PRELIMINARY SEARCH FOR $\beta \beta$ DECAY PROCESSES IN $^{106}\text{Cd}$ USING $^{106}\text{CdWO}_4$ SCINTILLATOR

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Introduction to Double beta decay

- It can be studied in even-even nuclei when the single $\beta$ decay is energetically forbidden due to the pairing interaction.
- For example, the decay of $^{106}$Cd to $^{106}$Ag is energetically forbidden.

$$ ^{106}\text{Cd} \rightarrow ^{106}\text{Pd} + 2e^+ + 2\nu_e $$

$2\nu2\beta^+ : \frac{A}{Z}X \rightarrow \frac{A}{Z-2}X + 2e^+ + 2\nu_e$

$L$ conserved

$0\nu2\beta^+ : \frac{A}{Z}X \rightarrow \frac{A}{Z-2}X + 2e^+$

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

Preliminary search for $\beta\beta$ decay processes in $^{100}$Cd using $^{100}$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:
  
  \[ 0\nu 2\beta^+ : \frac{A}{Z}X \rightarrow \frac{A}{Z-2}X + 2e^+ \]
  
  \[ 0\nu \epsilon \beta^+ : e^- + \frac{A}{Z}X \rightarrow \frac{A}{Z-2}X + e^+ + X\text{-rays} \]
  
  \[ 0\nu 2\epsilon : e^- + e^- + \frac{A}{Z}X \rightarrow \frac{A}{Z-2}X^* \rightarrow \frac{A}{Z-2}X + \gamma + X\text{-rays} \]

- Positron(s) annihilation gives rise to 511 keV $\gamma$ rays.

- The coincident detection of positron(s) and 511 keV $\gamma$ rays would be used as highly reliable condition for selecting such events.

- $0\nu \epsilon \beta^+$ and $0\nu 2\beta^+$ can clarify the possible contribution of the right-handed currents to the $0\nu \beta^-\beta^-$ decay rate;

- Possibility of a resonant $0\nu 2\epsilon$ process → in case of close degeneracy of the initial and final (excited) nuclear states → \[ \frac{1}{T_{1/2}} \propto \frac{\Gamma}{(Q-E)^2 + \Gamma^2/4} \]
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 $2\nu$ modes ($T_{1/2} \sim 10^{21} - 10^{22}$ yr) that could be reached by modern low-counting techniques;
- Possibility of resonant $2\epsilon$ 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
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 $\gamma$ quanta emitted in the $\beta\beta$ processes in $^{106}$Cd.
THE NEW EXPERIMENT INSTALLED IN THE DAMA/R&D SETUP AT LNGS

Preliminary search for $\beta\beta$ decay processes in $^{100}\text{Cd}$ using $^{100}\text{CdWO}_4$ scintillator
106 CdWO4 is housed in a cylindrical cut-out of the two CdWO4 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 CdWO4 detector;
• 106 CdWO4 detector in coincidence with at least one of the CdWO4 counters.
MONTE CARLO SIMULATION: Detector construction

Using Geant 4 toolkit

Preliminary search for $\beta\beta$ decay processes in $^{100}$Cd using $^{100}$CdWO$_4$ scintillator
Radioactive Contaminants simulation

- $^{238}\text{U chain}$: $^{238}\text{U} \rightarrow ^{234}\text{U}$, $^{234}\text{U} \rightarrow ^{230}\text{Th}$, $^{230}\text{Th} \rightarrow ^{226}\text{Ra}$, $^{226}\text{Ra} \rightarrow ^{210}\text{Pb}$, $^{210}\text{Pb} \rightarrow ^{206}\text{Pb}$.

- $^{232}\text{Th chain}$: $^{232}\text{Th} \rightarrow ^{228}\text{Ra}$, $^{228}\text{Ra} \rightarrow ^{228}\text{Th}$, $^{228}\text{Th} \rightarrow ^{208}\text{Pb}$.

- $^{40}\text{K}$

These were simulated in the following materials of the setup:

1) $^{106}\text{CdWO}_4$;  
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 $^{106}\text{CdWO}_4$;  
9) the "copper internal" volume;  
10) the "copper external" volume;  
11) the PMTs coupled to CdWO$_4$s;  
12) the PMT coupled to the $^{106}\text{CdWO}_4$ detector.

Also: $^{56}\text{Co}$, $^{60}\text{Co}$ in copper internal and $^{113}\text{Cd}$, $^{113m}\text{Cd}$ in the three CdWO$_4$ crystals.

Preliminary search for $\beta\beta$ decay processes in $^{106}\text{Cd}$ using $^{106}\text{CdWO}_4$ scintillator
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.

