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Investigation of $\beta^+\beta^+$ and β^+/EC decay of ^{106}Cd

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Abstract. A low background scintillation detector with a $CdWO_4$ crystal of 1.046 kg was used to search for $\beta^+\beta^+$ and β^+/EC processes in ^{106}Cd. For the neutrinoless mode the limits $T_{1/2}(0\nu\beta^+\beta^+) \geq 2.2 \cdot 10^{19}$ y and $T_{1/2}(0\nu\beta^+/\text{EC}) \geq 5.5 \cdot 10^{19}$ y were obtained with 90% C.L. For the possible two neutrino decay limits of $T_{1/2}(2\nu\beta^+\beta^+) \geq 9.2 \cdot 10^{17}$ y and $T_{1/2}(2\nu\beta^+/\text{EC}) \geq 2.6 \cdot 10^{17}$ y have been determined with 99% C.L.

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1 Introduction

The considerable interest in double beta decay of atomic nuclei is related with the unique role of neutrino physics in modern theories beyond the Standard Model. Double beta decay represents the only way to measure an effective Majorana mass of the electron neutrino and yields the most stringent limits on lepton charge nonconservation, right-handed admixtures in the weak interaction, the neutrino coupling constant with Majorons and other parameters as well.

At present efforts of many experimental groups are aimed mainly to search for $0\nu\beta^-\beta^-$ decay. In the most sensitive experiments lower half-life limits on a level of 10^{21}–10^{24} y were obtained [1] - [8]. In particular, $T_{1/2}(0\nu\beta^-\beta^-) \geq 9.1 \cdot 10^{24}$ y (90% C.L.) has been reached for ^{76}Ge from which the following limits on an effective Majorana mass of an electron neutrino and parameters of right-handed admixtures in a weak interaction are deduced: $< m_\nu > \leq 0.50$ eV, $< \eta > \leq 6.9 \cdot 10^{-9}$, $< \lambda > \leq 0.9 \cdot 10^{-6}$) [1], [2]. The results of investigations of double positron emission ($\beta^+\beta^+$), positron emission/electron capture (β^+/EC) and double electron capture (EC/EC) are significantly more modest. The sensitivity of the best experiments is within 10^{16}–10^{21} years [9] – [15]. At the same time, taking into account the calculation of probabilities of $\beta^+\beta^+$ and β^+/EC decays [16], the search for the neutrinoless modes could help for a refined investigation of the neutrino nature and weak interaction. If the $0\nu\beta^-\beta^-$ decay ever would be observed, the question will arise what mechanism (Majorana mass of the neutrino or right-handed admixtures in weak interaction) gives the main contribution to this process.

There are, in principle, different possibilities to decide this question. One is to measure the angular distribution of the outgoing leptons, in addition to the half life [17] (the angular distribution for the $< \lambda >$-terms differs from the one for the mass mechanism). However, such an experiment would require quite large statistics and moreover can not be done within an experiment using semiconductors, such as ^{76}Ge. Also the observation of $0\nu\beta\beta(0^+ \rightarrow 2^+)$ decays might be helpful. However, in that case very long half-lives are expected. For example (suppose that $0\nu\beta\beta$ decay of ^{76}Ge will be observed with $T_{1/2} \approx 10^{25}$ year), taking the coefficients of [18] for the ^{76}Ge $0\nu\beta\beta(0^+ \rightarrow 2^+)$ decay the following half-lives can be estimated: $< \lambda >=9.0 \cdot 10^{-6}$ ($< \eta >=5.5 \cdot 10^{-9}$) leads to $T_{1/2}(0^+ \rightarrow 2^+) \simeq 9 \cdot 10^{29}$ years ($T_{1/2}(0^+ \rightarrow 2^+) \simeq 5 \cdot 10^{32}$ years).

