Low background experiment to find the double beta decay of the ^{106}Cd nuclide with a ^{106}CdWO$_4$ scintillator

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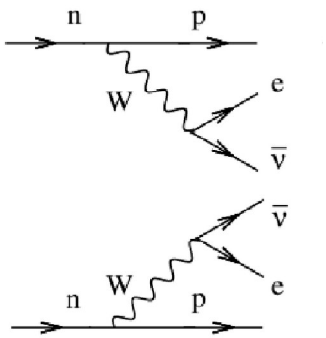
Double beta decay

Observations of the neutrino oscillations suggest the neutrinos are **massive**, which calls for an extension of the Standard Model of particles and fields (SM). However, oscillation experiments cannot determine the neutrino mass and the neutrino mass hierarchy.

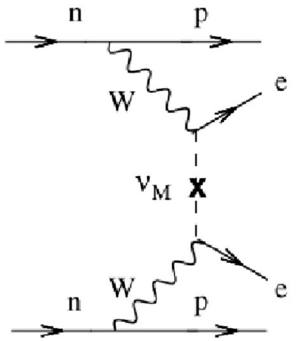
Double beta decay is one of the most promising tools to determine the absolute neutrino mass scale and the neutrino mass hierarchy.

Two neutrino double beta decay



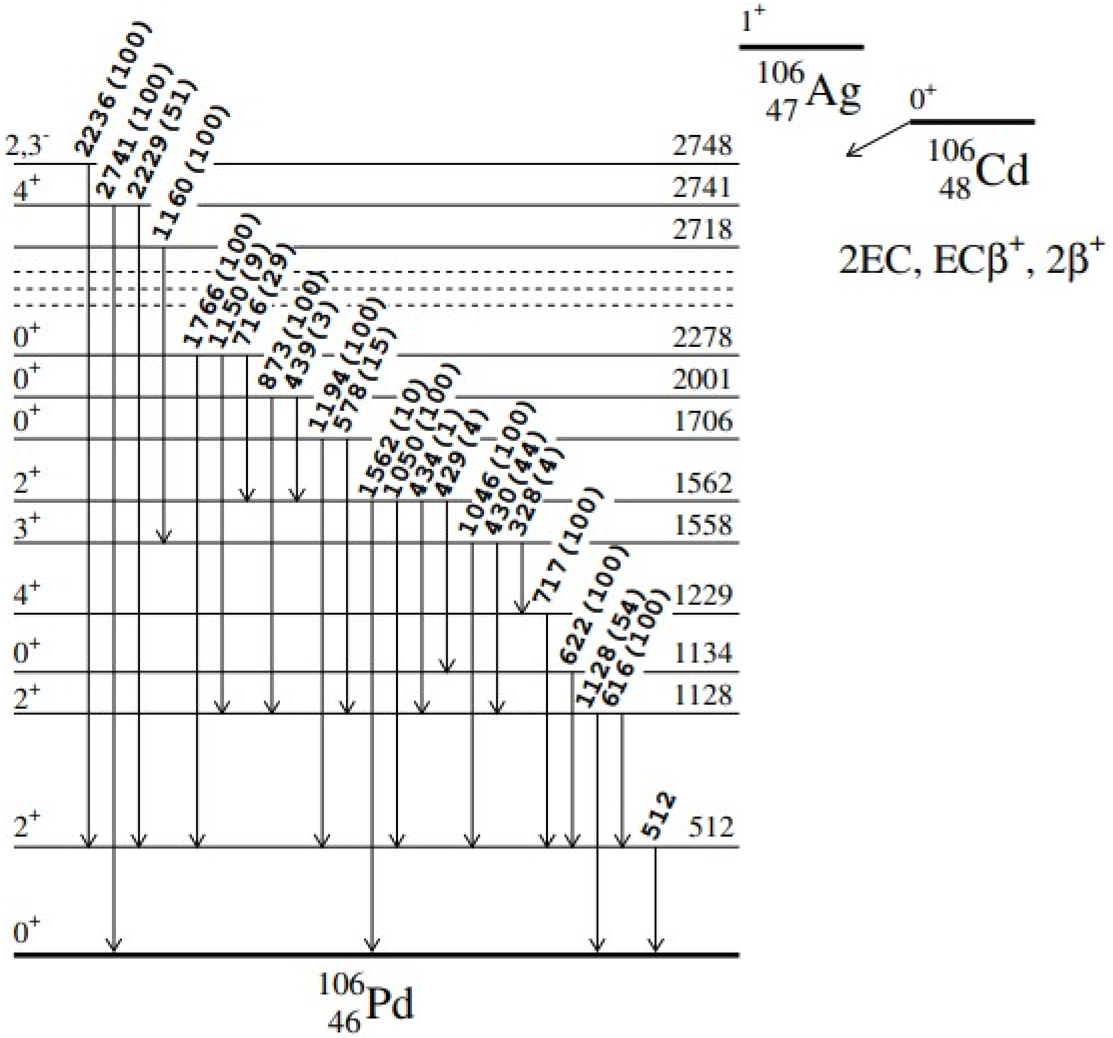
- Radioactive process allowed in the SM.
- Neutrino is Dirac or Majorana particle.
- Has been observed in several nuclides with the half-lives $10^{18} - 10^{24}$ yr.
  - $2\nu2\beta^-$: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U$^{(?)}$
  - 2ν2EC: ^{130}Ba$^{(?)}$, ^{78}Kr$^{(?)}$, ^{124}Xe$^{(?)}$
  - 2νECβ^+ and $2\nu2\beta^+$ are not observed

