Scintillating bolometers for the LUCIFER project

L Pattavina for the LUCIFER Collaboration
INFN Laboratori Nazionali del Gran Sasso, I-67100 Assergi (AQ), Italy
E-mail: luca.pattavina@lngs.infn.it

Abstract. Neutrinoless double beta decay ($0\nu\beta\beta$) is one of the most sensitive probes for physics beyond the Standard Model, providing unique information on the nature and masses of neutrinos. In order to explore the so-called inverted neutrino mass hierarchy region a further improvement on the upcoming $0\nu\beta\beta$ experiment is needed. In this respect, scintillating bolometers are the suitable technology for achieving such goal: they ensure excellent energy resolution and highly efficient particle discrimination. The LUCIFER project aims at deploying the first array of enriched scintillating bolometers for the investigation of $0\nu\beta\beta$ of $^{82}$Se. The matrix which embeds the source is an array of Zn$^{82}$Se crystals, where enriched $^{82}$Se is used as decay isotope. Taking advantage of the large Q-value (2997 keV) and of the particle discrimination, the expected background rate in the region of interest is as low as $10^{-3}$ c/keV/kg/y. The foreseen sensitivity after 2 years of live time will be $1.8\times10^{25}$ years. We will report on the potential of such technology and on the present status of the project.

1. Introduction
The study of neutrinoless double-beta ($0\nu\beta\beta$) decay is intrinsically connected with the complete characterization of neutrino properties [1]. This very elusive decay, if observed, implies the lepton number violation by 2 units, and proves the existence of massive Majorana neutrinos. In the spectrum of the summed kinetic energy of the two emitted electrons this decay produces a monochromatic signature. The position of the peak in the energy spectrum is crucial for handling against any peaking background, like a full-energy peak induced by environmental $\gamma$s. This implies that energy resolution and low backgrounds are fundamental parameters for a meaningful discovery.

In recent years, strong efforts were spent for improving the $0\nu\beta\beta$ experimental sensitivity, leading to a competition for the construction of experiments with increasingly higher sensitivities [2]. This requires an increase of the experimental mass, that has led to the construction of ton-scale detectors, and by the struggling against backgrounds that can interfere with the observation of a $0\nu\beta\beta$ decay and therefore spoil the sensitivity. Nowadays, background abatement is the key point where most of the experimentalists efforts are addressed, this has led to the development of improved detection techniques and to the study of different candidate nuclei.

In this field, it is undoubtedly proved that cryogenic particle detectors, namely bolometers, are one of the most attractive devices for the construction of $0\nu\beta\beta$ experiments with a sizeable discovery potential. The excellent energy resolution allows to get rid of the irreducible $2\nu\beta\beta$ background, the Standard Model counterpart of $0\nu\beta\beta$ decay. In the spectrum of the summed kinetic energy of the two emitted electrons, this produces a continuum, which may induce a misidentification of a $0\nu\beta\beta$ signal if detector features a poor energy resolution.
In the last decade, bolometers strongly improved their performance in terms of: detector mass, resolution, reproducibility, background level. TeO$_2$ based bolometers are used in competitive 0$\nu$ββ experiments like Cuore-0 [3, 4] and CUORE [5]. Moreover, bolometers made with other molecular compounds, containing different ββ candidates such as $^{82}$Se, $^{100}$Mo and $^{116}$Cd, were proved to be equally well performing, and an active background rejection have been successfully demonstrated [6, 7, 8, 9] with the scintillating bolometric technique.

2. Experimental sensitivity

The sensitivity of a 0$\nu$ββ experiment ($S^{0\nu\beta\beta}$) is usually defined as half-life corresponding to the maximum signal event that could be hidden by a background fluctuation $n_B$ at a given statistical Confidence Level (C.L.). At 1 $\sigma$ level this is given by:

$$S^{0\nu\beta\beta} = T_{1/2} = \ln(2) \frac{N_{\beta\beta}}{n_B} = \ln(2) \frac{x \eta \epsilon N_A}{A} \sqrt{\frac{MT}{B \Delta}}.$$

(1)

Here we have used the gaussian approximation for background fluctuations $n_B = \sqrt{(B T M \Delta)}$, where $B$ is the background level per unit mass, energy, and time, $M$ is the detector mass, $T$ is the measuring time, $\Delta$ is the FWHM energy resolution of the detector at the $\beta\beta$ transition energy, $N_{\beta\beta}$ is the number of $\beta\beta$ decaying nuclei under observation, $x$ is the stoichiometric multiplicity of the element containing the $\beta\beta$ candidate, $\eta$ is the $\beta\beta$ candidate isotopic abundance, $N_A$ is the Avogadro number, $A$ is the compound molecular mass, and finally $\epsilon$ is the detection efficiency.

