PRELIMINARY SEARCH FOR $\beta\beta$ DECAY PROCESSES IN ^{106}Cd USING $^{106}CdWO_4$ SCINTILLATOR

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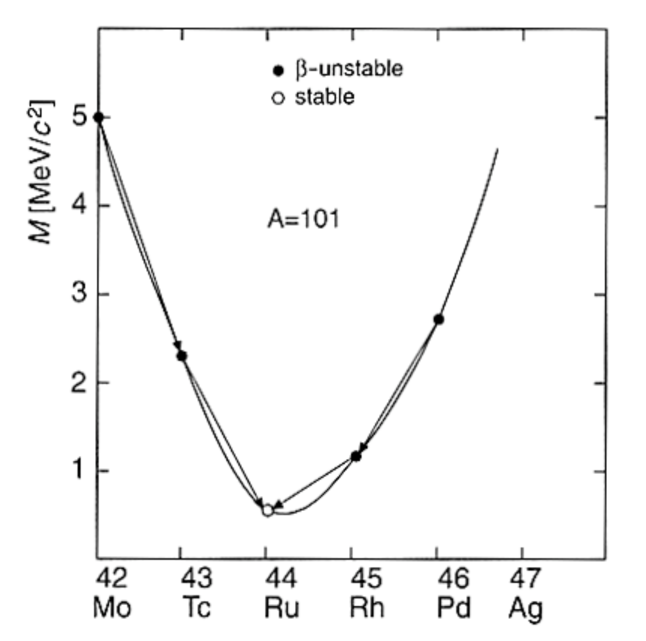
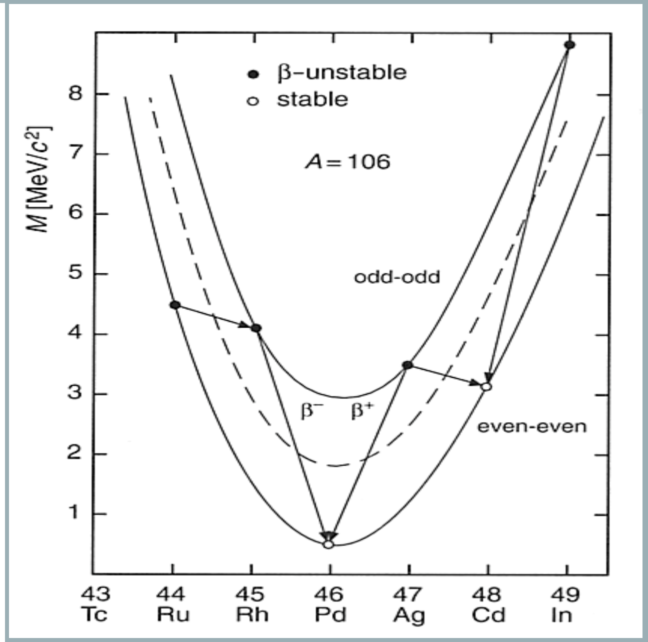
Introduction to Double beta decay

- It can be studied in even-even nuclei when the single β decay is energetically forbidden due to the pairing interaction.

- For example, the decay of ^{106}Cd to ^{106}Ag is energetically forbidden.

$$^{106}_{48}\mathrm{Cd} \rightarrow ^{106}_{46}\mathrm{Pd} + 2e^{+} + 2\nu_e$$



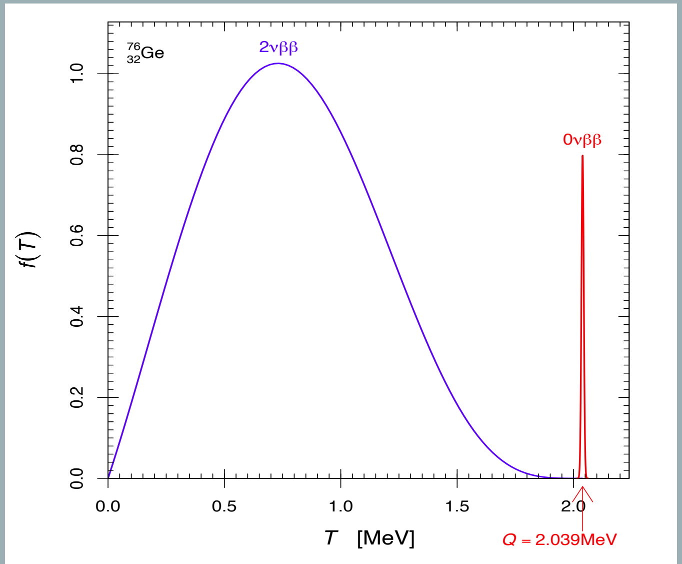


$$2\nu 2\beta^{+}:\ ^{A}_{Z}X \rightarrow ^{A}_{Z-2}X + 2e^{+} + 2\nu_e$$

L conserved

$$0\nu 2\beta^{+}:\ ^{A}_{Z}X \rightarrow ^{A}_{Z-2}X + 2e^{+}$$

L violated ($\Delta L = 2$) → massive Majorana neutrino



Preliminary search for $\beta\beta$ decay processes in ^{106}Cd using $^{106}CdWO_4$ scintillator

WHY STUDYING $\beta^+\beta^+$ DECAY PROCESSES?

- If the total lepton number L is violated, also the following $\beta^+\beta^+$ processes are possible:

$$0\nu2\beta^+ : \; {}^A_Z X \rightarrow {}^A_{Z-2} X + 2e^+$$

$$0\nu\epsilon\beta^+ : \; e^- + {}^A_Z X \rightarrow {}^A_{Z-2} X + e^+ + \text{X-rays}$$

$$0\nu2\epsilon : \; e^- + e^- + {}^A_Z X \rightarrow {}^A_{Z-2} X^* \rightarrow {}^A_{Z-2} X + \gamma + \text{X-rays}$$

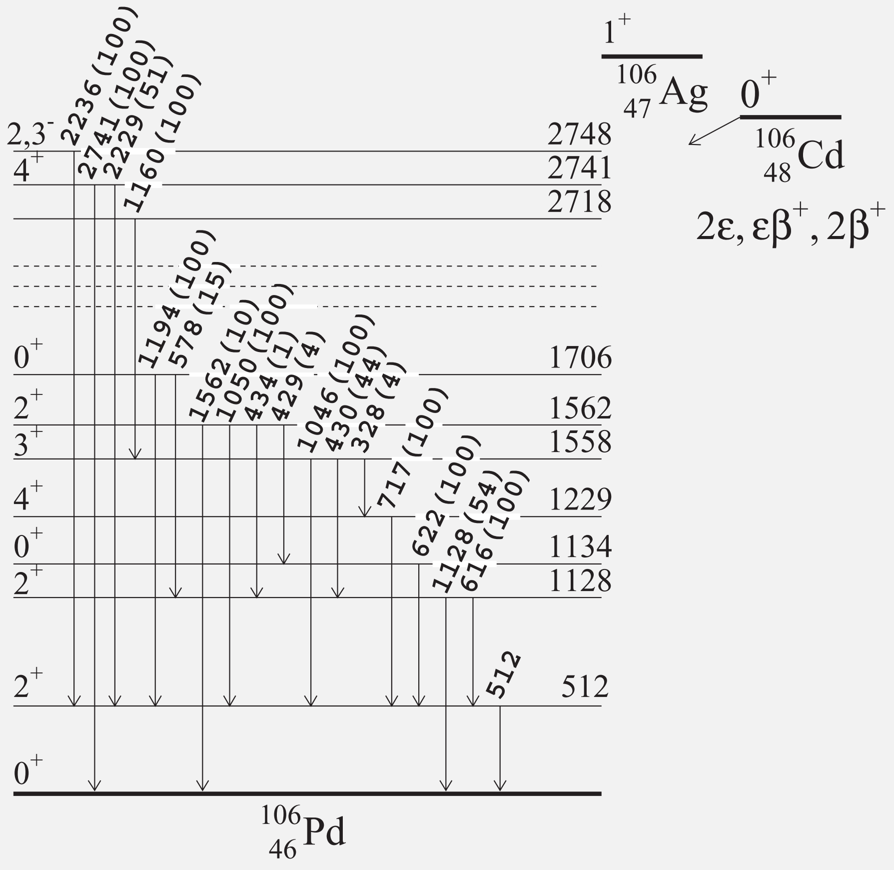
- Positron(s) annihilation gives rise to 511 keV γ rays.
- The coincident detection of positron(s) and 511 keV γ rays would be used as highly reliable condition for selecting such events.

