Search for double beta decay of ^{106}Cd

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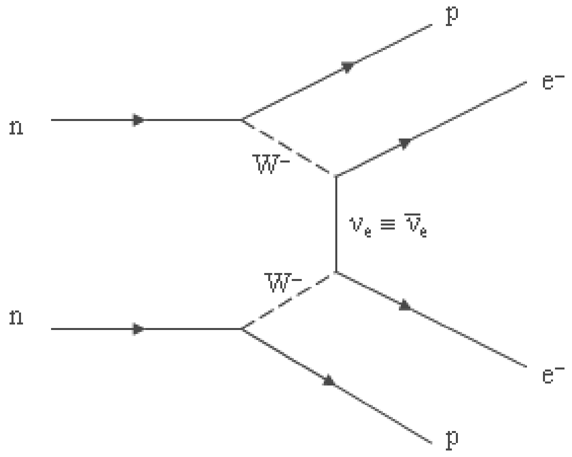
Contents

- Double beta decay
- Experiment
- Results
- Conclusions

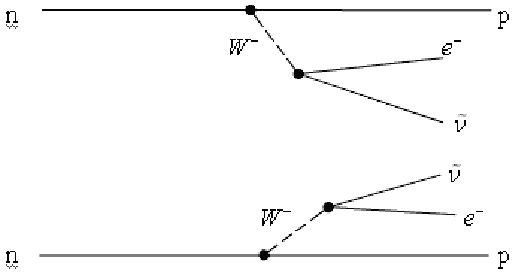
Double beta decay

Neutrinoless mode



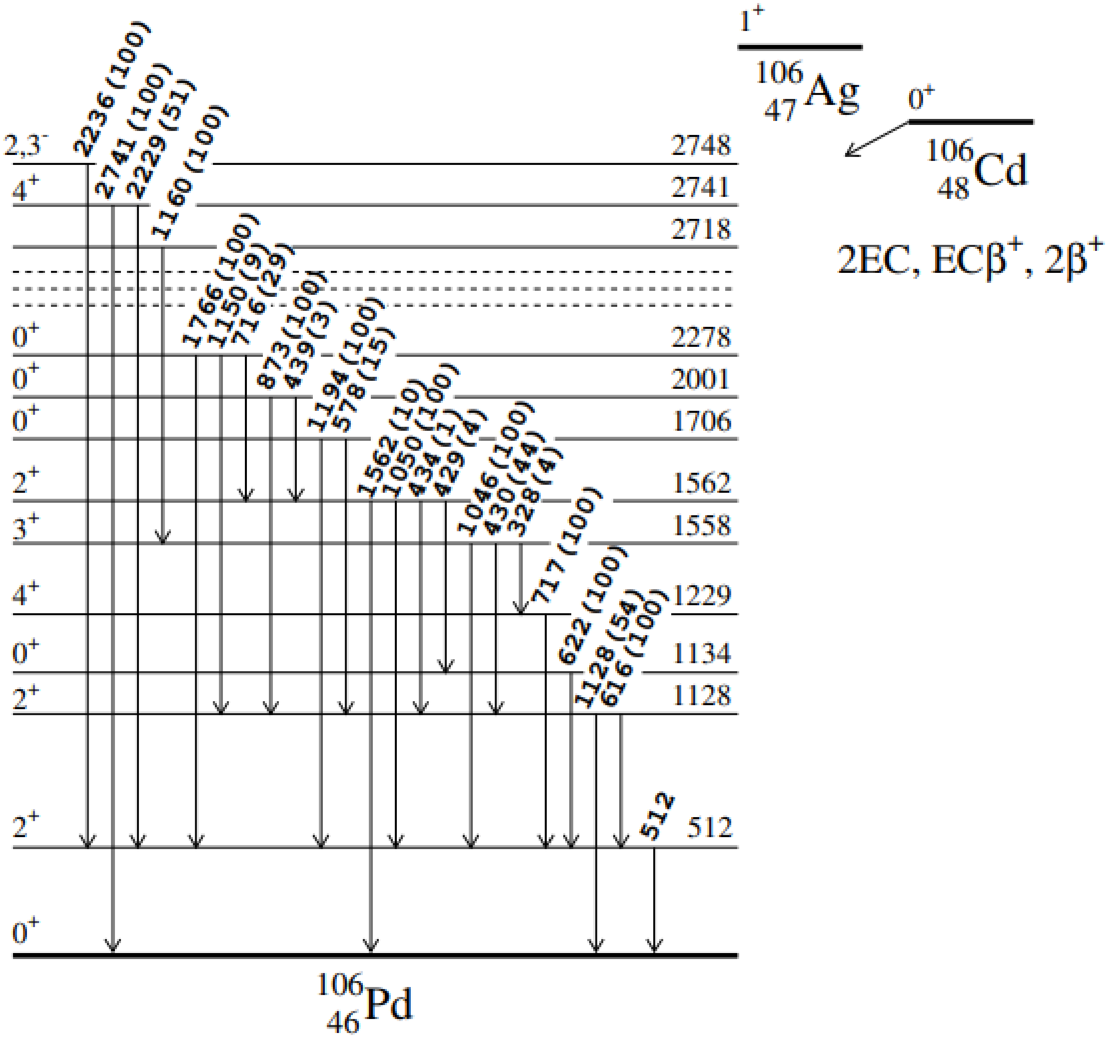
- Process beyond the Standard Model of particles and fields (SM)
- Neutrino is Majorana particle
- Process hasn't been observed
- The neutrinoless mode of the decay violates the lepton number conservation law
- The Majorana nature of the neutrino might shed light on the Universe baryon asymmetry problem
- Half-life limits at level $T_{1/2} > (10^{24} - 10^{26})$ yr. → $\langle m_\nu \rangle < (0{,}06\ - 0{,}6)\ \mathrm{eV}$

