PROCEEDINGS OF SCIENCE

Search for double beta decay of ^{106}Cd with the TGV-2 spectrometer

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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. The spectrometer consists 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 - $T_{1/2} > 4.7 \times 10^{20}$ y at 90% C.L was obtained from the preliminary calculation of experimental data accumulated for 13632 h of measurement. The limits on EC/EC decay of ^{106}Cd to excited states of ^{106}Pd, and $\beta^+\beta^+$, β^+EC decays to the ground and excited states of ^{106}Pd were improved in present investigation.

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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 capture. Experimental studies of 2νEC/EC capture yielded positive result for ^{130}Ba using a geochemical technique [3]. However, the robustness of this implicit experimental method is debatable, and this result has to be confirmed by direct measurements. ^{106}Cd is one of the most promising candidates for the investigation of two-neutrino double electron capture due to the high decay energy ($Q_{\mathrm{EC/EC}}$ = 2775.39 ± 0.10 keV). The 2νEC/EC decay of ^{106}Cd (Fig.1) with a transition to the ground state of ^{106}Pd ($0^+\rightarrow0^+$, 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 [4].

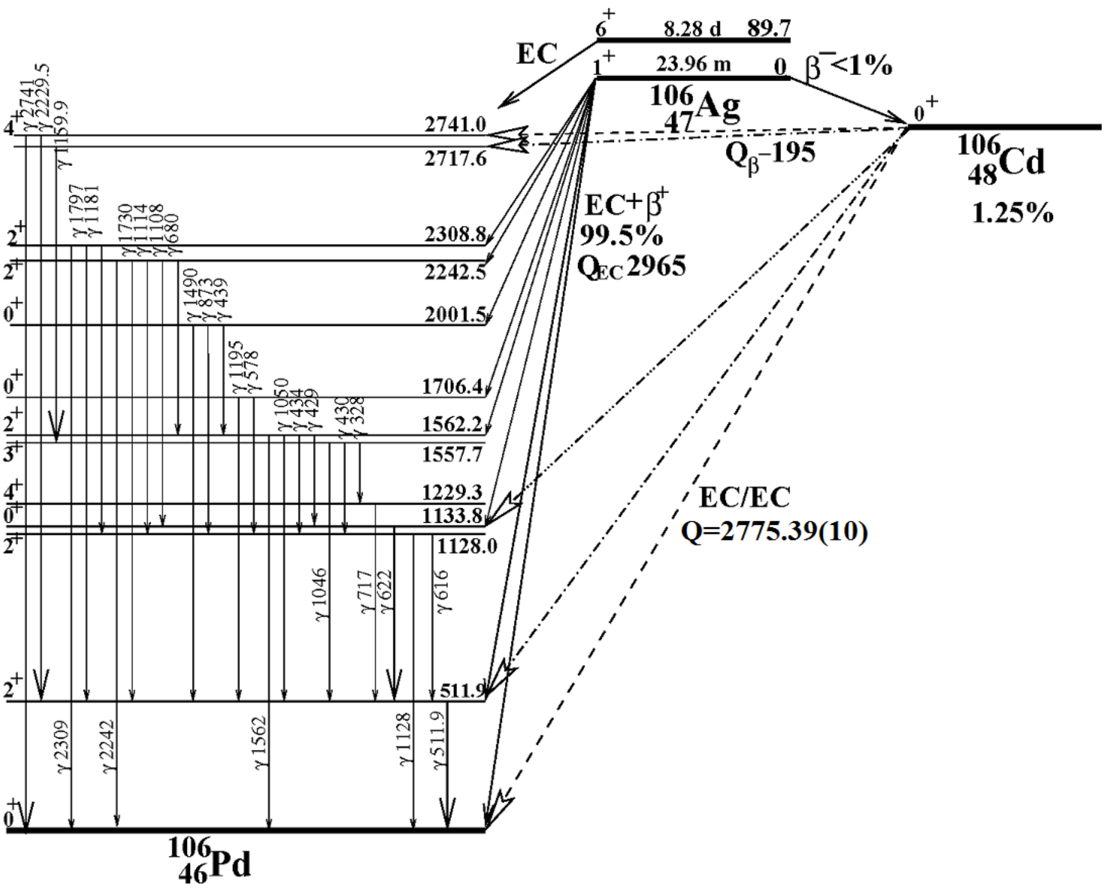

Fig.1. Decay scheme of ^{106}Cd.

