Status of the LUCIFER experiment: results and prospects

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When energy is released in the absorber, there is a temperature change in the absorber itself. Heat propagates to the sensor, changing its resistance to a signal.

\[ \Delta E \rightarrow \Delta T = \Delta E / C \]

\[ \Delta T \rightarrow \Delta R \rightarrow \Delta V \]

Very low working temperature (~10 mK)

- To reduce the heat capacity C
- To be sensitive to the temperature variation due to a 0νββ event (0.1 mK/MeV \rightarrow 1 mV/MeV)

The energy released in the absorber creates phonons. Low energy needed to producing a phonon \rightarrow high energy resolution

The resolution is limited by the statistical fluctuations of the phonons exchanged with the bath through the thermal conductance G \rightarrow \Delta E_{rms} \sim (K_B T^2 C)^{1/2}

\[ \Delta T(t) = E/C e^{-t/\tau} \] with \( \tau = C/G \) thermal decay time \rightarrow slow signals (~0.5 s)
Bolometers

Bolometers have proven to be very good detectors for 0νββ experiments aiming to investigate the inverted hierarchy region of neutrino masses (m_{ββ} < 50meV)

- ability to sustain large source masses
  - large amount of the appropriate 0νββ candidate isotope
- excellent energy resolution (FWHM ~0.2-0.5 % above 2.5MeV)
  - to separate the 0νββ peak from the background, in particular the one coming from the 2νββ
Bolometers

Bolometers have proven to be very good detectors for $0\nu\beta\beta$ experiments aiming to investigate the inverted hierarchy region of neutrino masses ($m_{\beta\beta} < 50\text{meV}$)

- ability to sustain large source masses
  - large amount of the appropriate $0\nu\beta\beta$ candidate isotope
- excellent energy resolution (FWHM $\sim 0.2$-$0.5\%$ above $2.5\text{MeV}$)
  - to separate the $0\nu\beta\beta$ peak from the background, in particular the one coming from the $2\nu\beta\beta$

![CUORE-0 Preliminary Phase II]

<table>
<thead>
<tr>
<th></th>
<th>$0\nu\beta\beta$ region $\text{cnts}/(\text{keV kg y})$</th>
<th>$2700$-$3900\text{keV}$</th>
<th>$\varepsilon(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuoricino</td>
<td>$0.153 \pm 0.006$</td>
<td>$0.110 \pm 0.001$</td>
<td>$83$</td>
</tr>
<tr>
<td>CUORE-0</td>
<td>$0.063 \pm 0.006$</td>
<td>$0.020 \pm 0.001$</td>
<td>$78$</td>
</tr>
</tbody>
</table>

* O. Cremonesi, 06/06/2014, Neutrino 2014 @Boston, USA
Bolometers

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- ability to sustain large source masses
  - large amount of the appropriate 0νββ candidate isotope
- excellent energy resolution (FWHM $\sim$0.2-0.5 % above 2.5MeV)
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- possibility to exploit the simultaneous collection of heat and light
  - low backgrounds in the region of interest
Scintillating bolometers

The release of energy in a scintillating crystal follows two channels:

- **Thermal excitation**
  - Heat signal

- **Light production**
  - Light detector

 Different light output produced by $\alpha$ or $\beta/\gamma$ events with same energy

$$Q_F = \frac{\alpha \text{ light}}{\beta/\gamma \text{ light}}$$

Simultaneous read-out of the energy deposed in the main crystal and the scintillation light allows the discrimination of signal events from the $\alpha$ bkg.
The LUCIFER experiment

Low-background Underground Cryogenic Installation for Elusive Rates

A scintillating bolometers array to search for the $0\nu\beta\beta$ decay of candidates with a $Q_{\text{value}}$ higher than 2.6 MeV

α and β/γ event discrimination thanks to the double read-out

outside the natural γ radioactivity range: αs are the dominant disturbing background sources

LUCIFER will search for the $0\nu\beta\beta$ of $^{82}\text{Se}/^{100}\text{Mo}$ using ZnSe/ZnMoO$_4$ scintillating compounds

A complete elimination of αs for these candidates can lead to specific bkg levels of $\sim 10^{-3} \text{ c/(keV·kg·y)}$ or lower
The LUCIFER detector

- LUCIFER baseline: 36 ZnSe crystals enriched at 95% for ~15kg of total isotope mass
- Light detectors sandwiched between two crystal floors
- In the CUORE-0 cryostat @ LNGS
- R&D on ZnMoO₄ crystal for a 10kg experiment in collab* with LUMINEU