On the other hand, according to theoretical calculations, half-lives for $0\nu\beta^+$/EC decay depend strongly on whether the decay is dominated by the mass mechanism or right-handed weak current. For example, the expected half-lives decay of ^{106}Cd for the $0\nu\beta^+$/EC mode (if we insert the values for $< m_\nu >$, $< \lambda >$ and $< \eta >$ quoted above) will be $1.5 \cdot 10^{27}$ y, $1.2 \cdot 10^{26}$ y and $2.1 \cdot 10^{27}$ y, respectively. Therefore, even the non-observation of the $0\nu\beta^+$/EC mode decay could be helpful in obtaining additional information.

There are 34 isotopes in nature which can decay with a decrease of nucleus charge by two units. Besides of $\beta^+\beta^+$ decay, the processes with electron capture can occur also:

$$\begin{aligned} \beta^+\beta^+ &: \ (Z, A) \rightarrow (Z\text{–}2, A) + 2e^+ + (2\nu_e), \\ \beta^+/\text{EC} &: \ e^- + (Z, A) \rightarrow (Z\text{–}2, A) + e^+ + (2\nu_e), \\ \text{EC/EC} &: \ 2e^- + (Z, A) \rightarrow (Z\text{–}2, A) + (2\nu_e). \end{aligned}$$

The most interesting nuclei for the experimental search are the ones with a big conversion energy and a high isotopic abundance. Table 1 represents the characteristics of

Table 1. The properties of the most promising isotopes for the study of $\beta^+\beta^+$ and β^+/EC decays. The most sensitive experimental results are taken from [19]

Isotope	Q ($\beta\beta$) value	Abundance	$\beta\beta$–decay channel,	mode	Half-life limit (years),	Confidence level,	Reference
^{58}Ni	1925.9(0.7)	68.077(0.009)%	β^+/EC	$(0\nu + 2\nu)$	$7.0 \cdot 10^{20}$	68%	[9]
^{64}Zn	1096.3(0.9)	48.6(0.3)%	β^+/EC	$(0\nu + 2\nu)$	$2.3 \cdot 10^{18}$	68%	[10]
^{78}Kr	2867(7)	0.35(0.02)%	$\beta^+\beta^+$	$(0\nu + 2\nu)$	$2.0 \cdot 10^{21}$	68%	[12]
			β^+/K	0ν	$5.1 \cdot 10^{21}$	68%	[12]
				2ν	$1.1 \cdot 10^{20}$	68%	[12]
^{92}Mo	1650(4)	14.84(0.04)%	β^+/EC	0ν	$2.7 \cdot 10^{18}$	68%	[11]
^{96}Ru	2725(8)	5.52(0.06)%	$\beta^+\beta^+$	$(0\nu + 2\nu)$	$3.1 \cdot 10^{16}$	68%	[10]
			β^+/EC	$(0\nu + 2\nu)$	$6.7 \cdot 10^{16}$	68%	[10]
^{106}Cd	2771(8)	1.25(0.04)%	$\beta^+\beta^+$	0ν	$1.4 \cdot 10^{18}$	90%	[13]
				0ν	$2.2 \cdot 10^{19}$	90%	(a)
				2ν	$9.2 \cdot 10^{17}$	99%	(a)
				$(0\nu + 2\nu)$	$2.6 \cdot 10^{17}$	68%	[14]
			β^+/EC	0ν	$1.1 \cdot 10^{19}$	90%	[13]
				0ν	$5.5 \cdot 10^{19}$	90%	(a)
				2ν	$2.6 \cdot 10^{17}$	99%	(a)
				$(0\nu + 2\nu)$	$5.7 \cdot 10^{17}$	68%	[14]
^{124}Xe	2865.9(2.2)	0.10(0.01)%	$\beta^+\beta^+$	0ν	$4.2 \cdot 10^{17}$	68%	[15]
				2ν	$2.0 \cdot 10^{14}$		[15]
			β^+/K	0ν	$1.2 \cdot 10^{18}$	68%	[15]
				2ν	$4.8 \cdot 10^{16}$	68%	[15]
^{130}Ba	2610(7)	0.106(0.002)%	$\beta^+\beta^+$	0ν	$2.7 \cdot 10^{11}$		[20]
			β^+/EC	0ν	$1.5 \cdot 10^{12}$		[20]
^{136}Ce	2400(50)	0.19(0.01)			no results		