Neutrinoless double beta decay



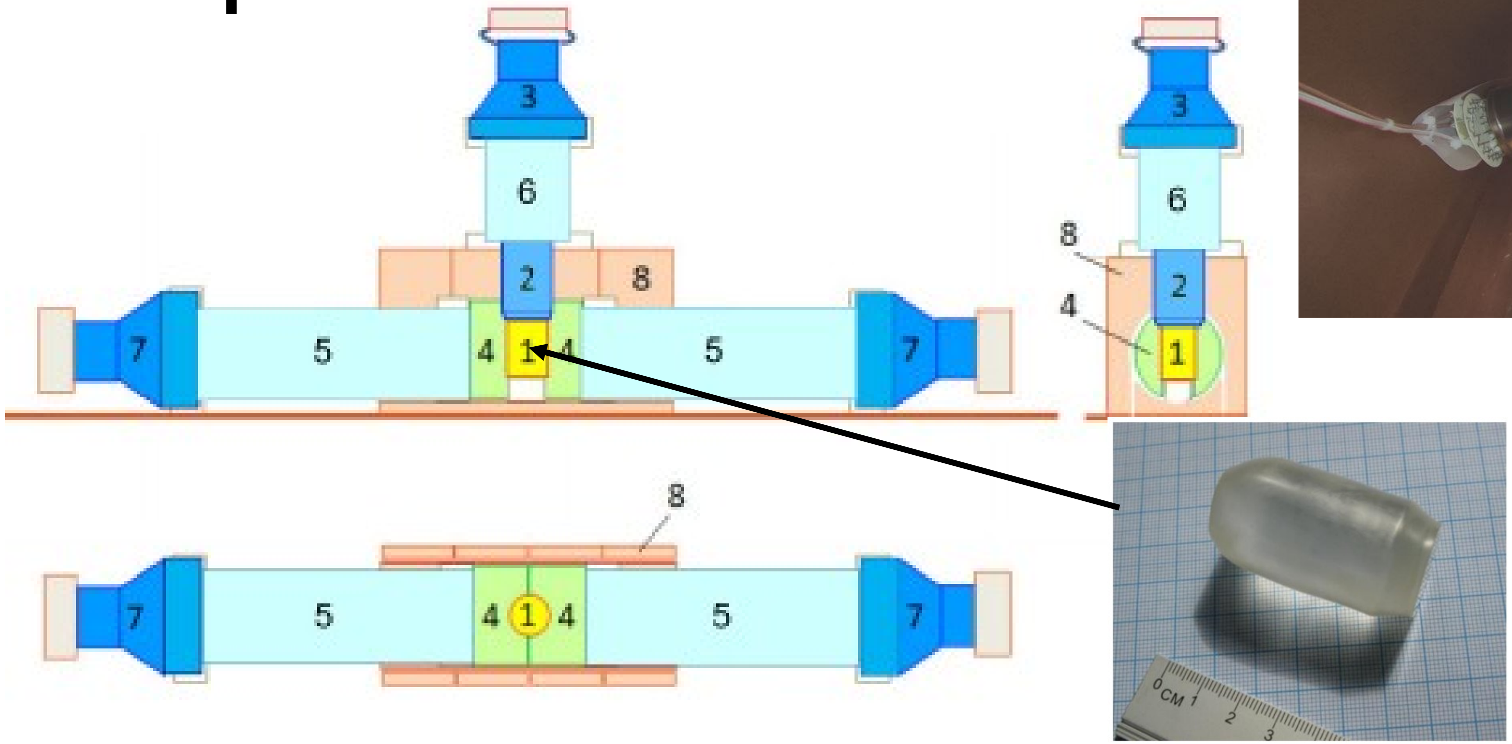
- Process beyond SM.
- Process hasn’t been observed.
- Neutrino is Majorana particle.
- Violates the lepton number conservation law.
- Might shed light on the Universe baryon asymmetry problem.
- $T_{1/2} > 10^{24} - 10^{26}$ y → $m_\nu < 0.06 - 0.6$ eV

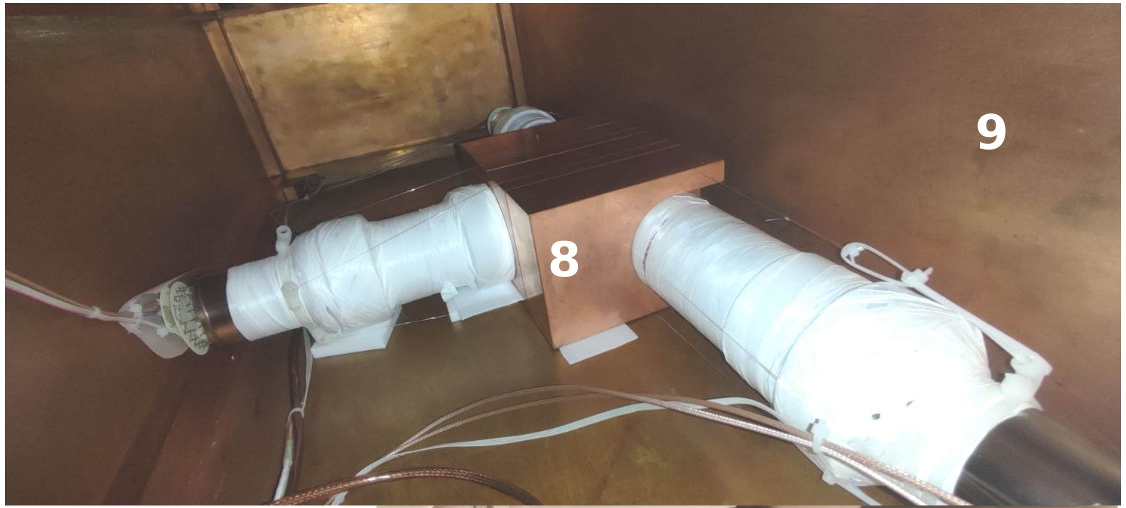
^{106}Cd is one of the most promising double beta plus decay nuclei

