Luminescent bolometers for the study of double beta decay

Claudia Nones
CEA-IRFU
Outline

Neutrinoless double beta decay: experimental challenges

Merits and limits of the pure bolometric technique

Advantages offered by luminescent bolometers

Present scenario of luminescent bolometers for double beta decay

Detection of Cherenkov light in TeO$_2$ bolometers

$^{116}$CdWO$_4$ program in France

Study of $^{100}$Mo in the AMoRE project
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¹¹⁶CdWO₄ program in France

Study of ¹⁰⁰Mo in the AMoRE project
Neutrinoless double beta decay ($0\nu 2\beta$): standard and non-standard mechanisms

$0\nu 2\beta$ is a test for «creation of leptons»: $2n \rightarrow 2p + 2e^- \Rightarrow \text{LNV}$

This test is implemented in the nuclear matter: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

Energetically possible for 35 nuclei
Only a few are experimentally relevant

Standard mechanism: **neutrino physics**
- $0\nu 2\beta$ is mediated by **light massive Majorana neutrinos** (exactly those which oscillate)

Non-standard mechanism: **BSM, LNV**
Not necessarily neutrino physics
The shape of the two-electron sum-energy spectrum enables to distinguish between the 0ν (new physics) and the 2ν decay modes

\[ Q \approx 2 - 3 \text{ MeV} \] for the most promising candidates

The signal is a peak (at the Q-value) over an almost flat background
Goal of next-generation searches

\[ \langle M_{0\beta\beta} \rangle \text{ [eV]} \]

\[ M_{\text{lightest}} \text{ [eV]} \]

\[ T_{1/2} \sim 10^{27-28} \text{ y} \]

\[ g_A = 1.269 \text{ (no quenching)} \]

\[ O(1 \text{ ton}) + \sim \text{zero background} \]
Request for the background index

Background index

\[ b \ [\text{counts/(keV kg y)}] \]

number of background counts

detector (isotope) mass \times live time \times energy interval

around the Region of Interest

In the source=detector approach

with high energy resolution technique (\[ \Delta E_{\text{FWHM}} < 10 \text{ keV} \])

zero background at the tonne scale means

\[ b \lesssim 10^{-4} \ [\text{counts/(keV kg y)}] \]

Present record: GERDA (\(^{76}\text{Ge}\)) <

\[ b \sim 7 \times 10^{-4} \text{ counts/(keV kg y)} - \Delta E_{\text{FWHM}} \sim 3 \text{ keV} \]

Talk of Ann-Kathrin Schuetz
Silver and golden isotopes

Golden isotopes:
- $^{48}\text{Ca}$ – $^{150}\text{Nd}$ – $^{96}\text{Zr}$ – $^{100}\text{Mo}$ – $^{82}\text{Se}$ – $^{116}\text{Cd}$

Silver isotopes:
- $^{76}\text{Ge}$ – $^{130}\text{Te}$ – $^{136}\text{Xe}$

$Q$-value [MeV]

Natural $\gamma$ radioactivity limit

$^{208}\text{TI} \gamma$

130$\text{Te}$ is almost golden: $Q$-value (2527 keV) in a clean window between 2615 keV $\gamma$ peak and its Compton edge (2382 keV)

$G(Q,Z) \propto Q^5$

Background

Large-scale enrichment is possible

Magnificent Nine candidates

Phase space: $G(Q,Z) \propto Q^5$

$^{208}\text{Tl} \gamma$

2.6 MeV $^{208}\text{Tl} \gamma$
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Bolometers: ideal detectors for $0^\nu 2\beta$

**Bolometric approach**: the source is embedded in a crystal, which is cooled down to 10-20 mK and works as a perfect calorimeter

\[ \Delta T = \frac{E}{C} \]

**Attractive features of bolometers for $0^\nu 2\beta$ decay**

- High energy resolution (~ down to 4 keV FWHM in the ROI)
- ~ 0.1-0.5 kg source in each crystal → large masses achievable through arrays
- Crystals can achieve very high radiopurity
- High efficiency (~ 80 – 90 %)
- Experience: Cuoricino/CUORE experiments → crystals of TeO$_2$ (isotope $^{130}$Te)
- Large flexibility in the detector material choice: $^{130}$Te, and three golden isotopes ($^{82}$Se, $^{100}$Mo, $^{116}$Cd) can be studied
Are pure bolometers enough to fully explore the IH region?

