LUCIFER: AN EXPERIMENTAL BREAKTHROUGH IN THE SEARCH FOR NEUTRINOLESS DOUBLE BETA DECAY

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LUCIFER (Low-background Underground Cryogenic Installation For Elusive Rates) is a new project for the study of neutrinoless Double Beta Decay, based on the technology of the scintillating bolometers. These devices promise a very efficient rejection of the α background, opening the way to a virtually background-free experiment if candidates with a transition energy higher than 2615 keV are investigated. The baseline candidate for LUCIFER is ^{82}Se. This isotope will be embedded in ZnSe crystals grown with enriched selenium and operated as scintillating bolometers in a low-radioactivity underground dilution refrigerator. In this paper, the LUCIFER concept will be introduced and the sensitivity and the prospects related to this project will be discussed.

Keywords: Neutrino Mass; Double Beta Decay; Scintillating Bolometers.

1. Introduction

Neutrinoless double beta decay $(0\nu\beta\beta)^1$ is a very rare nuclear transition which violates by two units the total lepton number conservation. The observation of this process would unquestionably proof that neutrinos are self-conjugate particles, i.e. Majorana fermions. In addition, if the transition proceeds through the so-called mass mechanism, it enables the determination of the neutrino mass scale and the ordering of the mass values of the three neutrino mass eigenstates.

Low temperature calorimeters, or bolometers, were proposed more than 20 years ago as sensitive devices for the study of $0\nu\beta\beta$.[2] Currently, experiments based on bolometers, like Cuoricino[3] (now closed) and CUORE[4] (in preparation), are among the most sensitive in the world for the study of this phenomenon and among the most promising for next-generation searches. In this approach, the detector is made of an array of single dielectric diamagnetic crystals cooled down below 20 mK. The crystals contain the isotope under study in their basic chemical formula. This allows to achieve an efficiency close to 1 for the $0\nu\beta\beta$ signal joined with the very high energy resolution (a fraction of percent) characteristic of the bolometric technique. In a sentence, the bolometric approach represents the generalization to a multi-isotope search of the classical Ge diode technology, which enables the investigation of the isotope ^{76}Ge only.

Bolometer-based $0\nu\beta\beta$ searches require extremely low levels of background, especially that arising from radioactive contaminants in the bolometers themselves and in the surrounding materials. Surface contamination is of particular concern. In fact, α's arising from radioactive impurities located on the surfaces of the detector or of passive elements facing them can lose part of their energy in a few microns and deposit in the detector an energy close to that of the signal, thus mimicking a $0\nu\beta\beta$ event. The experience of Cuoricino[3] shows clearly that energy-degraded α's, emitted by surface radioactive contamination, populate the spectral region between 2.5 and 4 MeV with a dangerous continuum at the level of 0.1 counts/keV/kg/y, hardly reducible by a factor ~ 5 with surface cleaning techinques.

Therefore, the ability to tag α particles is a formidable asset in the search for $0\nu\beta\beta$. This improvement would be particulary effective if the investigated isotope presented an energy transition higher than the end point of the bulk of the natural γ radioactivity, i.e. 2615 keV. In this case, the simultaneous suppression of the γ background (thanks to the location of the transition energy) and of the α background (thanks to the identification of these particles), would provide a virtually zero background experiment. In practice, a specific background index better than 1 counts/y/ton looks feasible if both conditions are met.

2. Scintillating bolometers and Double Beta Decay

When the energy absorber in a bolometer 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 as usual in the form of heat. The simultaneous detection of the scintillation light and heat is a very powerful tool to identify the nature of the interacting particle, since the energy partition between phonons and photons is different for different types of quanta. In particular, a nuclear recoil can be distinguished from an electron recoil (much lower light yield), and an α particle from an electron or γ (different, not always lower, light yield). The ratio of the light yield for an α particle or nuclear recoil to that of an electron or γ is defined quenching factor (QF).

The most obvious and effective method to detect scintillation photons in a very low temperature environment is to develop a dedicated bolometer, in the form of a thin slab, opaque to the emitted light and provided with its own phonon sensor. This auxiliary bolometer, normally a Si or Ge slab, is placed very close to a flat optically polished side of the main scintillating bolometer. The whole bolometric set-up can be surrounded by a reflecting foil in order to maximise the light collection. More scintillating crystals can be read out by the same light detector. The very low threshold achievable with bolometers (tens of eV) makes them suitable devices for few-photon counting.

The scheme reported in Fig. 1 illustrates the concept of the detector (left) and of the discrimination method (right).

