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.):

$\frac{T}{2}(0\nu 2\epsilon) > 3.6 \cdot 10^{20}$ yr,

$\frac{T}{2}(2\nu\beta^+) > 7.2 \cdot 10^{19}$ yr, and

$\frac{T}{2}(2\nu 2\beta^+) > 2.5 \cdot 10^{20}$ yr.

Resonant $0\nu 2\epsilon$ processes have been restricted as $\frac{T}{2}(0\nu 2K) > 1.4 \cdot 10^{20}$ yr and $\frac{T}{2}(0\nu LK) > 3.2 \cdot 10^{20}$ yr. A possible resonant enhancement of the $0\nu 2\epsilon$ 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 ($0\nu 2\beta$) 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 ($\delta = 1.25 \pm 0.06$ % [2]). The decay scheme of the triplet $^{106}$Cd $\rightarrow$ $^{106}$Ag $\rightarrow$ $^{106}$Pd is presented in Fig. 1. Experiments fulfilled to-date give only $\frac{T}{2}$ 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.
Experiment

The $^{106}$CdWO$_4$ scintillator (Ø27·50 mm, mass of 215.4 g) is fixed inside a cavity Ø47·59 mm (filled with high-purity silicon oil) in the polystyrene light-guide Ø66·312 mm. Two high purity quartz light-guides Ø66·100 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 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, $^{208}$Tl and $^{241}$Am sources as FWHM = $\gamma$ E, where $E_\gamma$ is the energy of γ quanta; FWHM$_\gamma$ and $E_\gamma$ 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. 2. The $\gamma(\beta)$ events were selected by pulse-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 ($Q_\beta$ = 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

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Activity (mBq/kg) in crystals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{106}$CdWO$_4$</td>
<td>$^{116}$CdWO$_4$</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>$^{228}$Th</td>
<td>$^{228}$Th</td>
<td>0.053(5)</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>≤ 0.3</td>
</tr>
<tr>
<td>$^{208}$Tl</td>
<td>$^{208}$Tl</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{206}$Ra</td>
<td>$^{206}$Ra</td>
<td>≤ 0.3</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>$^{210}$Po</td>
<td>≤ 0.3</td>
</tr>
<tr>
<td>Total α activity (U/Th)</td>
<td>2.1(1)</td>
<td>1.40(10)</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>≤ 11</td>
<td>0.3(1)</td>
</tr>
<tr>
<td>$^{113}$Cd</td>
<td>$^{113m}$Cd</td>
<td>174$^*$</td>
</tr>
<tr>
<td>$^{113m}$Cd</td>
<td>$^{113m}$Cd</td>
<td>112 000(5 000)</td>
</tr>
<tr>
<td>$^{207}$Bi</td>
<td>$^{207}$Bi</td>
<td>1.3(3)</td>
</tr>
</tbody>
</table>

*$^*$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: $\text{lim}T_{1/2} = N \eta \ln2 / \text{lim}S$, where $N$ is the number of $^{106}$Cd nuclei (2.420 · 10$^{23}$), $\eta$ is the detection efficiency, $t$ is the measuring time, and $\text{lim}S$ 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 $\text{lim}S$, 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 2$\beta$ processes in $^{106}$Cd.

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

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Level of $^{106}$Pd</th>
<th>Experimental limit on $T_{1/2}$ at 90 % C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Present work</td>
</tr>
<tr>
<td>0$\nu 2\varepsilon$</td>
<td>g.s.</td>
<td>$\geq 3.6 \times 10^{20}$</td>
</tr>
<tr>
<td>2$\nu 2\varepsilon$</td>
<td>g.s.</td>
<td>$\geq 7.2 \times 10^{19}$</td>
</tr>
<tr>
<td></td>
<td>$2^+_1$ 512 keV</td>
<td>$\geq 9.0 \times 10^{19}$</td>
</tr>
<tr>
<td></td>
<td>$2^+_1$ 1128 keV</td>
<td>$\geq 3.2 \times 10^{20}$</td>
</tr>
<tr>
<td></td>
<td>$0^+_1$ 1134 keV</td>
<td>$\geq 3.5 \times 10^{20}$</td>
</tr>
<tr>
<td>0$\nu 2\beta$</td>
<td>g.s.</td>
<td>$\geq 2.1 \times 10^{20}$</td>
</tr>
<tr>
<td>2$\nu 2\beta$</td>
<td>g.s.</td>
<td>$\geq 2.5 \times 10^{20}$</td>
</tr>
<tr>
<td></td>
<td>$2^+_1$ 512 keV</td>
<td>$\geq 3.2 \times 10^{20}$</td>
</tr>
<tr>
<td>0$\nu 2\beta$</td>
<td>g.s.</td>
<td>$\geq 2.1 \times 10^{20}$</td>
</tr>
<tr>
<td>Resonant 0$\nu 2K$</td>
<td>2718 keV</td>
<td>$\geq 1.4 \times 10^{20}$</td>
</tr>
<tr>
<td>Resonant 0$\nu KL$</td>
<td>2741 keV</td>
<td>$\geq 3.2 \times 10^{20}$</td>
</tr>
</tbody>
</table>