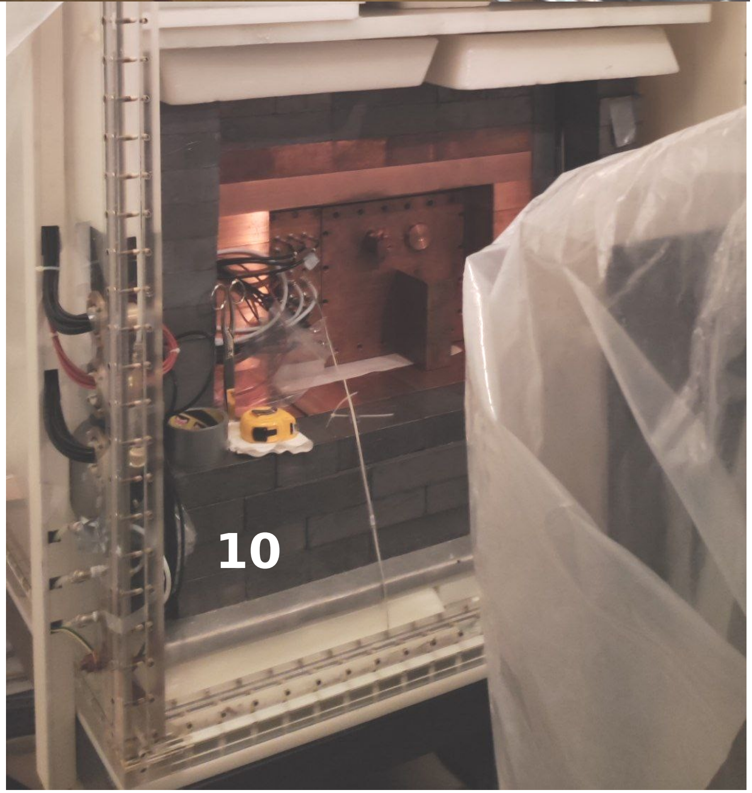


- The nuclide is one of the most appealing candidates to search for 2EC, ECβ^+ and $2\beta^+$ decays;
- One of the biggest decay energy $Q_{2\beta}$ = 2775 keV
- Comparatively high isotopic abundance δ = 1.25 %.
- Possibility of gas centrifugation for enrichment
- Existing technologies of deep cadmium purification
- Availability of Cd-containing detectors to realize calorimetric experiments with a high detection efficiency