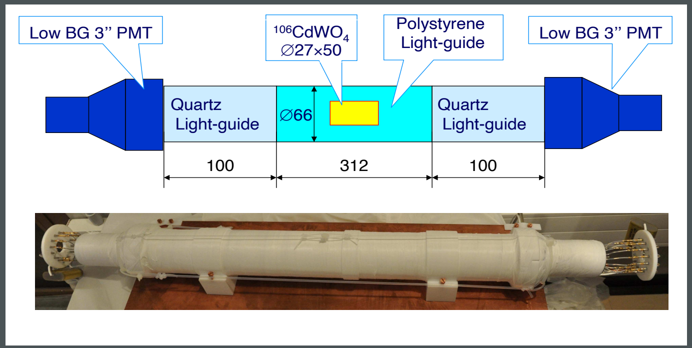
- $0\nu\epsilon\beta^+$ and $0\nu2\beta^+$ can clarify the possible contribution of the right-handed currents to the $0\nu\beta^-\beta^-$ decay rate;
- Possibility of a resonant $0\nu2\epsilon$ process $\rightarrow$ in case of close degeneracy of the initial and final (excited) nuclear states $\rightarrow \frac{1}{T_{1/2}} \propto \frac{\Gamma}{(Q-E)^2+\Gamma^2/4}$

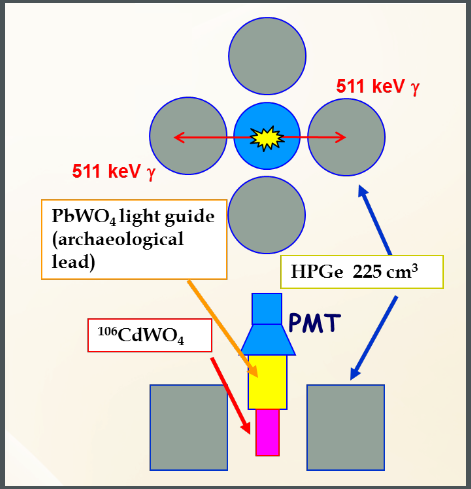
DOUBLE BETA DECAY IN ^{106}Cd

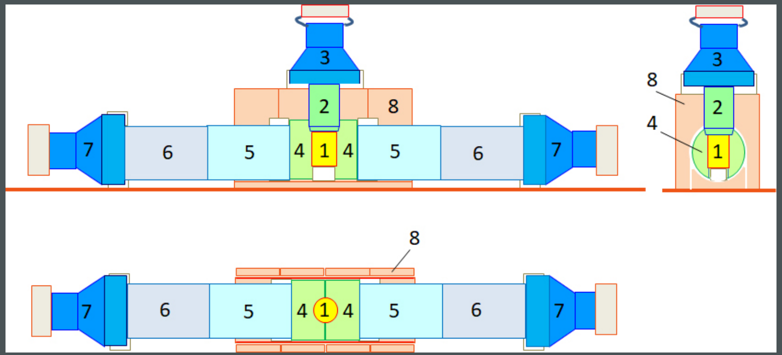
Advantages in the use of ^{106}Cd:

- One of the biggest decay energy: $Q_{\beta\beta} = (2775.39 \pm 0.10)$ keV;
- High isotopic abundance: $\delta = (1.245 \pm 0.022)$ %;
- Favorable theoretical predictions for half-lives for some 2ν modes ($T_{1/2} \sim 10^{21} - 10^{22}$ yr) that could be reached by modern low-counting techniques;
- Possibility of resonant 2ϵ to excited levels of ^{106}Pd;
- Possibility of enrichment by gas centrifugation, existing technologies of cadmium purification and availability of Cd-containing detectors to realize calorimetric experiments with a high detection efficiency.









Preliminary search for
$\beta\beta$ decay processes in ^{106}Cd using $^{106}CdWO_4$ scintillator

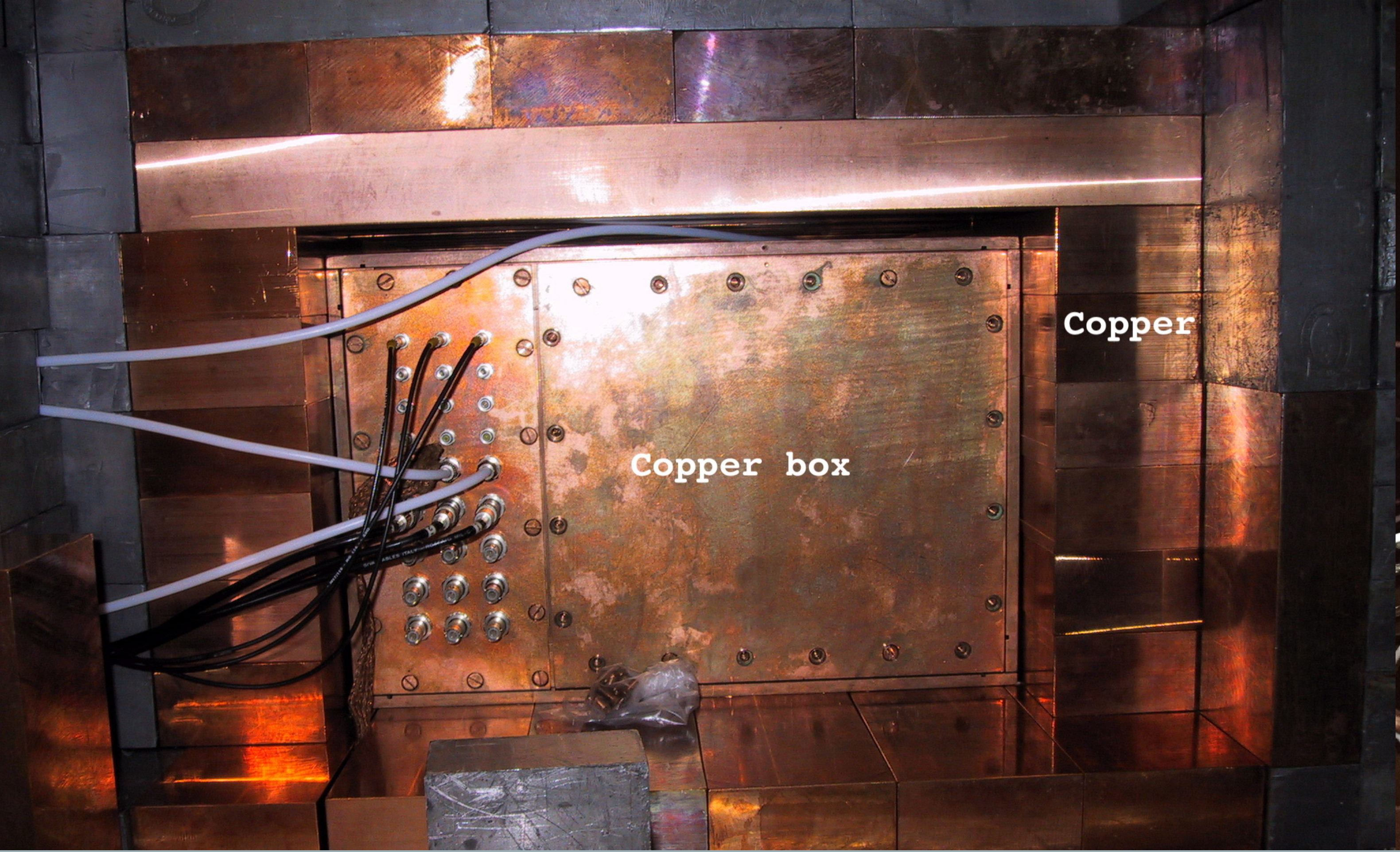
SEARCHES FOR $\beta\beta$ DECAY IN ^{106}Cd at GRAN SASSO: PREVIOUS STAGES OF THE EXPERIMENT

A $^{106}CdWO_4$ crystal (215.4 g) enriched in ^{106}Cd at 66 % was grown and used in three previous stages of the experiment:

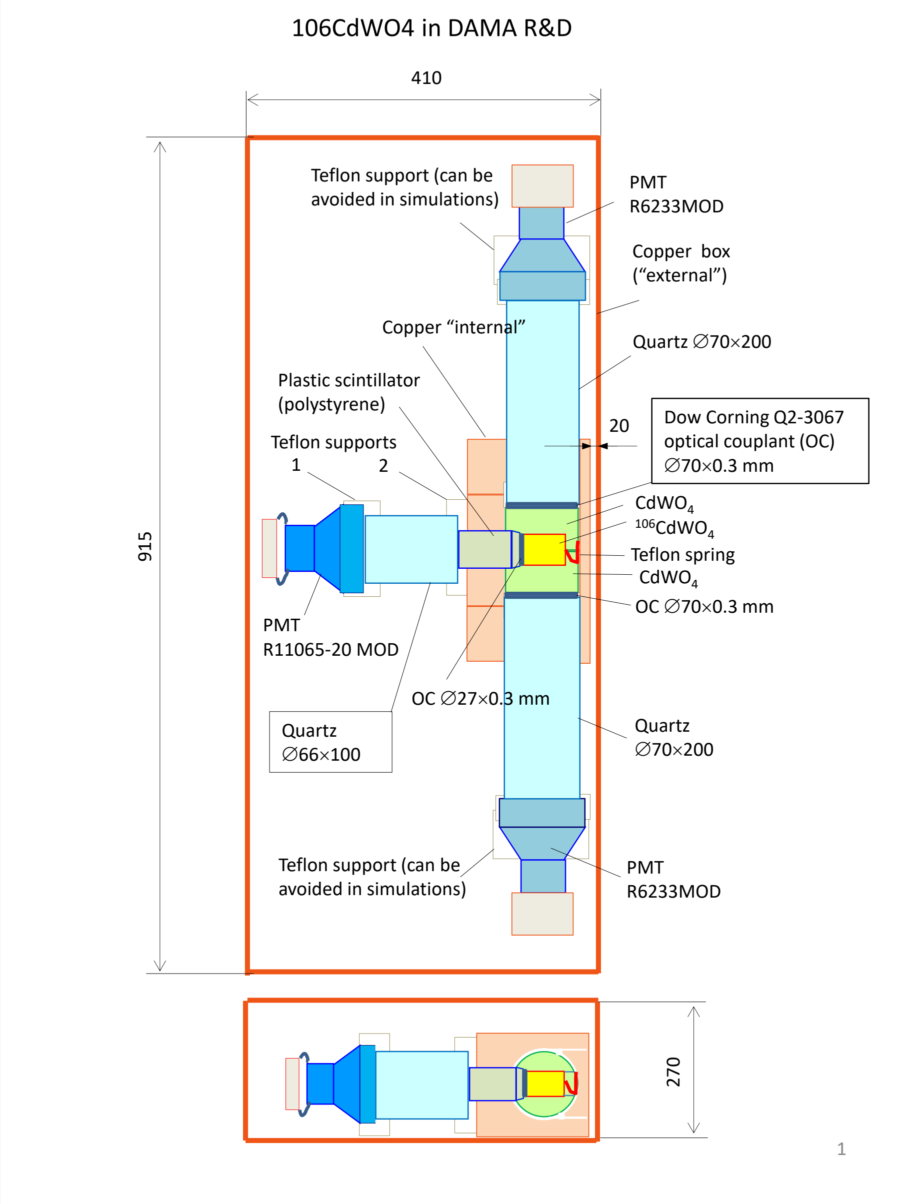
Stage 1 (2012): $^{106}CdWO_4$ crystal was fixed inside a cavity in the central part of a polystyrene light-guide. The experimental apparatus was located in the DAMA/R&D setup at LNGS.

