Status and plans of the LUCIFER Experiment

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Neutrinoless Double Beta Decay searches are the only way to give an answer to the neutrino mass nature, Dirac or Majorana. These experiments are extremely delicate and the greatest obstacle to improve their sensitivity is the background level that can be achieved. LUCIFER is a project, financed by a ERC-AdG, that would like to build a demonstrator of a technique based on the double read-out (scintillation light + heat) of ZnSe crystals used as bolometers. The goal is to reach a background lower than 0.001 counts/kg/keV/year. Along the way we would like to learn how practical is the enrichment of Se into ^{82}Se, how efficient is the process of crystallization and how radiopure the crystals can be grown. In this talk we will discuss the properties of ZnSe crystals and sketch the layout of the project.

Keywords: Neutrino mass; Double Beta Decay; Scintillating Bolometers; LUCIFER

1. Introduction

In the last decade much progress has been made in neutrino physics. Oscillation experiments created a clear picture of this elusive particle and we are now entering the era of precision measurements. There are however questions that cannot be addressed by oscillation experiments. The absolute mass scale of the neutrino is one of these, and it is considered a key quantity in many theories beyond the Standard Model of particle physics. Being only sensitive to square mass differences, oscillation experiments are not able to measure this parameter. Moreover, the mechanism that is responsible for the generation of neutrino masses is still unknown. Neutrinos are electrically neutral particles, and the only carried charge is that of weak interactions. In the Standard Model there is no symmetry constraining the conservation of lepton number, even though a non-conservation has never been observed. If lepton number is not conserved, neutrinos could be equal to their antiparticles, thus being Majorana particles.

The Double Beta decay without emission of neutrinos (0νDBD) violates the lepton number by two units, and has never been observed. The observation of this nuclear decay would imply that neutrinos are Majorana particles, a breakthrough in the picture of nature we have. Moreover it could provide information on the absolute mass scale of neutrinos because a virtual neutrino is exchanged and the propagator is proportional to its mass $m_{\beta\beta}$.

Neutrinoless Double Beta decay is, at present, the most sensitive method to study neutrino properties and bolometers[1] are - together with germanium diodes - the detectors which have provided the best results so far. Bolometers allow the application of the so-called "source=detector" approach, where the detector is composed of the same material candidate to decay, and in the mean time allow the study of many isotopes by means of high resolution devices (FWHM around 0.2-0.5 % above 2500 keV), this latter feature being necessary to resolve the searched peak from background.

The purpose of the 0νDBD new generation experiments is to reach a sensitivity on $m_{\beta\beta}$ of the order of 50 meV.[2–5] The high sensitivity required implies excellent energy resolution, a low number of spurious counts within the region of interest (low background) and a high quantity of the isotope on which the study focuses (large mass).

Further improvements cannot rely simply on the mass increase or on a better energy resolution but will require the implementation of innovative techniques for background discrimination.

In the case of a scintillating bolometer the double independent read-out (heat and scintillation) will allow, thanks to the different scintillation yield between α and β - γ particles, the suppression of α background events. These have been identified as the most important background source in bolometers dedicated to 0νDBD searches.[2,6] Furthermore, the contribution of environmental gammas can be strongly reduced using a scintillating bolometer containing a DBD emitter whose transition energy exceeds the highest gamma line due to natural radioactivity (the 2615 keV line of ^{208}Tl). Examples are ^{116}Cd ($Q_{\beta\beta}$ = 2805 keV), ^{82}Se ($Q_{\beta\beta}$ = 3000 keV) and ^{100}Mo ($Q_{\beta\beta}$ = 3030 keV). Finally, this technique is also extremely helpful for rejecting other unavoidable sources of background such as direct interactions of neutrons.

2. Bolometric detectors

Bolometers are calorimeters operating at low temperature, in which the energy deposited by a particle is converted into phonons and is detected as a temperature variation. In this approach, the energy deposited by a single particle into an energy absorber (weakly connected to a heat sink) determines an increase of its temperature T. This variation corresponds simply to the ratio between the energy released by the particle and the heat capacity of the absorber. The only requirements are therefore to operate the device at low temperatures (less than $0.015\,\mathrm{K}$), in order to make the heat capacity low enough, and to have a sensitive thermometer coupled to the energy absorber. The thermometer is usually a thermistor, a resistive device with a steep dependence of the resistance on the temperature.