The equation is slightly modified for close-to-zero background counting rates. In order to fulfill this condition, we require that:

$$B \Delta M T << 1,$$

(2)

so that, in the approximation of low counting rate, the sensitivity can be re-defined as:

$$S^{0\nu\beta\beta} = T_{1/2} = \ln(2) \frac{x \eta \epsilon N_A}{A} MT.$$

(3)

It is important to highlight the linear dependence of the sensitivity to the measurement time and detector mass. In this case there is a sizeable improvement in sensitivity even in a small mass experiment run on a time scale of few years, with respect to the case of large background counting rate.

In this context the detector must feature a low background in the region of interest (ROI) and a mass at least at the level of tens of kg. The sensitivity can be further improved when dealing with enriched isotopes, which in most cases such as $^{82}$Se, $^{100}$Mo and $^{116}$Cd is mandatory due to their low natural isotopic abundance.

The LUCIFER project (Low Underground Cryogenic Installation For Elusive Rates) aims at deploying a small scale detector of enriched scintillating bolometer for the investigation of $^{82}$Se $0\nu\beta\beta$ in Zn$^{82}$Se and possibly of $^{100}$Mo in Zn$^{100}$MoO$_4$ crystals.

3. Scintillating bolometer for LUCIFER

LUCIFER will be the first demonstrator of the scintillating bolometer technique for $0\nu\beta\beta$ investigations. This will have an experimental sensitivity competitive with other presently founded experiments, at the level of $10^{25}$ years, running a detector of 14 kg. The working principle of scintillating bolometers consists of measuring the temperature rise induced by particle interactions in the main absorber, which is operated at mK-temperature. When ionizing particle releases energy in the crystal, a large fraction is converted into heat, while the remaining is converted into scintillation light. The scintillation light is detected by an auxiliary bolometer
facing the main absorber, namely a light detector (LD). In order to maximize the light collection efficiency the crystal is surrounded by a reflecting foil. The temperature rises induced in the main absorber and in the LD are measured by Germanium Neutron Transmutation Doped thermistors (Ge-NTD) operated as thermal sensors. Details on the operational features of these devices can be found in [10, 11].

The double read-out heat-light allows for an event-by-event identification of the nature of the interacting particle. While searching for $0\nu\beta\beta$ this feature is fundamental for a highly sensitive investigation. In fact, as demonstrated by the CUORICINO experiment [12], most of the background in the ROI of bolometric $\beta\beta$ experiments, 2.5-3.5 MeV, is induced by degraded alpha particles escaping from the detector surfaces [13]. These will release in the main absorber only a fraction of their energy while the remain in some other detector component (e.g. the holding structure), leading to a flat continuum of events that extends to the $\beta\beta$ ROI.

The LUCIFER project focuses its effort for the development of two scintillating compounds: ZnSe and ZnMoO$_4$. They both are rather good scintillators at low temperature, thus allowing for an efficient particle discrimination. Furthermore, the $\beta/\gamma$ background in the ROI is strongly suppressed given the large $Q_{\beta\beta}$ for $^{82}$Se and $^{100}$Mo at 2997 keV [14] and 3034 keV [15], respectively. These features make the close-to-zero background investigation within the reach, and if it is combined with the isotope enrichment, then a small scale experiment with high sensitivity is feasible.

4. Zn$^{82}$Se crystals

ZnSe exhibits a highly efficient alpha-$\beta/\gamma$ identification capability, with the peculiar behaviour to have a photon emission larger for alpha particles with respect to $\beta/\gamma$ ones [6]. In Figure 1a, we show a calibration energy scatter plot of a large mass ZnSe crystal operated as scintillating bolometer. Even if the quenching factor for alpha particles has a value greater than 1, this does not prevent a full rejection of the alpha-induced background in the ROI. Furthermore, an additional discrimination parameter was implemented analyzing the decay components of the light pulses detected by the LD. In Figure 1b, we show the discrimination parameter as a function of the energy deposits in the ZnSe crystal for a zoom-in of the events shown in Fig. 1a. ZnSe ensures a full rejection of the alpha background in the ROI.

**Figure 1.** Particle discrimination in ZnSe. The light emitted by the ZnSe crystal (a) and a shape parameter of the same light pulses (b) are shown as a function of the ZnSe heat channel. A smeared $\alpha$ and $\gamma$ sources were used for the characterization of the discrimination potential in a proxy of the region of interest at 2.6 MeV.
In the last 2 years, we produced 15 kg of highly pure enriched $^{82}$Se to be used for the production of Zn$^{82}$Se crystals for $0\nu\beta\beta$ investigations. The production was carried out by the URENCO company that was also responsible of the first stage material purification. The radioactive purity level of the material was very good and within the requirements for a close-to-zero background $\beta\beta$ experiment. The final average enrichment level of $^{82}$Se was 96%, and only limits on internal contaminations of primordial decay chain elements of $^{232}$Th, $^{238}$U and $^{235}$U were set, respectively: $<61\ \mu\text{Bq/kg}$, $<110\ \mu\text{Bq/kg}$ and $<74\ \mu\text{Bq/kg}$ at 90% C.L. [16].