Experiment

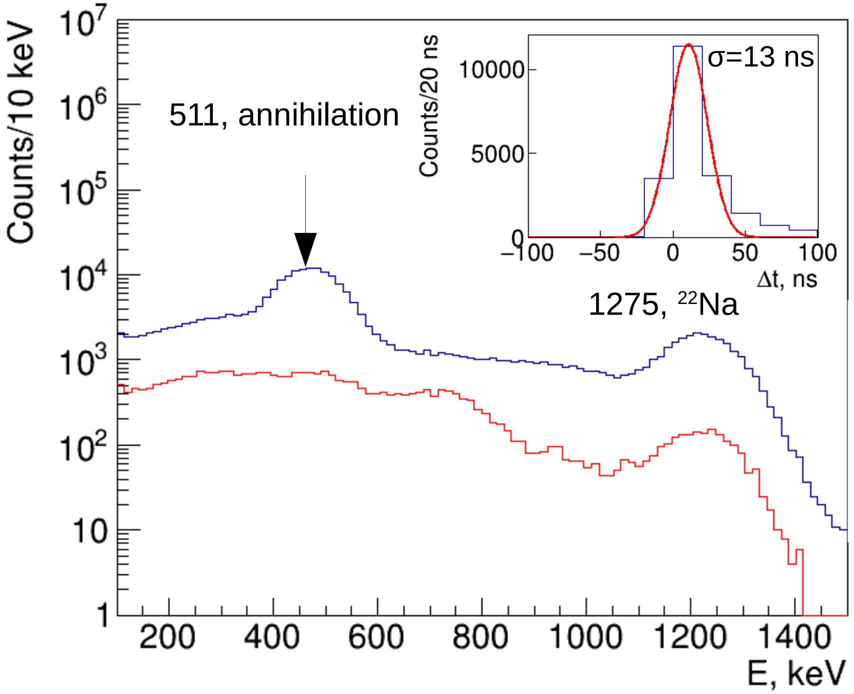




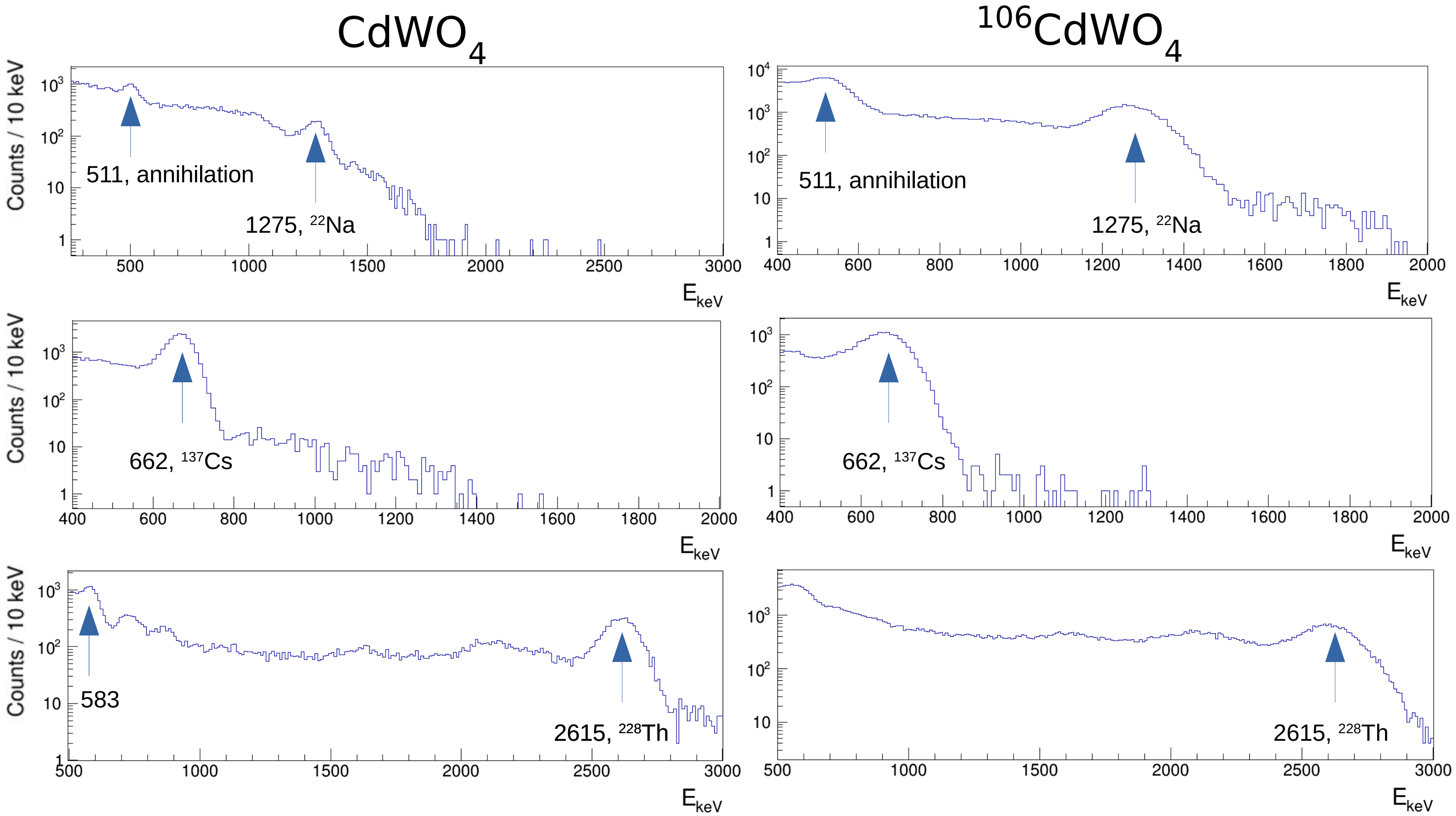


1. ^{106}CdWO$_4$ scintillation detector (m=215.4 g, δ(^{106}Cd)= 66%);
2. Plastic scintillator
3. PMT R11065-20 MOD Hamamatsu
4. Two CdWO4 crystal scintillators;
5. Long quartz light-guides;
6. Quartz light-guides;
7. PMTs R6233MOD Hamamatsu
8. “Internal copper” passive shield.
9. “External copper” passive shield.
10. Low radioactive lead passive shield.