The energy absorbing part of the detector is made usually of diamagnetic, dielectric crystal in order to avoid electron contributions to the specific heat in addition to the Debye term, proportional to T^3 at low temperatures.

Semiconductor thermistors consist usually of Ge or Si small crystals with a net dopant concentration slightly below the metal-insulator transition. This implies a strong dependence of the sensor resistivity on the temperature at low temperatures, where the Variable Range Hopping conduction mechanism dominates.

3. Scintillating bolometers

When the bolometer crystal is an efficient scintillator at low temperatures, a small but significant fraction of the deposited energy (up to a few %) is converted into scintillation photons while the remaining dominant part is detected in the form of heat. The emitted light can be measured by a light detector facing the scintillating bolometer[7] (see Fig 1).

The idea to use a bolometer as light detector was first developed by Bobin et al.[8] and then optimized[9,10] for Dark Matter (DM) searches. The first simultaneous detection of phonons and photons was achieved more than a decade ago by the Milano group with a CaF_2 bolometer and a conventional Si photodiode as light detector, developed as a pilot device for the search of 0νDBD in ^{48}Ca.

Nowadays it is clear that the effective method to detect scintillation photons in such a very low temperature environment is to develop a dedicated bolometer, in form of a thin slab, opaque to the emitted light and provided with its own phonon sensor. This auxiliar bolometer, normally a

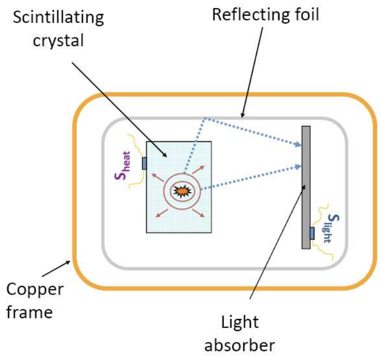

Fig. 1. Scheme of a scintillating bolometer.

Si or Ge slab, is positioned very close to a flat, optically polished, side of the main scintillating bolometer. In order to maximize the light collection, it is convenient to surround the whole set-up with a reflecting foil.

4. Environmental Background

In a bolometric experiment, the signature of the 0νDBD is a peak at the $Q_{\beta\beta}$ value of the transition, while in ordinary Double Beta decay (2νDBD) is a continuous beta-like spectrum. However, thanks to the excellent energy resolutions of bolometers, 2νDBD is seldom a significant source of background.

There are various sources that give rise to spurious counts in the region of interest such as external γ background, neutrons, surface contaminations, ^{238}U and ^{232}Th internal contaminations and cosmogenic activity. As already discussed, a way to eliminate the problem of γ lines is to study isotopes with transition energy above the 2615 keV line. This is the ^{208}Tl line that is the highest energy γ-ray line from natural radioactivity. Above this energy there are only extremely rare γ's from ^{214}Bi: the total Branching Ratio in the energy window from 2615 up to 3270 keV is 0.15 % in the ^{238}U decay chain. All the 0νDBD isotopes with $Q_{\beta\beta}$ >2615 keV are listed in Table 1.

The use of scintillating crystals as absorbers can further overcome the external background limitations, providing a powerful tool to improve the experimental 0νDBD sensitivities. In fact, thanks to the different scintillation yield of different particles (namely β - γ, α and neutrons) they can be very efficiently discriminated.