(a) results of the present work

all promising isotopes and the results of the most sensitive experiments for $\beta^+\beta^+$ and β^+/EC decays. As is shown in Table 1, in some experiments the limits are given only for the sum of the two-neutrino and neutrinoless modes. Taking into account the uncertainty of theoretical estimations for the two-neutrino processes it is obvious that an important requirement for experiments in the search for $\beta^+\beta^+$ and β^+/EC decay is the capability to distinguish between the 0ν and the 2ν modes. The only possibility for this is detecting the spectrum of emitted positrons. To obtain a high detection efficiency for the $\beta\beta$–particles in a calorimetric experiment the $\beta\beta$–emitter must be a part of the detector. It should be noted that in such experiments the highest sensitivity for the neutrinoless $\beta^-\beta^-$ decay mode has been achieved. In this paper, we study the possibility of applying cadmium tungstate scintillation crystals ($CdWO_4$) to the search for the ^{106}Cd double beta decay.

2 Detector and background measurements

Low background scintillation spectrometers based on $CdWO_4$ crystals of a large volume (up to 200 cm^3) with an improved energy resolution have been developed as a result of advance in crystal growth, optimization of light collection and design of a special electronic unit for amplification and shaping of the $CdWO_4$ signals: [5], [13], [21], [22]. Due to an extremely low intrinsic activity of the $CdWO_4$ crystals [23] these spectrometers were applied successfully in the investigation of $\beta^-\beta^-$ processes in ^{116}Cd [5], ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{180}W and ^{186}W [13], to measure the spectral shape of fourth-forbidden β^- decay of ^{113}Cd [24] and also in a search for α decay of naturally occurring tungsten isotopes [25]. The background rate (in the 2.7 - 2.9 MeV interval) obtained in the experiment [5] with cadmium tungstate enriched in ^{116}Cd (about 0.5 counts/(y·keV·kg)) is close to the corresponding background level of the best low background HPGe detectors.

A large $CdWO_4$ crystal with natural isotopic composition and a mass of 1.046 kg (6.4 cm long, 5.1 cm in diameter) was used in the experiment. The number of ^{106}Cd nuclei in this crystal is $2.22(0.07) \cdot 10^{22}$. The energy resolution with the Philips XP2412 photomultiplier was 13.2, 11.4 and 9.3% at energy 570, 662 and 1064 keV, respectively. The background measurement was performed first at the Solotvina Underground Laboratory (during 107 h) and later at the Gran Sasso Laboratory (6701 h). In both cases the spectrometer and shielding were similar. The $CdWO_4$ scintillator was viewed by a PMT (FEU-167), which was made of a special low radioactive glass. The radioactive impurities of this PMT were estimated in additional measurements as 2.0, 0.4 and 0.06 Bq for ^{40}K, ^{226}Ra and ^{232}Th, respectively. The PMT was connected to the crystal through a light guide (58 cm length and 10 cm in diameter) that was glued of two parts: quartz glass (50 cm length) and a plastic scintillator. The $CdWO_4$ crystal is coupled optically to the latter. The passive shielding for the $CdWO_4$ detector consists of OFHC copper (10 cm) and Boliden lead (10 cm) to reduce the external background. Plexiglas parts were mounted around crystal, light guide and PMT to remove the radon influence. Because the time constant of the $CdWO_4$ scintillator signal is about 10–15 μs, a special electronic unit was applied to integrate the signals from the PMT over a time of 40 μs and generate the short output pulses required by the ADCs. Addi-