Double neutrino mode



- radioactive process allowed in the SM
- Neutrino is Dirac or Majorana particle
- Has been observed in several nuclides with the half-lives $10^{18} - 10^{24}$ yr.
  - 2ν2β⁻ : $^{48}\mathrm{Ca}$, $^{76}\mathrm{Ge}$, $^{82}\mathrm{Se}$, $^{96}\mathrm{Zr}$, $^{100}\mathrm{Mo}$, $^{116}\mathrm{Cd}$, $^{128}\mathrm{Te}$, $^{130}\mathrm{Te}$, $^{136}\mathrm{Xe}$, $^{150}\mathrm{Nd}$, ^{238}
  - 2ν2EC: $^{130}\mathrm{Ba}$, $^{78}\mathrm{Kr}$, $^{124}\mathrm{Xe}$
  - 2νECβ^{+} and 2ν2β^{+} are not oberved

^{106}Cd is one of the most promising double beta plus decay nuclei

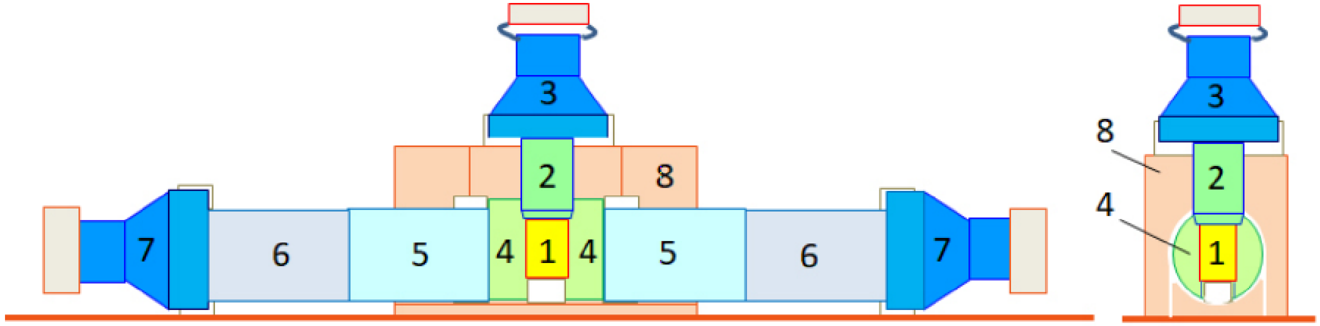


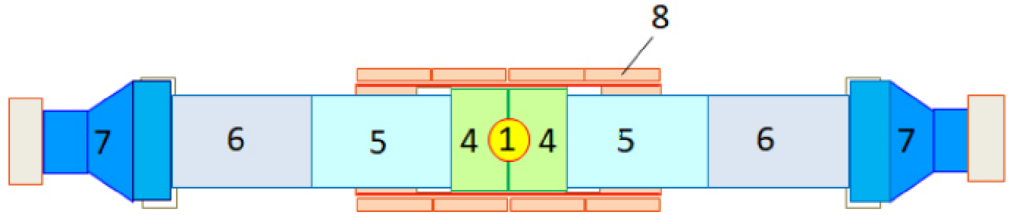
The nuclide ^{106}Cd is one of the most appealing candidates to search for 2EC, Ecβ^{+} and 2β^{+} decays;

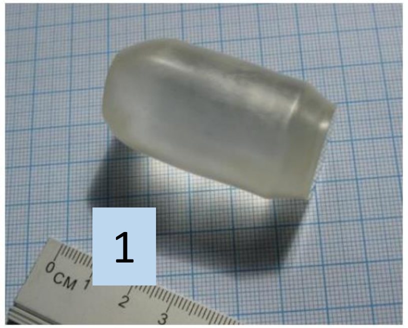
The interest to ^{106}Cd can be explained by

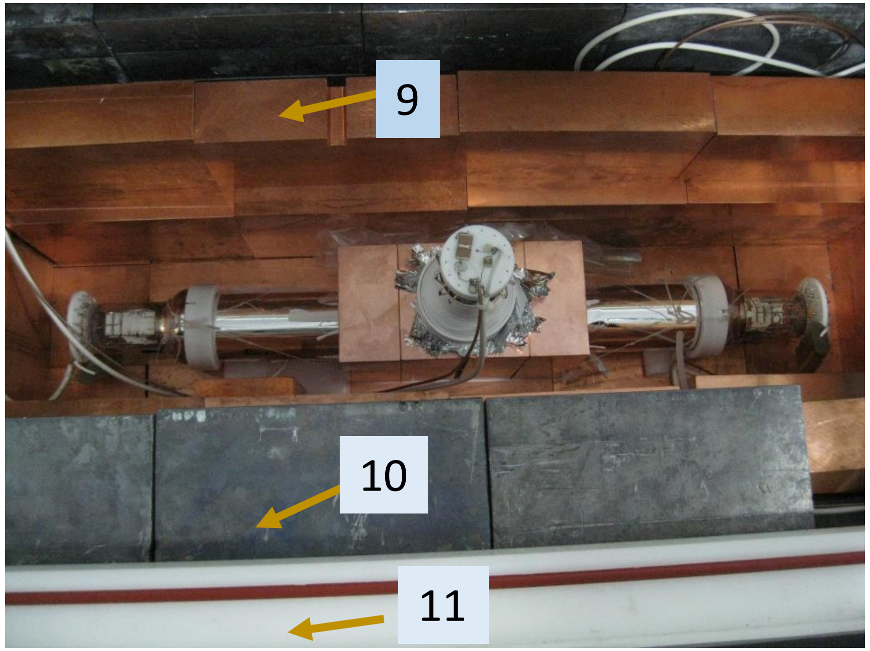
- one of the biggest decay energy $Q_{2\beta} =$ 2775.39(10) keV
- comparatively high isotopic abundance $\delta = 1.245(22)$ %
- possibility of gas centrifugation for enrichment
- existing technologies of deep cadmium purification
- availability of Cd-containing detectors to realize calorimetric experiments with a high detection efficiency