In particular, if the scintillating crystal is made of a 0νDBD candidate,

Table 1. Double Beta decay isotopes with endpoint energies above the ^{208}Tl line.[11]

Isotope	$Q_{\beta\beta}$ [MeV]	Natural abundance
^{116}Cd	2.80	7.5 %
^{82}Se	3.00	9.2 %
^{100}Mo	3.03	9.6 %
^{96}Zr	3.35	2.8 %
^{150}Nd	3.37	5.6 %
^{48}Ca	4.27	0.19 %

the 0νDBD signal (i.e. the energy deposition produced by the two electrons emitted in the decay) can be distinguished from an α signal. This makes feasible the rejection of α induced background, opening a new window in the future of 0νDBD with bolometers.[12] In fact, it is true that, in the recently concluded bolometric experiment CUORICINO, the major source of background is identified in α particles due to surface contaminations.[13]

5. The LUCIFER project

LUCIFER is a Double Beta decay pilot project based on scintillating bolometers, that has been recently financed by a ERC-AdG. The experimental basis for this project is the R&D activity performed by S. Pirro at Laboratori Nazionali del Gran Sasso (LNGS) in the framework of the programs BOLUX and ILIAS-IDEA.

5.1. *Isotope choice*

Not all the 0νDBD isotopes can be used to fabricate a good scintillating crystal. In the last years different crystals were tested in dedicated runs to study their characteristics such as their thermal response, light yield and radio purity. Practical scintillators can be built out Mo, Cd and Se.
In Table 2 the three LUCIFER candidates are compared with respect to the physics sensitivity achievable with 48 125 cm^3 crystals. Since sensitivity is the figure of merit of the experiment, LUCIFER baseline choice is ^{82}Se.
In Table 3 the same three candidates are compared with respect to the measured light yields. As can bee observed in the table, α particles in ZnSe have higher light yield than β particles. Although not welcome, this unexpected characteristic, according to results of preliminary investigations, does not degrade the discrimination power of this material (see Fig. 2). Preliminary studies, in particular, reveal the capability of an α rejection in

excess of 99%. Since the characteristic α background of such experiments is about 0.1 counts/kg/keV/year, LUCIFER aims to reach a value lower than 0.001 counts/kg/keV/year. In order to confirm these statements, a careful study on the prototype crystals for the experiment is foreseen.

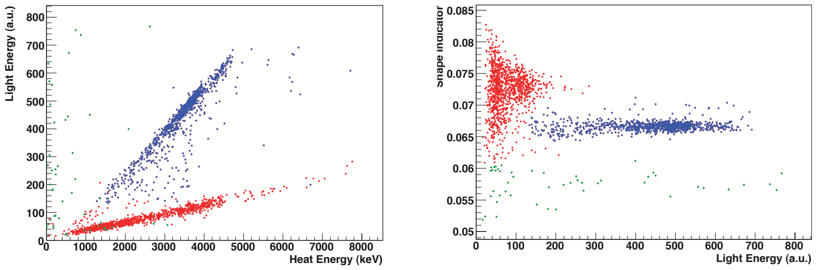

Fig. 2. Comparison between α events from ^{234}U and ^{238}U sources (in blue) and γ events generated by neutrons from AmBe source (in red). Combining the informations of the two plots, more than 99% of α particles can be rejected, maintaining a γ identification efficiency in excess of 98%. Left: Scatter plot of light signal amplitudes vs. heat signal amplitudes (calibrated in energy). Right: Scatter plot of shape sensitive parameter values vs light signal amplitudes.

Table 2. Sensitivity of the three experimental options for LUCIFER.

Crystal	Isotope weight[a]	Useful material[b]	$Q_{\beta\beta}$ value [keV]	Sensitivity[c] to m_{ee} [meV]
$CdWO_4$	^{116}Cd 15.1 kg	32%	2809	65-80
$ZnMoO_4$	^{100}Mo 11.3 kg	44%	3034	67-73
ZnSe	^{82}Se 17.6 kg	56%	2995	52-65

Note: [a] It has been considered a detector made of 48 125 cm^3 crystals.

[b] The percentages take into account an enrichment level of the 0νDBD candidate isotope as high as 97%. The feasibility and the cost of the enrichment procedure are under control thanks to the experience gathered by the NEMO3 collaboration and the investigation performed in the framework of ILIAS.

[c] The 1 σ sensitivity is calculated with the Feldman Cousin approach for 5 y running, considering a background of 10^{-3} counts/keV/kg/y, the matrix element coming from the two most recent QRPA calculations[14–17] and a resolution of 5 keV.

Table 3. β light yields (LY) and quenching factors (QF) for interesting scintillating bolometers.

