LUCIFER
TAUP 2011 – Munich

A Scintillating Bolometer Array for the Search of Neutrinoless Double Beta Decay

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La Sapienza, University of Roma
(0ν)DBD

Importance of the process:
- it can happen only if ν is a Majorana particle;
- its observation could lead to a measure of the effective mass:

\[
m_{\beta\beta} = \left| \sum_{j=1}^{3} U_{ej}^2 m_j \right| = \left| \sum_{j=1}^{3} U_{ej}^2 e^{i\phi_j} m_j \right|
\]

\[
\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^2 \left\langle m_{\beta\beta} \right\rangle^2
\]

What are we looking for?

This process is very rare so:

→ Low background

→ Large source mass

→ Good energy resolution
The Sensitivity $S^{0\nu}$ of an experiment is defined as the half-life corresponding to the minimum number of signal events observable above background at a given statistical significance.

$$S^{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

Where:

$\varepsilon$ = efficiency

i.a. = isotopic abundance

$A$ = atomic mass number

$M$ = detector mass [kg]

$t$ = live time of the experiment [y]

$\Delta E$ = energy resolution

$b$ = background [counts/keV/kg/y]
Bolometer Search for \((0\nu)\text{DBD}\)

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\]

What can we improve?

\(\varepsilon = \text{efficiency} \quad \rightarrow \quad \approx 100\% \text{ for bolometers}\)

\(i.a. = \text{isotopic abundance} \quad \rightarrow \quad \text{enrichment feasibility?}\)

\(A = \text{atomic mass number}\)

\(M = \text{detector mass \([kg]\)} \quad \rightarrow \quad \text{For the next generation is already } \approx 1 \text{ ton}\)

\(t = \text{live time of the experiment \([y]\)} \quad \rightarrow \quad \text{For the next generation is already } \approx 5 \text{ y}\)

\(\Delta E = \text{energy resolution} \quad \rightarrow \quad \approx 5 \text{ keV for bolometers}\)

\(b = \text{background \([\text{counts/keV/kg/y}]\)} \quad \text{main challenge!}\)
Background Reduction

How can we suppress the background in the energy region of interest?

Underground laboratories.

Ex: the detectors we will present have been studied in LNGS (Italy) → 3650 m.w.e.

muon flux: \( (2.58 \pm 0.3) \times 10^{-8} \, \mu/(s \, cm^2) \)


neutron flux [<10MeV] : \( \approx 4 \times 10^{-6} \, n/(s \, cm^2) \)

F. Arneodo et al., Il Nuovo Cim. 112A, 819, 1999

gamma flux: \( \approx 0.73 \, \gamma/(s \, cm^2) \)

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Proper shieldings or vetoes.

$\rightarrow$ “External” contributions to the background suppressed
$\rightarrow$ Ultimate limit given by contaminations of the detector itself (and materials in the nearby)

Bolometers background dominated by surface $\alpha$ contaminations of the materials:
contributions $\approx 10^{-2}$ counts/keV/kg/y
Scintillating Bolometers

Scintillating bolometers can overcome this problem by tagging the events!

Working principle: BOLOMETERS

A bolometer can be sketched as:

Absorber
If the interaction releases an energy $E$, we have a temperature increase:

$$\Delta T = \frac{E}{C}$$

$$\Delta T(t) = \frac{E}{C} \exp\left(-\frac{t}{\tau}\right) \quad \tau = \frac{C}{G}$$

→ dielectric and diamagnetic crystals ($C \div T^3$) operated at low temperatures (0.01 K).

Sensor
That converts $\Delta T$ into a readable voltage signal.

Proved technique
See S. Di Domizio’s and P. Gorla’s talks
Advantages of this technique

• Different isotopes can be tested
• Very high efficiency
• Excellent energy resolution (‰)
• Possibility of growing radio—pure crystals.

But...no possibility to tag the event

poor background rejection (α events)
Scintillating Bolometers

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Solution: Scintillating Bolometers!
Based on double read-out: HEAT + LIGHT

e⁻ and α of the same energy:
- Release the same heat in the bolometer
- Produce a different amount of light → discrimination

A. Alessandrello et al., Nuclear Physics B 28 (1992) 233-235
Scintillating Bolometers

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The light can be detected by means of a second bolometer (usually Ge or Si disk)

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α background eliminated \(\rightarrow\) the main problem is given by the γ contaminations
Scintillating Bolometers

$\alpha$ background eliminated $\rightarrow$ the main problem is given by the $\gamma$ contaminations.

$\rightarrow$ Which isotope?
Selenium, Cadmium and Molibdenum

...according to the enrichment feasibility!
An extensive R&D activity was performed in the last years.

*arXiv:nucl-ex/0510074v11*
## Promising Crystals

<table>
<thead>
<tr>
<th>Material</th>
<th>Q-value [keV]</th>
<th>Useful material [%]</th>
<th>LY [keV/MeV]</th>
<th>QF</th>
<th>Enrichment [€/g]</th>
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<tbody>
<tr>
<td>CdWO₄</td>
<td>2809</td>
<td>32%</td>
<td>17.6</td>
<td>0.19</td>
<td>&gt;150 - 200</td>
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<td>ZnMoO₄</td>
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A CdWO₄ array (mass of the single crystal = 0.51 kg) was successfully tested some years ago.

**Problems:** Presence of $^{113}$Cd Enrichment
# Promising Crystals

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An intense R&D activity on ZnMoO₄ on-going².

But no large crystals (yet). Radiopurity?

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2) JINST 5 (2010) P11007
Promising Crystals

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Several samples of ZnSe have been recently tested\(^3\).

