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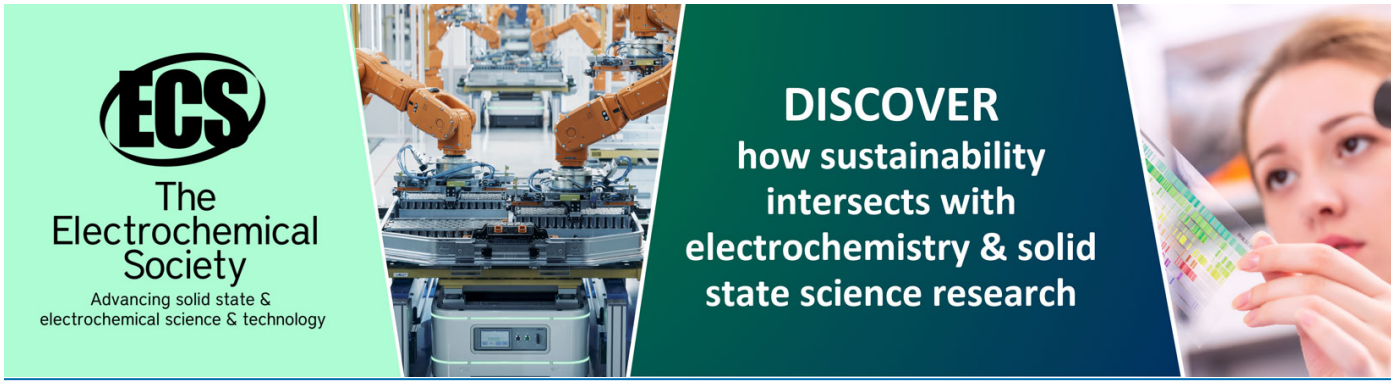

Search for double beta decay of ^{106}Cd in the TGV-2 experiment

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Abstract. A new experimental run of searching for double beta decay of ^{106}Cd was performed at the Modane underground laboratory (LSM, France, 4800 m w.e.) using the TGV-2 spectrometer, consisting of 32 planar type HPGe detectors with a total sensitive volume of ~400 cm^3. 16 foils of ^{106}Cd with an enrichment of 99.57% and a total mass of ~ 23.2 g were inserted between the entrance windows of face-to-face detectors. The limit on 2νEC/EC decay of ^{106}Cd - $T_{1/2} > 3.7 \times 10^{20}$ y at 90% C.L was obtained from the preliminary calculation of experimental data accumulated for 8198 h of measurement. The limits on the resonance 0νEC/EC decay of ^{106}Cd were obtained from the measurement of ~23.2 g of ^{106}Cd with the low-background HPGe spectrometer Obelix lasted 395 h -$T_{1/2}$ (KL, 2741 keV) $> 0.9 \times 10^{20}$ y and $T_{1/2}$ (KK, 2718 keV) $> 1.4 \times 10^{20}$ y at 90% C.L.

1. Introduction

Investigation of double-beta decay processes ($\beta^-\beta^-$, $\beta^+\beta^+$, β^+/EC, EC/EC) are of great importance for particle and nuclear physics as a sensitive tool for the study of lepton number conservation and the properties of neutrino [1]. Up to now more attention has been given to $\beta^-\beta^-$ decay. As a result, two-neutrino ($2\nu\beta^-\beta^-$) decay was detected for 11 nuclei: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, and ^{238}U [2]. Recently, interest in other double-beta processes has significantly increased, in particular, in EC/EC decay. Experimental studies of 2νEC/EC decay yielded positive result for ^{130}Ba using a geochemical technique [3] and an indication of the observation of such process in ^{78}Kr decay [4]. ^{106}Cd is one of the most promising candidates for the investigation of two-neutrino double electron capture due to the high decay energy ($Q_{EC/EC} = 2775.39 \pm 0.10$ keV). The 2νEC/EC decay of ^{106}Cd with a transition to the ground state of ^{106}Pd ($0^+ \rightarrow 0^+$, g.s.) is characterized by emission of two Palladium (Pd) X–rays each with an energy of ~ 21 keV. Theoretical predictions of half-lives for this process are ranged between 1.0×10^{20} and 5.5×10^{21} y [5]. ^{106}Cd is also a favourable candidate for searching for a resonance neutrino-less EC/EC decay to excited states of daughter nuclei [6, 7]. The TGV-2 experiment is focused on the study of the double beta decay of ^{106}Cd for several years [8-10] and is one of the leaders of investigations of EC/EC process [8–10]. The best experimental limit on 2νEC/EC decay of ^{106}Cd - $T_{1/2} \geq 4.2 \times 10^{20}$ y (90% CL) [9, 10] was obtained using the TGV-2 spectrometer