In case of 0$\nu$ capture of two electrons from the $K$ shell (or $L$ and $K$ shells) of cadmium atom, energy release of $2721 \pm 7$ keV ($2742 \pm 7$ 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 0$\nu 2\varepsilon$ capture [27, 28]. The limits on the resonant 2$\varepsilon$ processes obtained by fit of the experimental data are presented in Table 2.

The resonant 2$\beta$ 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:

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

(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.

**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 $\alpha$ activity) on the level of $\approx 2$ mBq/kg. The main components of background of the detector

Fig. 4. Calculated dependence of the half-life of $^{106}$Cd relatively to the resonant 0$\nu 2\varepsilon$ capture to excited levels of $^{106}$Pd on parameter $x$ (see text) for different values of the effective neutrino mass.
are $\beta$ active $^{113m}$Cd (112 Bq/kg) and $^{207}$Bi (1.3 mBq/kg). By analysis of the experimental data we have set limits on $2\beta$ processes in $^{106}$Cd on the level of $10^{15} - 10^{20}$ yr. A possible resonant enhancement of $0\nu2\beta$ processes was estimated in the framework of QRPA approach. A sensitivity of the experiment to different $2\beta$ processes in $^{106}$Cd after $\approx 3$ yr of measurements is expected to be on the level of $\approx 10^{21}$ yr.

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ПЕРШІ РЕЗУЛЬТАТИ ЕКСПЕРIMENTУ ПО ПОШУКУ 2β-РОЗПАДУ 106Cd ЗА ДОПОМОГОЮ КРИСТАЛІЧНИХ СЦИНТИЛЯТОРІВ 106CdWO4

Експеримент по пошуку 2β-процесів у 106Cd за допомогою кристалічних сцинтилляторів 106CdWO4 (з масою 215 г), збагачених 106Cd 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 106Cd на рівні 1019 - 1020 років, зокрема (усі результати даються з 90 %-ніою довірчою ймовірністю): T1/2(0e2e) > 3,6 · 1020 років, T1/2(2νββ) > 7,2 · 1020 років та T1/2(2ν2β) > 2,5 · 1020 років. Резонансні 0v2e процеси обмежені як T1/2(0ν2K) > 1,4 · 1020 років та T1/2(0νLK) > 3,2 · 1020 років. Можливе резонансне підсилення 0v2e процесів розраховано в рамках моделі QRPA.


ПЕРВЫЕ РЕЗУЛЬТАТЫ ЭКСПЕРИМЕНТА ПО ПОИСКУ 2β-РАСПАДА 106Cd С ПОМОЩЬЮ КРИСТАЛЛИЧЕСКИХ СЦИНТИЛЯТОРОВ 106CdWO4

Эксперимент по поиску 2β-процессов в 106Cd с помощью кристаллических сцинтилляторов 106CdWO4 (с массой 215 г), обогащенных 106Cd до 66 %, проходит в Национальной лаборатории Гран Сассо Национального института ядерной физики (Италия). После накопления данных на протяжении 1320 ч получены ограничения на период полуразпада для двойных бета-процессов в 106Cd на уровне 1019 - 1020 лет, в частности (все результаты даются с 90 %-ной доверительной вероятностью): T1/2(0e2e) > 3,6 · 1020 лет, T1/2(2νββ) > 7,2 · 1020 лет и T1/2(2ν2β) > 2,5 · 1020 лет. Резонансные 0ν2e процессы ограничены как T1/2(0ν2K) > 1,4 · 1020 лет и T1/2(0νLK) > 3,2 · 1020 лет. Возможное резонансное усиление 0ν2e процессов оценино в рамках модели QRPA.


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