Stage 2 (2016): $^{106}CdWO_4$ crystal **in coincidence with 4 ultra-low-background HPGe detectors of the GeMulti setup** of the STELLA (SubTErranean Low Level Assay) facility at LNGS.

Stage 3 (2020): at low background DAMA/CRYS setup located at LNGS. $^{106}CdWO_4$ detector in coincidence with two large-volume $CdWO_4$ scintillators detectors in close geometry to improve the detection efficiency to γ quanta emitted in the $\beta\beta$ processes in ^{106}Cd.

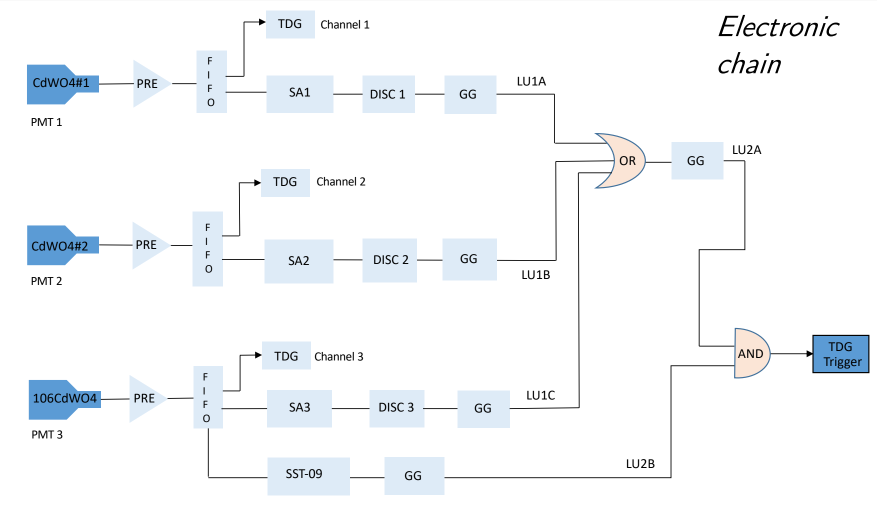


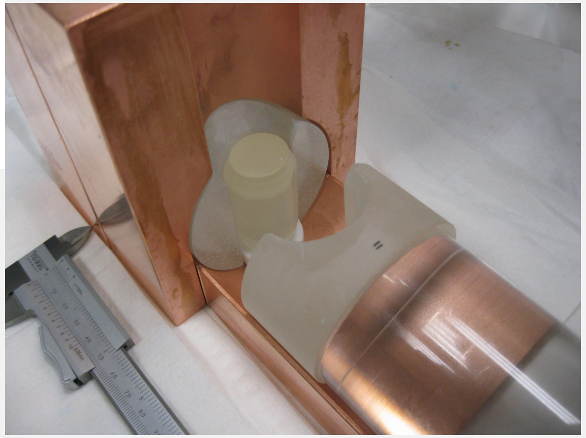
THE NEW EXPERIMENT INSTALLED IN THE DAMA/R&D SETUP AT LNGS

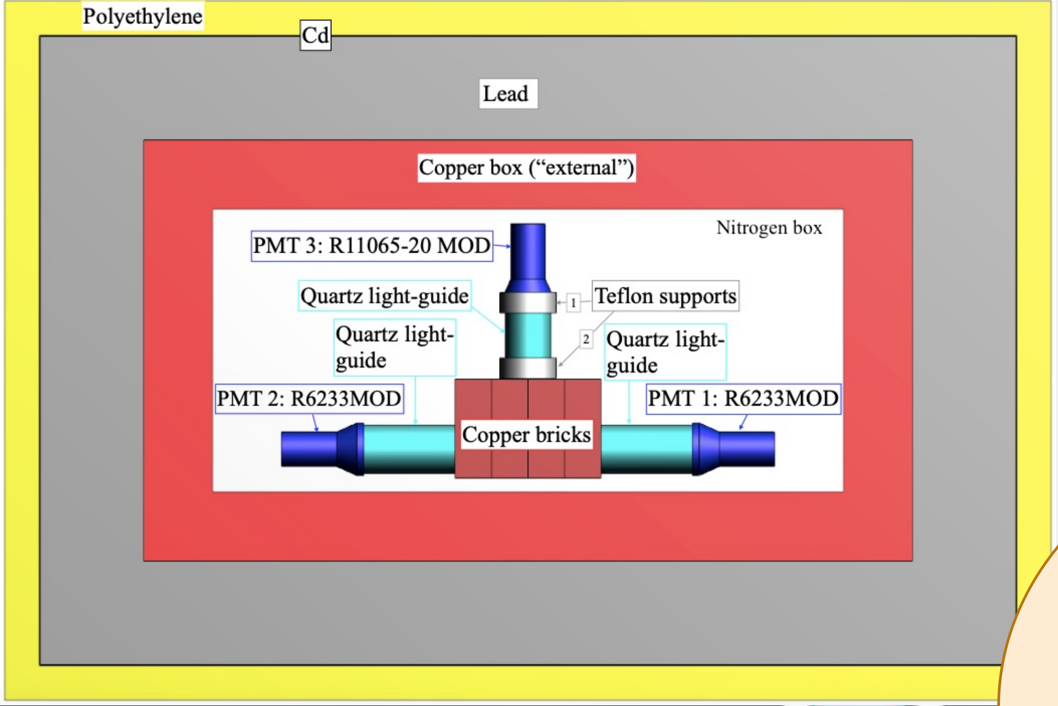


- $^{106}CdWO_4$ is housed in a cylindrical cut-out of the two $CdWO_4$ scintillators which almost completely envelop the enriched crystal.

- An event-by-event DAQ records pulses in case of:
  - an event with E>500 keV in $^{106}CdWO_4$ detector;
  - $^{106}CdWO_4$ detector in coincidence with at least one of the $CdWO_4$ counters.

