Investigation of $\beta^+\beta^+$, β^+EC, EC/EC decay of ^{106}Cd with the spectrometer TGV-2

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Abstract. The III phase of experiment TGV-2 to search for $\beta^+\beta^+$, β^+EC, EC/EC decay of ^{106}Cd was performed at the Modane underground laboratory (LSM, France, 4800 m w.e.). 16 foils (~23.2 g) of enriched ^{106}Cd were measured using the 32-detector low background HPGe spectrometer TGV-2 during 42500 h. New limit on 2νEC/EC decay of ^{106}Cd to the ground 0^+ state of ^{106}Pd - $T_{1/2} > 7.2 \times 10^{20}$ y at 90% C.L was obtained. The limits on $2\nu\beta^+\beta^+$, $2\nu\beta^+$EC decay of ^{106}Cd, and 2νECEC decay of ^{106}Cd to excited states of ^{106}Pd were significantly improved in comparison with previous phase II of the TGV-2 experiment.

1. Introduction

Investigation of double-beta decay processes are of great importance for particle and nuclear physics for the studying the properties of neutrino and weak interactions [1]. Neutrino-less double beta decay has not been detected experimentally till now. Two-neutrino ($2\nu\beta^-\beta^-$) decay was detected for 11 nuclei [2]. Two neutrino EC/EC decay was detected in ^{130}Ba using a geochemical technique [3]. There are also an indication on the possible 2νEC/EC decay in ^{78}Kr [4], and observation of 2νEC/EC decay in ^{124}Xe [5]. In contrast to the listed experiments on searching for 2νEC/EC decay, experiment TGV-2 is focused on the direct detection of 2νEC/EC decay of ^{106}Cd by registration of coincidences of two Palladium (Pd) X–rays (energy ~ 21 keV) emitting in this rare decay. ^{106}Cd is one of the most promising candidates to search for 2νEC/EC decay (Figure 1). Theoretical predictions of half-lives for this process are ranged between 1.1×10^{20} and 2.5×10^{22} y [6]. ^{106}Cd is also a real candidate for searching for resonance neutrino-less EC/EC decay to excited states of daughter nuclei – ^{106}Pd [7, 8]. The TGV-2 experiment was lasted for several years. As a result of this investigation the best experimental limit on 2νEC/EC decay of ^{106}Cd - $T_{1/2} \geq 4.2 \times 10^{20}$ y (90% CL) [9] was obtained in the previous phase II of experiment. In principle phase II of the experiment showed some indication on the possible 2νEC/EC decay of ^{106}Cd. But statistics of KX(Pd)-KX(Pd) coincidence events in this phase was not enough to declare the detection of this process. Experimental possibilities of phase II was also limited by the presence of radioactive contamination of ^{241}Am on several investigated foils of ^{106}Cd. Therefore the mass of investigated isotope in experiment TGV-2 was highly increased - from ~5.787×10^{22} atoms of ^{106}Cd

(~13.6 g of ^{106}Cd with enrichment of 75%).in phase II to ~1.3 × 10^{23} atoms of ^{106}Cd (~23.2 g of ^{106}Cd with enrichment of 99.57%) in current phase III. And investigated foils used in phase III were preliminary tested on radioactive contamination with low background detector Obelix [10].

