different values of the effective neutrino mass.

TABLE 1. 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.	$\geq 3.6\times10^{20}$	$\geq 8.0\times10^{18}$ [6]
2νεβ$^+$	g.s.	$\geq 7.2\times10^{19}$	$\geq 4.1\times10^{20}$ [5]
	2_1^+ 512 keV	$\geq 9.0\times10^{19}$	$\geq 2.6\times10^{20}$ [5]
	2_2^+ 1128 keV	$\geq 3.2\times10^{20}$	$\geq 1.4\times10^{20}$ [5]
	0_1^+ 1134 keV	$\geq 3.5\times10^{20}$	$\geq 1.6\times10^{20}$ [8]
0νεβ$^+$	g.s.	$\geq 2.1\times10^{20}$	$\geq 3.7\times10^{20}$ [5]
2ν2β$^+$	g.s.	$\geq 2.5\times10^{20}$	$\geq 2.4\times10^{20}$ [5]
	2_1^+ 512 keV	$\geq 3.2\times10^{20}$	$\geq 1.7\times10^{20}$ [8]
0ν2β$^+$	g.s.	$\geq 2.1\times10^{20}$	$\geq 2.4\times10^{20}$ [5]
Resonant 0ν2*K*	2718 keV	$\geq 1.4\times10^{20}$	–
Resonant 0ν*KL*	2741 keV	$\geq 3.2\times10^{20}$	$\geq 1.6\times10^{20}$ [8]

The half-life can be written as:

$$T_{1/2} = 5.561\times10^{23}\,\frac{x^2+9.42}{\langle m_\nu\rangle^2}\ \text{yr}, \tag{1}$$

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, E contains the nuclear excitation energy and the hole energies in the atomic s orbitals. The dependence of the half-life on x (see Fig. 3) 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.

CONCLUSIONS

An experiment using a cadmium tungstate crystal scintillator enriched in ^{106}Cd to 66% is in progress in the DAMA R&D set-up at the LNGS. After 1320 h of data taking we have estimated radioactive contamination of the $^{106}CdWO_4$ scintillator (in particular the total α activity of U/Th is on the level of ≈ 2 mBq/kg). The main components of background are β active ^{113m}Cd (112 Bq/kg) and ^{207}Bi (2.3 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 $0\nu 2\varepsilon$ processes was estimated in the framework of QRPA approach. A sensitivity of the experiment to different 2β decays in ^{106}Cd after ≈ 3 yr of measurements is expected to be on the level of $\sim 10^{21}$ yr.

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