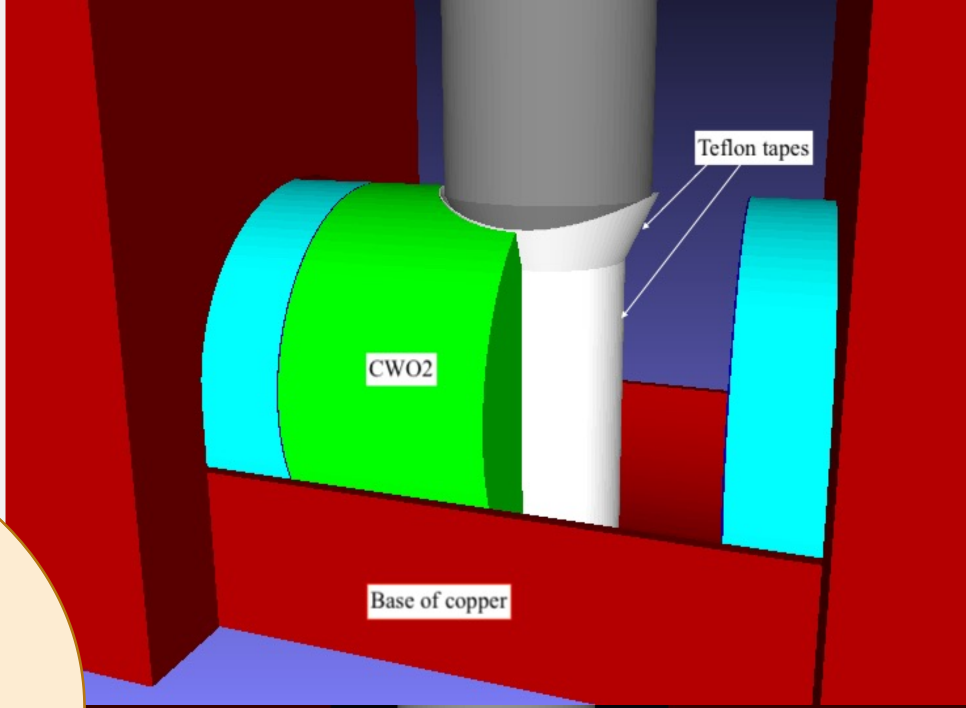


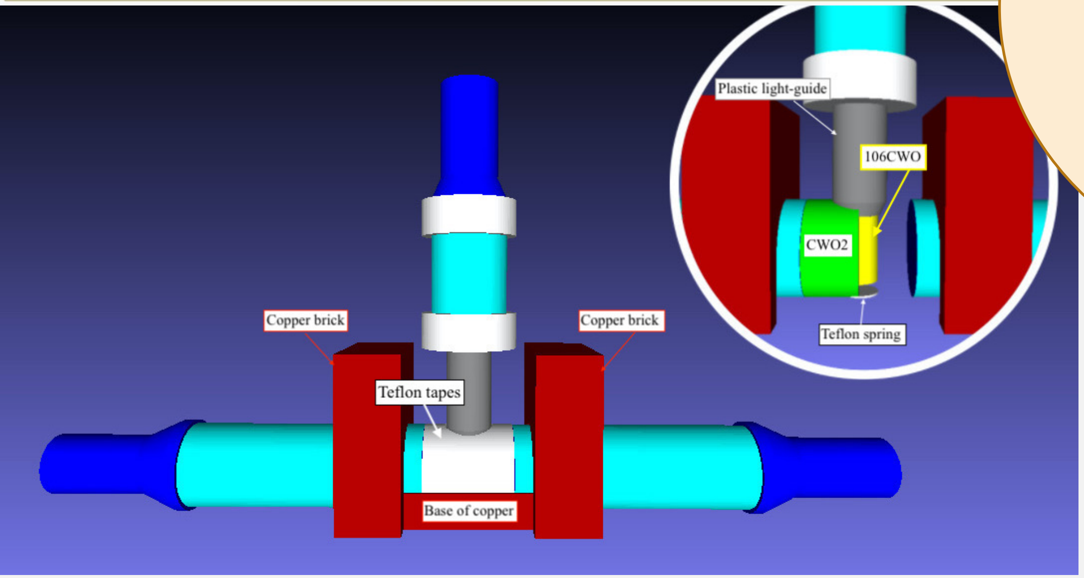


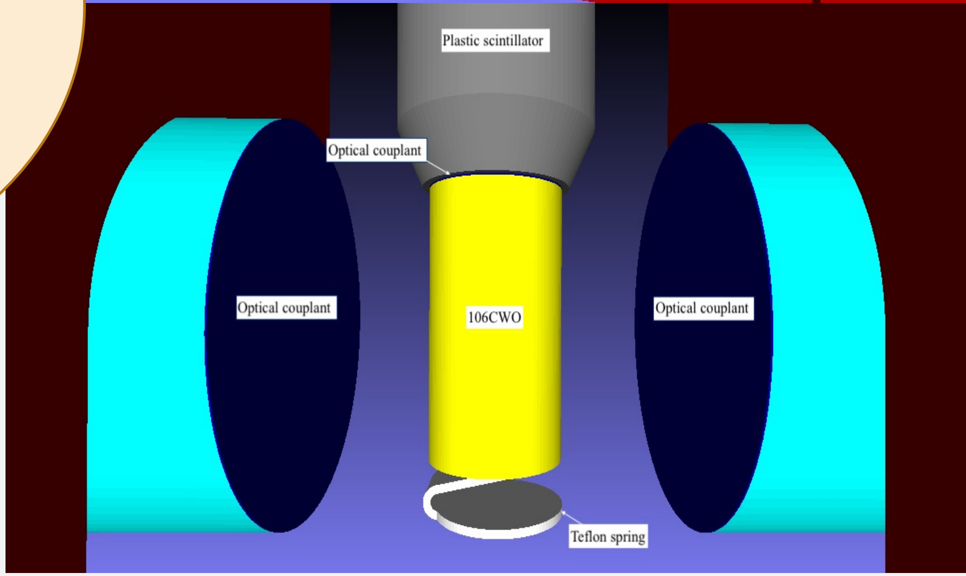


MONTE CARLO SIMULATION: Detector construction

Using Geant 4 toolkit







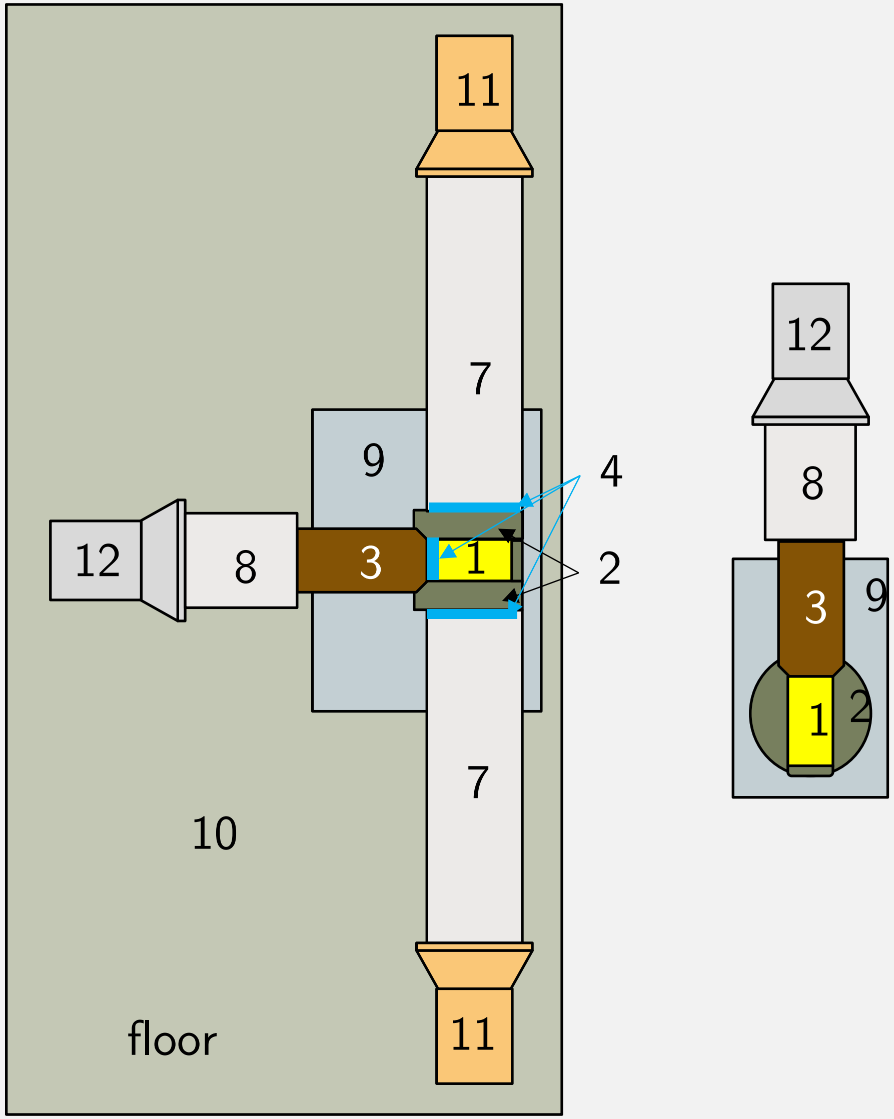
Radioactive Contaminants simulation

- **^{238}U chain**: ^{238}U→ ^{234}U, ^{234}U→ ^{230}Th, ^{230}Th→ ^{226}Ra, ^{226}Ra→ ^{210}Pb, ^{210}Pb→ ^{206}Pb.
- **^{232}Th chain**: ^{232}Th→ ^{228}Ra, ^{228}Ra→ ^{228}Th, ^{228}Th→ ^{208}Pb.
- ^{40}K

These were simulated in the following materials of the setup:

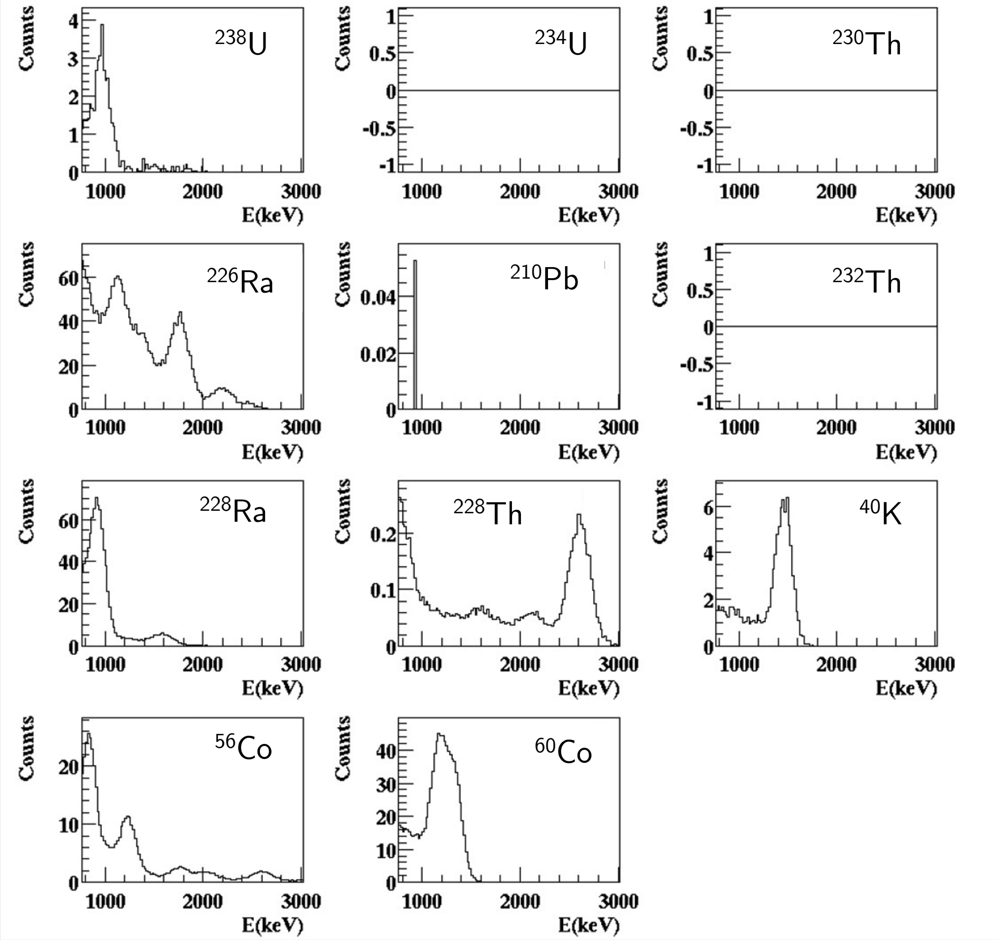
1) $^{106}CdWO_4$;
2) the two natural $CdWO_4$ crystals;
3) Plastic light-guide;
4) the optical couplants;
5) the teflon tapes;
6) the teflon details, which include the teflon spring and support 1 and 2;
7) the two quartz light-guides connected to $CdWO_4$s;
8) the quartz light-guide connected to $^{106}CdWO_4$;
9) the "copper internal" volume;
10) the "copper external" volume;
11) the PMTs coupled to $CdWO_4$s;
12) the PMT coupled to the $^{106}CdWO_4$ detector.