Neutrinoless double electron capture decay (0νEC/EC) is strongly suppressed in comparison with other double beta decay modes due to the requirement of the emission of an additional particle(s) (γ_{brem}, 2γ, e+e-, e-$_{\mathrm{int}}$) in order to satisfy the energy-momentum conservation. Bernabéu, De Rujula, and Jarlskog [5] pointed out to the possibility of a resonant enhancement of the neutrinoless double electron capture (0νEC/EC) in case of a mass degeneracy between the initial and final atoms. The degeneracy condition is expressed as $Q = \Delta M - B_{2h} - E_\gamma \approx 0$, where ΔM is the difference between the initial and final atomic masses, B_{2h} in the energy of double electron holes in the atomic shell of the daughter atom and E_γ is the excitation energy of the daughter nucleus. The isotope ^{106}Cd is one of a favourable candidate for searching for a resonant neutrino-less double electron capture decay (0νEC/EC) to excited states of ^{106}Pd [5, 6]. The possible 0νEC/EC resonant transitions in ^{106}Cd→^{106}Pd decay are KL, 2741 keV; KK, 2718 keV; KL, 2737 keV. The TGV-2 experiment is focused on the study of the double beta decay of ^{106}Cd for several years [7-9] and TGV collaboration (JINR, Dubna; IEAP CTU, Prague; LSM, Modane) is one of the leaders in investigations of EC/EC process. The best experimental limit on 2*ν*EC/EC decay of ^{106}Cd - $T_{1/2} \geq 4.2 \times 10^{20}$ y (90% CL) [8] was obtained using the TGV-2 spectrometer (Telescope Germanium Vertical) [10] 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 [4]. The analysis of KX-KX coincidences obtained in the previous run [8] showed a small increase in the number of measured events in the region of ~21 keV (KXPd), which might be the 2*ν*EC/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 [9] 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. Description of the TGV-2 spectrometer

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 [10] 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 $20.4\ \mathrm{cm}^2 \times 0.6\ \mathrm{cm}$. 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 (Fig.2). 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 design of the detector part of the TGV-2 spectrometer delivers high detection efficiency for multiple coincidence events resulting in strong suppression of the background. The detector part of the TGV-2 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 $\sim 2\times 10^6$) and fast neutrons (reduction factor of $\sim 10^3$). 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) [10]. 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) mg/cm^2 and a total mass of ~23.2 g (about 1.3 × 10^{23} atoms of ^{106}Cd).