- Several simulations for $^{106}$CdWO$_4$ were also executed for different double beta decay modes and energy levels of $^{106}$Pd: thus $2\epsilon$, $\epsilon\beta^+$ and $2\beta^+$ processes with and without neutrino emission were simulated and analyzed using various experimental selections.

$2\nu\beta^+$ 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.
The energy scale was calibrated using $^{22}\text{Na}$, $^{60}\text{Co}$, $^{133}\text{Ba}$, $^{137}\text{Cs}$, and $^{228}\text{Th}$ 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 $^{106}\text{CdWO}_4$ detector.

The energy spectrum of raw data, without selection cuts, accumulated with the $^{106}\text{CdWO}_4$ detector.

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

$^{106}\text{CdWO}_4$ - 1

$^{106}\text{CdWO}_4$ - 2

Preliminary search for $\beta\beta$ decay processes in $^{100}\text{Cd}$ using $^{106}\text{CdWO}_4$ scintillator
The difference in CdWO₄ 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 ²³²Th and ²³⁸U 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 ¹⁰⁶CdWO₄ detector and also 2σ, 3σ intervals for the CdWO₄ scintillators.

Preliminary search for β decay processes in ¹⁰⁶Cd using ¹⁰⁶CdWO₄ scintillator
Slices for the $^{106}$CdWO$_4$:
1) $\Delta E = 740-800$ keV; 2) $\Delta E = 780-860$ keV; 3) $\Delta E = 840-920$ keV; 4) $\Delta E = 900-980$ keV; 5) $\Delta E = 960-1060$ keV; 6) $\Delta E = 1040-1140$ keV; 7) $\Delta E = 1120-1280$ keV; 8) $\Delta E = 1260-1680$ keV; 9) $\Delta E = 1660-2080$ keV.

- Data were analyzed by dividing them into 9 energy slices.
- A fit of $\alpha$ 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 $\alpha$ 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
- $SI > \mu_{S1} - 1\sigma_{S1}$ for the $^{106}$CdWO$_4$ detector
- PSD efficiency: $\eta_B = 0.84$

**Coincidence mode (CC511):**
- $E$ (one of the two CdWO$_4$) = $(511 \pm 2\sigma)$ keV
- $SI > \mu_{S1} - 3\sigma_{S1}$ for the two CdWO$_4$ crystals
- NO PSD efficiency

**Double coincidence mode (CC511&511):**
- $E$ (both CdWO$_4$) = $(511 \pm 2\sigma)$ keV
- $SI > \mu_{S1} - 3\sigma_{S1}$ for the two CdWO$_4$ crystals
- NO PSD efficiency

Preliminary search for $\beta\beta$ decay processes in $^{106}$Cd using $^{106}$CdWO$_4$ scintillator
A background model of the anticoincidence (AC) and coincidence (CC511) spectra has been reconstructed fitting the data with the calculated background models.

The $\chi^2$ 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 $^{238}\text{U}\rightarrow^{234}\text{U}$, and $^{40}\text{K}$, simulated in the $^{106}\text{CdWO}_4$ detector;
- "external" sources (" ext $\gamma$ "): $^{226}\text{Ra}\rightarrow^{210}\text{Pb}$, $^{228}\text{Ra}\rightarrow^{228}\text{Th}$, $^{228}\text{Th}\rightarrow^{208}\text{Pb}$ and $^{40}\text{K}$ in the surrounding materials;
- "internal" $^{228}\text{Th}\rightarrow^{208}\text{Pb}$ and $^{226}\text{Ra}\rightarrow^{210}\text{Pb}$;
- in AC case, distribution of residual $\alpha$ particles of $^{232}\text{Th}$ and $^{238}\text{U}$ with their daughters, not discarded by the pulse-shape analysis.
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).

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

<table>
<thead>
<tr>
<th>Material</th>
<th>$^{238}$U</th>
<th>$^{226}$Ra</th>
<th>$^{228}$Ac</th>
<th>$^{228}$Th</th>
<th>$^{40}$K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{106}$CdWO$_4$</td>
<td>0.60(2)</td>
<td>0.018(8)</td>
<td>-</td>
<td>0.034(12)</td>
<td>&lt;1.6</td>
</tr>
<tr>
<td>CdWO$_4$ crystals</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Plastic light-guide</td>
<td>-</td>
<td>&lt;20</td>
<td>&lt;30</td>
<td>&lt;5</td>
<td>&lt;18</td>
</tr>
<tr>
<td>Quartz light-guides</td>
<td>-</td>
<td>&lt;6</td>
<td>&lt;15</td>
<td>&lt;1.2</td>
<td>&lt;6</td>
</tr>
<tr>
<td>Copper</td>
<td>-</td>
<td>&lt;0.4</td>
<td>&lt;1.0</td>
<td>&lt;0.10</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>PMTs</td>
<td>-</td>
<td>&lt;1000</td>
<td>&lt;4000</td>
<td>&lt;160</td>
<td>&lt;1600</td>
</tr>
</tbody>
</table>
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:

\[ \lim T_{1/2} = \frac{N \cdot \eta \cdot t \cdot \ln 2}{\lim S} \]

where:

- $N$ is the number of $^{106}$Cd nuclei in the $^{106}$CdWO$_4$ crystal ($N = 2.42 \times 10^{23}$);
- $\eta$ 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 $\eta$ = 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.

