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I. Štekl, P. Čermák, P. Beneš, V.B. Brudanin, K.N. Gusev, et al.. First results for the measurement of double-electron capture of ^{106}Cd in the experiment TGV II. Workshop on calculation of double-beta-decay matrix elements (MEDEX'05), Sep 2005, Corfu, Greece. pp.505-510, 10.1007/s10582-006-0114-6 . in2p3-00087532

HAL Id: in2p3-00087532

<https://in2p3.hal.science/in2p3-00087532v1>

Submitted on 19 Nov 2024

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First results for the measurement of double-electron capture of ^{106}Cd in the experiment TGV II*)

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Present status of the experiment TGV II which is devoted to the measurement of double-beta decay of ^{106}Cd is given. The low background spectrometer TGV II is installed in the Modane Underground Laboratory and has been running from February 2005 with approx 10 grams of ^{106}Cd enriched at 75%. After an analysis of 3736 hours of experimental data the new improved half-life limit for $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd ($0_{\text{g.s.}}^+ \rightarrow 0_{\text{g.s.}}^+$) is given as $T_{1/2}^{2\nu} > 4.8 \times 10^{19}$ years (90% CL). The search for $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd to the excited states of ^{106}Pd allows to determine the limits of the half-lives $T_{1/2}^{2\nu}(0_{\text{g.s.}}^+ \rightarrow 2_1^+) > 3.9 \times 10^{19}$ years (90% CL) and $T_{1/2}^{2\nu}(0_{\text{g.s.}}^+ \rightarrow 0_1^+) > 5.8 \times 10^{19}$ years (90% CL).

PACS: 23.40.-s, 14.60.Pq

Key words: double-beta decay, double-electron capture, cadmium 106

1 Introduction

From the point of view of particle and nuclear physics the double-beta decay ($\beta\beta$) is one of the most important and effective tools for testing lepton number conservation, the study of neutrino properties (neutrinoless modes of double-beta decay) and nuclear structure (two-neutrino modes of double-beta decay).

*) Presented by I. Štekl at the Workshop on calculation of double-beta-decay matrix elements (MEDEX'05), Corfu, Greece, September 26–29, 2005.

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Up to now, close attention has been primarily given to the $\beta^-\beta^-$ channels (two-neutrino emitting and neutrinoless modes). There are also other channels of double-beta decay, in particular the double capture of two bound atomic electrons (EC/EC), capture of bound electron with emission of positron (β^+/EC) and double-beta decay with emission of two positrons ($\beta^+\beta^+$). In comparison with $\beta^-\beta^-$ decay these channels are disfavored by smaller available kinetic energy, by Coulomb repulsion on positron or due to a small overlap of bound electron wave function with nucleus.

Due to the low Q values of the $\beta^+\beta^+$ candidates and difficulties connected with experimental detection, the current level of experimental sensitivity to obtain half-life limits is in the range 10^{18} – 10^{20} years [1–4]. On the other hand, $2\nu\text{EC}/\text{EC}$ mode ($0_{g.s.}^+ \rightarrow 0_{g.s.}^+$), which is characterized by emission of only two X-rays, was measured at the level of 10^{17} years [3–6]. The energies and relative intensities of the X-ray K_{α_2} , K_{α_1} , K'_{β_1} , K'_{β_2} lines are following: 21.02 keV (52.9), 21.18 keV (100), 23.81 keV (27.3), 24.30 keV (4.8) (intensities are normalized to 100 for the K_{α_1} line).