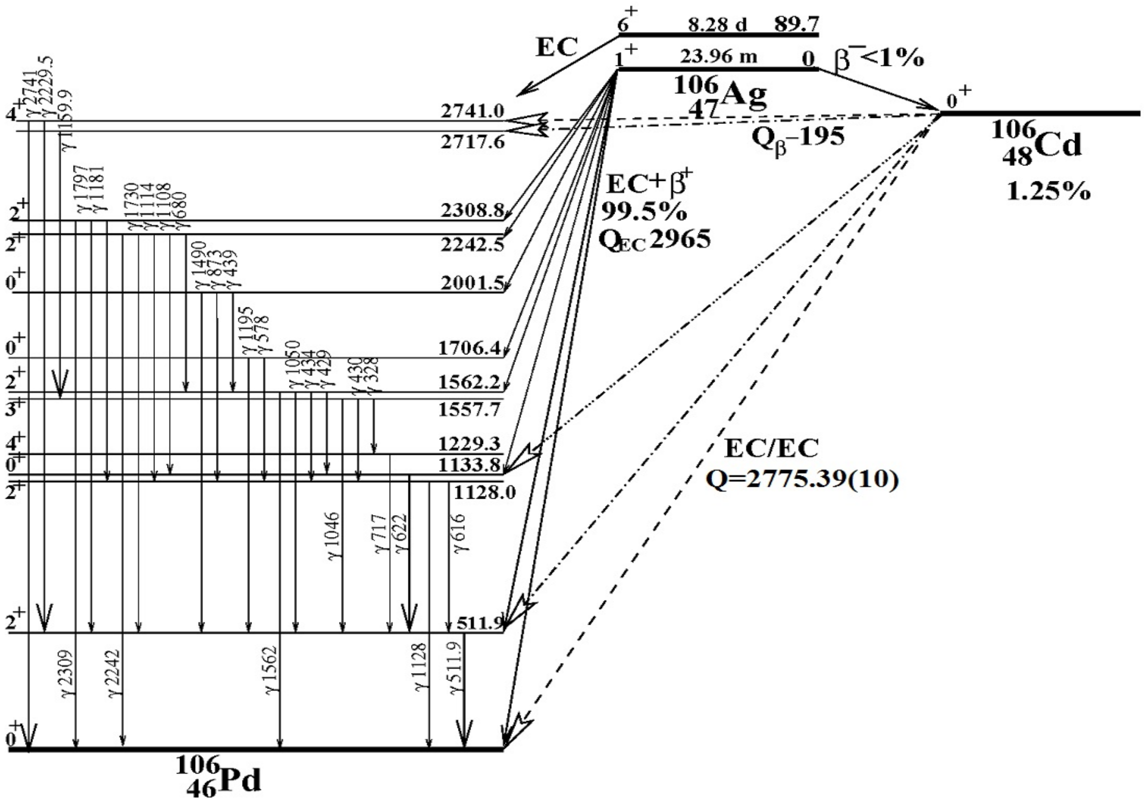

Figure 1. Decay scheme of ^{106}Cd.

2. Conditions of the phase III of the experiment TGV-2

Experiment TGV-2 of searching for $\beta^+\beta^+$, β^+EC, EC/EC 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 (enrichment of 99.57%) and a total mass of ~23.2 g. Investigated samples were made by rolling in a form of metallic foils and had a diameter of 52 mm, and a thickness of ~70(10) µm 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 (Figure 2). 16 foils of ^{106}Cd foils used in current investigation (phase III) (~1.3 × 10^{23} atoms of ^{106}Cd) were inserted between the entrance windows of detectors. The distance from foils to detectors is about 1.5 mm. The 16 pairs of detectors with cadmium foils were mounted one over another in a common cryostat tower. The total sensitive volume of 32 TGV-2 detectors is about 400 cm^3 and the total mass of them is about 3 kg of Ge. The energy resolution of the detectors measured at 1332 keV γ-line of ^{60}Co were ranged from 3.0 to 4.0 keV. The design of the detector part of TGV-2 spectrometer delivers high detection efficiency for useful events (single and multiple coincidence) and strong suppression of external background. The detector part of the TGV-2 spectrometer is surrounded by a passive shielding consisting of copper (≥20 cm), an airtight box against radon, lead (≥10 cm) and a neutron shielding made of borated polyethylene (16 cm). Location of the TGV-2 spectrometer in the deep underground laboratory (4800 m w.e.) allows us to suppress cosmic rays (reduction factor of ~2×10^6) and fast neutrons (reduction factor of ~10^3). Additional suppression of background in the low energy region (<50 keV) may be achieved by filtering the electronic and microphone noise by digitizing the detector response with different shaping times (2 and 8 µs) [10].