Also: **^{56}Co, ^{60}Co** in copper internal and **^{113}Cd, ^{113m}Cd** in the three $CdWO_4$ crystals.



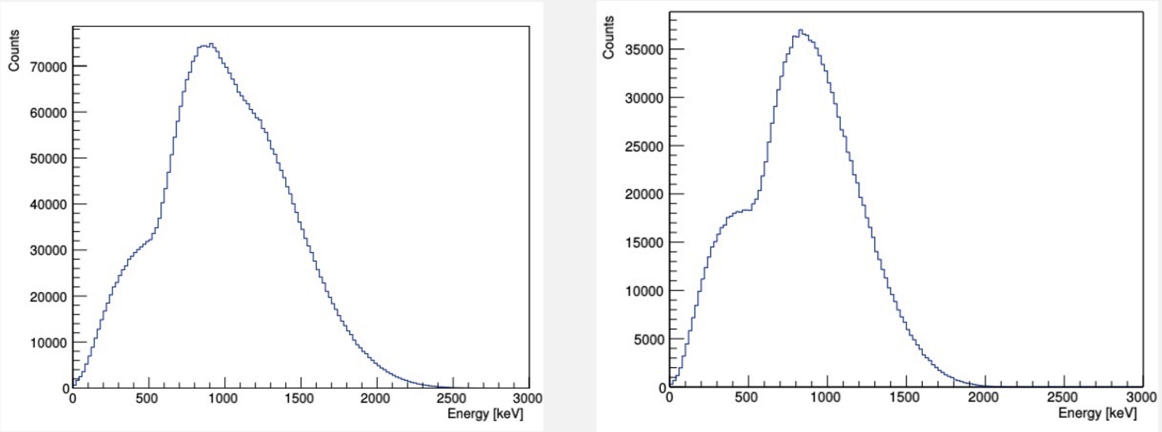
Example of simulated energy spectra due to contaminants in the copper internal volume expected in the $^{106}CdWO_4$ detector, in anti-coincidence with events in the two $CdWO_4$ counters. The energy threshold considered is E>760 keV.

SIMULATION MODELS



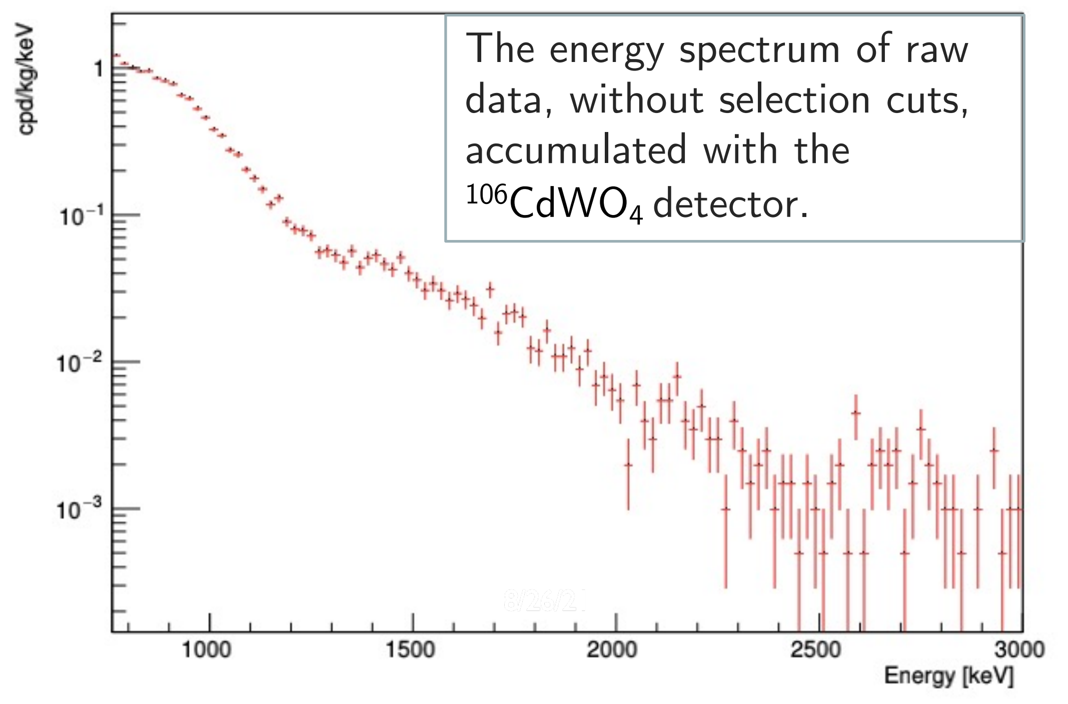
- Several simulations for $^{106}CdWO_4$ were also executed for different double beta decay modes and energy levels of ^{106}Pd: thus 2ϵ, $\epsilon\beta^+$and $2\beta^+$ processes with and without neutrino emission were simulated and analyzed using various experimental selections.

$2\nu\epsilon\beta^+$ g.s. decay mode in the $^{106}CdWO_4$, without experimental selections and in coincidence with events at $(511 \pm 2\sigma)$ keV in one of the two $CdWO_4$ counters.



Data taking and energy calibration

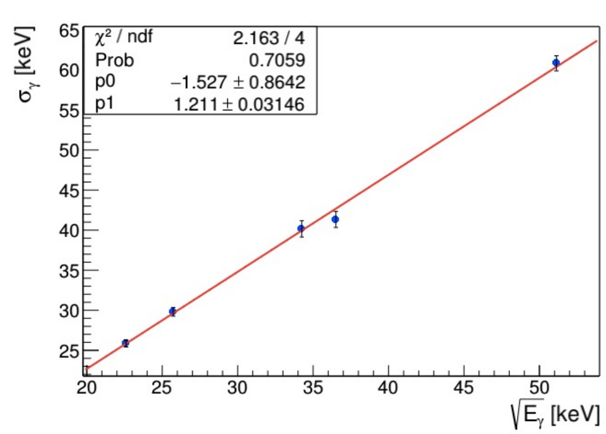
- The energy scale was calibrated using ^{22}Na, ^{60}Co, ^{133}Ba, ^{137}Cs, and ^{228}Th γ sources. The data taking started in October 2019 and it is still in progress. In this work, a total time of accumulated data of 466.64 d is considered.



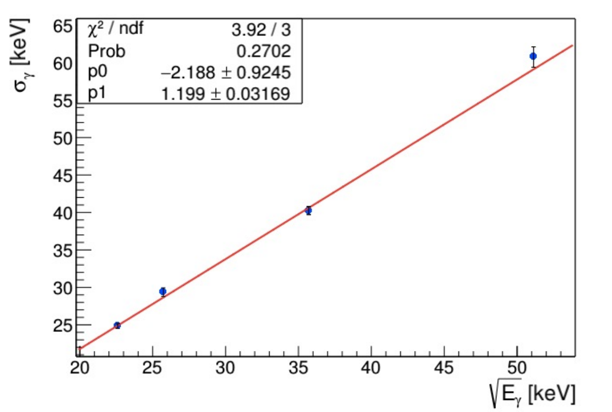
The energy spectrum of raw data, without selection cuts, accumulated with the $^{106}CdWO_4$ detector.

$\sigma_\gamma = p_1\sqrt{E_\gamma}$ where E_γ is expressed in keV.

