LUCIFER:
an Experimental Breakthrough in the Search for Neutrinoless Double Beta Decay

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LUCIFER
Low-background Underground Cryogenics Installation For Elusive Rates

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Double Beta Decay pilot project based on scintillating bolometers
Outline

- Double Beta Decay
- Experimental challenge and role of the background
- Silver and golden isotopes
- The bolometric technique and the golden isotopes
- The LUCIFER way
- Prospects and conclusions
Decay modes for Double Beta Decay

Two decay modes are usually discussed:

\[(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e\]  
2ν Double Beta Decay allowed by the Standard Model already observed  
\[\tau \sim 10^{19} - 10^{21} \text{ y}\]

\[(A, Z) \rightarrow (A, Z+2) + 2e^-\]  
Neutrinoless Double Beta Decay  
\[76\text{Ge claim}\]  
\[\tau \geq 10^{25} \text{ y}\]

**Neutrinoless process** would imply new physics beyond the Standard Model

violation of lepton number conservation

It is a very sensitive test to new physics since the phase space term is much larger than for the standard process

If observed:

\[m_\nu \neq 0\]
\[\nu \equiv \nu\]
**0ν-DBD and neutrino masses**

how **0ν-DBD** is connected to **neutrino mixing matrix and masses** in case of process induced by **mass mechanism**

- **neutrinoless Double Beta Decay rate**
  \[ \frac{1}{\tau} = G(Q,Z) \left| M_{\text{nucl}} \right|^2 \langle M_{\beta\beta} \rangle^2 \]

- **Phase space**

- **Nuclear matrix elements**

- **Effective Majorana mass**

- **what the experimentalists try to measure**
- **what the nuclear theorists try to calculate**

\[ \langle M_{\beta\beta} \rangle = \left| U_{e1} \right|^2 M_1 + e^{i\alpha_1} \left| U_{e2} \right|^2 M_2 + e^{i\alpha_2} \left| U_{e3} \right|^2 M_3 \]
The size of the challenge

$^{76}\text{Ge}$ result

- $\sim 100 - \sim 1000$ counts / y ton
- $\sim 1 - \sim 10$ counts / y ton
- $\sim 0.1 - \sim 1$ counts / y ton

$^{80}\text{Se}$

- $50$ meV
- $20$ meV

Log $|\langle m \rangle|$ vs. Log $m_{\text{MIN}}$ [eV]
Electron sum energy spectra in DBD

The shape of the two electron sum energy spectrum enables to distinguish among the two different decay modes.

For a detector with few keV energy resolution, the background index must be of the order of or better than

10^{-3} \text{ counts / keV kg y}

Q \sim 2-3 \text{ MeV} for the most promising candidates.

The order of magnitude of the target background is \sim \text{ few counts / y ton}.
The importance of a high Q-value

A high Q-value is important for two reasons:

- High phase space for the decay: $\propto Q^5$
- If $Q > 2615$ keV, the signal is out of the bulk of the natural $\gamma$ radioactivity

Position of the Q-values for some interesting candidates superimposed to a $\gamma$ spectrum taken underground without any form of passive shielding
Silver and golden isotopes

Only a few isotopes are really in the game for the search for neutrinoless Double Beta Decay.

From the point of view of the Q-value, they can be divided into:

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

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

Other factors favour certain isotopes with respect to others:

- Easy association to an experimental technique
- High isotopic abundance and/or easy enrichment
- Achievable radiopurity
The role of nuclear matrix elements in isotope choice

\[
\left[ T^{0\nu}_{1/2} \right]^{-1} = C \cdot \frac{\left< m_{\beta\beta} \right>^2}{m_e^2} \quad \Rightarrow \quad C = |M^{0\nu}|^2 \cdot G^{0\nu} \quad [y^{-1}]
\]

the real figure of merit: the higher the better

No superisotope!
Which technique can study one or more golden isotopes?

1. **Tracko-calo approach**: the source is a thin foil inserted in a nuclear detector with tracking and calorimetric capability → ~5 kg source in each module.
   - *NEMO – SuperNEMO experiments* → $^{100}$Mo, $^{82}$Se or $^{150}$Nd

2. **Bolomteric approach**: the source is embedded in a crystal which is cooled down at ~10 mK and work as a bolometer → only energy is measured but with high resolution → ~0.5 kg source in each crystal.
   - *Cuoricino – CUORE experiments* → $^{130}$Te, but potentially most of golden isotopes

Silvia Capelli, Thursday

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The nuclear energy is measured as a temperature increase of a single crystal.

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

In order to get low heat capacities, the temperature must be very low (5 – 10 mK).