(Telescope Germanium Vertical) [11] and ~13.6 g of ^{106}Cd with enrichment of 75%. The result obtained improved existing experimental limits by more than two orders of magnitude and reached the range of theoretical predictions for this decay [5]. The analysis of KX-KX coincidences obtained in the last run [9, 10] showed a small increase in the number of measured events in the region of ~21 keV (KXPd), which might be the 2νEC/EC decay of ^{106}Cd. But the statistics was not enough to make any significant claim about the presence of the process searched. A new experimental run was performed at LSM using the TGV-2 spectrometer and highly increased mass of enriched ^{106}Cd (from ~13.6 g of ^{106}Cd with enrichment of 75% in the previous run to ~23.2 g of ^{106}Cd with enrichment of 99.57% in current measurement) to accumulate larger statistics of KX-KX coincidence events in the region of interest.

2. Spectrometer TGV-2

Experiment TGV-2 of searching for double beta decay of ^{106}Cd was performed at the Modane underground laboratory (LSM, France, 4800 m w.e.) using the TGV-2 spectrometer [11] and 16 samples of enriched ^{106}Cd. The detector part of the spectrometer is composed of 32 HPGe planar type detectors each with sensitive volume of 20.4 cm^2 · 0.6 cm. The basic detection cell is a sandwich-like pair of face-to-face detectors with thin foils made of a double beta emitter placed between them. The distance between investigated samples and detectors is ≤1.5 mm. The 16 pairs are mounted one over another in a common cryostat tower. The total sensitive volume of TGV-2 detectors is as large as 400 cm^3 and the total mass of the detectors is about 3 kg of Germanium. The energy resolution of the detectors ranged from 3.0 to 4.0 keV at the 1332 keV ^{60}Co γ-line. The total efficiency of the TGV-2 spectrometer is 50-70% depending on the energy threshold. The detector design delivers high detection efficiency for multiple coincidence events resulting in strong suppression of the background. The detector part of the TGV-2 spectrometer is surrounded by: i) a copper shielding with a thickness of ≥20 cm; ii) a steel airtight box protecting from radon accumulation near the detectors; iii) a lead shielding with a thickness of ≥10 cm; iv) a neutron shielding made of borated polyethylene with a thickness of 16 cm. The spectrometer is located in the deep underground laboratory (4800 m w.e.) which allows us to suppress cosmic rays (reduction factor of ~2×10^6) and fast neutrons (reduction factor of ~10^3). Further suppression of background was achieved by using coincidence techniques and filtering the electronic and microphone noise in the low energy region (<50 keV) by digitizing the detector response with different shaping times (2 and 8 μs) [11]. Investigated foils used in a new run (the phase III of the experiment TGV-2) were produced from ^{106}Cd with enrichment of 99.57% and had a diameter of 52 mm, a thickness of ~70(10) μm and a total mass of ~23.2 g (about 1.3 × 10^{23} atoms of ^{106}Cd).

3. Experimental results

The foils of ^{106}Cd (enrichment 99.57%) with a total mass of ~23.2 g were preliminary measured during 395 h at LSM with the high-efficiency low-background HPGe spectrometer Obelix [12] to obtain their contaminations. In processing of data obtained in this measurement (Figure 1), we also analysed events corresponding to possible resonance transitions in the 0νEC/EC decay of ^{106}Cd. This process may proceed via KL-capture to the 2741 keV excited state of ^{106}Pd and via KK-capture to 2718 keV excited state of ^{106}Pd. The level of 2741 keV will be then depopulated either by emission of a 2741 keV γ -ray or by a 2229 keV and 512 keV γ -quanta cascade [9]. While the level of 2718 keV will be depopulated via the emission of 1160-, 1046-, and 512-keV γ -quanta cascade [9]. The limits of $T_{1/2}$(*KL*, 2741 keV) > 0.9 × 10^{20} y and $T_{1/2}$(KK, 2718 keV) > 1.4 × 10^{20} y at a 90% C.L. on resonance neutrino-less transitions in double electron capture (0νEC/EC) decay of ^{106}Cd were obtained in processing of data accumulated in this measurement.