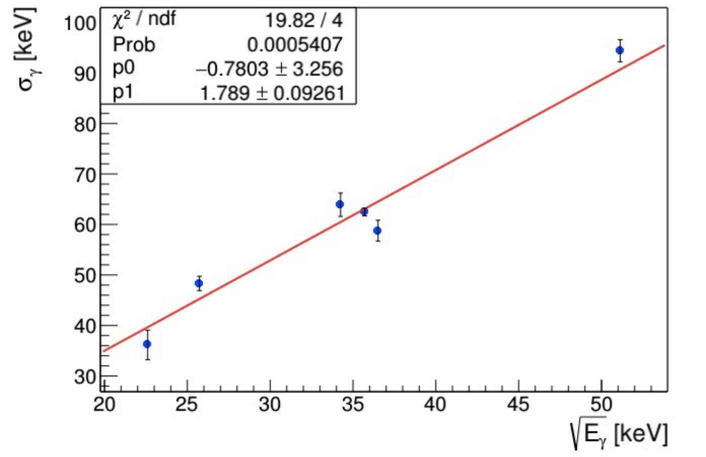
$CdWO_4$ -1

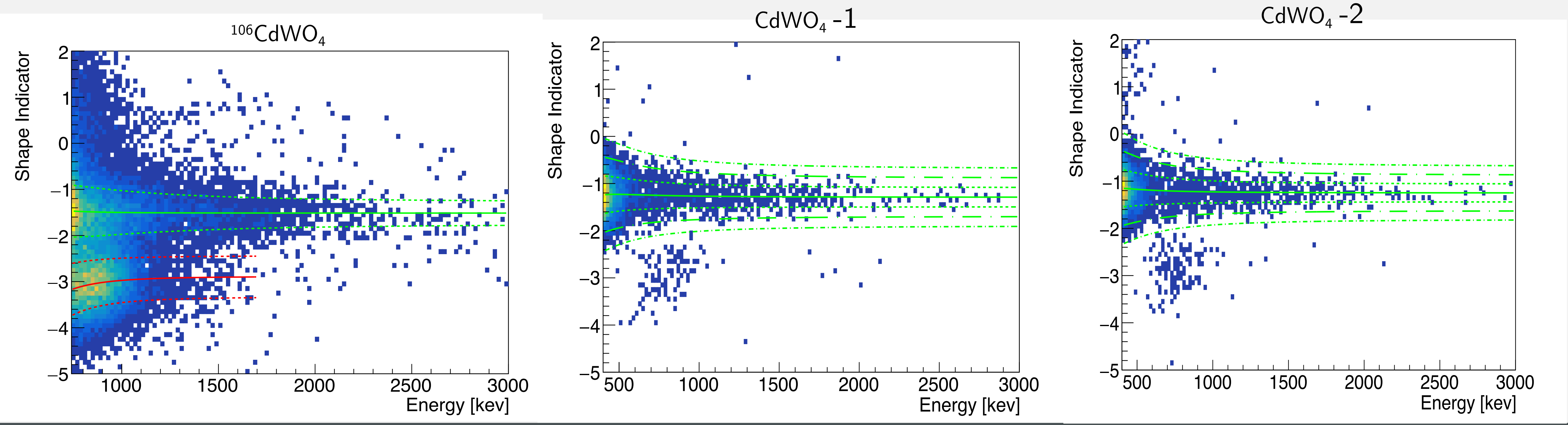


$CdWO_4$ -2



$^{106}CdWO_4$





PULSE SHAPE DISCRIMINATION OF α AND $\gamma(\beta)$ EVENTS

- The difference in $CdWO_4$ scintillation pulse shape for β particles (γ quanta) and α particles can be used in order to suppress the background caused by α radioactive contamination of the detectors due to the residual contamination in ^{232}Th and ^{238}U with their daughters.

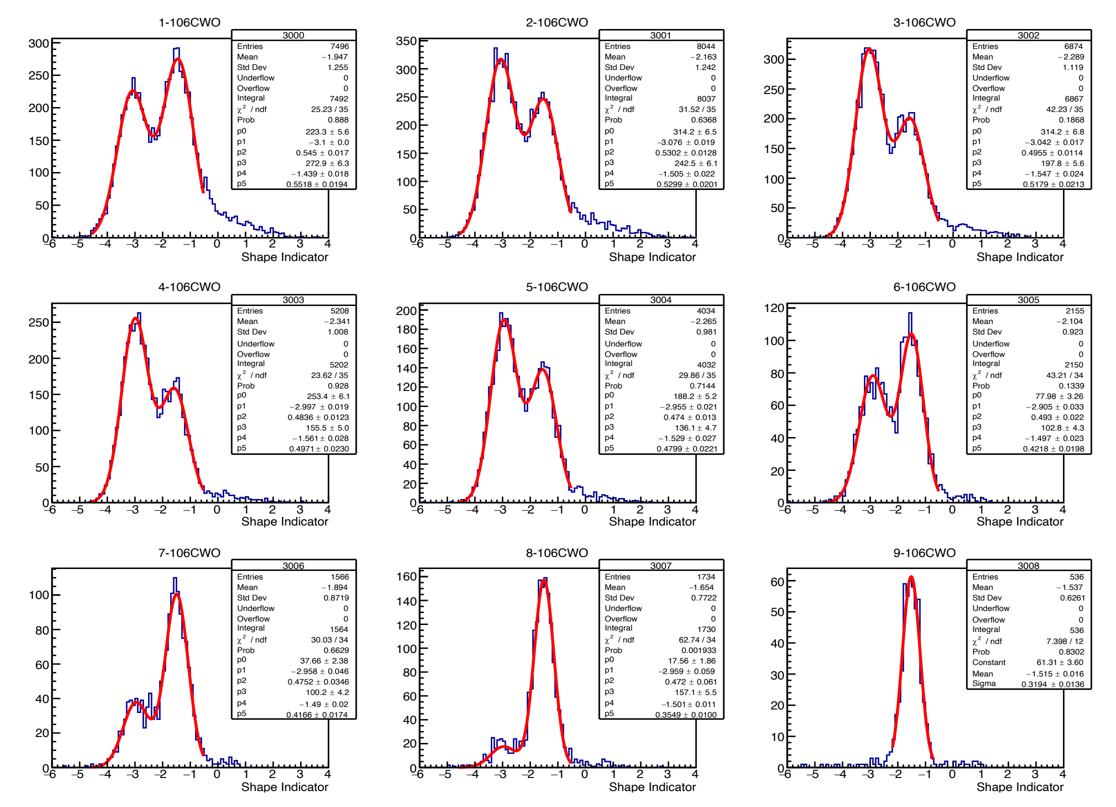
$$SI = \sum f(t_k) \times P(t_k) / \sum f(t_k)$$

The mean value of the shape indicator vs energy is represented together with 1σ intervals for the $^{106}CdWO_4$ detector and also 2σ, 3σ intervals for the $CdWO_4$ scintillators.

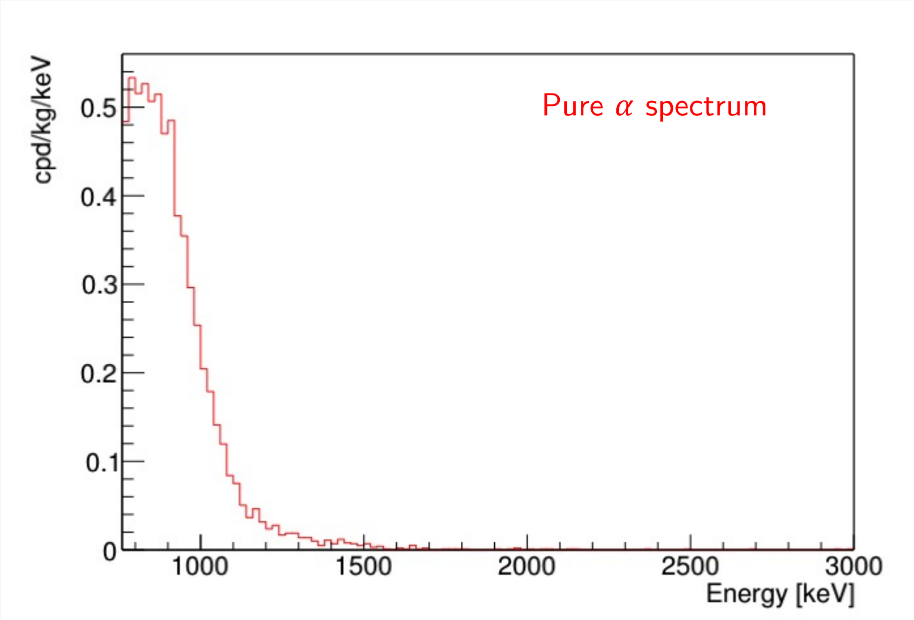
DISTRIBUTIONS OF SHAPE INDICATORS

Slices for the $^{106}CdWO_4$:

1) ΔE=740-800 keV; 2) ΔE =780-860 keV; 3) ΔE =840-920 keV; 4) ΔE =900-980 keV; 5) ΔE =960-1060 keV; 6) ΔE = 1040-1140 keV; 7) ΔE = 1120-1280 keV; 8) ΔE = 1260-1680 keV; 9) ΔE = 1660-2080 keV.



- Data were analyzed by dividing them into 9 energy slices.
- A fit of α and $\beta(\gamma)$ SI distributions with two Gaussian functions has been applied (red solid line in the figures).
- The obtained mean and sigma values were used in new fits to determine the contour lines for α and $\beta(\gamma)$ events.
- Same analysis done for the two $CdWO_4$.



EXPERIMENTAL SPECTRA AFTER EVENT SELECTIONS

Anticoincidence mode (AC):

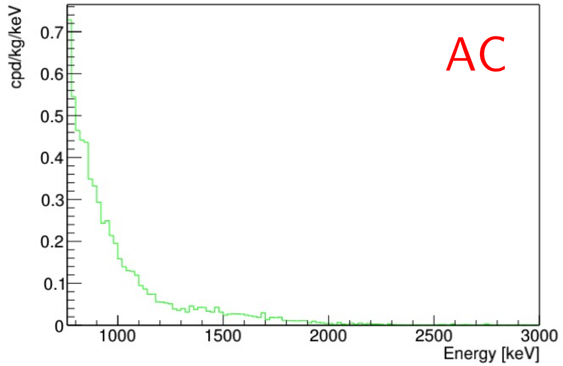
- E (both $CdWO_4$)$<$ 100 keV
- $SI > \mu_{SI\beta} - 1\sigma_{SI\beta}$ for the $^{106}CdWO_4$ detector
- PSD efficiency: $\eta_\beta = 0.84$

Coincidence mode (CC511):

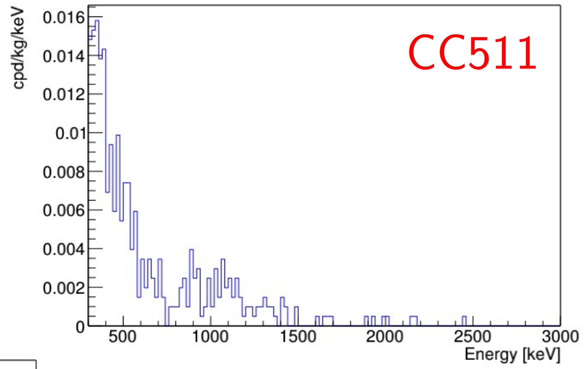
- E (one of the two $CdWO_4$) $=(511 \pm 2\sigma)$ keV
- $SI > \mu_{SI\beta} - 3\sigma_{SI\beta}$ for the two $CdWO_4$ crystals
- NO PSD efficiency