Characteristics of the detector system

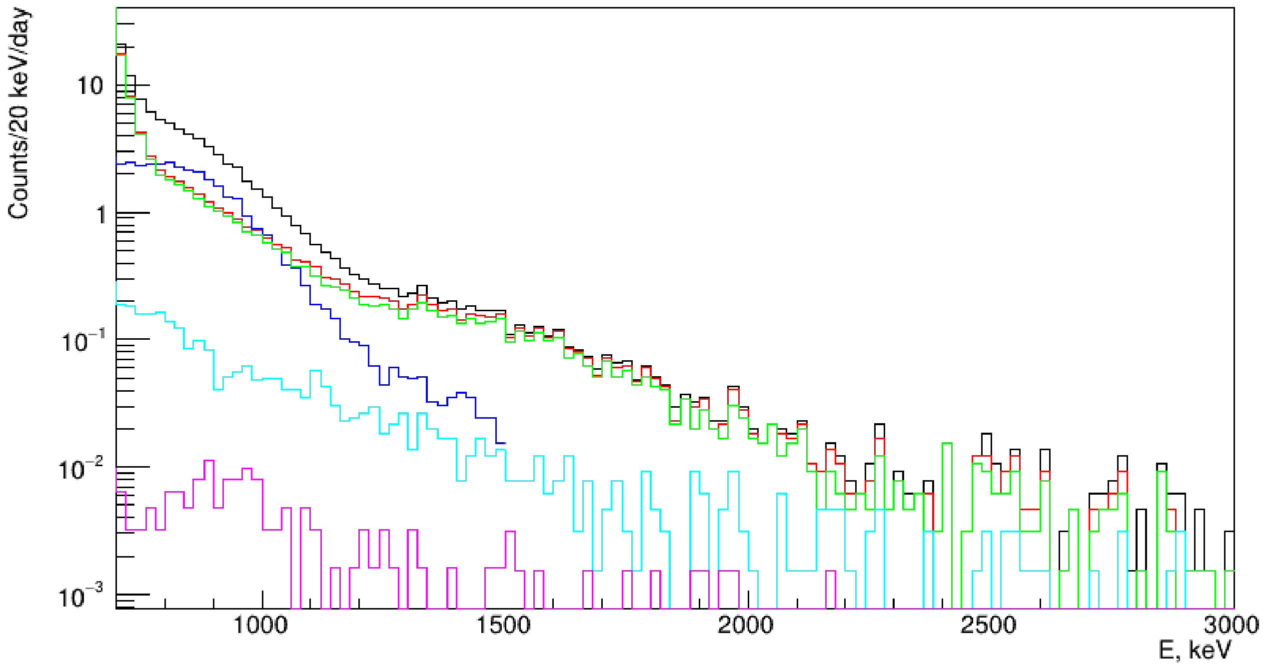


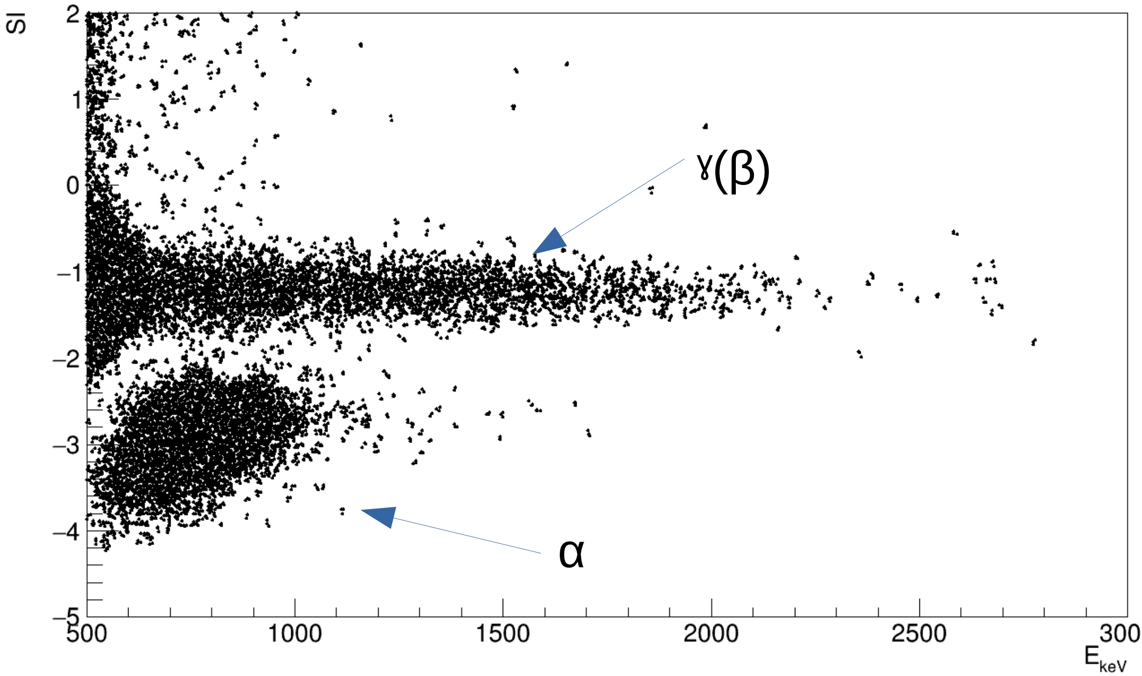
- The spectrum of ^{22}Na gamma-quanta measured by $^{106}CWO_4$ detector without coincidences.
- The spectrum measured by $^{106}CWO_4$ detector in coincidences with 511keV gamma quanta in at least one of the $CdWO_4$ counters.



Energy spectra of calibration gamma sources measured by one of the $CdWO_4$ detectors and $^{106}CdWO_4$.