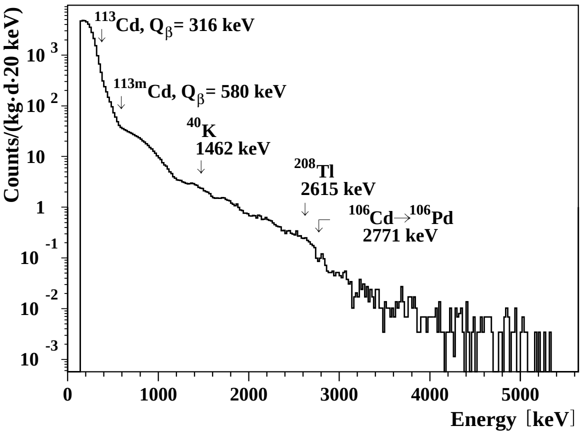

Fig. 1. Background spectrum of the $CdWO_4$ scintillator (1.046 kg) measured in the Gran Sasso Laboratory for 6701 h

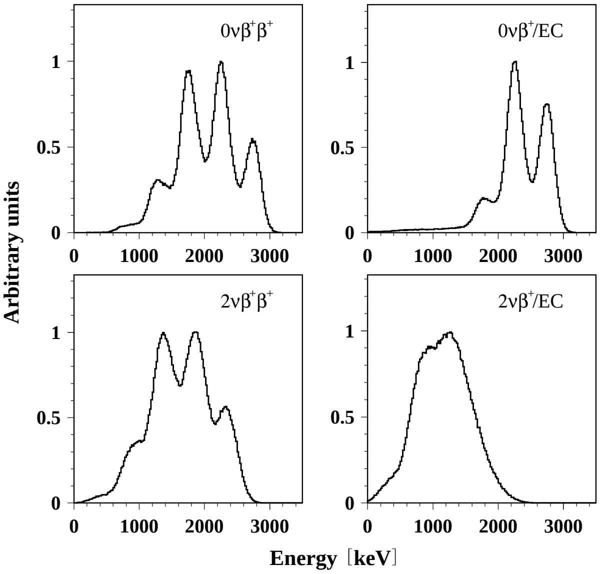

Fig. 2. The expected response functions of the $CdWO_4$ detector (1.046 kg) for various modes of ^{106}Cd double beta decay (results of GEANT3 simulation)

tionally, a built-in pulse shape discrimination circuit allows rejection of the PMT noise pulses and scintillation signals of the plastic part of the light guide. The energy resolution of the spectrometer on the whole was tested with ^{40}K, ^{207}Bi and ^{228}Th sources and can be parametrized by the function: $FWHM(E_\gamma) = \sqrt{-1100 + 25.6E_\gamma}$ ($FWHM$ and E_γ in keV). During the experiment energy calibration was carried out with ^{228}Th every 2–4 days. Remaining shifts in the gain were corrected by the software. The analysis of all calibration spectra of ^{228}Th shows that a precision of the energy determination in the sum background spectrum for the γ line of ^{208}Tl (2615 keV) is ± 27 keV and that the resolution of this line is wider only about one tenth of its initial value in the calibration spectra.

Figure 1 shows the background spectrum of the $CdWO_4$ scintillator measured at the Gran Sasso Laboratory during 6701 h. The low energy part of the spectrum represents the β^- spectra of ^{113}Cd ($T_{1/2}$ = 7.7(0.3) · 10^{15} y [24], Q_β=316 keV [26]) with activity of 0.58(0.02) Bq/kg and ^{113m}Cd

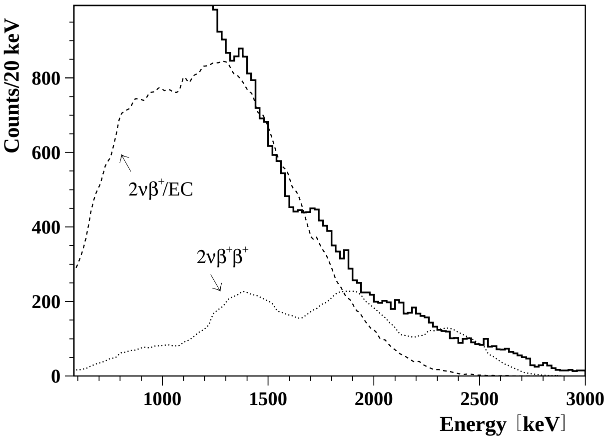

Fig. 3. The background spectrum of the $CdWO_4$ crystal together with the calculated distribution of $2\nu\beta^+\beta^+$ and $2\nu\beta^+$/EC processes excluded with 99% C.L.