Several years ago, the collaboration TGV proposed measurement of double-electron capture of ^{106}Cd (for details of the proposal see [7]). For such measurement the new HPGe spectrometer TGV II has been constructed and installed in the Modane Underground Laboratory (LSM). The detailed description of the TGV II detector is given in [8]. The most important feature of the TGV II is its ability to study small amount of materials with high efficiency (especially samples made of isotopes available only in small quantities, e.g. ^{48}Ca or ^{106}Cd). ^{106}Cd isotope is one of the most favorable candidates to study EC/EC decay channel, due to the high energy of decay involved ($Q_{\text{EC}/\text{EC}} = 2771$ keV). TGV II is the only set-up prepared for measurement of such exotic decay mode as $2\nu\text{EC}/\text{EC}$ decay from $0_{g.s.}^+$ level of ^{106}Cd to $0_{g.s.}^+$ level of ^{106}Pd . Theoretical predictions for the half-life of neutrino accompanying EC/EC decay of ^{106}Cd [9–11] differ significantly from each other. Within the QRPA approach Aunola and Suhonen calculated the half-life and obtained the value of 1.0×10^{20} years [9]. By using the same approach Hirsch et al. end up with a larger value 8.7×10^{20} years [10]. Recently, by assuming the SSD hypothesis and taking into account the dependence of energy denominators on lepton energies the half-life of the EC/EC decay of ^{106}Cd was found to be above 4.4×10^{21} years [11].

2 Experimental setup

The TGV II spectrometer is composed of a detector part, an electronics (NIM, CAMAC modules), and a shielding. The detector part (see Fig. 1) consists of 32 HPGe detectors of a planar type mounted one over another in a custom low-background U-style cryostat. The diameter of the sensitive area of each detector is 51 mm and its thickness is 6 mm. The total sensitive volume and the total mass of Ge detectors used in the TGV II spectrometer is about 400 cm^3 and 3 kg, respectively. The double-beta emitters prepared in a form of a foil (thickness $\approx 50\ \mu\text{m}$ for ^{106}Cd) can be inserted between neighbouring detectors. The distance between

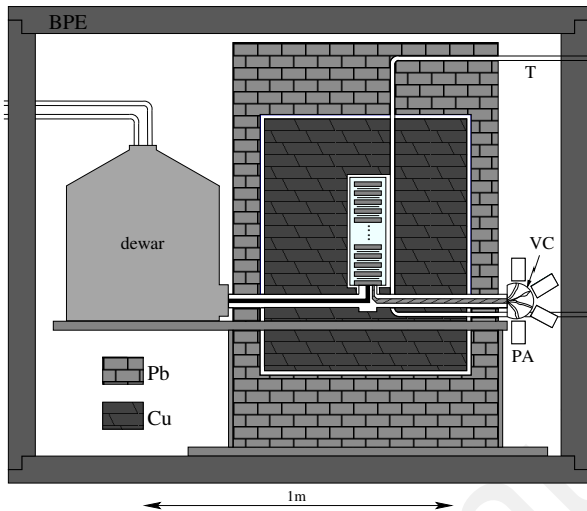


Fig. 1. The schematic view of the TGV II detector part illustrating the vertically located cryostat surrounded by a copper shielding, an airtight box against radon, and a lead shielding. The detector part of the TGV II apparatus is enclosed in an anti-neutron shielding made of borated polyethylene (BPE). PA stands for preamplifiers, VC for vacuum chamber, T for tube in which a source is moved during calibration.

emitters and detectors is about 1.5 mm in order to reach high efficiency of detection. The energy resolution of detectors is in the range from 3.0 to 4.0 keV at 1332 keV (^{60}Co). The main components surrounding detectors are made of low-background Al-Si(1%) alloy (contamination due to U and Th is less than 0.1 ppb), oxygen-free copper, and teflon. Several standard passive methods are used to minimize possible background. The cryostat itself is surrounded by a passive shielding made of copper (20 cm) and lead (10 cm). The cryostat and the copper shielding are enclosed in a steel (3 mm) airtight box against a penetration of radon gas. Anti-neutron shielding (16 cm) made of boron doped polyethylene was constructed to minimize the background caused by neutrons (e.g. neutron capture on copper which gives high energy gammas). All parts of the spectrometer (e.g. preamplifiers, dewar, etc.) which could increase the level of background are placed outside the Cu and Pb passive shielding. The experimental facility is located in LSM (4800 m.w.e.), where the flux of muons is very low ($4.2 \text{ m}^{-2} \cdot \text{day}^{-1}$).