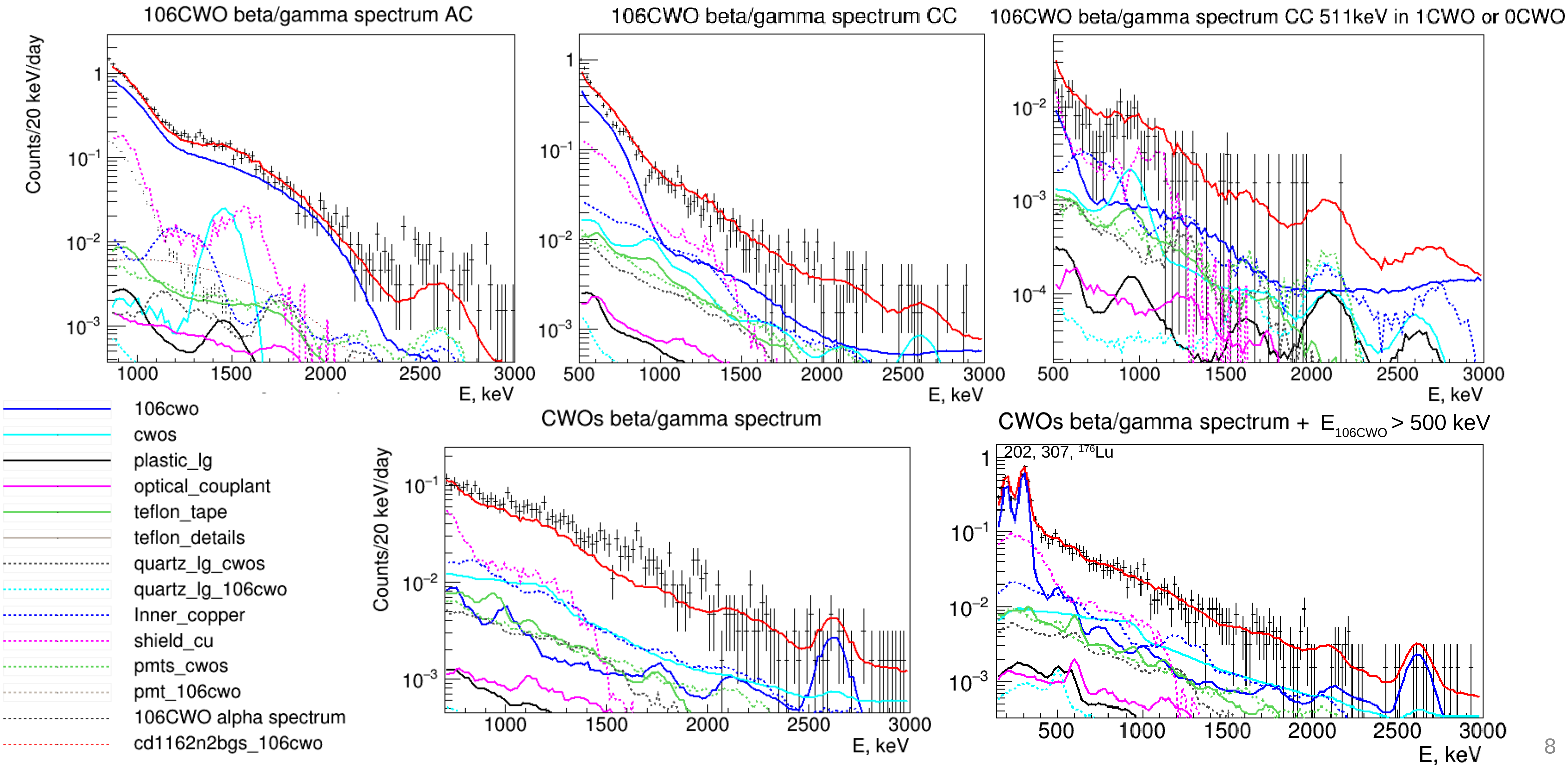
Data selection





- ● Energy spectra measured by the $^{106}CdWO_4$ detector for 15573 h without selection cuts
- ● Energy spectra after selection of γ and β events by optimal filter method (SI = $\Sigma f(t_k) \times P(t_k) / \Sigma f(t_k)$, f(t)-signal, P(t)-weight function).
- ● The γ and β events in anti-coincidence with the $CdWO_4$ counters
- ● The γ and β events in coincidence with the $CdWO_4$ counters
- ● the γ and β events in coincidence with energy 511 keV in at least one of the $CdWO_4$ counters
- ● the α events measured by the $^{106}CdWO_4$ detector

Background model

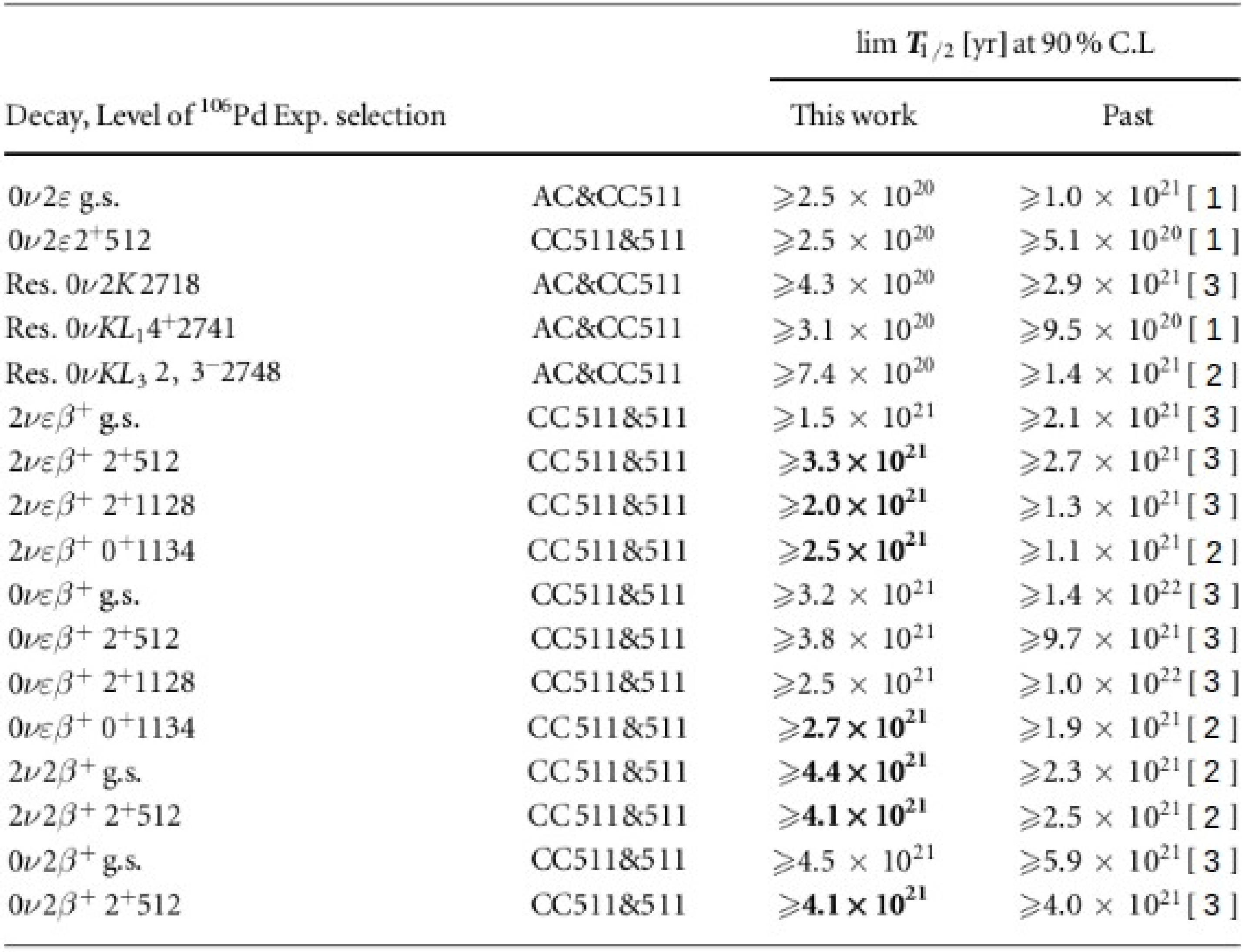


Radioactive contamination

Radioactive contamination (mBq/kg) of the materials of the low-background set-up estimated by using the fit of the energy spectra. All limits are given with 90% CL, the values are given with standard uncertinties.