Thanks to a proper thermometer, \( \Delta T \Rightarrow \Delta V \)

Typical signal sizes: 0.1 mK / MeV, converted to about 1 mV / MeV
### Silver and golden isotopes with the bolometric technique

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>I. A. [%]</th>
<th>Q-value [keV]</th>
<th>Materials successfully tested as bolometers in crystalline form</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>7.8</td>
<td>2039</td>
<td>Ge</td>
</tr>
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<td>$^{136}$Xe</td>
<td>8.9</td>
<td>2479</td>
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<td>$^{82}$Se</td>
<td>9.2</td>
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<td>ZnSe</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>9.6</td>
<td>3034</td>
<td>PbMoO$_4$, CaMoO$_4$, SrMoO$_4$, CdMoO$_4$, SrMoO$_4$, ZnMoO$_4$, Li$_2$MoO$_4$, MgMoO$_4$</td>
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<td>$^{96}$Zr</td>
<td>2.8</td>
<td>3350</td>
<td>ZrO$_2$</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>5.6</td>
<td>3367</td>
<td>NONE $\rightarrow$ many attempts</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>0.187</td>
<td>4270</td>
<td>CaF$_2$, CaMoO$_4$</td>
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Seven excellent candidates can be studied with high energy resolution and with the bolometric approach.
Is a pure bolometer the best device to study a golden isotope?

Following the previous arguments, an obvious way to get low background and to perform multi-isotope search with high sensitivity would be:

- Invest money in enrichment
- Invest money in crystal growth with radio-clean procedures
- Exploit the existing facilities for large mass bolometric experiments (Cuoricino, CUORE at LNGS)

In parallel to $^{130}$Te, study the potentially much better candidates $^{82}$Se, $^{116}$Cd, $^{100}$Mo, $^{48}$Ca and others

Unfortunately, the Cuoricino / CUORE R&D experience tells us that the improvement with respect to $^{130}$Te study would be minor or negligible

Why?
The Cuoricino background and the surface radioactivity

Typical shape of a background spectrum in Cuoricino, a pure bolometric experiment

Alpha region, dominated by $\alpha$ peaks (internal or surface contaminations)

$^{214}$Bi

$^{60}$Co sum energy

$2615 \text{ keV}$

$^{208}$Tl

$\sim 0.1 - 0.2 \text{ c/keV kg y}$
The origin of the continuum above ~2.5 MeV

Bolometers are fully sensitive, up to the detector surface → no dead layer
Shallow (up to 10 µm deep) surface contamination (for example $^{210}$Pb) of the bolometers themselves or of the materials surrounding them emit alpha particles

The attempts to control this phenomenon show that it is very difficult to reduce this continuum below 0.05 c/keV kg y, below and above 2615 keV

The golden isotopes become silver!

The dual mission is:
(1) Investigate golden isotopes + (2) Kill alpha particles

The LUCIFER way
The fundamental idea and the LUCIFER precursors

A device able to measure simultaneously the phonon (heat) excitations and the photon (scintillation) excitations generated in a crystal by the same nuclear event can efficiently discriminate alphas from betas / gammas.

Alphas emit a different amount of light with respect to beta/gamma of the same energy (normally lower → $\alpha$ QF $< 1$, but not in all cases).

A scatter plot light vs. heat separates alphas from betas / gammas.

The experimental basis for LUCIFER is the R&D activity performed by Stefano Pirro at LNGS, in the framework of the programs:

- **BOLUX**, funded by INFN – CSN5
- **ILIAS-IDEA** funded by the European Commission (WP2-P2)
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.
## Silver and golden isotopes in scintillating bolometers

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Four golden candidates ($^{116}\text{Cd} - ^{100}\text{Mo} - ^{82}\text{Se} - ^{48}\text{Ca}$) can studied as scintillating bolometers.

Underlined compounds are good scintillators.
The best technical results so far: CdWO$_4$

S. Pirro
Discrimination power in CdWO₄

Totally background free area

3x3x6 cm crystal

44 days background

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

betas/gammas

Q-value of $^{116}$Cd

alphas

S. Pirro
A good compromise: ZnSe

CdWO$_4$ is an excellent candidate for a DBD experiment based on scintillating bolometers. However, three drawbacks:
- High atomic mass of W → only 32% useful material in case of 100% enrichment
- Crystals examined so far exhibit a huge internal alpha contamination
- $^{109}$Cd has a huge neutron cross section → residual abundance in enriched material

ZnSe is another excellent candidate which is not affected by these problems:
- $\langle A \rangle_{Zn} = 64.4$ → 56% useful material
- Preliminary measurements show that the crystals are reasonably radiopure
- No isotope with particularly high neutron cross sections

Several ZnSe crystals have been tested, with masses up to 337 g → excellent bolometric performance, similar to those observed in TeO$_2$ for CUORE
Two surprises for ZnSe (1)

...one is interesting but not really welcome

$\alpha \ QF > 1$: alphas give more light than gammas $\rightarrow$ risk of leakage in the beta/gamma region?
Two surprises for ZnSe (2)

...the other one is very exciting → improve dramatically the discrimination power.