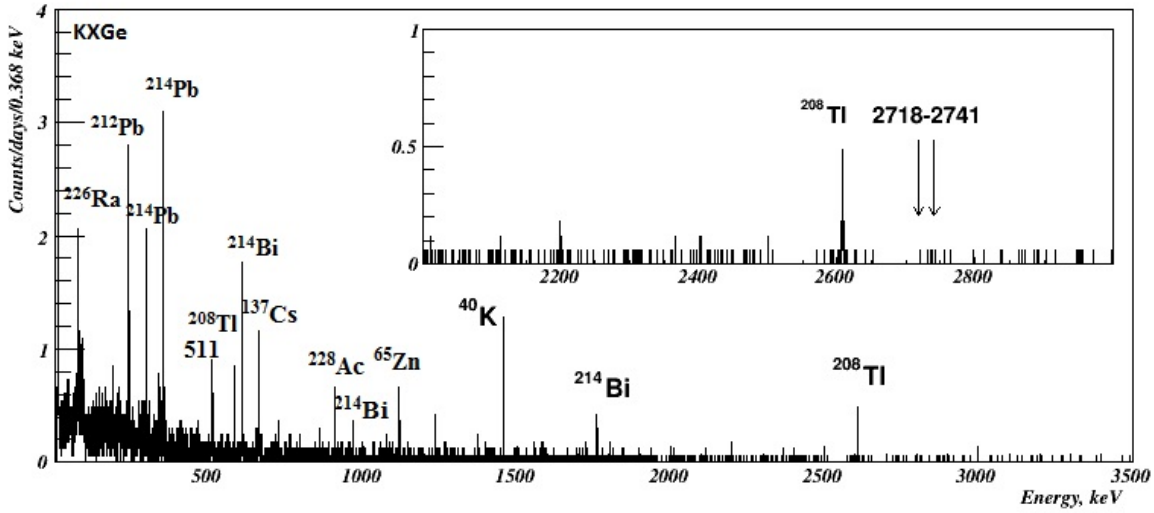

Figure 1. Experimental spectrum obtained in the measurement of 16 foils of ^{106}Cd with enrichment of 99.57% and a total mass of ~23.2 g with the Obelix spectrometer during 395 h. The upper inset at the figure shows the region of interest for investigation of the resonant 0νEC/EC decay of ^{106}Cd.

A new investigation of double beta decay of ^{106}Cd (phase III of the experiment TGV-2) was started at the Modane underground laboratory (LSM) at the end of February 2014 using the TGV-2 spectrometer and 16 samples of ^{106}Cd with enrichment of 99.57% and a total mass of ~23.2 g. The level of background obtained in the new measurement (phase III) was lower in comparison with the previous phase of experiment due to the reduced level of radioactive contamination of new samples (Figure 2).