**NO !!**

**CUORE will not** be a zero-background search (~50 counts/y expected in the ROI)

**WHY ??**
Residual surface $\alpha$ background

Lessons learned from TeO$_2$ bolometric experiments (CUORE and predecessors)

Irreducible background due to alpha particles, emitted at the surfaces and energy-degraded

$b \sim 10^{-2} \text{ [counts/(keV kg y)]}$
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Luminescent bolometers: the solution!

Bolometric technique (CUORE, EDELWEISS…) + Simultaneous detection of heat and light (CRESST)

Choice of the candidate: Golden or almost golden isotope
“zero” gamma background

Full α/β separation
“zero” alpha background

= zero background at the ≈ 1 ton x year scale

- First demonstration (in the 0ν2β context): E. Fiorini’s group (Milano) in 1992
- First optical bolometer: N. Coron’s group (IAS, Orsay) in 1995
- Extensive application in Dark Matter for electron/nuclear recoil separation (CRESST)
- First proposal (Cherenkov): T. Tabarelli de Fatis (2010)
The most convenient method to realize a light detector at low temperatures is the development of an auxiliary bolometer, made with a thin absorber opaque to the light emitted by the main bolometer, and facing one polished side of it.

Luminescent bolometer <

Actual light and heat signals acquired with a \( \text{CdWO}_4 \) scintillating bolometer

\[ 2615 \text{ keV } \gamma \text{-ray} \]
α / β separation

α's emit a different amount of light with respect to β/γ of the same energy. Separation can be achieved also with pulse shape discrimination in the light signal (ex. ZnSe).

A scatter plot light vs. heat or plot light-yield vs. heat separates α's from β’s / γ’s.

Example of a luminescent bolometer with bolometric light detector.

ZnSe only!
## Extensive bolometric test of $0\nu 2\beta$ candidates

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>I. A. [%]</th>
<th>Q-value [keV]</th>
<th>Materials successfully tested as bolometers in crystalline form (underlined compounds: scintillators)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.8</td>
<td>2039</td>
<td>$\text{Ge}$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>8.9</td>
<td>2479</td>
<td>$\text{TeO}_2$, $\text{CdWO}_4$, $\text{CdMoO}_4$, $\text{ZnSe}$, $\text{LiInSe}_2$, $\text{PbMoO}_4$, $\text{CaMoO}_4$, $\text{SrMoO}_4$, $\text{CdMoO}_4$, $\text{SrMoO}_4$, $\text{ZnMoO}_4$, $\text{Li}_2\text{MoO}_4$, $\text{MgMoO}_4$</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>33.8</td>
<td>2527</td>
<td>$\text{TeO}_2$ is a very weak scintillator</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>7.5</td>
<td>2802</td>
<td>$\text{CdWO}_4$, $\text{CdMoO}_4$, $\text{ZnSe}$, $\text{LiInSe}_2$, $\text{PbMoO}_4$, $\text{CaMoO}_4$, $\text{SrMoO}_4$, $\text{CdMoO}_4$, $\text{SrMoO}_4$, $\text{ZnMoO}_4$, $\text{Li}_2\text{MoO}_4$, $\text{MgMoO}_4$</td>
</tr>
<tr>
<td>$^{62}\text{Se}$</td>
<td>9.2</td>
<td>2995</td>
<td>$\text{ZnMoO}_4$, $\text{Li}_2\text{MoO}_4$, $\text{MgMoO}_4$, $\text{CaF}_2$, $\text{CaMoO}_4$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>9.6</td>
<td>3034</td>
<td>$\text{ZrO}_2$, $\text{CaF}_2$, $\text{CaMoO}_4$</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>2.8</td>
<td>3350</td>
<td>NONE $\rightarrow$ many attempts</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>5.6</td>
<td>3367</td>
<td>NONE $\rightarrow$ many attempts</td>
</tr>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>0.187</td>
<td>4270</td>
<td>NONE $\rightarrow$ many attempts</td>
</tr>
</tbody>
</table>

Most of the compounds have been studied also as **luminescent bolometers**

- Pioneering work of S. Pirro and his group at LNGS
- LUCIFER group
- LUMINEU group
- AMoRE group

Luminescent bolometers are excellent candidates for the technology of **CUPID**, proposed follow-up of the CUORE experiment.
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Study of $^{100}$Mo in the AMoRE project
**Current scenario**

- **Detection of Cherenkov light**
  - Light detector technology
  - TES-based
  - NTD-Ge-thermistor based
  - MKIDs based
  - Neganov-Luke-effect assisted