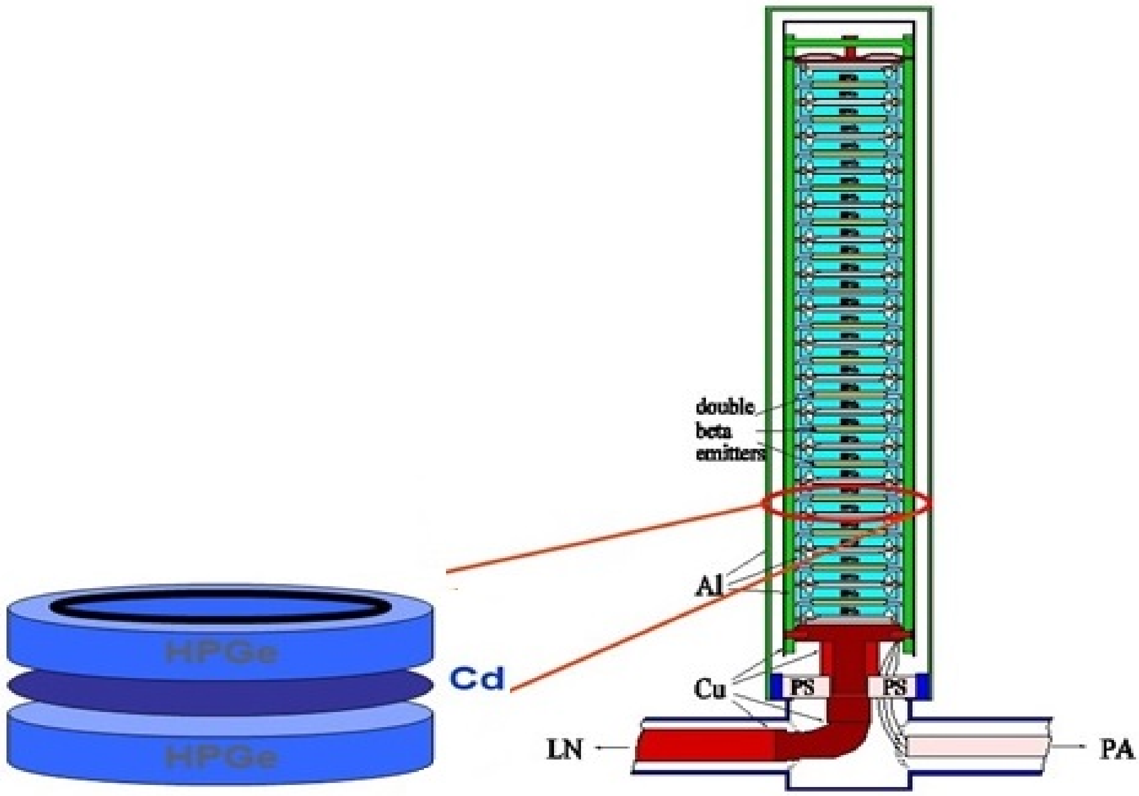

Figure 2. The geometry of measurement ^{106}Cd foils with TGV-2 HPGe detectors.