Experiment



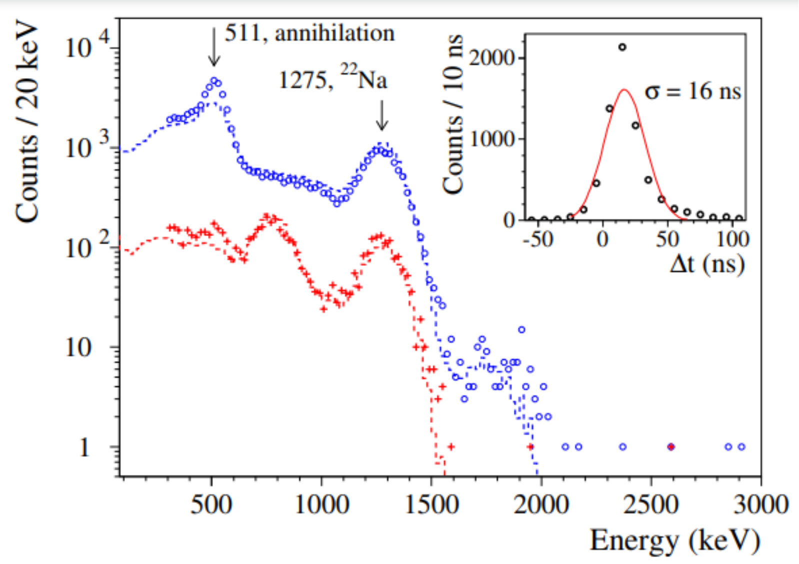






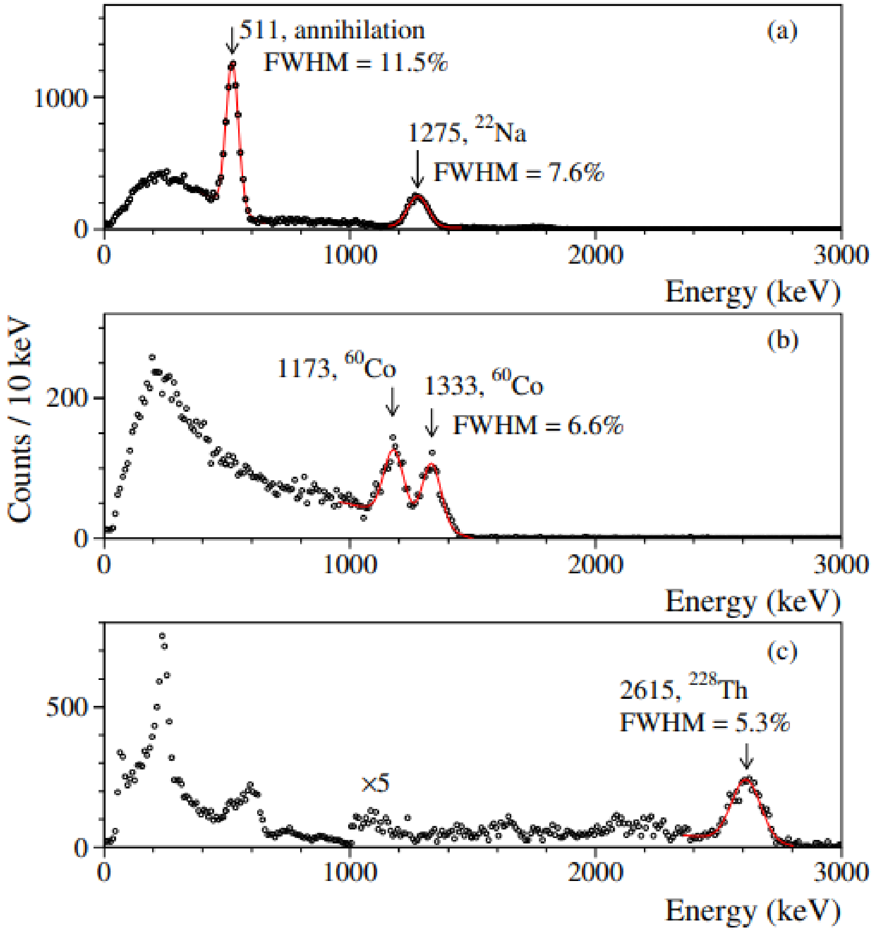
1. Enriched in ^{106}Cd to 66% cadmium tungstate crystal scintillator ($^{106}CdWO_4$) with mass 215 g
2. $PbWO_4$ light-guide from archaeological lead
3. Low radioactive photo-multiplier tube (PMT) Hamamatsu R6233MOD
4. Two $CdWO_4$ crystal scintillators
5. High-purity quartz light guides
6. Polystyrene light guides
7. low radioactive PMTs EMI9265B53/FL
8. Internal copper bricks
9. External copper bricks
10. lead bricks
11. polyethylene shield

Detection efficiency, calibration, energy and time resolution



- ○ Energy spectra of ^{22}Na γ quanta measured by the ^{106}CdWO$_4$ detector with no coincidence
- + Energy spectra of ^{22}Na γ quanta measured by the ^{106}CdWO$_4$ detector in coincidence with energy 511 keV in at least one of the CdWO$_4$ counters