	^{106}CWO	CWOs	Plastic light guide	optical couplant	Teflon tape	Teflon details	quartz light guide CWOs	quartz light guide ^{106}CWO	Internal Cu	External Cu	PMTs CWOs	PMT ^{106}CWO
^{238}U	0.59(2)	<0.36	<3.8	<33	<2.3	<0.9	<0.5	<3.3	<0.84	<9.6	<1217	<15
^{226}Ra	0.009(4)	0.010(1)	<0.3	<29	<2.0	<0.9	0.60(5)	<0.3	<0.12	<0.07	<563	<6.3
^{210}Pb	<0.13	0.9(1)	<5.0	12.3(6.6)	<12.5	5.0(2.5)	<1.1	<12.4	<24.8			
^{228}Ra	<0.002	<0.054	<0.8	<4.9	<5.24	<3.2	<0.17	<3.4	<0.03	3.1(2)	<273	<27
^{228}Th	0.038(1)	0.022(2)	0.40(8)	<0.4	<0.06	<0.06	<0.01	<4.0	<0.0007	<0.0012	<204	<2.1
^{40}K	<0.02	<1.13	<4.3	<44	<5	<4.6	<0.63	<7.3	<0.06	<0.23	<1081	<28
^{176}Lu	1.50(3)											
^{56}Co									<0.06			
^{60}Co									<0.1			

Limits on half-life on 2β processes in ^{106}Cd



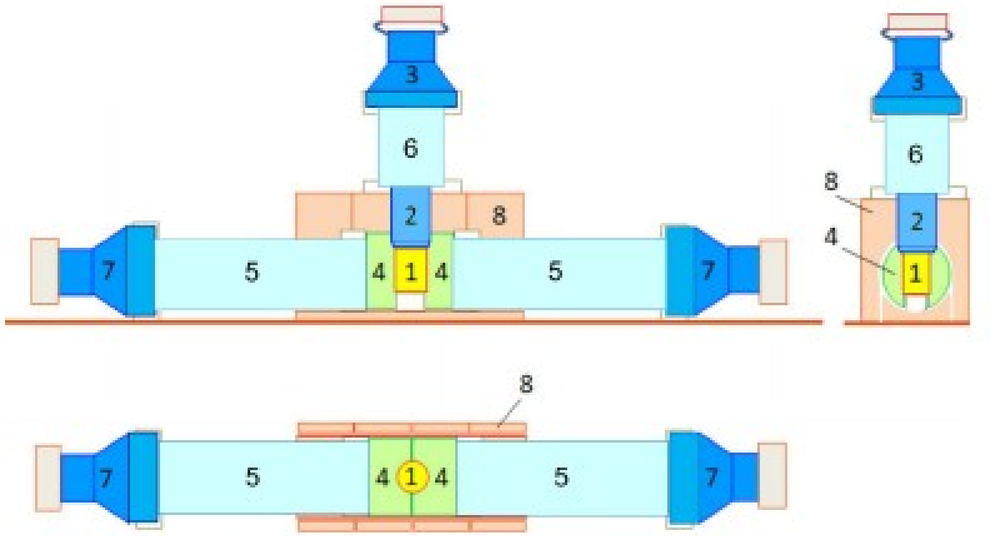
		lim $T_{1/2}$ [yr] at 90 % C.L	
Decay, Level of ^{106}Pd	Exp. selection	This work	Past
$0\nu 2\varepsilon$ g.s.	AC&CC511	$\geqslant 2.5\times 10^{20}$	$\geqslant 1.0\times 10^{21}$ [1]
$0\nu 2\varepsilon\, 2^+ 512$	CC511&511	$\geqslant 2.5\times 10^{20}$	$\geqslant 5.1\times 10^{20}$ [1]
Res. $0\nu 2K\, 2718$	AC&CC511	$\geqslant 4.3\times 10^{20}$	$\geqslant 2.9\times 10^{21}$ [3]
Res. $0\nu KL_1 4^+ 2741$	AC&CC511	$\geqslant 3.1\times 10^{20}$	$\geqslant 9.5\times 10^{20}$ [1]
Res. $0\nu KL_3\, 2,\, 3^- 2748$	AC&CC511	$\geqslant 7.4\times 10^{20}$	$\geqslant 1.4\times 10^{21}$ [2]
$2\nu\varepsilon\beta^+$ g.s.	CC511&511	$\geqslant 1.5\times 10^{21}$	$\geqslant 2.1\times 10^{21}$ [3]
$2\nu\varepsilon\beta^+\ 2^+ 512$	CC511&511	**$\geqslant 3.3\times 10^{21}$**	$\geqslant 2.7\times 10^{21}$ [3]
$2\nu\varepsilon\beta^+\ 2^+ 1128$	CC511&511	**$\geqslant 2.0\times 10^{21}$**	$\geqslant 1.3\times 10^{21}$ [3]
$2\nu\varepsilon\beta^+\ 0^+ 1134$	CC511&511	**$\geqslant 2.5\times 10^{21}$**	$\geqslant 1.1\times 10^{21}$ [2]
$0\nu\varepsilon\beta^+$ g.s.	CC511&511	$\geqslant 3.2\times 10^{21}$	$\geqslant 1.4\times 10^{22}$ [3]
$0\nu\varepsilon\beta^+\ 2^+ 512$	CC511&511	$\geqslant 3.8\times 10^{21}$	$\geqslant 9.7\times 10^{21}$ [3]
$0\nu\varepsilon\beta^+\ 2^+ 1128$	CC511&511	$\geqslant 2.5\times 10^{21}$	$\geqslant 1.0\times 10^{22}$ [3]
$0\nu\varepsilon\beta^+\ 0^+ 1134$	CC511&511	**$\geqslant 2.7\times 10^{21}$**	$\geqslant 1.9\times 10^{21}$ [2]
$2\nu 2\beta^+$ g.s.	CC511&511	**$\geqslant 4.4\times 10^{21}$**	$\geqslant 2.3\times 10^{21}$ [2]
$2\nu 2\beta^+\ 2^+ 512$	CC511&511	**$\geqslant 4.1\times 10^{21}$**	$\geqslant 2.5\times 10^{21}$ [2]
$0\nu 2\beta^+$ g.s.	CC511&511	$\geqslant 4.5\times 10^{21}$	$\geqslant 5.9\times 10^{21}$ [3]
$0\nu 2\beta^+\ 2^+ 512$	CC511&511	**$\geqslant 4.1\times 10^{21}$**	$\geqslant 4.0\times 10^{21}$ [3]