3. Experimental results of phase III

Current phase III of the experiment TGV-2 was started at the Modane underground laboratory (LSM) at the end of February 2014 with 32-detector spectrometer TGV-2 and 16 samples of ^{106}Cd with a total mass of ~23.2 g ((~1.3 × 10^{23} atoms of ^{106}Cd). The level of background in current phase III of experiment is now much lower (especially in a low energy region) than it was in previous phase II due to the lower level of radioactive contamination in investigated samples [10]. Additional suppression of TGV-2 background by using coincidence techniques is shown on Figure 3.The upper spectrum on the Figure 3 represents the total spectrum of single events detected from all 32 detectors during 42500 h. The middle spectrum is the double coincidence events collected in neighboring detectors during the same time, and the lower spectrum is the double coincidence events from neighboring detectors with selection of events accumulated in the energy window of 19-22 keV (region of KXPd) in one of the coincidence detectors. The last spectrum was used to analyze double coincidences between two characteristic KX-rays of Pd detected in neighboring detectors and search for 2νEC/EC decay of ^{106}Cd to the ground 0^+ state of ^{106}Pd [6]. The analysis of KX-KX coincidences (Figure 4) showed an increased numbers of measured events in the region of ~21 keV (KXPd) (Figure 4), which might be searching events from the 2νEC/EC decay of ^{106}Cd. But the statistics is still not enough to make the declaration about the experimental observation of 2νEC/EC decay of ^{106}Cd in experiment TGV-2.

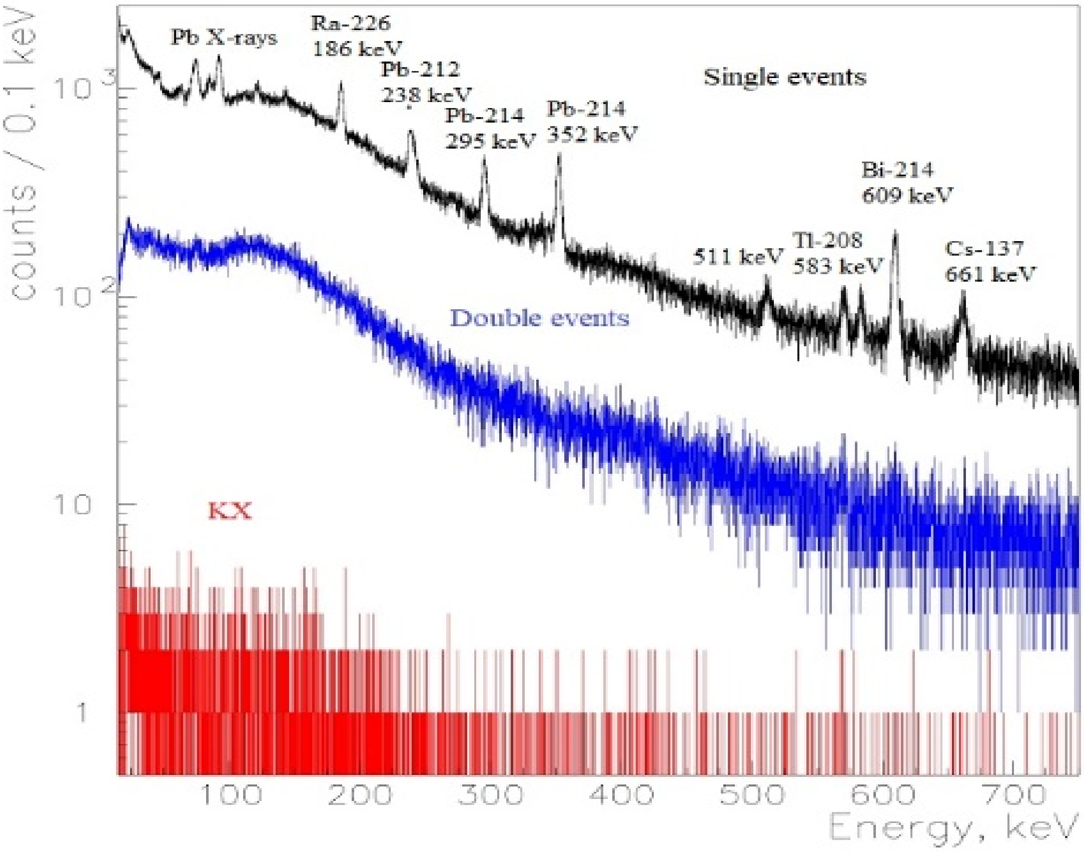

Figure 3. Single, double coincidence and double coincidences events with 19-22 keV window set in one of coincidence detectors.