($T_{1/2}$=13.7 y, Q_β=580 keV [26]) with A(^{113m}Cd)=0.15(0.01) Bq/kg. The background component up to the energy of 1.3 MeV is not clearly identified. However, taking into account the results of the earlier measurements with cadmium tungstate crystals [5], [13], [23], the continuous spectrum in that region can be caused by ^{40}K and nuclides of ^{238}U series inside the crystal. Upper limits on activities of these nuclides in the $CdWO_4$ are $\leq$1.7 mBq/kg for ^{40}K and $\leq$1.3 mBq/kg for ^{238}U.

The activities for ^{232}Th, ^{235}U and ^{238}U series were estimated by an off-line analysis of the arrival time of the background events measured at the Solotvina Underground Laboratory over 107 h. For instance, the sequence of two α decays belonging to the ^{232}Th series was searched for: ^{220}Rn (E_α=6.29 MeV, $T_{1/2}$=55.6 s) $\rightarrow$ ^{216}Po (E_α=6.78 MeV, $T_{1/2}$=0.145 s) $\rightarrow$ ^{212}Pb. In a time window of 0.01–0.5 s (which includes 86% of the ^{216}Po decays) no couple of events corresponding to such a process was found. Since the number of events ruled out is 1.2 with 68% C.L. [27], the limit of the ^{228}Th activity in the $CdWO_4$ crystal is less than 0.003 mBq/kg. Applying the same method to ^{227}Ac and ^{226}R the limits of $\leq$0.005 mBq/kg and $\leq$0.007 mBq/kg, respectively, were obtained. At energies above 1.3 MeV the background of the detector is mainly due to external γ rays. The background rate in the region of the maximal energy release in $\beta^+\beta^+$ decay of ^{106}Cd (2.64–2.90 MeV) is 2.3 counts/(y·keV·kg).

3 The half-life limits on $\beta^+\beta^+$ and β^+/EC decay of ^{106}Cd

The expected response functions and detection efficiencies of the $CdWO_4$ crystal for various modes of ^{106}Cd double beta decay were calculated using the GEANT3 software package [28]. The positron energy distribution for the $\beta\beta$–decay of ^{106}Cd was calculated taking into account the influence of the electric field of the nucleus on the emitted particles without the usual Primakoff-Rosen approximation for the Fermi function which is not reliable in the case of β^+/EC and $\beta^+\beta^+$ decays. The simulated spectra of the different $\beta\beta$–decay modes are presented in Fig. 2. The measured experimental spectrum displays no evidence for $\beta\beta$ processes in

^{106}Cd. Therefore, only half-life limits can be obtained from the experimental data. The limits on $T_{1/2}$ for the neutrinoless decay modes ($0\nu\beta^+\beta^+$ and $0\nu\beta^+$/EC) were determined by an analysis of the background spectrum in the energy region which corresponds to the maximal transition energy (2771 keV) for ^{106}Cd $\beta\beta$–decay. The peak at this energy would be observed if all particles emitted in ^{106}Cd $0\nu\beta^+\beta^+$ or $0\nu\beta^+$/EC decay were completely absorbed in the $CdWO_4$ crystal. For the data evaluation, the energy interval 2.2–3.7 MeV around the expected peak was chosen. It was assumed that the measured spectrum of the $CdWO_4$ crystal in this interval is represented by a sum of three functions, two corresponding to the background (the 2615 keV peak of ^{208}Tl and an exponential function for the undefined continuous background), while the third corresponds to the expected $0\nu\beta\beta$–signals. To take into account the uncertainties of the energy calibration, the centers of the ^{208}Tl line and the expected $\beta\beta$–peaks were varied in an energy interval of ± 30 keV. The energy resolution was varied within the limits of (1–1.11) FWHM. From the least-square fits of the above described model in the energy region (2.3 ± 0.1)–(3.3 ± 0.4) MeV the maximum excluded signals of 536(315) events for $0\nu\beta^+\beta^+$ decay and 217(126) events for $0\nu\beta^+$/EC decay were obtained with a confidence level of 90% (68%) (according to [27]). This leads to the following half-life limits:

$$T_{1/2}(0\nu\beta^+\beta^+) \geq 2.2(3.8)\cdot 10^{19} \text{ y with 90\% (68\%) C.L.,}$$
$$T_{1/2}(0\nu\beta^+/\text{EC}) \geq 5.5(8.6)\cdot 10^{19} \text{ y with 90\% (68\%) C.L.}$$

For the estimation of the half-life limits for the two-neutrino $\beta\beta$ decay modes, no background model was considered because of uncertainties in the spectral shape of possible background components. The limits

$$T_{1/2}(2\nu\beta^+\beta^+) \geq 9.2\cdot 10^{17} \text{ y with 99\% C.L.,}$$
$$T_{1/2}(2\nu\beta^+/\text{EC}) \geq 2.6\cdot 10^{17} \text{ y with 99\% C.L.}$$

were obtained by a least square fit of the simulated detector response for the $2\nu\beta^+\beta^+$ decay modes to the experimental data under the very conservative assumption of zero background. The energy region of 2.3-2.5 MeV for $2\nu\beta^+\beta^+$ decay and 1.4-1.7 MeV for $2\nu\beta^+$/EC decay was chosen to deduce the above quoted half-life limits. Figure 3 depicts the signals which correspond to the two neutrino $\beta\beta$-decay modes ($2\nu\beta^+\beta^+$ and $2\nu\beta^+$/EC) of ^{106}Cd excluded with 99% C.L.

4 Conclusions

In this work the following limits for $\beta^+\beta^+$ and β^+/EC processes in ^{106}Cd have been deduced separately for the neutrinoless and two neutrino modes:

$$T_{1/2}(0\nu\beta^+\beta^+) \geq 2.2(3.8)\cdot 10^{19} \text{ y with 90\% (68\%) C.L.,}$$
$$T_{1/2}(0\nu\beta^+/\text{EC}) \geq 5.5(8.6)\cdot 10^{19} \text{ y with 90\% (68\%) C.L.}$$
$$T_{1/2}(2\nu\beta^+\beta^+) \geq 9.2\cdot 10^{17} \text{ y with 99\% C.L.,}$$
$$T_{1/2}(2\nu\beta^+/\text{EC}) \geq 2.6\cdot 10^{17} \text{ y with 99\% C.L.}$$

These half-life limits for $0\nu\beta\beta$ decay of ^{106}Cd improve the existing ones of Ref. [13] by a factor of 5-10. Higher sensitivity for neutrinoless $\beta^+\beta^+$ and β^+/EC decay was reached only in the experiment with ^{78}Kr , where enriched $\beta\beta$-source was applied. For the 2ν modes of ^{106}Cd decay more stringent limits were obtained in [29], but the technique used in that work (a passive cadmium target and a low background HPGe detector) does not allow to distinguish between the 0ν and the 2ν modes. The results of the present work demonstrate that application of $CdWO_4$ detectors with a low intrinsic activity (≤0.01 mBq/kg for ^{228}Th and ^{226}Ra) is suitable for the search of extreme rare processes. The sensitivity for the half-life of ^{106}Cd $\beta^+\beta^+$ and β^+/EC decay could be increased to a level of about 10^{22} y by using cadmium tungstate crystals enriched in ^{106}Cd in a multidetector low background spectrometer.

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