The crystal growth process is carried out in Ukraine at the ISMA institute. The critical parameters for the production of high quality large mass crystal is the stoichiometry level of the initial materials: metal Zn and metal $^{82}$Se. After the development of dedicated procedures for the quality control, the final production has started. The outcome from the 27 kg of starting material will be 25-30 crystals, for a total detector mass of about 15 kg.

5. Detector design
Scintillating bolometers requires a rather complex detector design, when operated in arrays for the investigation of elusive events such as $0\nu\beta\beta$. In fact, some crucial requirements must be fulfilled in order to be able to perform a high sensitivity investigations: reduced mass of copper for the detector holding structure, tightly packed configuration of the detector and optimized distance between LDs and ZnSe crystals. While the first two points help in reducing the background [17] the latter maximizes the light collection efficiency and thus the discrimination potential between $\alpha$ and $\beta/\gamma$ events [10].

The LUCIFER detector has been designed taking into account all the previously mentioned requirements. In Fig. 2 we show the mechanical design of the experimental set-up. The detector

![Figure 2.](image)

*Figure 2.* Left: Rendering of the LUCIFER detector. Right: A single LUCIFER detector floor, in which the ZnSe crystal, LD detector, PTFE holders, and copper frames and columns are indicated. The copper frames are shared between adjacent floors.

...
towers are all connected to a common copper plate that acts both as support plate but also as thermal link to the coldest part of the cryostat. The detector single module is designed in a strategic manner, so that each ZnSe crystal is faced to two LDs, the double light read-out minimize the losses of light during its propagation in the experimental set-up. Furthermore the synchronization of heat and light channels, as described in [18], prevent from any misidentification of heat events and their relative light signals.

A successful test of the detector prototype with enriched Zn\textsuperscript{82}Se crystals has been carried out in the Hall C cryogenic facility of the LNGS laboratory. In Fig. 3 we show a photo of the experimental set-up before its installation.

![Photo of the first detector prototype structure of the LUCIFER experiment.](image)

**Figure 3.** Photo of the first detector prototype structure of the LUCIFER experiment.

### 6. Conclusion

LUCIFER will operate for the first time a large array of enriched scintillating bolometer, this will demonstrate the reproducibility, the stability and the robustness of the scintillating detector approach. Such innovative technique will be highly efficient for particle identification and thus background rejection, and hopefully it will measure the effective background levels achievable with scintillating bolometers in view of a future implementation of this technique on much larger arrays [19, 20].
The detector described in this work will have an experimental sensitivity comparable with other ton-scale experiment, even if its mass will be at the level of tens of kilograms. LUCIFER will start to take background data in summer 2016 and will have a sensitivity projection of $1.8(2.7) \times 10^{-25}$ y at 90% C.L. in 2(3) years of live time, with a background rate in the ROI of $10^{-3}$ c/keV/kg/y.

Acknowledgments
This work was made in the frame of the LUCIFER experiment, funded by the European Research Council under the European Unions Seventh Framework Programme (FP7/20072013)/ERC Grant Agreement no. 247115.

References
[1] Verma E 2015 Adv. High Energy Phys. 385968
[2] Cremonesi et al 2014 Adv. High Energy Phys. 951432
[3] CUORE Collaboration 2015 Phys. Rev. Lett. 115 102502
[4] Artusa D et al 2014 Eur. Phys. J. C 74 2956
[5] CUORE Collaboration 2015 Adv. High Energy Phys. 879871
[6] Beeman J et al 2013 JINST 8 P05021
[7] Beeman J et al 2012 Eur. Phys. J. C 72 2142
[8] Cardani L et al 2013 JINST 8 P10002
[9] Arnaboldi C et al 2010 Astropart. Phys. 34 143
[10] Beeman J et al 2013 JINST 8 P07021
[11] Beeman J et al 2013 Adv. High Energy Phys. 2013 237973
[12] Andreotti E et al 2011 Astropart.Phys. 34 822
[13] Clemenza M et al 2011 Eur. Phys. J. C 71 1805
[14] Lincoln D et al 2013 Phys. Rev. Lett. 110 012501
[15] Rahaman et al 2008 Phys. Lett. B 662 111
[16] LUCIFER Collaboration 2015 Eur. Phys. J. C 75 591
[17] Bucci C et al 2009 Eur. Phys. J. A 41 155
[18] Piperno G et al 2011 JINST 6 P10005
[19] CUPID Interest Group 2015 Preprint arXiv:1504.03599
[20] CUPID Interest Group 2015 Preprint arXiv:1504.0361