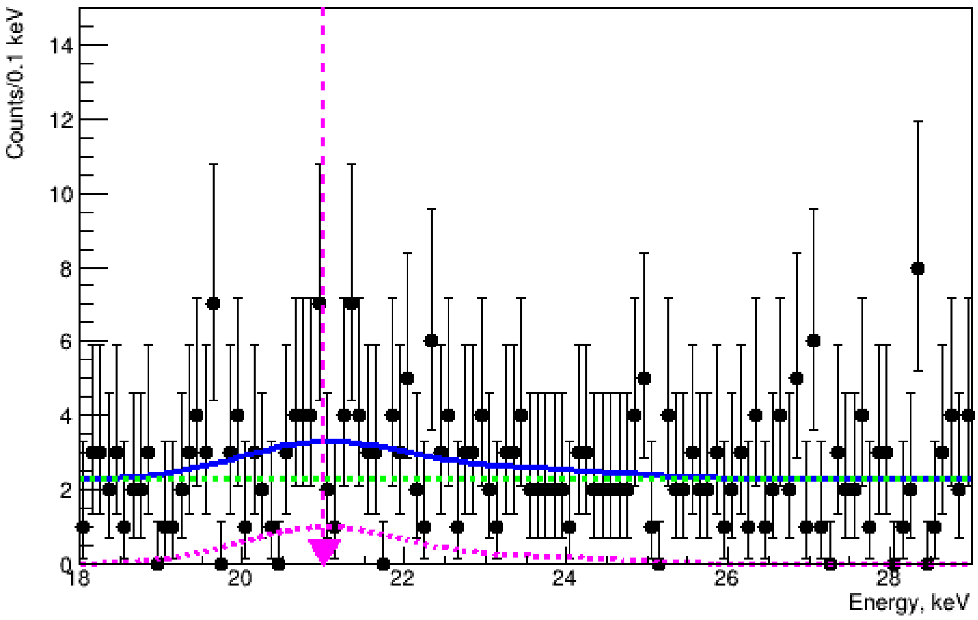

Figure 4. Region of interest of double coincidence (KX-KX) events, obtained from neighboring detectors with 19-22 keV energy window set in one of coincidence detectors.

Based on the analysis of data accumulated in phase III of experiment TGV-2 during 42500 h the new limit on two-neutrino double electron capture decay of ^{106}Cd to the ground 0^+ state of ^{106}Pd - $T_{1/2}(2\nu EC/EC, 0^+ \rightarrow 0^+) > 7.2 \times 10^{20}$ y (90% C.L.) was obtained. Calculation of other branches of double beta decay of ^{106}Cd (Figure 1) were based on the analysis of various types of KX-γ, γ-γ, and KX-γ-γ coincidences. New experimental results (at 90% C.l.) obtained on the present stage of phase III of the TGV-2 experiment are presented in Table 1 in comparison with results of previous phase II of TGV-2.

Table 1. Phase III of TGV-2 results for 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
$2\nu EC/EC$	$0^+_{g.s.}$	4.2×10^{20}	7.2×10^{20}
	2^+, 511.9 keV	1.2×10^{20}	8.9×10^{20}
	0^+_1, 1134 keV	1.0×10^{20}	7.2×10^{20}
$2\nu\beta^+/EC$	$0^+_{g.s.}$	1.1×10^{20}	6.6×10^{20}
	2^+, 511.9 keV	1.1×10^{20}	7.9×10^{20}
	0^+_1, 1134 keV	1.6×10^{20}	9.0×10^{20}
$2\nu\beta^+\beta^+$	$0^+_{g.s.}$	1.4×10^{20}	3.9×10^{20}
	2^+, 511.9 keV	1.7×10^{20}	4.7×10^{20}

4. Acknowledgments

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