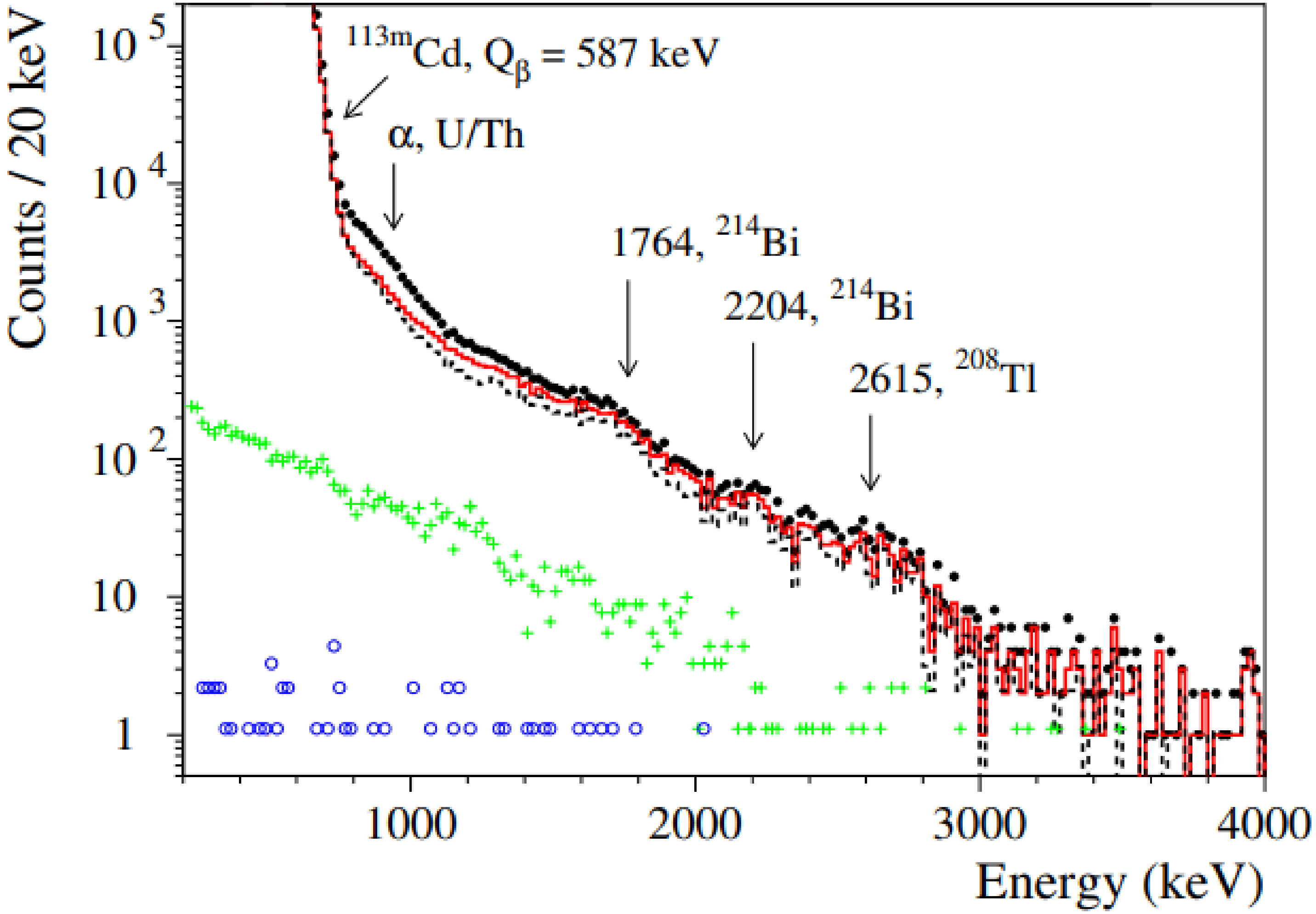
Monte Carlo simulated distributions are shown by dashed lines



Energy spectra of ^{22}Na (a), ^{60}Co (b) and ^{228}Th (c) measured by one of the CdWO$_4$ detectors.

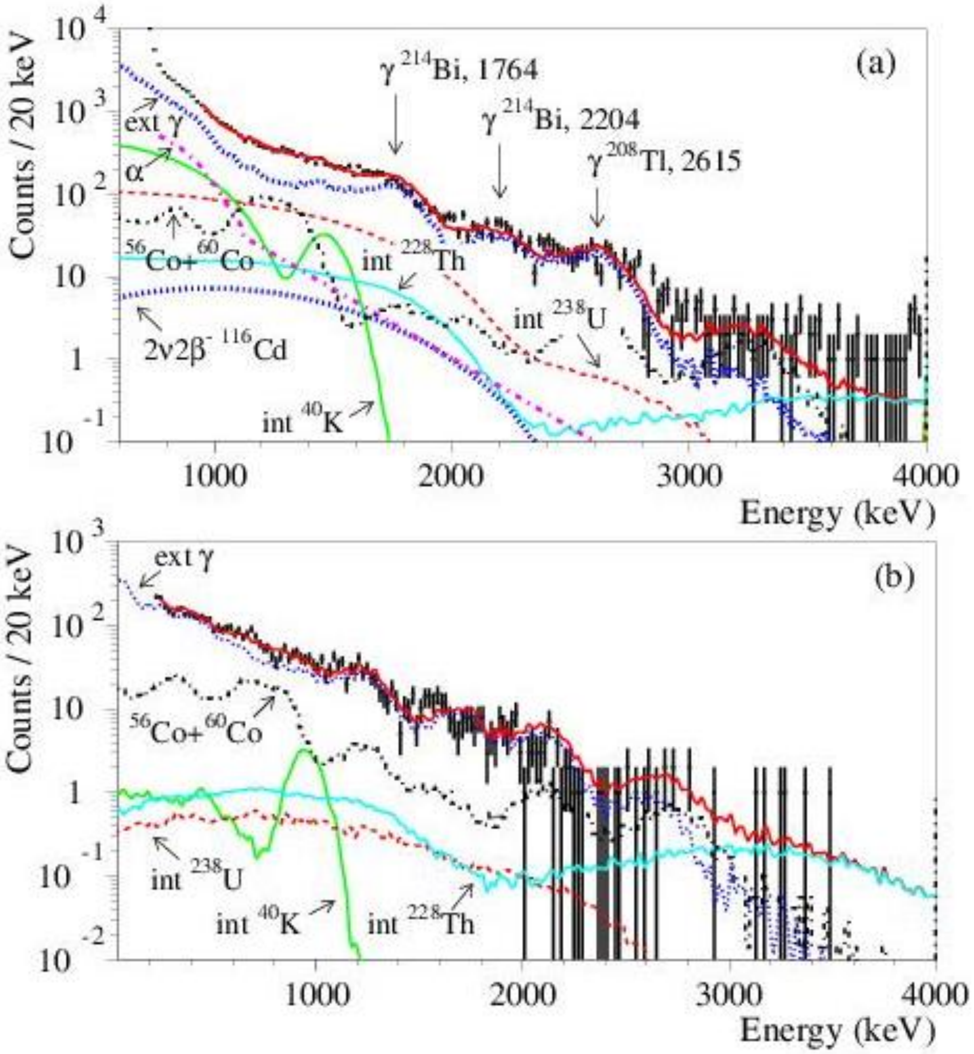
Fits of intensive γ peaks by Gaussian functions are shown by solid lines. Energies of γ quanta are in keV.