- **Tests with natural crystals** (Milano/LNGS group)
- **First enriched crystal test** (CSNSM-IRFU)

- **Increasing Q-value**
  - **$^{130}\text{Te}$**
    - LUCIFER program
  - **$^{116}\text{Cd}$**
    - CUPID-O experiment
  - **$^{82}\text{Se}$**
    - AMoRE experiment
    - LUMINEU / LUCIFER
    - CUPID-Mo experiment
  - **$^{100}\text{Mo}$**
Current scenario

Detection of Cherenkov light
Light detector technology
- TES-based
- NTD-Ge-thermistor based
- MKIDs based
- Neganov-Luke-effect assisted

Increasing Q-value

$^{130}$Te

$^{116}$Cd

$^{82}$Se

$^{100}$Mo

Covered in this conference

Talk of Laura Cardani

Tests with natural crystals (Milano/LNGS group)
First enriched crystal test (CSNSM-IRFU)

LUCIFER program
CUPID-0 experiment
AMoRE experiment
LUMINEU / LUCIFER
CUPID-Mo experiment

Talk of Nicola Casali
Talk of Andrea Giuliani
Current scenario

- Detection of Cherenkov light
  - Light detector technology
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Increasing Q-value
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The case of $^{130}$Te

Cherenkov light emission induced by $\gamma(\beta)$ interactions in TeO$_2$ is expected


Cherenkov thresholds:

<table>
<thead>
<tr>
<th>$E_e &gt; 50$ keV</th>
<th>$E_\alpha &gt; 400$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{130}$Te $Q_{\beta\beta}$ ($\sim$2.5 MeV)</td>
<td>~220 Cherenkov photons (300-900 nm) $\rightarrow$ ~600 eV</td>
</tr>
<tr>
<td>No Cherenkov photons from natural $\alpha$ radioactivity</td>
<td></td>
</tr>
</tbody>
</table>

In real life, for TeO$_2$ CUORE-size crystals (5x5x5 cm$^3$), collected light corresponds to a total energy of $\sim$100 eV

**Discrimination Power (DP)** (to quantify $\alpha/\beta$ separation)

$$DP = \frac{|\mu_{\beta/\gamma} - \mu_\alpha|}{\sqrt{\sigma_{\beta/\gamma}^2 + \sigma_\alpha^2}}$$

Vibrant R&D activities (variegate technologies)

<table>
<thead>
<tr>
<th>Crystal</th>
<th>LD sensor</th>
<th>LD RMS [eV]</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeO$_2$, 6 g</td>
<td>NTD Ge</td>
<td>n.a.</td>
<td>4.70</td>
</tr>
<tr>
<td>TeO$_2$, 23 g</td>
<td>TES IrAu</td>
<td>8</td>
<td>3.59</td>
</tr>
<tr>
<td>TeO$_2$, 117 g</td>
<td>NTD Ge*</td>
<td>97</td>
<td>1.37</td>
</tr>
<tr>
<td>TeO$_2$, 285 g</td>
<td>TES W*</td>
<td>23</td>
<td>3.69</td>
</tr>
<tr>
<td>TeO$_2$, 750 g</td>
<td>NTD Ge</td>
<td>19</td>
<td>2.70</td>
</tr>
<tr>
<td>$^{130}$TeO$_2$, 435 g</td>
<td>NTD Ge</td>
<td>35</td>
<td>2.65</td>
</tr>
<tr>
<td>$^{130}$TeO$_2$, 435 g</td>
<td>NTD Ge</td>
<td>25</td>
<td>3.50</td>
</tr>
</tbody>
</table>

*Phys. Rev. C 94 (2016) 054608*  
*J. Instrum. 10 (2015) P03003*  
*Astropart. Phys. 35 (2012) 558*  
*Astropart. Phys. 69 (2015) 30*  
*J. Low Temp. Phys. 184 (2016) 286*  
**Neganov-Luke effect + NTD Ge thermistor readout**

**Goal**: get full event-by-event $\alpha/\beta$ separation with the same read-out as in CUORE and the same crystal size presently adopted in CUORE

\[ E = E_0 \cdot \left(1 + \frac{q \cdot V}{\varepsilon}\right) \]

$q$: electron charge  
$V$: voltage applied  
$\varepsilon$: energy used to produce an electron-hole pair
Development of Neganov-Luke light detectors at CSNSM using EDELWEISS electrode technology → Dedicated evaporators for Al and SiO films
Test with a CUORE-size crystal at Modane underground laboratory