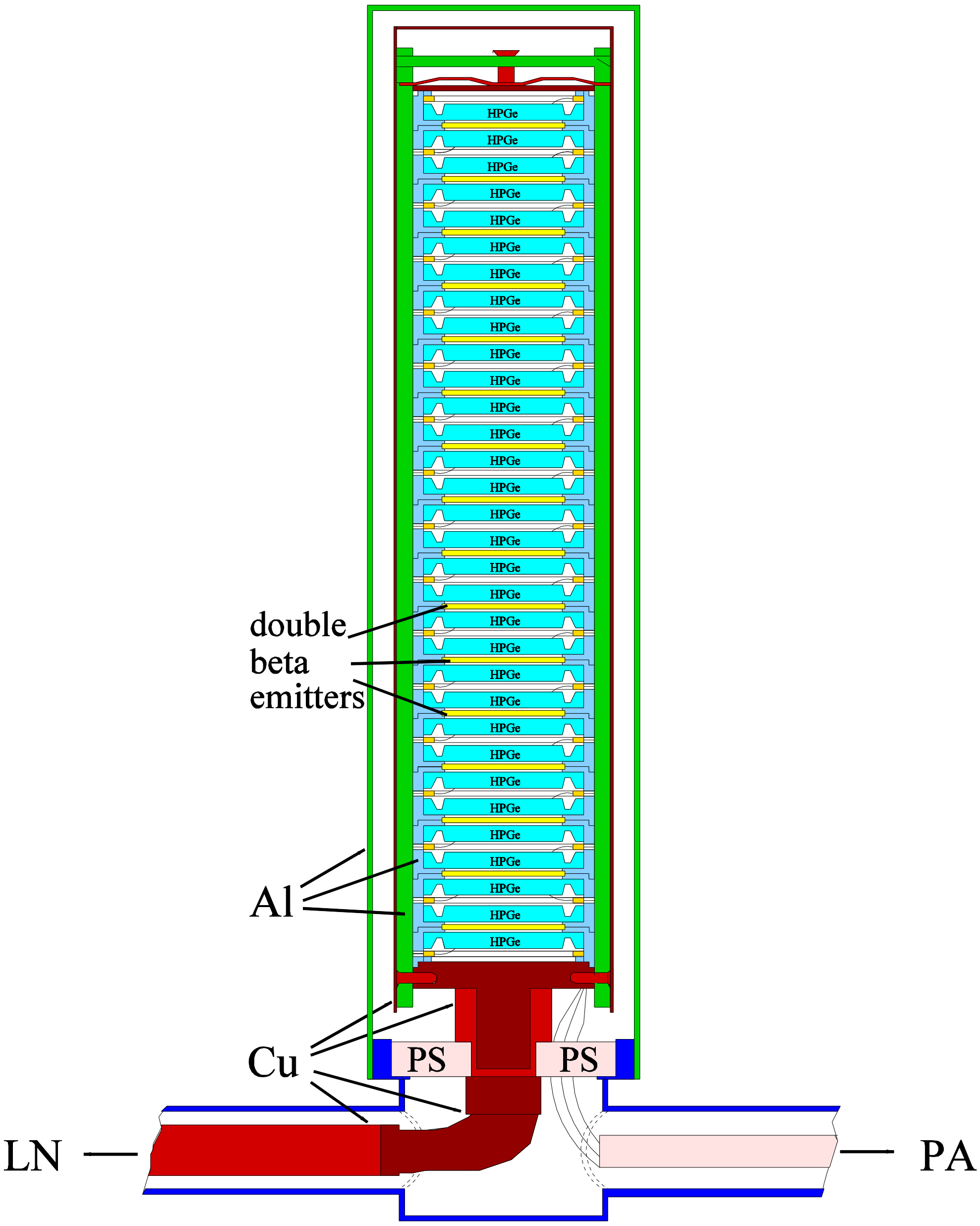

Fig.2. The detector part of TGV-2 spectrometer.

3. Experimental results

Sixteen foils of enriched ^{106}Cd with a total mass of ~23.2 g, prepared for the TGV-2 spectrometer, were preliminary measured at LSM using the high-efficiency low-background HPGe spectrometer Obelix [11] to obtain their contaminations. In processing of experimental data accumulated in this measurement lasted 395 h the analysis of events corresponding to the possible resonant 0νEC/EC decay of ^{106}Cd was also performed. 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 [8]. While the level of 2718 keV will be depopulated via the emission of 1160-, 1046-, and 512-keV γ-quanta cascade [8]. 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 90% C.L. on resonant neutrino-less transitions in double electron capture (0νEC/EC) decay of ^{106}Cd were obtained in processing of this measurement.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 II of experiment due to the reduced level of radioactive contamination of investigated samples (Fig.3).