Background suppression steps



- • Energy spectra measured by the $^{106}CdWO_4$ detector for 26033 h in the low-background set-up without selection cuts.
- – Energy spectra after selection of γ and β events by pulse-shape discrimination (PSD).
- – Energy spectra of γ and β events in anti-coincidence with the $CdWO_4$ counters.
- + Energy spectra of γ and β events in coincidence with event(s) in at least one of the $CdWO_4$ counters with the energy E = 511 ± 2σ keV. (where σ is energy resolution of the CdWO4 counters at 511 keV)
- ○ Energy spectra of γ and β events in coincidence with events in both the $CdWO_4$ counters with the energy E = 511 ± 2σ keV.

Energy spectra analysis: model of backgrounds



- Energy spectra of γ and β events in anti-coincidence with the $CdWO_4$ counters (a) and in coincidence with 511 ± 2σ keV annihilation γ quanta in at least one of the $CdWO_4$ counters (b).

- Background model

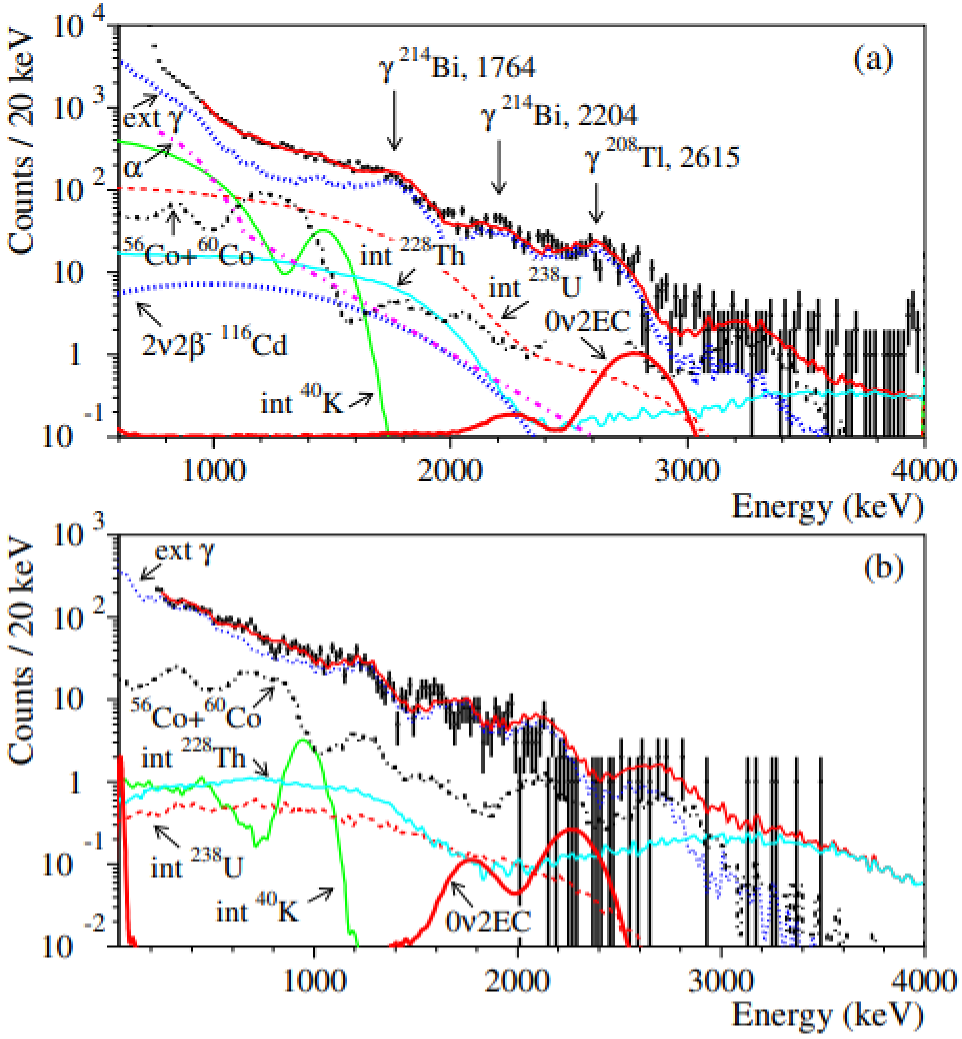
  Internal contaminations of $^{106}CdWO_4$ scintilator:

  - ^{40}K, ^{228}Ra → ^{228}Th, ^{228}Th → ^{208}Pb, ^{226}Ra → ^{210}Pb and ^{210}Pb → ^{206}Pb;
  - 2ν2β decay of ^{116}Cd with the half-life $T_{1/2} = 2.63 \times 10^{19}$ p.