3 Data analysis and preliminary results

As mentioned before, the data analysis concentrates on the three processes of $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd : $0_{\text{g.s.}}^+ \rightarrow 0_{\text{g.s.}}^+$, $0_{\text{g.s.}}^+ \rightarrow 2_1^+$ (512 keV) and $0_{\text{g.s.}}^+ \rightarrow 0_1^+$ (1134 keV). The first process ($0_{\text{g.s.}}^+ \rightarrow 0_{\text{g.s.}}^+$) is characterized by the emission of two X-rays with energies around 21 keV. The transition to 2_1^+ excited state produces

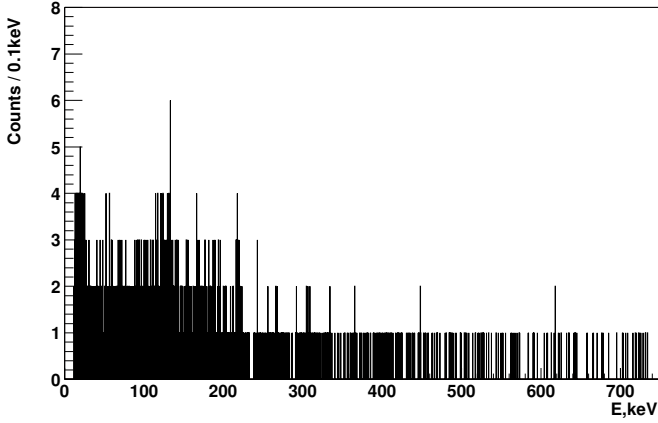


Fig. 2. The result of measurement performed during 3736 hours with the TGV II spectrometer with ^{106}Cd sources between HPGe detectors after applying of all rejection criteria (double coincidences of neighbouring detectors with an energy window appropriate to the region of interest, (19–22) keV).

two X-rays and one photon with energy 511.9 keV, while the decay to 0_1^+ excited state generates two X-rays and two photons with energies 511.9 keV and 621.8 keV.

To study these decays a data analysis with different selection criteria (double coincidences of neighbouring detectors with proper energy windows, e.g. 21 keV + 21 keV, 21 keV + 512 keV or 21 keV + 622 keV) is performed. The obtained half-life $T_{1/2}$ for such type of measurement is expressed as

$$T_{1/2} \geq \frac{\ln 2 N_0 \epsilon t}{N}, \quad (1)$$

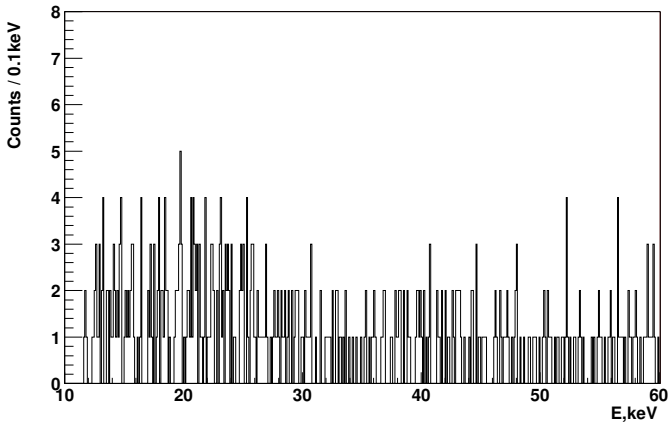


Fig. 3. Low energy region of the spectrum of double coincidence events with the selection of K_α line of Pd.

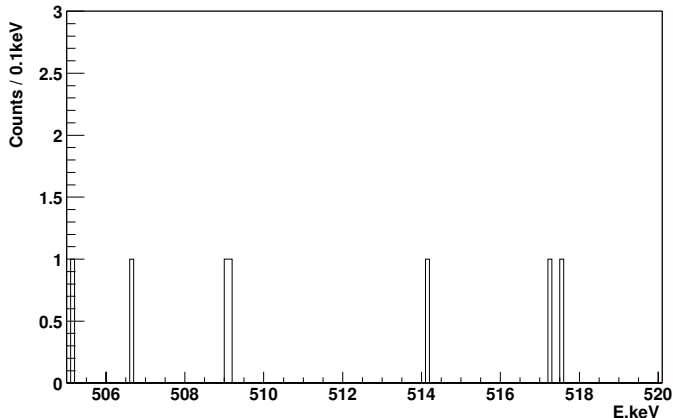


Fig. 4. The detail of the spectrum of $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd related to the excited state $0_{\text{g.s.}}^+ \rightarrow 2_1^+$.