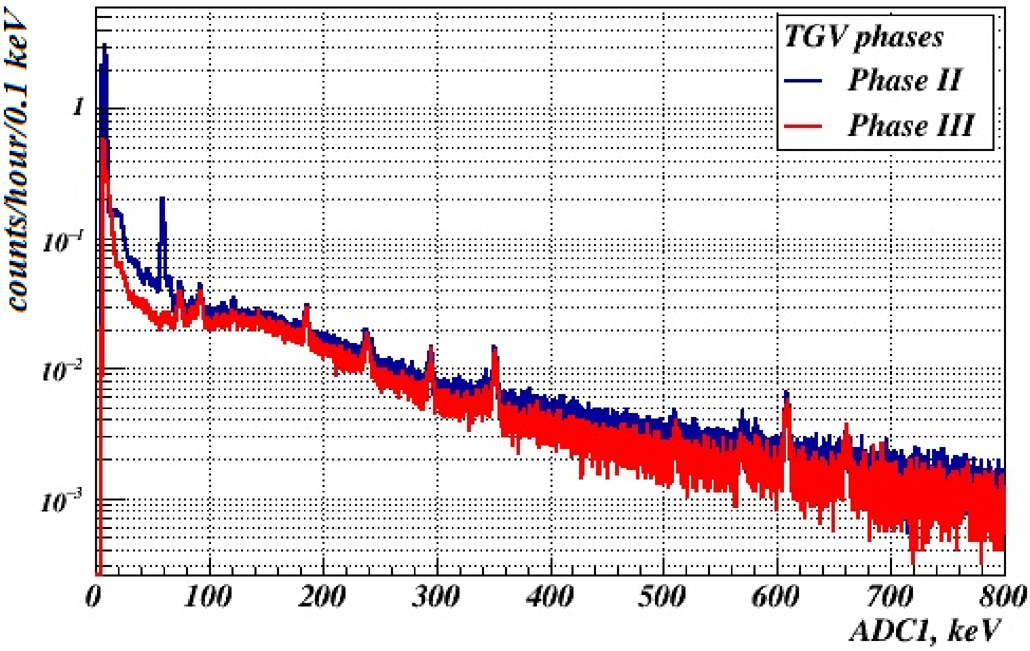

Fig.3. Comparison of single events obtained in phase II (upper spectrum) and phase III (lower spectrum) of the experiment TGV-2.

Suppression of TGV-2 background by using coincidence techniques is shown on Fig.4. Where the upper spectrum represents the total spectrum of single events from all 32 detectors, the middle spectrum is the double coincidence events collected in neighboring detectors, the lower spectrum is the double coincidence events of neighboring detectors with the energy window of 19-22 keV, set in one of the coincidence detectors. 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 [7] were performed to find the possible KXPd-KXPd events - the analysis of two-dimensional matrix of double coincidence events (Fig.6) and the “traditional” analysis of one-dimensional spectrum of double coincidence events with KX(Pd) in one of detectors (Fig.7). From the preliminary calculation of data accumulated in phase III of the TGV-2 experiment during 13632h the limit on two-neutrino double electron capture of ^{106}Cd to the ground 0^+ state of ^{106}Pd - $T_{1/2}$(2νEC/EC,$0^+ \rightarrow 0^+$) >4.7 × 10^{20} y (90% C.L.) was obtained.

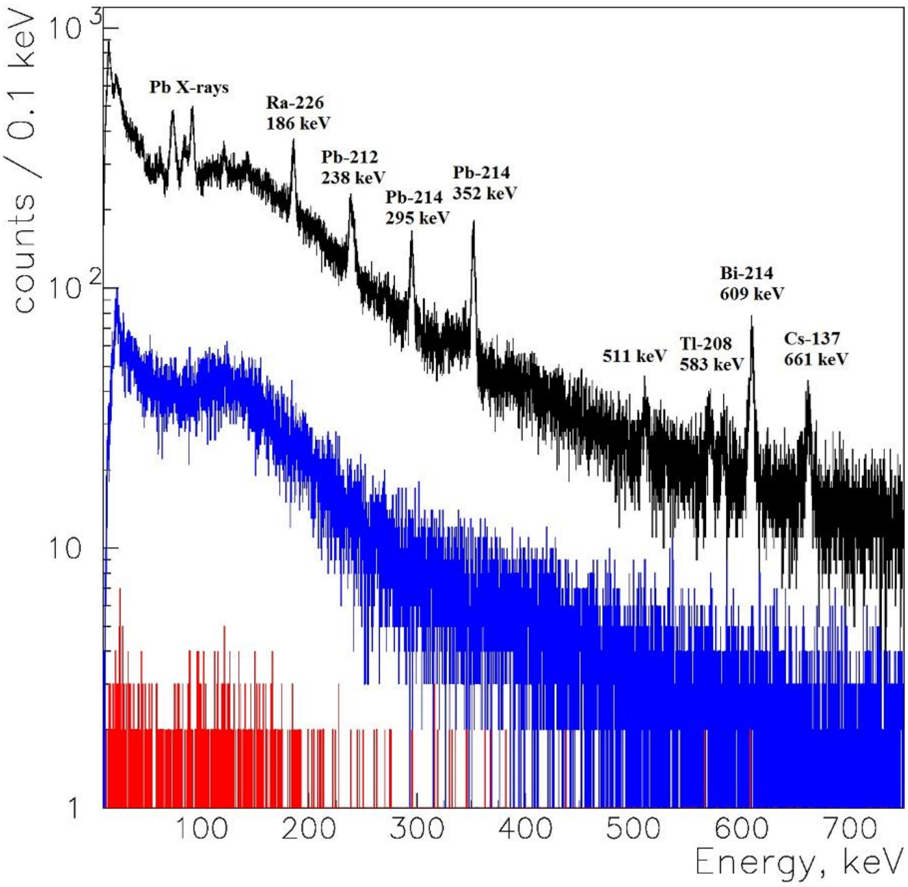

Fig.4. Suppression of TGV-2 background by using coincidence techniques.