  External contaminations :

  - ^{40}K, ^{228}Ra → ^{228}Th, ^{228}Th → ^{208}Pb and ^{226}Ra → ^{210}Pb in the internal and external copper details, the quartz light guides, the $PbWO_4$ crystal light-guide and PMTs;
  - ^{210}Pb → ^{206}Pb in the $PbWO_4$ crystal light-guide;
  - ^{228}Th → ^{208}Pb and ^{226}Ra → ^{210}Pb in the $CdWO_4$ crystal scintillators;
  - ^{60}Co and ^{56}Co in the internal copper bricks.

Lower limits on the half-life of ^{106}Cd



There are no peculiarities in the experimental data that could be ascribed to 2β processes in ^{106}Cd.

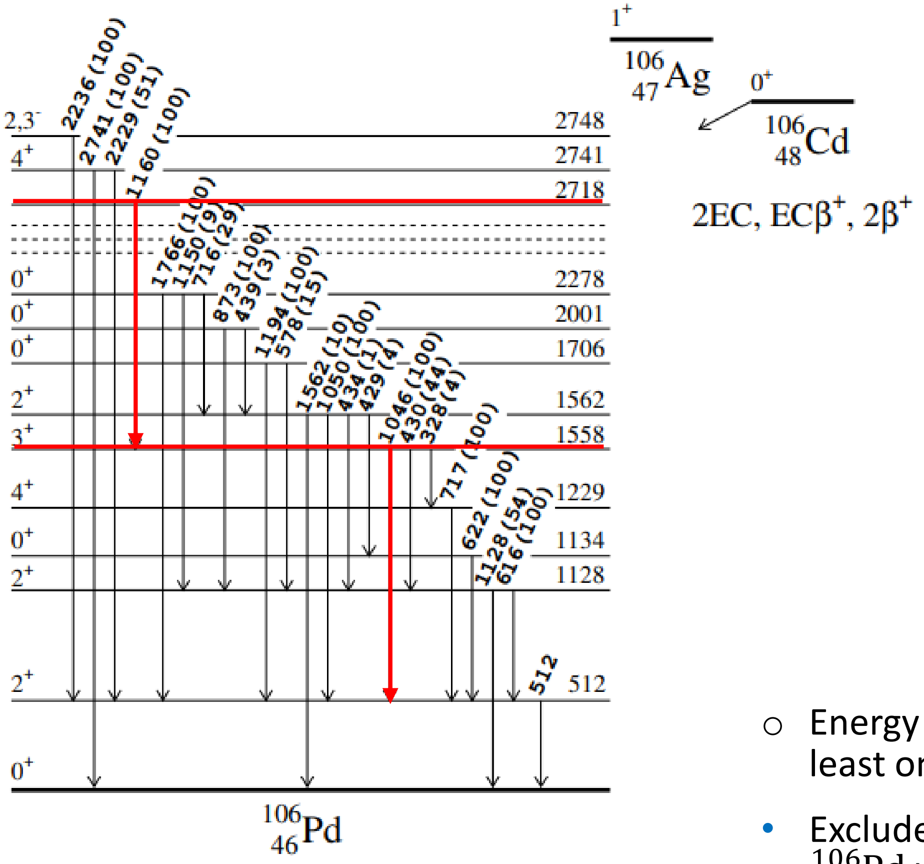
Lower limits on the half-life of ^{106}Cd relatively to different 2β decay channels and modes can be estimated by using the following formula

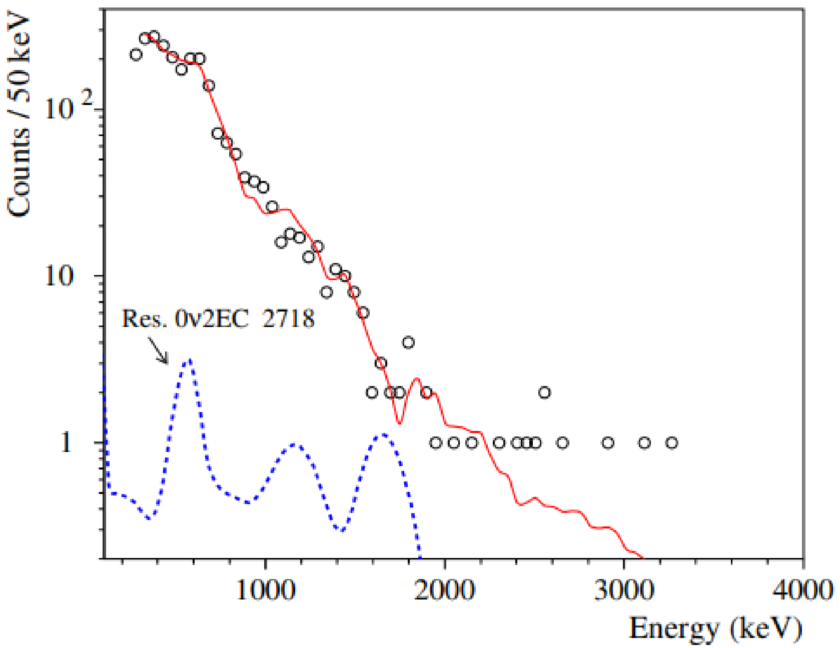
$$\lim T_{1/2} = N \cdot \ln 2 \cdot \eta_{det} \cdot \eta_{sel} \cdot t / \lim S,$$

where N – is the number of ^{106}Cd nuclei in the ^{106}CdWO$_4$ crystal;
η_{det} - the detection efficiency for the process of decay;
η_{sel} - the selection cuts efficiency (selection by PSD, time coincidence, energy interval);
t – the time of measurements;
$\lim S$ – is the number of events of the effect searched for, which can be excluded at a given confidence level (C.L.).