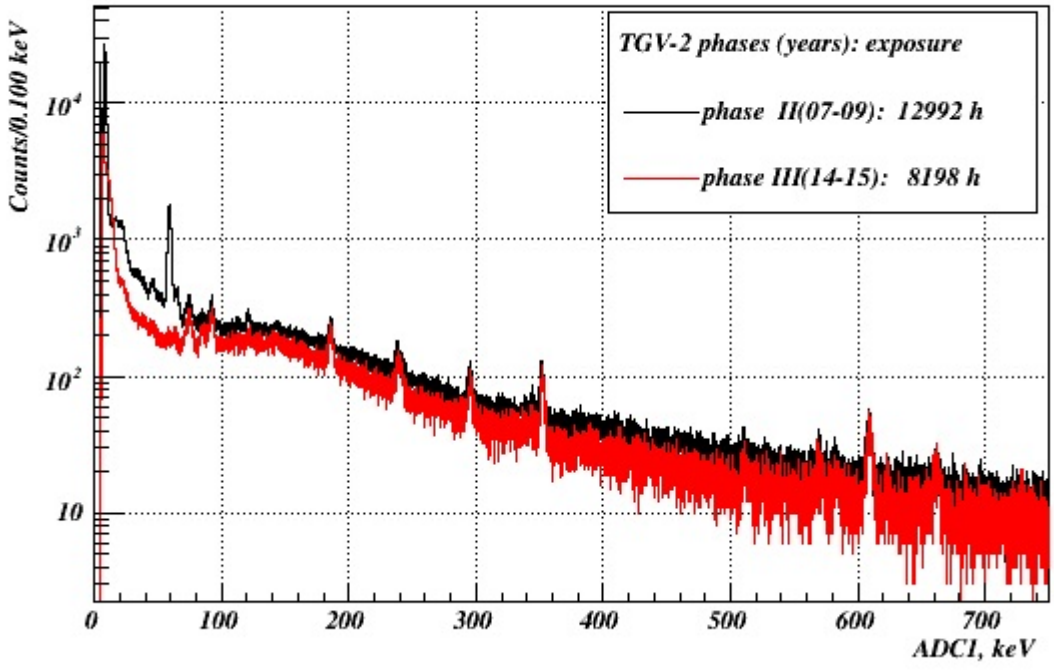

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Figure 2. Comparison of single events obtained in phase II (upper spectrum) and phase III (lower spectrum) of the experiment TGV-2. Spectra are normalized at the same time of measurement.

The double coincidences between two characteristic KX- rays of Pd detected in neighboring detectors were analyzed to search for 2νEC/EC decay of ^{106}Cd to the ground 0^+ state of ^{106}Pd. Two types of analysis [8] were performed to find the possible KXPd-KXPd events - the analysis of two-dimensional matrix of double coincidence events (Figure3) and the "traditional" analysis of one-dimensional spectrum of double coincidence events with KX(Pd) in one of detectors (Figure 4). From the preliminary calculation of experimental data accumulated in phase III of the TGV-2 experiment during 8198h the limit on two-neutrino double electron capture of ^{106}Cd to the ground 0^+ state of ^{106}Pd - $T_{1/2}(2\nu EC/EC,0^+ \rightarrow 0^+) > 3.7 \times 10^{20}$ y (90% C.L.) was obtained.

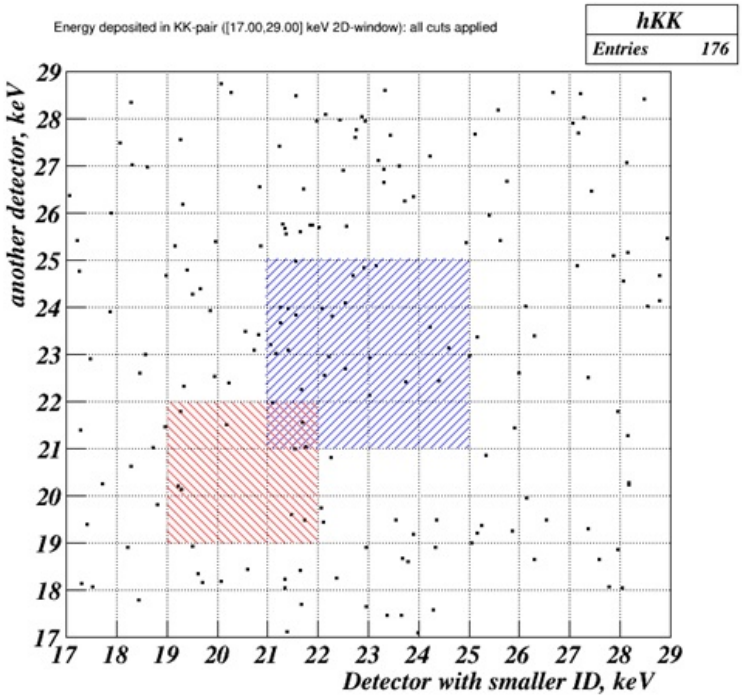

Figure 3. Two-dimensional plot of double coincidence events (right), obtained in the measurement of enriched ^{106}Cd in phase III of experiment TGV-2 during 8198 h.