*MoU between INFN, IN2P3 & ITEP

<table>
<thead>
<tr>
<th></th>
<th>ZnSe</th>
<th>ZnMoO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>0νββ isotope</td>
<td>⁸²Se</td>
<td>¹⁰⁰Mo</td>
</tr>
<tr>
<td>Q-value [kev]</td>
<td>2995</td>
<td>3034</td>
</tr>
<tr>
<td>Useful material</td>
<td>56%</td>
<td>44%</td>
</tr>
<tr>
<td>LY_{β/γ} [keV/MeV]</td>
<td>6.5</td>
<td>1.5</td>
</tr>
<tr>
<td>QF_{α}</td>
<td>4.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Light Detectors

LUCIFER light detectors = Ge slabs, operating as bolometers

- Opaque semiconductors → sensitive over a wide range of γ wavelengths
- Radiopure crystals
- Ø = 44 mm
- thickness = 180 μm
- grown using Czochralski technique
- NTD Ge thermistor as temperature sensor

Light collection increased with a SiO₂ dark layer deposited on the surface of the Ge crystal


Several tests were carried on to investigate the performances of Ge light detectors in terms of signal amplitude, energy resolution and signal time development to identify the best working conditions
Light detectors

To allow proper calibration of the LD a $^{55}$Fe source, producing two X-rays at 5.9 and 6.5 keV, is used

→ comparable with typical light signals produced in scintillating bolometers (order of $\sim$10 keV)
Light detectors

- LD performances dependence on the applied bias current
  - Best values: 2–7nA. At higher currents signal to noise ratio limited by preamplifier noise

- LD performances uninfluenced by the value of the load resistance
  - LDs not affected by Johnson noise

- LD performances influenced by the working temperature
  - at ~20mK FWHM is significantly better with respect to that observed at ~ 10mK, the standard working temperature of bolometers for rare events searches

![Graph showing RT, Signal, and FWHM vs. I_{bol}](image)

- ● = 11GΩ Load resistance; ○ = 2GΩ Load resistance
Crystal absorber - ZnMoO$_4$

Bolometric test with a 330 g ZnMoO$_4$ crystal


✓ Excellent particle discrimination using light vs heat or the shape of the heat pulses

First bolometric measurement of 2v$\beta\beta$ of $^{100}$Mo with a ZnMoO$_4$ crystal array


✓ 3 natural ZnMoO$_4$ crystals
✓ Total exposure 1.3 kg*d of $^{100}$Mo

$T^{2\nu}_{1/2} = [7.15 \pm 0.37_{(\text{stat})} \pm 0.66_{(\text{syst})}] \times 10^{18}$ y

In agreement with the NEMO3 result
Crystal absorber - ZnSe

Characterisation of the largest ZnSe bolometer ever realized (431 g crystal) (JW Beeman et al, 2013 JINST8 P05021)

- FWHM energy resolution of 12.2±0.8 keV at 1461 keV and 13.4±1.3 keV at 2615 keV
- Excellent particle discrimination using Light vs. Heat or the shape of the light pulses
Crystal absorber - ZnSe

Low background measurement (t=524h)

From α spectrum:
✓ internal contamination: $3 \times 10^{-4}$ c/keV/kg/y $^{238}$U and $3 \times 10^{-3}$ c/keV/kg/y $^{232}$Th @ROI

From β/γ spectrum:
✓ natural contamination of $^{40}$K and $^{208}$Tl
✓ contaminations in $^{75}$Se and $^{65}$Zn for the cosmogenic activation of $^{74}$Se and $^{64}$Zn, not affecting the bkg in the DBD region for their short half-lives and low Q-values
✓ Single event above 2615 keV, likely produced by a muon interaction

1 event in ROI in 5yrs with a 20kg detector

zero-background is achievable
Conclusions

✓ Bolometers have proved to be excellent detectors for 0νββ search
✓ Discrimination of α and β/γ events makes a background free detector possible
✓ LUCIFER is a next generation 0νββ experiment demonstrator using the scintillating bolometer technique
✓ LUCIFER goals are: bkg ≤ 10^{-3} c/keV/kg/y and FWHM ≤ 10 keV @ ROI
✓ LUCIFER baseline is a detector with 15kg enriched ZnSe crystal
✓ Further option: a 10kg enriched ZnMoO₄ search in collab. with LUMINEU & ITEP
✓ Several detector components have been defined and characterized
✓ LUCIFER will start in 2015

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Live time [y]</th>
<th>$T_{1/2}^{0\nu}$ [10^{26}y]</th>
<th>$&lt;m_{\beta\beta}&gt;$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnSe</td>
<td>5</td>
<td>0.6</td>
<td>65-194</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.2</td>
<td>46-138</td>
</tr>
<tr>
<td>ZnMoO₄</td>
<td>5</td>
<td>0.3</td>
<td>60-170</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.6</td>
<td>42-120</td>
</tr>
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