As an example the distributions of 0ν2EC decay of ^{106}Cd to the ground state of ^{106}Pd with the half-life $T_{1/2}$= 6.8 × 10^{20} yr excluded at 90% C.L. are shown by red solid line.

Search for resonant 0ν2EC decay of ^{106}Cd to the 2718 keV excited level of ^{106}Pd



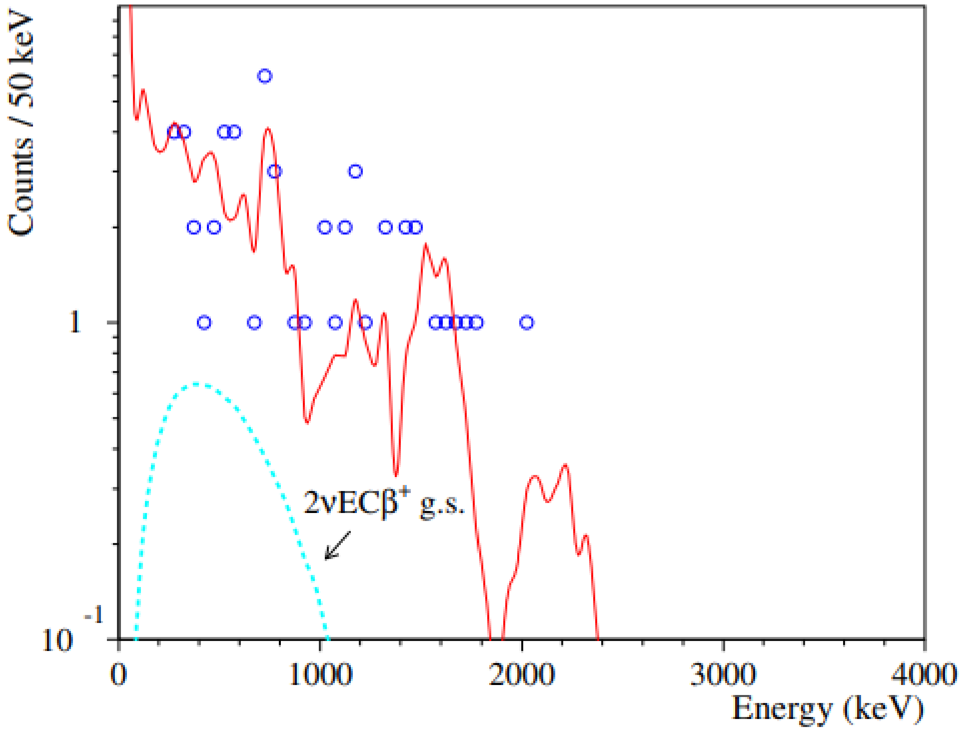


○ Energy spectra measured by the ^{106}CdWO$_4$ detector for 26033 h in coincidence with events in at least one of the CdWO$_4$ counters with energy (1046 − 1.5σ)–(1160 + 1.7σ) keV

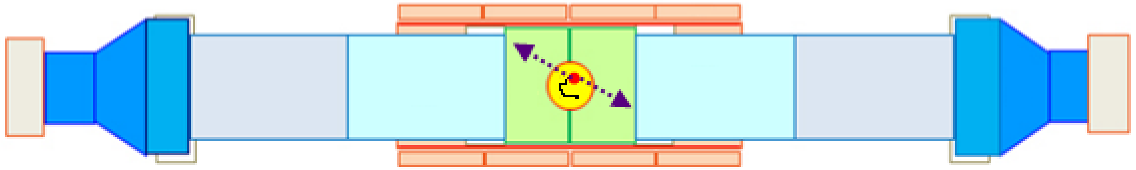
• Excluded distribution of the resonant 0ν2EC decay of ^{106}Cd to the 2718 keV excited level of ^{106}Pd with the half-life $T_{1/2}$= 2.9 × 10^{21} yr

– Background model

Limit on 2νECβ^+ decay of ^{106}Cd to the ground state of ^{106}Pd



- ○ Energy spectra of γ and β events in coincidence with events in both the CdWO$_4$ counters with the energy E = 511 ± 2σ keV.
- ● Excluded distribution of 2νECβ^+ decay of ^{106}Cd to the ground state of ^{106}Pd with the half-life $T_{1/2}$= 2.1 × 10^{21} yr
- – Background model