Crystal	LY_β [keV/MeV]	QF (LY_α/LY_β)
$CdWO_4$	34	0.19
$ZnMoO_4$	1.4	0.16
ZnSe	7.4	4.2

5.2. *Single module structure*

LUCIFER will consist of an array of tens of individual bolometers arranged in a close-packed configuration and housed by the same cryogenic infrastructure. This approach allows one to achieve large masses keeping the single-crystal mass reasonable and providing a rough granularity, very helpful for background identification and rejection.

The foreseen elementary module structure is shown in Fig. 3. Four ZnSe cubic crystals are arranged in each module. The cubes will have 5 cm side, leading to a single crystal mass of 660 g ($\rho_{ZnSe} = 5.27\,\mathrm{g/cm^3}$).

Two copper frames, connected by four copper columns, bound the module above and below. These frames, which act as a 10 mK heat sink for the bolometers, hold 14 PTFE elements, serving as mechanical support and thermal link for the crystals.

One Neutron Transmutation Doped (NTD) Ge thermistor is glued on each crystal. Two Au wires are ball-bonded from the thermistor contacts to pads located on the frames for the signal read-out. A resistive heater, to be use for the offline correction of the gain variations, is glued on the crystal as well and read out as the thermistors.

The module upper frame is designed so as to house an intrinsic-Si disk-shaped slab 0.5 mm thick and 9.5 cm diameter, acting as a photon absorber for the light collection. The slab is placed above the ZnSe crystals and the PTFE elements supporting them, and will be kept by four PTFE clamps fixed at the frame. A NTD Ge thermistor will be glued on the slab. This configuration allows the light detector to see the four crystals underneath and to offer its upper face to the four crystals of the adjacent module.

The module can be inscribed in a cylinder with 18 cm diameter and a total height of 7 cm. A reflecting foil will be placed laterally, connecting the two frames, to improve the light collection.

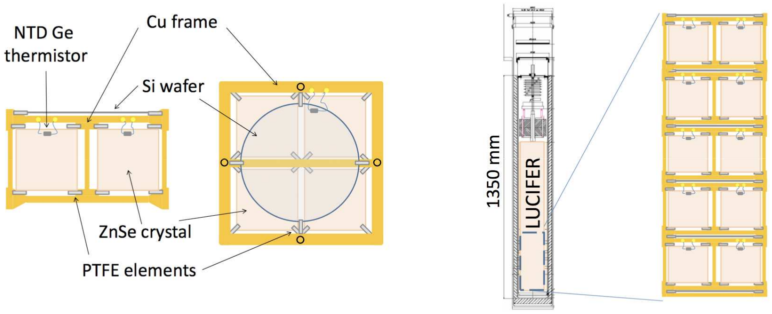

Fig. 3. Left: Elementary module of LUCIFER, with four ZnSe scintillating crystals read out by a single light detector. Right: The LUCIFER tower inside the cryostat. A detail of the tower, comprising 5 elementary modules, is shown on the right.

5.3. *Full detector structure*

The described modules will be stacked so as to form a tower of 12 floors as in Fig. 3. The sequence will start from below with an isolated frame similar to the upper frame of a single module, containing a light detector. The 12 modules will be then assembled one above the other, giving a total tower height of 85 cm.

The detector array will be placed inside a dilution cryostat, yet to be defined. One of the most feasible options is the one previously used for the CUORICINO experiment at LNGS. The tower will be then surrounded by a copper thermal shield and suspended using a stainless steel spring connected to the 50 mK plate of the fridge.

The front end electronics, the post-amplifiers and the DAQ system will be the same that were used for CUORICINO.[18]

6. Present status and future plans

The project is at the phase of procuring the enriched material and establishing a vigorous effort for the production of high quality, reproducible ZnSe crystals. As for the enrichment, the project is at the negotiation phase with potential companies in western Europe and Russia. The crystals will be produced at ISMA (Ukraine) where a detailed R&D program has been agreed.

Great effort is dedicated to the study of the ZnSe stoichiometry, looking for the solution that maximizes the light yield. Concerning the light detectors, ultrapure Ge thin slabs are the baseline choice but different options, like Si slabs, are currently in phase of study.

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