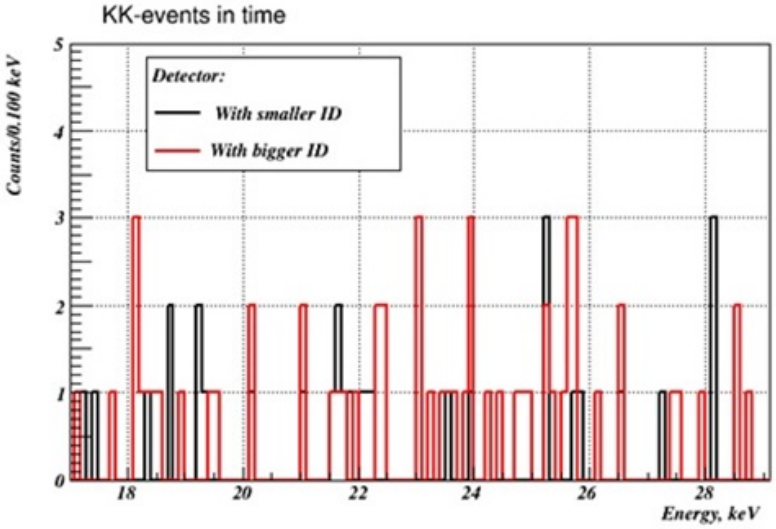

Figure 4. One-dimensional spectrum of double coincidence events, obtained in the measurement of enriched ^{106}Cd in phase III of experiment TGV-2 during 8198 h.

Investigations of other branches of double beta decay of ^{106}Cd were based on the analysis of KX-γ and γ-γ coincidences. The main results obtained in the preliminary calculation of experimental data accumulated in 8198 h of measurement using the TGV-2 spectrometer and ~23.2 g of ^{106}Cd with enrichment of 99.57% (phase III of the experiment) are presented in Table 1 in comparison with results of previous phase II [9]. The limits on resonance 0νEC/EC decay of ^{106}Cd to the excited states of ^{106}Pd were obtained in the measurement of ~23.2 g of ^{106}Cd with enrichment of 99.57%with the Obelix spectrometer during 395 h. All limits are at 90% C.L.

Table 1. TGV-2 limits on double beta decay of ^{106}Cd.

Decay mode	Final level of ^{106}Pd	$T_{1/2}$, y Phase II [9]	$T_{1/2}$, y Phase III
2ν*EC*/*EC*	$0^+_{g.s.}$	$4.2 \cdot 10^{20}$	$3.7 \cdot 10^{20}$
	2^+, 511.9 keV	$1.2 \cdot 10^{20}$	$8.5 \cdot 10^{19}$
	0^+_1 , 1134 keV	$1.0 \cdot 10^{20}$	$6.0 \cdot 10^{19}$
0ν*EC*/*EC*	2717.6 keV	$1.6 \cdot 10^{20}$	$1.4 \cdot 10^{20}$
0ν*EC*/*EC*	4^+, 2741 keV	$1.8 \cdot 10^{20}$	$0.9 \cdot 10^{20}$
2νβ$^+$/*EC*	$0^+_{g.s.}$	$1.1 \cdot 10^{20}$	$1.7 \cdot 10^{20}$
	2^+, 511.9 keV	$1.1 \cdot 10^{20}$	$1.3 \cdot 10^{20}$
	0^+_1 , 1134 keV	$1.6 \cdot 10^{20}$	$1.9 \cdot 10^{20}$
2νβ$^+$β$^+$	$0^+_{g.s.}$	$1.4 \cdot 10^{20}$	$1.6 \cdot 10^{20}$
	2^+, 511.9 keV	$1.7 \cdot 10^{20}$	$1.9 \cdot 10^{20}$

Measurement of enriched ^{106}Cd with the TGV-2 spectrometer is planned to continue for three years. The sensitivity of the measurement over this period is expected to be about $T_{1/2} \sim 10^{21}$ y for 2νEC/EC decay of ^{106}Cd. Taking into account theoretical predictions for this process we hope to detect 2*ν*EC/EC capture in ^{106}Cd decay within the current experimental run.

4. Acknowledgments

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