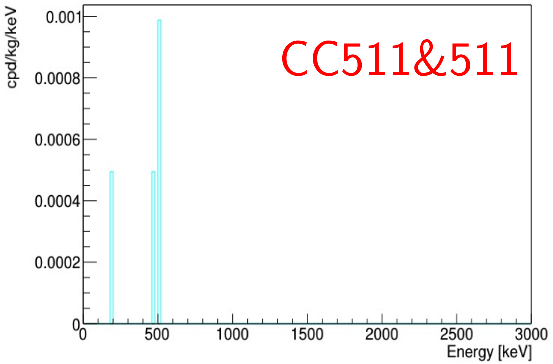
Double coincidence mode (CC511&511):

- E (both $CdWO_4$) $=(511 \pm 2\sigma)$ keV
- $SI > \mu_{SI\beta} - 3\sigma_{SI\beta}$ for the two $CdWO_4$ crystals
- NO PSD efficiency



Energy spectra of β(γ)events





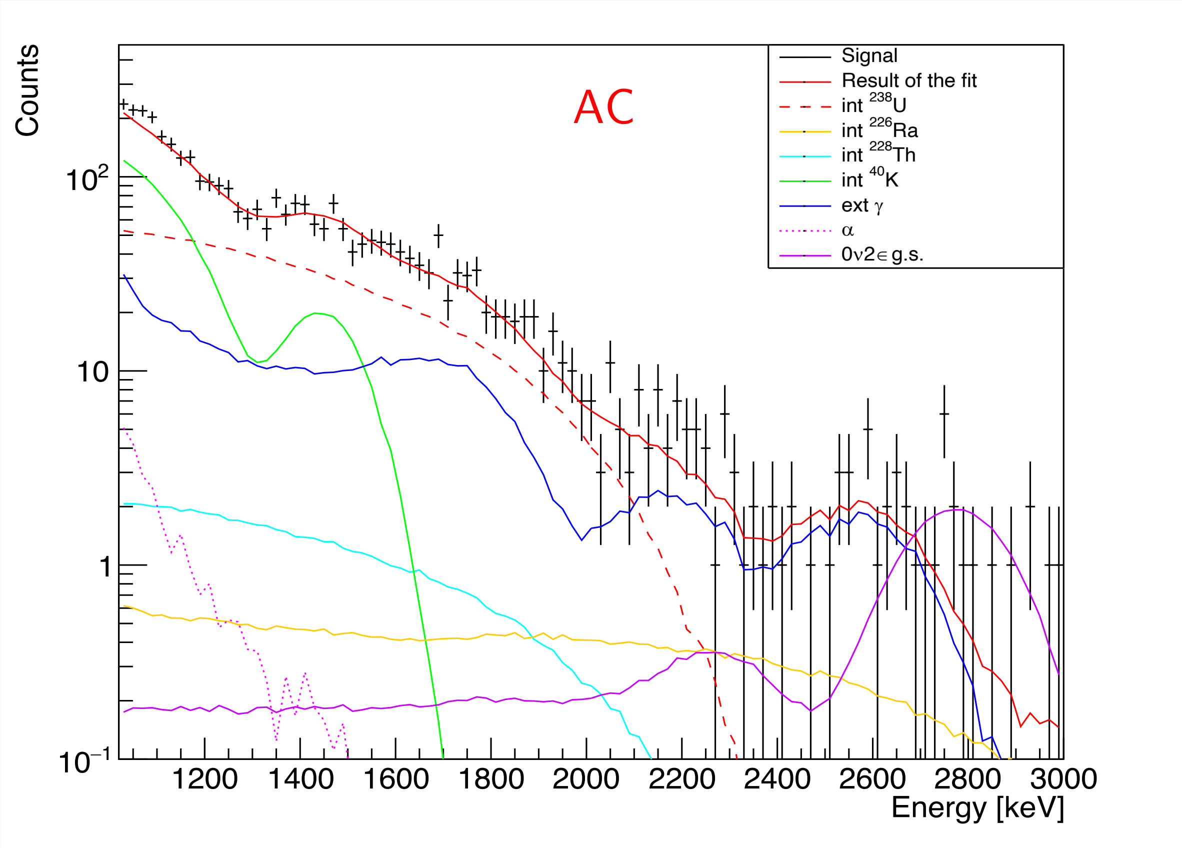
BACKGROUND MODEL OF THE MEASURED SPECTRA

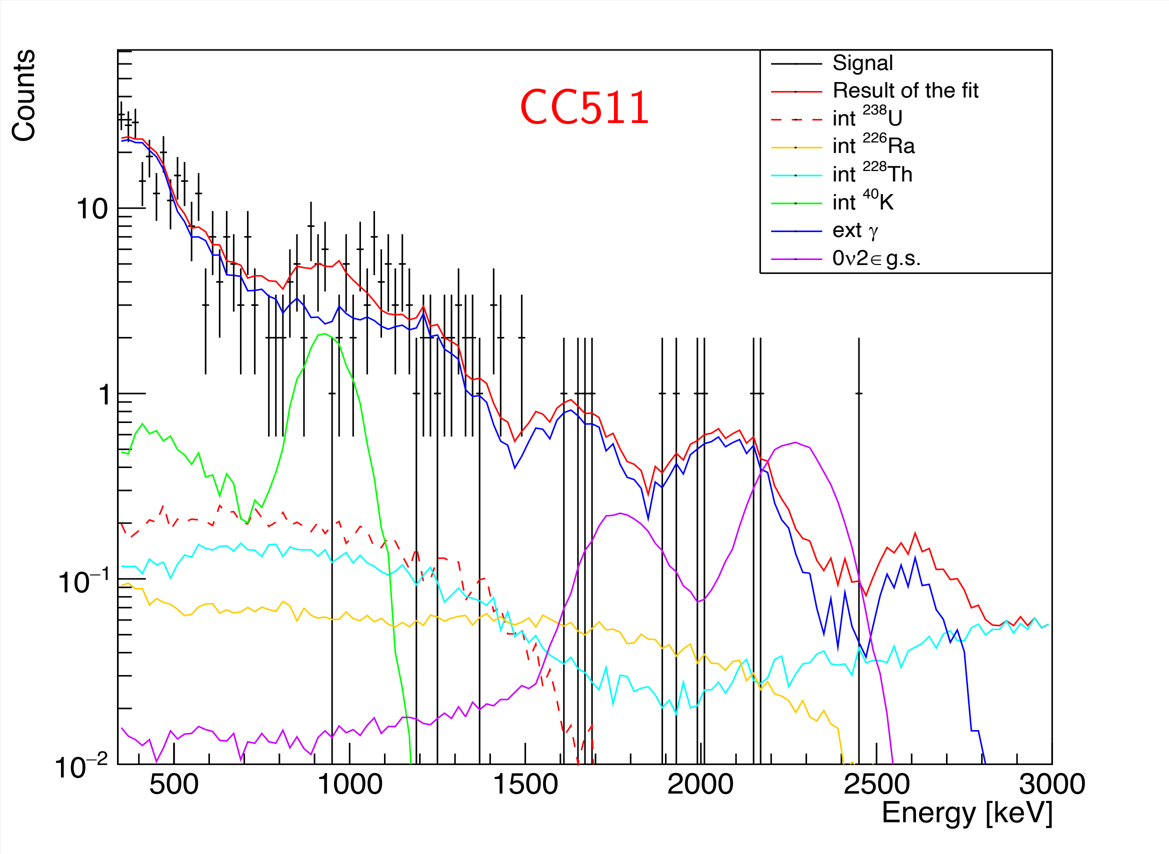
- A background model of the anticoincidence (AC) and coincidence (CC511) spectra has been reconstructed fitting the data with the calculated background models.

- The χ^2 function used for the fit was estimated with the maximum likelihood estimator, which takes into account the Poissonian nature of the fluctuations in the experimental bins.

Main components of the background considered in the fit:

- "internal" sources of $^{238}U \rightarrow ^{234}U$, and ^{40}K, simulated in the $^{106}CdWO_4$ detector;
- "external" sources (" ext γ "): $^{226}Ra \rightarrow ^{210}Pb$, $^{228}Ra \rightarrow ^{228}Th$, $^{228}Th \rightarrow ^{208}Pb$ and ^{40}K in the surrounding materials;
- "internal" $^{228}Th \rightarrow ^{208}Pb$ and $^{226}Ra \rightarrow ^{210}Pb$;
- in AC case, distribution of residual α particles of ^{232}Th and ^{238}U with their daughters, not discarded by the pulse-shape analysis.





Radioactive contamination (mBq/kg) of the materials of the setup.

Material	^{238}U	^{226}Ra	^{228}Ac	^{228}Th	^{40}K
$^{106}CdWO_4$	0.60(2)	0.018(8)	-	0.034(12)	<1.6
$CdWO_4$ crystals	-	-	-	-	<0.5
Plastic light-guide	-	<20	<30	<5	<18
Quartz light-guides	-	<6	<15	<1.2	<6
Copper	-	<0.4	<1.0	<0.10	<0.5
PMTs	-	<1000	<4000	<160	<1600

- For each contaminant considered, the relative model was introduced for each of the two spectra, but with a single free parameter (proportional to the activity of the contaminant).

Search for 2ϵ, $\epsilon\beta^+$ and $2\beta^+$ processes in ^{106}Cd

- The measured energy spectrum does not contain peculiarities which could be ascribed to $\beta\beta$ decay processes in ^{106}Cd. Therefore, the data have been analyzed estimating lower half-life limits, using the following formula:

$$lim\ T_{1/2} = N \cdot \eta \cdot t \cdot ln\ 2 / lim\ S$$

where:

- N is the number of ^{106}Cd nuclei in the $^{106}CdWO_4$ crystal ($N = 2.42 \times 10^{23}$);
- η is the detection efficiency for the process of decay (calculated as a ratio of the events number in the signal model which satisfies the investigated experimental condition, to the number of generated events);
- t is the time of measurements (466.64 d);
- lim S is the number of events of the effect searched for, which can be excluded at a given confidence level (C.L.; all limits on $\beta\beta$ processes in ^{106}Cd are given at the 90% C.L. in the present study).