where N_0 is the number of atoms in the source, t is the time of measurement (in years), ϵ is efficiency of the process registration by the TGV II detector and N is the number of observed events or the number of excluded events (leading to the limit for half-life). All efficiencies have been calculated by the Monte Carlo simulations. The TGV II spectrometer allows to distinguish EC/EC decay to the ground state and to the both excited states by the detection of corresponding gammas.

Figure 2 shows a spectrum obtained from measurement with ^{106}Cd sources. Spectrum was recorded for 3736 hours and all kinds of background suppression used in the TGV II spectrometer were applied (double coincidences of neighbouring detectors, selection of energy of detected particles in the interval (19–22) keV, microphonic noise suppression). The detail (energy region (10–60) keV) of this spectrum is shown in Fig. 3. The analysis of the low-energy part of the ^{106}Cd spectrum (see Fig. 3) shows a small increase in the number of detected events in the energy

Table 1. Lower limits for $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd to the ground state and excited states obtained from the TGV II experiment after 3736 hours of data taking.

Transition	$T_{1/2}$ (yrs)		
	(this work)	(existing limit)	(theory)
$0_{\text{g.s.}}^+ \rightarrow 0_{\text{g.s.}}^+$	$> 4.8 \times 10^{19}$	$> 5.8 \times 10^{17}$ [4]	1.0×10^{20} [10] 4.4×10^{21} [11]
$0_{\text{g.s.}}^+ \rightarrow 2_1^+$	$> 3.9 \times 10^{19}$	$> 3.5 \times 10^{18}$ [1]	4.0×10^{26} [11]
$0_{\text{g.s.}}^+ \rightarrow 0_1^+$	$> 5.8 \times 10^{19}$	$> 7.3 \times 10^{19}$ [2]	1.1×10^{24} [11]

region relevant to $2\nu\text{EC}/\text{EC}(0_{\text{g.s.}}^+ \rightarrow 0_{\text{g.s.}}^+)$ decay (significance level $\approx 2.3\sigma$). The detail of spectrum of $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd , $0_{\text{g.s.}}^+ \rightarrow 2_1^+$ is given in Fig. 4. There is no event for 3736 hours of data taking for this excited state. The results of the preliminary analysis of the $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd are summarized in Table 1 along with previous experimental results and theoretical estimates for the half-lives.

4 Conclusion

New promising results from the TGV II experiment after 3736 hours of acquisition have been obtained. The main effort has been devoted to the evaluation of preliminary half-life limits for $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd ($0_{\text{g.s.}}^+ \rightarrow 0_{\text{g.s.}}^+$, $0_{\text{g.s.}}^+ \rightarrow 2_1^+$ and $0_{\text{g.s.}}^+ \rightarrow 0_1^+$). We were able to increase the experimental limit for $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd ($0_{\text{g.s.}}^+ \rightarrow 0_{\text{g.s.}}^+$) by almost two orders of magnitude. In the case of decay to the 0_1^+ excited state the new limit is improved more than one order of magnitude. At the moment collaboration TGV II has experimental data for one year of measurement. The data processing is still in progress and using one year data there is a realistic assumption to reach the level of half-lives for $2\nu\text{EC}/\text{EC}$ decay of ^{106}Cd around 10^{20} years. The obtained results show also the reliability of the TGV II spectrometer for search of rare nuclear processes, e.g. EC/EC decay.

This work was performed within the framework of collaboration agreement No. 04-66 between IN2P3 and JINR and was partly supported by the Russian Foundation for Basic Research under grant No. 04-02-16957. The work was also supported by grant No. MSM6840770029 and by the Grant Agency of the Czech Republic under contract No. 202/02/0157. We would like to thank the staff of the Modane Underground Laboratory (LSM) for their care and support during the TGV experiment.

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