There are detectable differences in the light-signal time development between alpha and beta events → Pulse Shape Discrimination is possible.

The definition and use of proper shape parameters seem to enable a full separation of beta and alpha in the region of the DBD Q-value of $^{82}\text{Se}$.
Two surprises for ZnSe (2)

A very simple log-log plot of the decay time of the light signal vs. amplitude of the light signal (energy in the light detector) shows three families of events:

- Alphas [GREEN]
- Ionizing particles impinging directly in the light detector [RED]
- Betas/gammas [BLACK]

Amplitude 2615 keV

Very preliminary
More effective shape parameters are under investigation

S. Pirro
Target background

Current background studies show that a background index $< 10^{-3}$ counts/keV kg y is achievable above 2.6 MeV IF one neglects the contribution from surface alphas.

The various techniques of surface cleaning developed in the CUORE collaboration shows that the contribution coming from surface alphas above 2.6 MeV can be reduced at least down to $5 \times 10^{-2}$ counts/keV kg y.

This shows that a rejection efficiency of only 98% would bring the surface alphas contribution down to $10^{-3}$ counts/keV kg y.

All but alphas $< 10^{-3}$

alphas $\sim 5 \times 10^{-2}$

Reject alphas at 99%

Target background $10^{-3}$ counts/keV kg y

The main purpose of LUCIFER is to show that this background is achievable with enriched material on a reasonable large scale (15 – 20 kg of isotope).

LUCIFER is a demonstrator...
Physics reach

...but has a remarkable physics reach by itself

From the LUCIFER proposal:

<table>
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<tr>
<th>Crystal</th>
<th>Isotope weight</th>
<th>Useful material</th>
<th>Half Life limit (10^{26}y)</th>
<th>Sensitivity* to m_{ee} (meV)</th>
</tr>
</thead>
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<tr>
<td>CdWO_4</td>
<td>^{116}\text{Cd}</td>
<td>15.1 kg</td>
<td>32%</td>
<td>1.15</td>
</tr>
<tr>
<td>ZnMoO_4</td>
<td>^{100}\text{Mo}</td>
<td>11.3 kg</td>
<td>44%</td>
<td>1.27</td>
</tr>
<tr>
<td>ZnSe [baseline]</td>
<td>^{82}\text{Se}</td>
<td>17.6 kg</td>
<td>56%</td>
<td>2.31</td>
</tr>
<tr>
<td>ZnSe [option 1]</td>
<td>^{82}\text{Se}</td>
<td>20.5 kg</td>
<td>56%</td>
<td>2.59</td>
</tr>
<tr>
<td>ZnSe [option 2]</td>
<td>^{82}\text{Se}</td>
<td>27.8 kg</td>
<td>56%</td>
<td>3.20</td>
</tr>
</tbody>
</table>

* The 1σ sensitivity is calculated with the Feldman Cousins approach for 5 y running and a background index dΓ_b/dE = 10^{-3} c/keV/Kg/y. The matrix elements come from the two most recent QRPA calculations [ME08]; the energy window is taken as 5 keV, compatible with the resolution achieved in TeO_2 macrobolometers and in scintillating-bolometer R&D.

The most difficult tasks:
- negotiate a good contract for enrichment → Zelenogorsk (Siberia), Russia
- get radiopure and chemically pure isotope after enrichment
- efficient crystallization → Institute for Single Crystals, Kharkov, Ukraine
Structure of the detector

Single module:
4 ZnSe crystals and 1 light detector

Tower:
12 single modules

Side view

Top view

NTD Ge thermistor
Cu frame
Si wafer
ZnSe crystal
PTFE elements
Prospects and conclusion

- The **bolometric technique** joined with **scintillation** allows to approach zero background in high Q-value isotopes

- **LUCIFER** is a **demonstrator** of this concept

- LUCIFER will study $^{82}\text{Se}$ with **enriched ZnSe crystals** in its baseline version

- Technological problems of **enrichment, purification, crystallization**

- LUCIFER is a sensitive project by itself (it can **approach the inverted hierarchy region** of the neutrino mass pattern) but it can be seen as a **pilot project** preparing a possible (still to be discussed) **CUORE upgrade** after the TeO$_2$ run (**cover fully the inverted hierarchy region**).