The results of the most sensitive previous experiments are reported to be compared with the best results obtained in this work (bold).

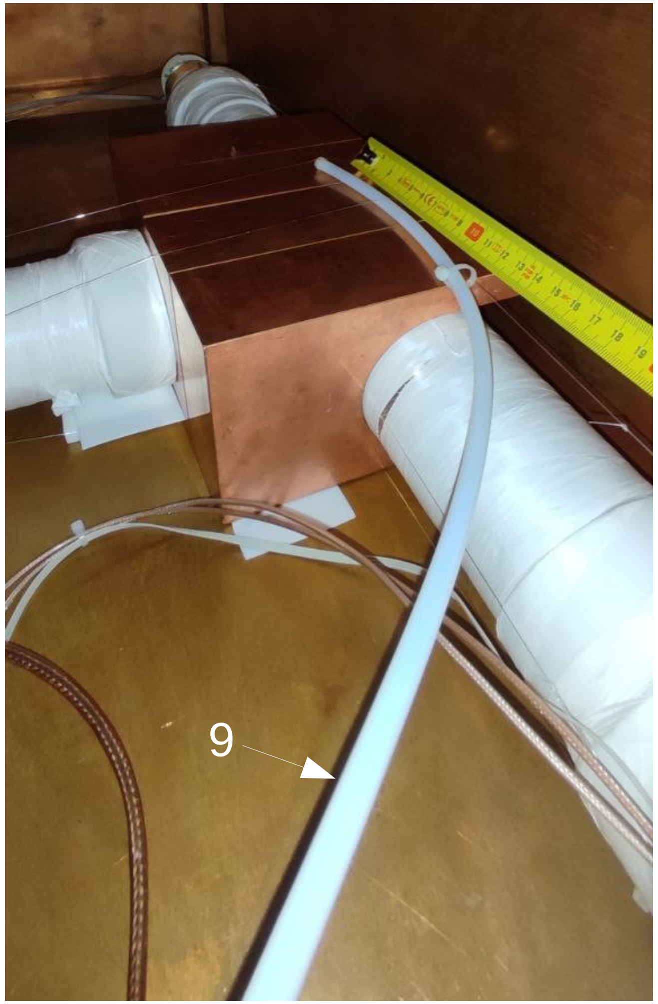
Table from A Leoncini et al., Phys. Scr. 97 (2022) 064006

[1] - P. Belli et al., Phys. Rev. C 85 (2012) 044610
[2] - P. Belli et al., Phys. Rev. C 93 (2016) 045502
[3] - P. Belli et al., Universe 6 (2020) 182

Advanced experimental setup



1. ^{106}CdWO$_4$ scintillation detector;
2. Plastic scintillator
3. PMT R11065-20 MOD Hamamatsu
4. CdWO4 scintillation detectors
5. Long quartz light-guides;
6. Quartz light-guides;
7. PMTs R6233MOD Hamamatsu
8. Internal copper passive shield
9. Tube for monitoring detectors system stability



Conclusions

- The experiment to search for double-beta decay of ^{106}Cd with the enriched ^{106}CdWO$_4$ scintillator in coincidence with two large volume CdWO$_4$ scintillation counters is in progress at the Gran Sasso underground laboratory of INFN (Italy).
- Limits on the different double-beta decay modes and channels of ^{106}Cd are set at the level of 10^{20} -10^{22} yr (one of the most sensitive "double-beta plus" experiments).
- The next stage of the experiment is running at the Gran Sasso National Laboratory in the DAMA/R&D set-up with more stable PMTs and monitoring detectors stability system by ^{228}Th periodic calibrations.
- The limit on the $2\nu EC\beta^+$ decay of ^{106}Cd to the ground state of ^{106}Pd was estimated as $\lim T_{1/2} \geq 1.5 \times 10^{21}$ yr, that approaches the region of the theoretical predictions. In particular the sensitivity to the $2\nu EC\beta^+$ decay of ^{106}Cd is expected to be high enough to detect the process with the half-life at the level of $\sim (0.5 - 1) \times 10^{22}$ yr over 5-7 yr of measurements