SEARCH FOR $\beta\beta$ PROCESSES WITH POSITRON EMISSION THROUGH THE STUDY OF TRIPLE COINCIDENCES

- Spectrum of $^{106}CdWO_4$ in coincidence with events at energy E=($511 \pm 2\sigma$) keV in both of the two natural $CdWO_4$ scintillators → NO events in the energy region >520 keV
  → $\lim S = 2.3$ (90% C. L.)

- Efficiency **η** = fraction of the simulated events which can produce a double coincidence at energy 511 keV in both of the two $CdWO_4$ counters and at the same time release an energy greater than 520 keV in the $^{106}CdWO_4$ detector.

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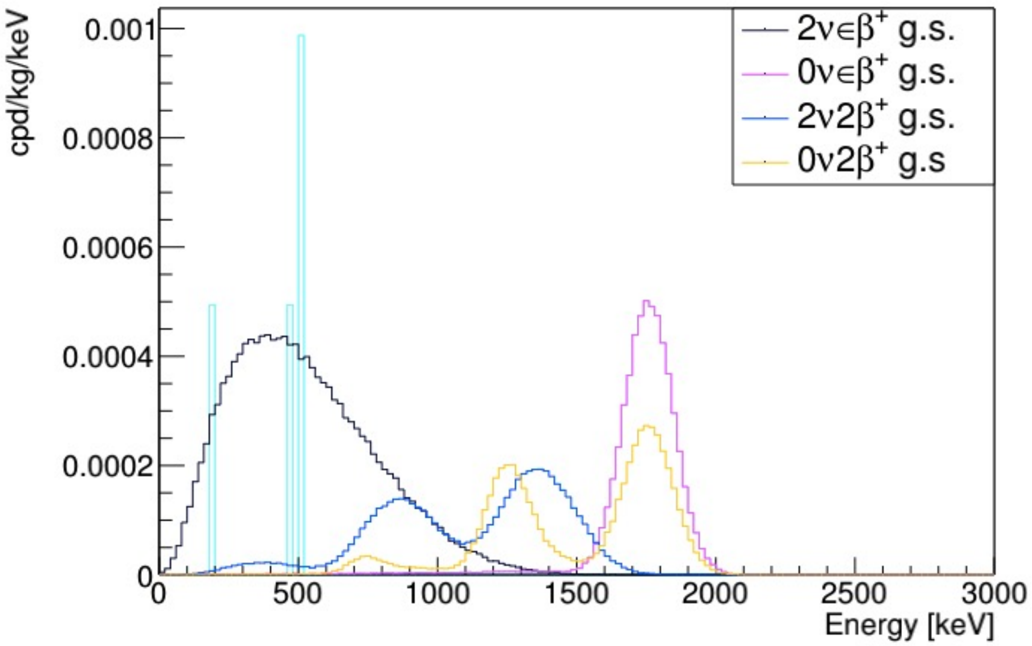
Data of CC511&511 with some of the $\beta\beta$ excluded distributions x 5



Decay, Level of ^{106}Pd	η	limit $T_{1/2}$ [yr] at 90% C.L.
$0\nu 2\epsilon$ 2^+512	0.003	$\geq 2.6 \times 10^{20}$
$2\nu\epsilon\beta^+$ g.s.	0.016	$\geq 1.6 \times 10^{21}$
$2\nu\epsilon\beta^+$ 2^+512	0.037	$\geq 3.5 \times 10^{21}$
$2\nu\epsilon\beta^+$ 2^+1128	0.023	$\geq 2.1 \times 10^{21}$
$2\nu\epsilon\beta^+$ 0^+1134	0.027	$\geq 2.6 \times 10^{21}$
$0\nu\epsilon\beta^+$ g.s.	0.035	$\geq 3.3 \times 10^{21}$
$0\nu\epsilon\beta^+$ 2^+512	0.043	$\geq 4.0 \times 10^{21}$
$0\nu\epsilon\beta^+$ 2^+1128	0.028	$\geq 2.6 \times 10^{21}$
$0\nu\epsilon\beta^+$ 0^+1134	0.030	$\geq 2.8 \times 10^{21}$
$2\nu 2\beta^+$ g.s.	0.050	$\geq 4.6 \times 10^{21}$
$2\nu 2\beta^+$ 2^+512	0.046	$\geq 4.3 \times 10^{21}$
$0\nu 2\beta^+$ g.s.	0.051	$\geq 4.7 \times 10^{21}$
$0\nu 2\beta^+$ 2^+512	0.046	$\geq 4.3 \times 10^{21}$

SEARCH FOR $\beta\beta$ PROCESSES BY FITTING THE MEASURED SPECTRA

- Simulated $\beta\beta$ models were added to the background model in the fit of the anticoincidence spectrum plus the coincidence spectrum with events at energy 511 keV.
- $\beta\beta$ decay model summed up to the background model is normalized to one decay, i.e. it is divided by the total number of generated decays (and the PSD cut efficiency is also taken into account).
- Therefore the fit directly returns the total number of decays attributable to the searched process i.e. S/η.
- According to Feldman & Cousins[127] procedure, an upper limit on S/η (90% C.L.) is calculated.

Decay, Level of ^{106}Pd	**S/η**	$lim(S/\eta)$	**limit $T_{1/2}$ [yr] at 90% C.L.**
$0\nu2\epsilon$ g.s.	194 ± 105	367	$\geq 2.5 \times 10^{20}$
Res. $0\nu2K$ 2718	-22 ± 143	214	$\geq 4.3 \times 10^{20}$
Res. $0\nu KL_1$ 4^+2741	132 ± 102	300	$\geq 3.1 \times 10^{20}$
Res. $0\nu KL_3$ $2,3^-2748$	-39 ± 98	124	$\geq 7.4 \times 10^{20}$

[127] Feldman, G.J.; Cousins, R.D. Unified approach to the classical statistical analysis of small signals. *Phys. Rev. D*57, 1998, 3873-3889.

Decay, Level of ^{106}Pd	Exp. selection	limit $T_{1/2}$ [yr] at 90% C.L.	
		Best present	Best previous
$0\nu2\epsilon$ g.s.	AC&CC511	$\geq 2.5 \times 10^{20}$	$\geq 1.0 \times 10^{21}$ [10]
$0\nu2\epsilon$ 2^+512	CC511&511	$\geq 2.6 \times 10^{20}$	$\geq 5.1 \times 10^{20}$ [10]
Res. $0\nu2K$ 2718	AC&CC511	$\geq 4.3 \times 10^{20}$	$\geq 2.9 \times 10^{21}$ [12]
Res. $0\nu KL_1$ 4^+2741	AC&CC511	$\geq 3.1 \times 10^{20}$	$\geq 9.0 \times 10^{20}$ [10]
Res. $0\nu KL_3$ $2,3^-2748$	AC&CC511	$\geq 7.4 \times 10^{20}$	$\geq 1.4 \times 10^{21}$ [11]
$2\nu\epsilon\beta^+$ g.s.	CC 511&511	$\geq 1.6 \times 10^{21}$	$\geq 2.1 \times 10^{21}$ [12]
$2\nu\epsilon\beta^+$ 2^+512	CC 511&511	**$\geq 3.5 \times 10^{21}$**	$\geq 2.7 \times 10^{21}$ [12]
$2\nu\epsilon\beta^+$ 2^+1128	CC 511&511	**$\geq 2.1 \times 10^{21}$**	$\geq 1.3 \times 10^{21}$ [12]
$2\nu\epsilon\beta^+$ 0^+1134	CC 511&511	**$\geq 2.6 \times 10^{21}$**	$\geq 1.1 \times 10^{21}$ [11]
$0\nu\epsilon\beta^+$ g.s.	CC511&511	$\geq 3.3 \times 10^{21}$	$\geq 1.4 \times 10^{22}$ [12]
$0\nu\epsilon\beta^+$ 2^+512	CC511&511	$\geq 4.0 \times 10^{21}$	$\geq 9.7 \times 10^{21}$ [12]
$0\nu\epsilon\beta^+$ 2^+1128	CC511&511	**$\geq 2.6 \times 10^{21}$**	$\geq 1.1 \times 10^{22}$ [12]
$0\nu\epsilon\beta^+$ 0^+1134	CC 511&511	**$\geq 2.8 \times 10^{21}$**	$\geq 1.9 \times 10^{21}$ [11]
$2\nu2\beta^+$ g.s.	CC 511&511	**$\geq 4.6 \times 10^{21}$**	$\geq 2.3 \times 10^{21}$ [11]
$2\nu2\beta^+$ 2^+512	CC 511&511	**$\geq 4.3 \times 10^{21}$**	$\geq 2.5 \times 10^{21}$ [11]
$0\nu2\beta^+$ g.s.	CC511&511	$\geq 4.7 \times 10^{21}$	$\geq 5.9 \times 10^{21}$ [12]
$0\nu2\beta^+$ 2^+512	CC511&511	**$\geq 4.3 \times 10^{21}$**	$\geq 4.0 \times 10^{21}$ [12]

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CONCLUSIONS & RESULTS

- The highest sensitivity to several decay channels with positron(s) emission was achieved using the data that were gathered by the $^{106}CdWO_4$ detector in coincidence with 511 keV annihilation γ quanta in both of the two $CdWO_4$ counters.
- Limits have been improved to a factor 2-3 with respect to the previous experiments.
- The sensitivity obtained on the $T_{1/2}$ for the case $2\nu\epsilon\beta^+$ approaches the theoretical predictions: $T_{1/2} \sim 10^{21} - 10^{22}$ yr.
- The experiment is still running with the purpose of improving the sensitivity to all the decay channels of ^{106}Cd.

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