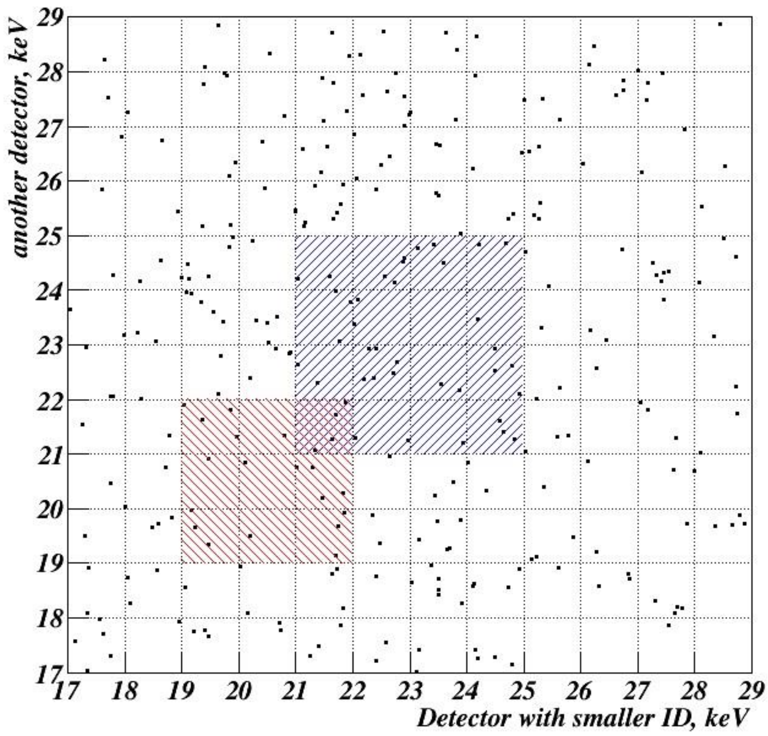

Fig.5. Two-dimensional plot of double coincidence events, obtained in measurement of enriched ^{106}Cd (phase III) during 13632 h with shown regions of interest -KXPd and KXCd.

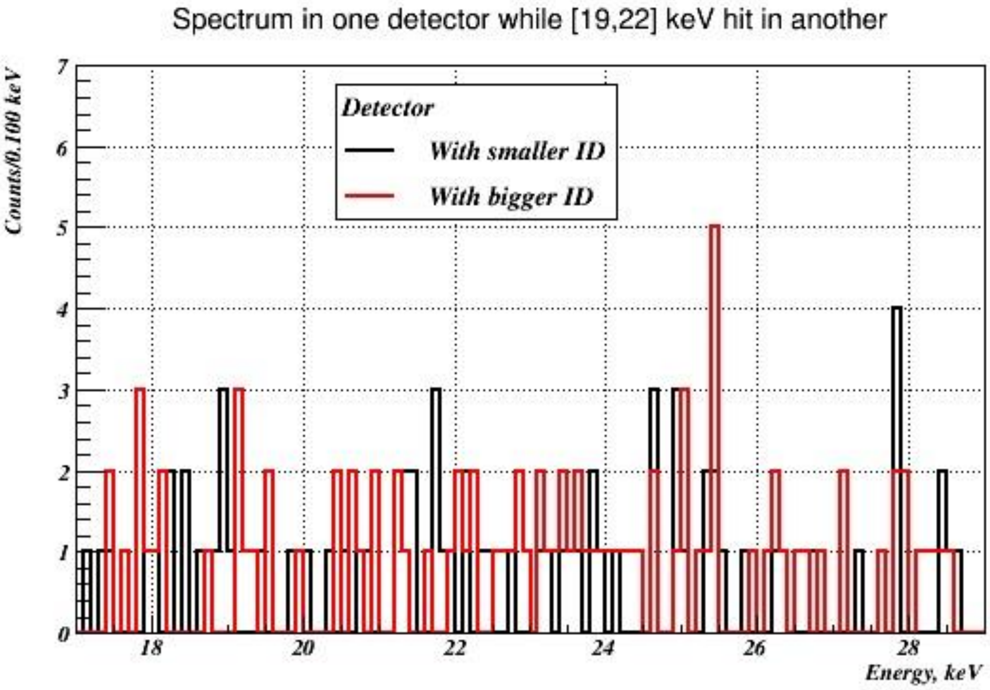

Fig.6. One-dimensional spectra of double coincidence events, obtained in measurement of enriched ^{106}Cd in phase III of experiment TGV-2 during 13632 h.