GeCo1 has also been tested coupled to a natural TeO₂ crystal (784 g) at a working temperature of 17 mK

This test has been performed in Laboratoire Souterrain de Modane (LSM, France)

EDELWEISS set-up
**Separated heat/light calibrations**

**Heat channel** - $^{232}$Th calibration

**Light channel** - X-ray fluorescence calibration
(Zero bias on Neganov-Luke electrodes)

Detector holder internally coated with silver
α/β separation

Neganov-Luke voltage = 0 V

Preliminary
\[ \alpha/\beta \text{ separation} \]

Neganov-Luke voltage = 0 V

Neganov-Luke voltage = 60 V (optimum performance)

DP = 3.17
2440-2790 keV

Preliminary
\[ \alpha/\beta \text{ separation} \]

Neganov-Luke voltage = 0 V

\[
\begin{array}{c|c|c}
\text{Grids bias} & \text{Baseline RMS} & \text{Signal/Noise} \\
0 V & 108 \text{ eV} & 0.6 \\
60 V & 10 \text{ eV} & 7 \\
\end{array}
\]

Neganov-Luke voltage = 60 V (optimum performance)

\[ \text{DP} = 3.17 \]

2440-2790 keV

\((210^{\text{Po}})\)
The best result ever obtained with a CUORE-size TeO$_2$ crystal

96.3% $0\nu\beta\beta$ signal acceptance with 99.9% $\alpha$ rejection

LSM results (preliminary, unpublished)

$J.\text{ Low Temp. Phys. 184 (2016) 286}$

(Obtained in LNGS hall C with a similar Neganov-Luke CSNSM detector)
Not only Cherenkov light...

First hint of TeO$_2$ scintillation: *Nucl. Instrum. Meth. A* **520**(1-3) (**2004**) 159-162
(N. Coron’s group (IAS, Orsay))
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The case of $^{116}$Cd

- $^{116}$Cd $\rightarrow$ $^{116}$Sn + 2e$^-$
- $Q_{bb} = 2814$ keV
- I.A.(100) = 7.5 %
- enrichable by gas centrifugation
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- $Q_{bb} = 2814$ keV
- I.A.(100) = 7.5 %
- enrichable by gas centrifugation

Caveats $^{113}$Cd

- Enrichment cost at least a factor 2 higher than $^{100}$Mo, $^{82}$Se, $^{130}$Te
- $^{214}$Bi line at 3054 keV - B.R. 0.021 % - Compton edge 2818 keV
Historical results on CdWO$_4$ scintillating bolometers

Tests performed in LNGS

Astropart. Phys. 34 (2010) 143
Historical results on $\text{CdWO}_4$ scintillating bolometers

2615 keV $^{208}\text{Tl} \gamma$

44 days background

High internal contamination
First results on an enriched $^{116}\text{CdWO}_4$ scintillating bolometer

Aboveground test (CSNSM) of a 32 g enriched CdWO$_4$ detector

Very good energy resolution: 7.5 keV FWHM
Excellent $\alpha/\beta$ separation

Double crystallization by low-thermal gradient Czochralski technique $\rightarrow$ excellent radiopurity

Very promising

Pilot experiment with $^{116}\text{CdWO}_4$ scintillating bolometers

**CYGNUS project**
- Use existing radiopure $^{116}\text{CdWO}_4$ enriched crystals (ITEP Moscow, KINR Kiev)
- Total mass 1.16 kg
- Array of two or four elements to be installed in LSM (together with CUPID-Mo)

From the total background budget (Monte Carlo simulation of the EDELWEISS set-up):

$$b = 2.4 \times 10^{-3} \text{ counts/(keV kg y)}$$

dominated by cosmogenic $^{110m}\text{Ag}$

3 y data taking: $T_{1/2} > 8.2 \times 10^{23}$ yr at 90% C.L. The half-life limit corresponds to the effective neutrino mass limit $m_{\beta\beta} < 0.6 - 0.9$ eV
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The case of $^{100}$Mo

- $^{100}$Mo $\rightarrow$ $^{100}$Ru + 2e$^-$
- $Q_{bb} = 3034$ keV
- I.A.(100) = 9.7 %
- Enrichable by gas centrifugation

Caveats $^{100}$Mo

- $T_{1/2}(2\nu) = 7.1 \times 10^{18}$ $\gamma$ - the fastest one in all $0\nu2\beta$ candidates