Half-life limits on2β processes in ^{106}Cd

Decay, level of ^{106}Pd (кеВ)	The experimental selection, coincidence energy (кеВ)	η_{det}	η_{sel}	lim S	lim $T_{1/2}$ (yr) with 90% C.L.	
					Present work	Best previous
2v2EC 2^+ 1128	CC 616	0.13513	0.9087	92	$\geq 6.6 \times 10^{20}$	$\geq 5.5 \times 10^{20}$
2v2EC 0^+ 1134	CC 622	0.18810	0.9087	86	$\geq 9.9 \times 10^{20}$	$\geq 1.0 \times 10^{21}$
2v2EC 2^+ 1562	CC 1050	0.13768	0.9087	80	$\geq 7.8 \times 10^{20}$	$\geq 7.4 \times 10^{20}$
2v2EC 0^+ 1706	CC 1194	0.13446	0.9087	90	$\geq 6.8 \times 10^{20}$	$\geq 7.1 \times 10^{20}$
2v2EC 0^+ 2001	CC 873	0.15329	0.9087	46	$\geq 1.5 \times 10^{21}$	$\geq 9.7 \times 10^{20}$
2v2EC 0^+ 2278	CC 1766	0.09087	0.9087	131	$\geq 3.1 \times 10^{20}$	$\geq 1.0 \times 10^{21}$
0v2EC g.s	AC	0.52243	0.9546	367	$\geq 6.8 \times 10^{20}$	$\geq 1.0 \times 10^{21}$
0v2EC 2^+ 512	AC	0.31930	0.9546	443	$\geq 3.4 \times 10^{20}$	$\geq 5.1 \times 10^{20}$
0v2EC 2^+ 1128	CC 616	0.11830	0.9087	110	$\geq 4.9 \times 10^{20}$	$\geq 5.1 \times 10^{20}$
0v2EC 0^+ 1134	CC 622	0.15539	0.9087	109	$\geq 6.5 \times 10^{20}$	$\geq 1.1 \times 10^{21}$
0v2EC 2^+ 1562	CC 1050	0.13622	0.9087	45	$\geq 1.4 \times 10^{21}$	$\geq 7.3 \times 10^{20}$
0v2EC 0^+ 1706	CC 1194	0.11984	0.9087	27	$\geq 2.0 \times 10^{21}$	$\geq 1.0 \times 10^{21}$
0v2EC 0+ 2001	CC 873	0.13524	0.9087	177	$\geq 3.5 \times 10^{20}$	$\geq 1.2 \times 10^{21}$
0v2EC 0+ 2278	CC 1766	0.07896	0.9087	29	$\geq 1.2 \times 10^{21}$	$\geq 8.6 \times 10^{20}$
Res. 0v2K 2718	CC 1046 + 1160	0.21491	0.9088	33	$\geq 2.9 \times 10^{21}$	$\geq 1.1 \times 10^{21}$
Res. 0vKL_1 4^+ 2741	AC	0.45360	0.9520	663	$\geq 3.2 \times 10^{20}$	$\geq 9.5 \times 10^{20}$
Res. 0vKL_3 $2,3^-$ 2748	AC	0.31767	0.9546	432	$\geq 3.5 \times 10^{20}$	$\geq 1.4 \times 10^{21}$
2vECβ^+ g.s	CC 511&511	0.03962	0.7032	6.7	$\geq 2.1 \times 10^{21}$	$\geq 1.1 \times 10^{21}$
2vECβ^+ 2^+ 512	CC 511&511	0.04733	0.4594	4.0	$\geq 2.7 \times 10^{21}$	$\geq 1.3 \times 10^{21}$
2vECβ^+ 2^+ 1128	CC 511&511	0.02904	0.5090	5.6	$\geq 1.3 \times 10^{21}$	$\geq 1.0 \times 10^{21}$
2vECβ^+ 2^+ 1134	CC 511&511	0.03102	0.6026	11	$\geq 8.5 \times 10^{20}$	$\geq 1.1 \times 10^{21}$
0vECβ^+ g.s.	CC 511	0.37638	0.9087	12	$\geq 1.4 \times 10^{22}$	$\geq 2.2 \times 10^{21}$
0vECβ^+ 2^+ 512	CC 511	0.38421	0.9087	18	$\geq 9.7 \times 10^{21}$	$\geq 1.9 \times 10^{21}$
0vECβ^+ 2^+ 1128	CC 511	0.31419	0.9087	14	$\geq 1.0 \times 10^{22}$	$\geq 1.3 \times 10^{21}$
0vECβ^+ 0^+ 1134	CC 511&511	0.03021	0.3854	5.0	$\geq 1.2 \times 10^{21}$	$\geq 1.9 \times 10^{21}$
2v2β^+ g.s	CC 511&511	0.05229	0.3845	5.8	$\geq 1.7 \times 10^{21}$	$\geq 2.3 \times 10^{21}$
2v2β^+ 2^+ 512	CC 511&511	0.04779	0.3233	3.4	$\geq 2.3 \times 10^{21}$	$\geq 2.5 \times 10^{21}$
0v2β^+ g.s.	CC 511	0.39098	0.9087	30	$\geq 5.9 \times 10^{21}$	$\geq 3.0 \times 10^{21}$
0v2β^+ 2^+ 512	CC 511	0.36954	0.9087	39	$\geq 4.3 \times 10^{21}$	$\geq 2.5 \times 10^{21}$

The experimental selection:
- ○ AC – anti-coincidence
- ○ CC – in coincidence,
- ○ η_{det} – detection efficiency
- ○ η_{sel} – selection cuts efficiency
- ○ lim$T_{1/2}$ – half-life limit

In the present work all the limits are given with 90% C.L.

Conclusions

- The experiment to search for double beta decay of ^{106}Cd with enriched $^{106}\mathrm{CdWO}_4$ scintillator in coincidence with two large volume CdWO_4 scintillation counters was performed at the Gran Sasso underground laboratory of INFN (Italy).
- New improved limits are set at level of $10^{20} - 10^{22}$ yr on the different channels of ^{106}Cd double beta decay (90% C.L.).
- The new improved limit on half-life of ^{106}Cd relative to the 2νECβ$^+$ decay was estimated as $T_{1/2} \geq 2.1 \times 10^{21}$ yr (90% C.L.). The sensitivity is within the region of the theoretical predictions for the decay probability that are in the range $T_{1/2} \sim 10^{21} - 10^{22}$ yr .
- A new improved limit was set for the resonant neutrinoless double-electron capture to the 2718 keV excited level of $^{106}\mathrm{Pd}$ as $T_{1/2} \geq 2.9 \times 10^{21}$ yr (90% C.L.)
- The next stage of experiment is running in the DAMA/R&D set-up with an improved sensitivity to all the decay channels thanks to reduction of the background approximately by a factor 3–5. In particular the sensitivity to the 2νECβ$^+$ decay of ^{106}Cd is expected to be high enough to detect the process with the half-life at level of $\sim (0.5 - 1) \times 10^{22}$ yr over 5 yr of measurements.