Preliminary search for $\beta \beta$ decay processes in $^{106}$Cd using $^{106}$CdWO$_4$ scintillator
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. $S/\eta$.
- According to Feldman & Cousins[127] procedure, an upper limit on $S/\eta$ (90% C.L.) is calculated.

![Table](image)

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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 $\gamma$ 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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<table>
<thead>
<tr>
<th>Decay, Level of $^{106}$Pd</th>
<th>Exp. selection</th>
<th>limit $T_{1/2}$ [yr] at 90% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0\nu 2\epsilon$ g.s.</td>
<td>AC/CC511</td>
<td>$\geq 2.5 \times 10^{20}$</td>
</tr>
<tr>
<td>$0\nu 2\epsilon$ 2$^+ 512$</td>
<td>CC511&amp;511</td>
<td>$\geq 2.6 \times 10^{20}$</td>
</tr>
<tr>
<td>Res. 0/2K 2718</td>
<td>AC/CC511</td>
<td>$\geq 4.3 \times 10^{20}$</td>
</tr>
<tr>
<td>Res. 0/KL$_2$ 4$^+$2741</td>
<td>AC/CC511</td>
<td>$\geq 3.1 \times 10^{20}$</td>
</tr>
<tr>
<td>Res. 0/KL$_2$ 2,3$^- 2748$</td>
<td>AC/CC511</td>
<td>$\geq 7.4 \times 10^{20}$</td>
</tr>
<tr>
<td>$2\nu\epsilon$ g.s.</td>
<td>CC 511&amp;511</td>
<td>$\geq 1.6 \times 10^{21}$</td>
</tr>
<tr>
<td>$2\nu\epsilon$ 2$^+ 512$</td>
<td>CC 511&amp;511</td>
<td>$\geq 5.5 \times 10^{21}$</td>
</tr>
<tr>
<td>$2\nu\epsilon$ 1$^+ 1228$</td>
<td>CC 511&amp;511</td>
<td>$\geq 2.1 \times 10^{21}$</td>
</tr>
<tr>
<td>$2\nu\epsilon$ 0$^+ 1134$</td>
<td>CC 511&amp;511</td>
<td>$\geq 2.6 \times 10^{21}$</td>
</tr>
<tr>
<td>$0\nu\epsilon$ g.s.</td>
<td>CC 511&amp;511</td>
<td>$\geq 3.3 \times 10^{21}$</td>
</tr>
<tr>
<td>$0\nu\epsilon$ 2$^+ 512$</td>
<td>CC 511&amp;511</td>
<td>$\geq 5.0 \times 10^{21}$</td>
</tr>
<tr>
<td>$0\nu\epsilon$ 2$^+ 1128$</td>
<td>CC 511&amp;511</td>
<td>$\geq 2.6 \times 10^{21}$</td>
</tr>
<tr>
<td>$0\nu\epsilon$ 0$^+ 1134$</td>
<td>CC 511&amp;511</td>
<td>$\geq 2.8 \times 10^{21}$</td>
</tr>
<tr>
<td>$2\nu\beta^+$ g.s.</td>
<td>CC 511&amp;511</td>
<td>$\geq 4.8 \times 10^{21}$</td>
</tr>
<tr>
<td>$2\nu\beta^+$ 2$^+ 512$</td>
<td>CC 511&amp;511</td>
<td>$\geq 4.3 \times 10^{21}$</td>
</tr>
<tr>
<td>$2\nu\beta^+$ 2$^+ 512$</td>
<td>CC 511&amp;511</td>
<td>$\geq 4.7 \times 10^{21}$</td>
</tr>
<tr>
<td>$0\nu\beta^+$ g.s.</td>
<td>CC 511&amp;511</td>
<td>$\geq 4.3 \times 10^{21}$</td>
</tr>
</tbody>
</table>


Preliminary search for $\beta\beta$ decay processes in $^{106}$Cd using $^{106}$CdWO$_4$ scintillator.
THANKS FOR ATTENTION!