- $^{214}$Bi line at 3054 keV - B.R. 0.021 % - Compton edge 2818 keV (less critical than for $^{116}$Cd)
Useful Mo-based crystals

Crystals successfully tested so far as scintillating bolometers:

- CdMoO$_4$
- PbMoO$_4$
- SrMoO$_4$
- ZnMoO$_4$
- Li$_2$MoO$_4$
- CaMoO$_4$

LUMINEU - CUPID-Mo
- Initial choice (2012): ZnMoO$_4$
- First tests on large Li$_2$MoO$_4$ crystals: spring 2014
- Choice in favour of Li$_2$MoO$_4$

AMoRE
- Advanced Mo-based Rare process Experiment

Drawbacks of CaMoO$_4$:
- Necessity of $^{48}$Ca depletion
- Radiopurity (difficult to purify Ca from U, Th, Ra)

New crystals will be studied
AMoRE-phased approach

AMoRE pilot
1.8 kg
now

AMoRE-I
5 kg
2018

AMoRE-II
200 kg
2020

From Yong-Hamb Kim’s talk
Shanghai double beta decay workshop – June 2017
AMoRE-phased approach

- MMC technology for heat and light measurement
- Crystal: $^{40}\text{Ca}^{100}\text{MoO}_4$, doubly enriched scintillating crystals (Pilot & I)
  
  For Phase II: $X^{100}\text{MoO}_4$ ($X$: Li, Na, $^{40}\text{Ca}$, Zn or Pb)

- Zero background condition in ROI
- Shield: Lead (Pilot, I), Water (II)
- Location: Y2L (Pilot, I) and a new deeper place (ARF at Handuk)

<table>
<thead>
<tr>
<th></th>
<th>Pilot</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1.8 kg</td>
<td>~5 kg</td>
<td>~200 kg</td>
</tr>
<tr>
<td>MMC Channel</td>
<td>12</td>
<td>28-36</td>
<td>1000</td>
</tr>
<tr>
<td>Required background (ckky)</td>
<td>0.01</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Sensitivity($T_{1/2}$) (year)</td>
<td>$\sim 10^{24}$</td>
<td>$\sim 10^{25}$</td>
<td>$\sim 5 \times 10^{26}$</td>
</tr>
<tr>
<td>Sensitivity($m_{ee}$) (meV)</td>
<td>380-720</td>
<td>120-230</td>
<td>17-32</td>
</tr>
<tr>
<td>Location</td>
<td>Y2L</td>
<td>Y2L</td>
<td>ARF</td>
</tr>
</tbody>
</table>

From Yong-Hamb Kim’s talk
Shanghai double beta decay workshop – June 2017
**AMoRE-single module**

\[ ^{40}\text{Ca}^{100}\text{MoO}_4 + \text{MMC} \]

**Phonon-Scintillation detection at mK**

**Sensor technology**

Metallic Magnetic Calorimeter

SQUID readout

*From Yong-Hamb Kim’s talk*

*Shanghai double beta decay workshop – June 2017*
AMoRE-particle discrimination

Particle discrimination by light heat ratio

4 MeV < $E_{ae}$ < 7 MeV

Phonon pulse shape discrimination (PSD)

From Yong-Hamb Kim's talk
Shanghai double beta decay workshop - June 2017
Conclusions

- $\alpha$ background is presently the limiting factor in bolometers for $0\nu2\beta$
- Luminescent bolometers have the potential to fully reject $\alpha$ events
- Luminescent bolometers are a mature technology: pilot experiments
  - CUPID-0 (ZnSe) \(\rightarrow\) presently in data taking
  - CUPID-Mo (Li$_2$MoO$_4$) \(\rightarrow\) data taking in 2018
  - AMoRE-I (CaMoO$_4 + X$MoO$_4$) \(\rightarrow\) data taking in 2018
- Encouraging R&D results on $^{116}$CdWO$_4$ and TeO$_2$
- Large-scale projects are envisaged: CUPID and AMoRE-II
Mechanism of surface $\alpha$ background

Bolometers are fully sensitive, up to the detector surface → no dead layer

Shallow (up to 10 $\mu$m deep) surface contamination (for example $^{210}$Po) of the bolometers themselves or of the materials surrounding them emit alpha particles

Challenging events:
They release in the detector only a part of the $\alpha$ energy and populate also the region above 2615 keV with a continuum