Investigations of other branches of ^{106}Cd decay (Fig.1) were based on the analysis of KX-γ and γ-γ coincidences. The main results obtained in the preliminary calculation of phase III experimental data for other branches of double beta decay of ^{106}Cd are presented in Table 1.

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 [8]	$T_{1/2}$, y Phase III
2ν*EC/EC*	$0^+_{g.s}$	4.2×10^{20}	4.7×10^{20}
	2^+, 511.9 keV	1.2×10^{20}	1.7×10^{20}
	0^+_1, 1134 keV	1.0×10^{20}	1.5×10^{20}
0ν*EC/EC*	2717.6 keV	1.6×10^{20}	1.4×10^{20}
0ν*EC/EC*	4^+, 2741 keV	1.8×10^{20}	0.9×10^{20}
2νβ^+/*EC*	$0^+_{g.s.}$	1.1×10^{20}	3.0×10^{20}
	2^+, 511.9 keV	1.1×10^{20}	3.0×10^{20}
	0^+_1, 1134 keV	1.6×10^{20}	4.5×10^{20}
2ν$\beta^+\beta^+$	$0^+_{g.s}$	1.4×10^{20}	3.9×10^{20}
	2^+, 511.9 keV	1.7×10^{20}	4.7×10^{20}

Measurement of enriched ^{106}Cd with the TGV-2 spectrometer are planned to continue for three years. The expected sensitivity of the phase III of the TGV-2 experiment for 2νEC/EC decay of ^{106}Cd over this period is about $T_{1/2} \sim 10^{21}$ y. Taking into account theoretical predictions for this process [4] we hope to detect 2*ν*EC/EC capture in ^{106}Cd decay within the current experimental run.

4. Acknowledgments

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References

[1] W.C. Haxton and G.S. Stephenson, *Double beta decay, Prog. Part. Nucl. Phys.* **12** (1984) 409.

[2] A.S. Barabash, *Average and recommended half-life values for two neutrino double beta decay: Upgrade-2013, AIP Conf. Proc*. **1572** (2013) 11.

[3] A.P. Meshik et al., *Weak decay of ^{130}Ba and ^{132}Ba: Geochemical measurements, Phys. Rev*. C **64** (2001) 035205.

[4] V.I. Tretyak and Yu.G. Zdesenko, *Tables of double beta decay- an update, At. Data Nucl. Data Tables* **80** (2002) 83.

[5] J. Bernabeu, A. De Rujula, C. Jarlskog, *Neutrinoless double electron capture as a tool to measure the electron neutrino mass*, *Nucl.Phys.* B **223** (1983) 15.

[6] M.I. Krivoruchenko, F. Šimkovic, D. Frekers, A. Faessler, *Resonance enhancement of neutrinoless double electron capture, Nucl. Phys.* A **859** (2011)140.

[7] N.I. Rukhadze et al,, *New limits on double beta decay of ^{106}Cd, Nucl. Phys.* A **852** (2011) 197.

[8] N.I. Rukhadze et al., *Experiment TGV-2. Search for double beta decay of ^{106}Cd, J. Phys.: Conf. Ser.* **375** (2012) 042020.

[9] N.I. Rukhadze et al., *Search for double beta decay of ^{106}Cd in the TGV-2 experiment, J. Phys.: Conf. Ser.* **718** (2016) 062049.

[10] P. Beneš et al.., *The low background spectrometer TGV II for double beta decay measurements*, *Nucl. Instr. Meth. in Phys. Res.* A **569** (2006) 737

[11] N.I. Rukhadze et al., *A Highly Efficient HPGE Gamma Ray Spectrometer for Investigating ββ Decay to Excited States*, *Bull. Russ. Acad. Sci.: Phys.* **77** (2013) 379