Search for double beta decay in $^{106}$Cd in the DAMA/Crys setup


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106Cd, a promising isotope:

1) One of the six isotopes candidate for 2\beta^+ decay
2) High natural abundance δ=(1.25±0.06)%; possible enrichment up to 100%;
3) Q_{2\beta} = (2775.39±0.10) keV; 2\beta^+, \epsilon\beta^+ and 2\epsilon decay modes possible
4) Possible resonant 2\epsilon0\nu captures to excited level of 106Pd (2718 keV – 2K0\nu, 2741 keV – KL_10\nu, 2748 keV – KL_30\nu)
5) Theoretical T_{1/2} favorable for some modes (10^{20} – 10^{22} yr) [1] (g.s. to g.s.)

Current activity on $2\beta$ decay of $^{106}\text{Cd}$

TGV-2 Experiment:
32 planar HPGe + 16 foils of $^{106}\text{Cd}$ ($\delta=75\%$, 13.6 g), LSM (France)

**Telescope Germanium Vertical (TGV-2)**

- 32 HPGe planar detectors $\varnothing 60$ mm x 6 mm
- with sensitive volume: $20.4$ cm$^2$ x 6 mm
- Total sensitive volume: $\sim 400$ cm$^3$
- Total mass of detectors: $\sim 3$ kg
- Total area of samples: $330$ cm$^2$
- Total mass of sample(s): $10 \div 25$ g
- Total efficiency: $50 \div 70 \%$
- E-resolution: $3 \div 4$ keV @ $^{60}\text{Co}$
- LE-threshold: $5 \div 6$ keV

Double beta emitters:
- 16 samples ($\sim 50 \mu$m) of $^{106}\text{Cd}$ (enrich.75%)
- 13.6 g $\sim 5.79 \times 10^{22}$ atoms of $^{106}\text{Cd}$

**Current sensitivity:** $T_{1/2} \approx 10^{20}$ yr

N.I. Rukhadze et al., NPA 852 (2011) 197, BRASP 75 (2011) 879

COBRA:
32 semiconductors CdZnTe (1 cm$^3$ each), LNGS (Italy)

**Current sensitivity:** $T_{1/2} \approx 10^{18}$ yr

K. Zuber, Prog. Part. Nucl. Phys. 64 (2010) 267
CdWO₄ as a 2β detector

CdWO₄ crystal scintillator:

- Good scintillation properties
- Low levels of internal contamination in U, Th and K
- α/β discrimination capability

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm³]</td>
<td>7.9</td>
</tr>
<tr>
<td>Melting point [K]</td>
<td>1598</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>No</td>
</tr>
<tr>
<td>Wavelength of max emission [nm]</td>
<td>475</td>
</tr>
<tr>
<td>Refractive index @ max em.</td>
<td>2.2-2.3</td>
</tr>
<tr>
<td>Primary decay time [µs]</td>
<td>14</td>
</tr>
<tr>
<td>Photoelectron yield [% of NaI(Tl)]</td>
<td>30-50</td>
</tr>
</tbody>
</table>

• DAMA and INR-Kiev Collaboration
• Samples of cadmium were purified by vacuum distillation (Institute of Physics and Technology, Kharkiv) and the Cadmium tungstate compounds were synthesized from solutions
• Crystal boule was grown by the low-thermal-gradient Czochralski technique (NIIC Novosibirsk) (initial powder 265 g)
• Crystal scintillator (216 g), 66.4% enrichment in $^{106}$Cd measured by thermal ionisation mass-spectrometry ($2.66 \times 10^{23}$ nuclei of $^{106}$Cd)
• 2$^{nd}$ enriched CdWO$_4$ crystal ever produced
• Measured in DAMA/R&D set-up and in LNGS Stella facility

$^{106}$CdWO$_4$ crystal scintillator

Crystal surface has been diffused to improve light collection
Excellent optical and luminescence properties were reached thanks to a special R&D (deep purification of raw materials and low-gradient crystal growth by the Czochralski method). High light output.