Disadvantages...
QF > 1  \(\Rightarrow\)  LY(\(\alpha\)) > LY(\(\beta/\gamma\))
No theoretical model can explain this behavior
We discarded this hypothesis:
1) ZnSe self—absorption
2) Light collection efficiency
3) Light detector transparent to certain wavelengths

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Disadvantages...
QF > 1 → LY(α) > LY(β/γ)
No theoretical model can explain this behavior
Other tests are needed
Promising Crystals

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Nevertheless...

- Very radio-pure compounds can be obtained
- Large LY
- Excellent discrimination
- Good energy resolution ($\approx$9 keV @ 2615 keV)

$\rightarrow$ Can be the baseline for LUCIFER project.
ZnSe: production

1. raw (elemental) Se
2. certification
3. SeF$_6$ synthesis
4. SeF$_6$ enrichment
5. Se conversion
6. Se beads production
7. Zn elemental
8. enriched Se elemental
9. purification
10. certification
11. ZnSe synthesis
12. certification
13. ZnSe crystal growth
14. mechanical processing
15. recovery and recycling
16. package and shipment
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1) Need radio-chemical pure Se → measurements with ICP-MS

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   The enrichment is feasible
   Chemical problems in Se conversion (mainly reagents contaminations!)
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   HpGe γ spectroscopy
   Purification (99.999%) → zone refining?
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   High temperature method or
   Low temperature method (CVD)
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5) Growth of ZnSe crystal:
   Avoiding twining and Reproducibility
Optimization of the Light Detectors (Si or Ge bolometers)

Excellent energy resolution: $\sigma \approx 140$ eV
Light Detectors

Optimization of the Light Detectors (Si or Ge bolometers)

Excellent energy resolution: $\sigma \approx 140$ eV

Test on the LD performances:
Measurement of TeO$_2$ (no scintillation!)
First detection of Cerenkov light!

Now R&D focused on the LD optimization (dimensions, surface treatments..) and reproducibility.
The produced crystals will be arranged in an array and operate deep underground.

This project, financed by an European Grant (ERC) will demonstrate the power of this technique.

However, a good sensitivity can be reached:
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Assuming:  
- $b = 10^{-3}$ counts/keV/kg/y  
- $\Delta E = 5$ keV  
- i.a. = 95%  
- Live Time = 5 y  

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<thead>
<tr>
<th>Option</th>
<th>Isotope weight</th>
<th>Half life limit ( x $10^{26}$ y)</th>
<th>Sensitivity to m$\beta\beta$ [meV]*</th>
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<td>ZnSe baseline</td>
<td>17.6 kg</td>
<td>2.31</td>
<td>52 -65</td>
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<td>20.5 kg</td>
<td>2.59</td>
<td>49 - 61</td>
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<td>Improvement 2</td>
<td>27.8 kg</td>
<td>3.20</td>
<td>44 - 55</td>
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* J. Mendez et al. arXiv:0801.3760;  
* F. Simkovic et al. Phys. Rev. C77 (2008);  
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Not too optimistic evaluation:
- 10 kg of $^{82}\text{Se}$
- $\sim 100$ meV as $<m_{\beta\beta}>$ sensitivity

Option | Improvement | Sensitivity to $m_{\beta\beta}$ [meV]  
--- | --- | ---  
1 | 20.5 kg | 2.59 $\times 10^{-26}$ y  
2 | 27.8 kg | 3.20 $\times 10^{-26}$ y  

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CONCLUSIONS

The main challenge for a next generation experiment on 0νDBD is the background reduction.

Scintillating bolometers allow to suppress the background. A smart choice of the isotope provides a further reduction. 
→Very low background in the energy region of interest!

The goal of LUCIFER is to demonstrate the feasibility of a large mass experiment based on this technique.

In addition, a good sensitivity on the decay will be achieved.

Data taking is foreseen for 2014!
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THANK YOU FOR THE ATTENTION
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<th>Crystal color</th>
<th>Mass [g]</th>
<th>LY [keV/MeV]</th>
<th>QF$_\alpha$</th>
</tr>
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<tr>
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<td>Yellow</td>
<td>37.5</td>
<td>1.3</td>
<td>4.4</td>
</tr>
<tr>
<td>Large</td>
<td>Red</td>
<td>120</td>
<td>7.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Huge</td>
<td>Orange</td>
<td>337</td>
<td>4.6</td>
<td>3</td>
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CONDUCTION BAND

\[ \lambda_{600} (2.067eV) \]
\[ \lambda_{635} (1.953eV) \]

Zn\textsubscript{i} \hspace{1cm} V_{Se} \hspace{1cm} Te_{Se}

VALENCE BAND

\[ V_{Zn} \]
\[ V_{Zn} M^{III} O_{Se} \]


LEGEND

- \( e^- \): free electron
- \( e^+ \): free hole
- Zn\textsubscript{i}: Zn interstitial position
- \( V_{Zn} \), \( V_{Se} \): Zn and Se vacancies
- Te\textsubscript{Se}: Te substitutional (Se position)
- complex defect with trivalent metal and substitutional Oxygen (Se position)
- \( \lambda_{600} \), \( \lambda_{635} \): emission wavelengths
ZnSe features

Molecular formula: ZnSe
Molar mass: 144.35 g/mol
Appearance: light yellow solid
Density: 5.27 g/cm³
Melting point: 1525 °C
Nonhygroscopic, insoluble in water
band gap: 2.70eV (@25°C)
Refractive index: 2.67 (@550 nm), 2.40 (@10.6 µm)

enriched Se specifications (URENCO)
form: beads
size: <4 mm
isotope 82Se concentration: > 95% 82Se
chemical purity: > 99.5% trace metals basis
description: gray
packaging: thick polyethylene (PE) bags inside PE recipient