**106CdWO₄ crystal scintillator**

Optical transmission curve

Response of the detector to γ sources

Emission spectra of ¹⁰⁶CdWO₄ crystal under ultraviolet (PL) and X-ray (RL) excitation

FWHM = 10% @ 662 keV
Searching for $2\beta$ decay by using $^{106}\text{CdWO}_4$ at LNGS

Experiment with $^{106}\text{CdWO}_4$ performed at LNGS in the framework of the DAMA and INR-Kiev Collaboration:

- single crystal in DAMA/R&D
- in coincidence with 4 HP-Ge in the Stella facility

1$^{\text{st}}$ exp in DAMA/R&D

2$^{\text{nd}}$ exp in HP-Ge Stella facility
Contamination level in $^{106}$CdWO$_4$ (mBq/Kg)

- $^{207}$Bi: <0.7
- $^{113m}$Cd: $116 \times 10^3$
- $^{232}$Th: < 0.07
- $^{228}$Th: 0.042(4)
- $^{238}$U: <0.6
- $^{226}$Ra: 0.012(3)
- $^{40}$K: <1.4
- $^{207}$Bi surface: 0.06 mBq/cm$^3$

Result:

$T_{1/2} (2\beta, ^{106}\text{Cd} \rightarrow ^{106}\text{Pd}) \geq 10^{19-21}$ yr

27 new results for $2\beta ^{106}\text{Cd}$
9 of them – for the first time
• $^{106}$CdWO$_4$ in coincidence / anticoincidence with 4-crystals HPGe detector (GeMulti)

• Crystal Surface cleaned

• Registration efficiency $\sim (3\%-8\%)$

• New limits on $2\epsilon, \epsilon\beta^+, 2\beta^+$ processes on the level of $T_{1/2} > 10^{20} - 10^{21}$ yr

• The half-life limit on the $2\nu\epsilon\beta^+$ decay, $T_{1/2} > 1.1 \times 10^{21}$ yr, reached the region of theoretical predictions

• For $0\nu\epsilon2$ resonant captures: $T_{1/2} > (8.5 \times 10^{20} - 1.4 \times 10^{21})$ yr

Energy spectrum of $^{106}$CdWO$_4$ detector in coincidence with 511 keV in HPGe (circles). Monte Carlo simulated distributions of $2\beta$ decay of $^{106}$Cd excluded at 90% CL.
PbWO₄ light-guide realized in order to suppress the radioactive components from the photomultiplier

Archaeological lead: A (²¹⁰Pb) <0.3 mBq/kg [3]

Purification Pb: Institute of Physics and Technology (Kharkiv)

Crystal growth: Institute of Scintillation Materials (Kharkiv)

Firstly used in the $^{106}$Cd experiment in GeMulti

New $^{106}$CdWO$_4$ experiment in DAMA/Crys set-up

1) New experiment with $^{106}$CdWO$_4$ in (anti)coincidence with two large CdWO$_4$ scintillators mounted in DAMA/Crys set-up at LNGS

2) High efficiency

3) Experiment in data taking since May 2016
New $^{106}\text{CdWO}_4$ experiment in DAMA/Crys set-up
Energy resolutions for $^{106}\text{CdWO}_4$ and $\text{CdWO}_4$

- $^{22}\text{Na}$, 511 keV: 17.5(1)%
- $^{22}\text{Na}$, 1274.5 keV: 12.9(2)%
- $^{137}\text{Cs}$, 662 keV: 16.3(2)%
- $^{22}\text{Na}$, 511 keV: 13.2(2)%
- $^{137}\text{Cs}$, 662 keV: 12.4(3)%
- $^{22}\text{Na}$, 1274.5 keV: 8.3(1)%

Counts / 10 keV / h

- $^{22}\text{Na}$, 511 keV: 17.5(1)%
- $^{22}\text{Na}$, 1274.5 keV: 12.9(2)%
- $^{137}\text{Cs}$, 662 keV: 16.3(2)%
- $^{22}\text{Na}$, 511 keV: 13.2(2)%
- $^{137}\text{Cs}$, 662 keV: 12.4(3)%
- $^{22}\text{Na}$, 1274.5 keV: 8.3(1)%

Energy, keV
Detector Performances

$^{106}$CdWO$_4$ detector pulses start positions relatively to the $^{nat}$CdWO$_4$ signals

$$\Delta T = T_{nat,i} - T_{106}$$

- $T_{nat,i}$: start of the signal in the $i$-th CdWO$_4$ detector
- $T_{106}$: start of the signal in $^{106}$CdWO$_4$ detector

- Events collected irradiating the detectors with a $^{22}$Na source.
- Event with energy 1273 keV in $^{106}$CdWO$_4$ and with 511 keV (within 3 $\sigma$) in the first (left) and second (right) CdWO$_4$. 
Pulse shape discrimination (PSD)

\[ SI = \frac{\sum f(t_k) \times P(t_k)}{\sum f(t_k)} \]

\[ P(t) = \frac{[f_\alpha(t) - f_\gamma(t)]}{[f_\alpha(t) + f_\gamma(t)]} \]

- \( f(t_k) \): amplitude at \( t_k \)
- \( P(t_k) \): weight function
- \( f_\alpha, f_\beta(t_k) \): reference pulse

\( \gamma(\beta), 88\% \)

\( \alpha, 88\% \)

\( 1.2\sigma \)

\( 3\sigma \)

\( \sigma \)
The $\alpha$ spectrum

Spectrum of $\alpha$ particles obtained by PSD over 3300 h with fit of radioactive contaminations

$$\alpha/\gamma = 0.102 + 0.112E^{-4}\times E_\alpha$$

$$\text{FWHM}_\alpha = 0.157\times E^\gamma_\alpha$$

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Activity, mBq/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$^{232}\text{Th}$</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>$^{228}\text{Th}$ + daughters</td>
<td>$^{228}\text{Th}$ + daughters</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$^{238}\text{U}$</td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>$^{234}\text{Th}$</td>
<td>$^{234}\text{Th}$</td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>$^{230}\text{Th}$</td>
<td>$^{230}\text{Th}$</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$^{210}\text{Po}$</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>
Activity of $^{228}\text{Th}$:

- The arrival time, the energy and the pulse shape of each event were used to select the fast decay chain in the $^{228}\text{Th}$ sub-chain of the $^{232}\text{Th}$ family:

  $^{224}\text{Ra}$ ($Q = 5.789$ MeV, $T_{1/2} = 3.66$ d)
  \[ \downarrow \]
  $^{220}\text{Rn}$ ($Q = 6.405$ MeV, $T_{1/2} = 55.6$ s)
  \[ \downarrow \]
  $^{216}\text{Po}$ ($Q = 6.906$ MeV, $T_{1/2} = 0.145$ s)
  \[ \downarrow \]
  $^{212}\text{Pb}$

Activity of $^{228}\text{Th}$ in $^{106}\text{CdWO}_4$ crystal was estimated as: $5(1)\, \mu\text{Bq/kg}$

Also was estimated $\alpha/\gamma$ ratio and energy resolution for alpha-particles.
The energy spectra accumulated over \textbf{6935 h} by the \(^{106}\text{CdWO}_4\) detector in anticoincidence with the \(^{nat}\text{CdWO}_4\) detectors, in coincidence with event(s) and when at least one of the \(^{nat}\text{CdWO}_4\) detectors with energy \(E > 200\) keV, \(E = 511\) keV, and \(E = 1160\) keV.
Sensitivity estimation

Expected signal for $^{106}\text{Cd} \, 0\nu 2\beta (0^+ \rightarrow 0^+)$:

- **Spectrum in $^{106}\text{CdWO}_4$ detector**
- **Spectrum in $^{106}\text{CdWO}_4$ detector when one of the two CdWO$_4$ detectors detects $\gamma$ of 511 keV ($\pm 2\sigma$)**
- **Spectrum in $^{106}\text{CdWO}_4$ detector when both the CdWO$_4$ detectors detect $\gamma$ of 511 keV ($\pm 2\sigma$)**

Sensitivity estimation after 1yr:

In the hypothesis of about 29 background counts in [0.-3.] MeV

\[ 0\nu\beta^+ \text{ (g.s.):} \quad T_{1/2} \approx 5. \times 10^{21} \text{ yr} \]

\[ 2\nu 2\beta^+ \text{ (g.s.):} \quad T_{1/2} \approx 2. \times 10^{21} \text{ yr} \]
Conclusion

- $^{106}$CdWO$_4$ successfully cleaned from the surface contamination ($^{207}$Bi).
- The detector is running in coincidence with two $^\text{nat}$CdWO$_4$ to search for 2$\beta$ processes in $^{106}$Cd.
- Deeply purified lead tungstate (PbWO$_4$) crystal light-guide from low-radioactive archaeological lead (that is free from $^{210}$Pb) used as light-guide to supress $\gamma$’s from PMT.
- Selection the events of $^{106}$CdWO$_4$ detector in coincidence with $^\text{nat}$CdWO$_4$ reduces background to search for 2$\beta^+$ processes $^{106}$Cd.
- Improvement in sensitivity expected for different of 2$\beta^+$ decay modes for $^{106}$Cd ($10^{20}$-10$^{21}$ years).
- Data taking and analysis of the experiment are in progress.
- Future production of $^{106}$CdWO4 depleted in $^{113}$Cd foreseen.