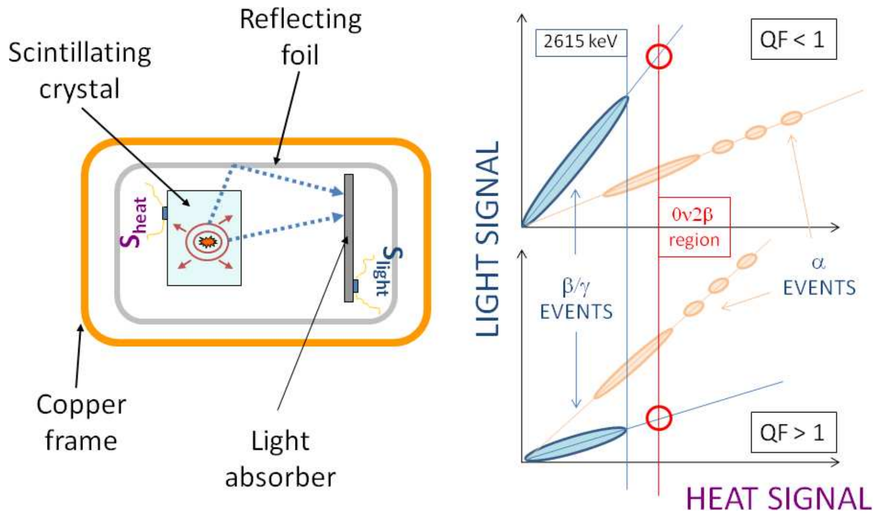

Fig. 1. Left: schematic structure of a double read-out scintillating bolometer. All the basic elements of the detector are shown. Right: schematic scatter plots of light signal amplitudes vs. heat signal amplitudes for events occurring in the scintillating bolometer. Cases with QF> 1 and QF< 1 are illustrated. In both circumstances, α events can be efficiently rejected and the $0\nu\beta\beta$ signal region, supposed above 2615 keV, is background free.

Nature has kindly provided us with a few $0\nu\beta\beta$ candidates presenting a transition energy higher than 2615 keV and forming chemical compounds suitable for the growth of large scintillating crystals, which proved to work as highly performing bolometers as well. A scintillating bolometer for $0\nu\beta\beta$ is no new concept in the field and was proposed more than one decade ago for ^{48}Ca with CaF$_2$ crystals.[5,6] We have today a long list of attractive possibilities:[7] CdWO$_4$, CdMoO$_4$ (for ^{116}Cd); PbMoO$_4$, CaMoO$_4$, SrMoO$_4$, ZnMoO$_4$ (for ^{100}Mo); CaF$_2$, CaMoO$_4$ (for ^{48}Ca); and last but not least ZnSe (for ^{82}Se).

One of the most striking features of ZnSe is the abnormal low-temperature QF, higher than 1 unlike all the other studied compounds (see the lower plot in the right part of Fig. 1). Although not really welcome, this unexpected property does not degrade substantially the discrimination power of this material compared to the others and makes it compatible with the requirement of a high sensitivity experiment. An additional very useful feature is the possibility to perform α/β discrimination on the basis of the temporal structure of the signals, both in the heat and light channel. A preliminary analysis suggests an α-rejection efficiency better than 99% on a very conservative basis. The already demonstrated α background level above 2615 keV, of the order of 0.05-0.1 counts/keV/kg/y and achieved by mere cleaning techniques in Cuoricino and CUORE R&D, can then be reduced down to 10^{-3} counts/keV/kg/y and below.

3. LUCIFER: structure and sensitivity

The sensitivity study of a future $0\nu\beta\beta$ experiment with scintillating bolometers can be performed assuming to exploit fully the experimental volume of the existing cryostat used for Cuoricino. This is a preliminary assumption. The space occupation of LUCIFER is not very large, and other existing or designed underground dilution fridges could house it. The total sensitive mass of LUCIFER has been estimated considering the largest crystals of ZnSe that can be grown with the present technology, which have a cylindrical shape with 5 cm in height and 5 cm in diameter. This is currently the baseline single-crystal size for LUCIFER.

A preliminary version of the LUCIFER structure consists of an array of 48 crystals fitting exactly the experimental volume of the Cuoricino cryostat. The total active volume would be $V = N_{cryst}V_{cryst} = 48 \times 98$ cm^3 ~ 4700 cm^3. The total detector mass would be 25 kg, with about 14 kg of enriched material assuming an enrichment level as high as 97%. The feasibility and the cost of the enrichment procedure are under control thanks to the investigation performed in the framework of ILIAS.[a] When applying different materials and nuclides to this scheme and considering all the relevant elements (scientific, technical, economical), the final balance is clearly in favour of ^{82}Se embedded in ZnSe crystals.

The LUCIFER elementary module currently under study would contain five bolometers:

- Four ZnSe cylindrical crystals (h=5 cm, Φ = 5 cm) will be arranged in each elementary module. One neutron transmutation doped (NTD) Ge thermistor, acting as temperature sensor, will be glued on each crystal.
- The elementary-module holder is designed so as to house in its upper part a single photon absorber placed above the ZnSe crystals, consisting of an ultrapure Ge disk-shaped slab with a sub-millimiter thickness. Its diameter should be very large, at least 10 cm, but the light-detector exact geometry is not defined yet. Again, an NTD Ge thermistor will be glued on the Ge disk.

This configuration allows the light detector to collect light from the four crystals underneath, and to offer its upper face to the adjacent elementary module with

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[a] ILIAS (Integrated Large Infrastructures for Astroparticle Science) was a European Project promoting Astroparticle Physics active between 2004 and 2009, `http://www-ilias.cea.fr/`

its four ZnSe crystals. These modules will be stacked so as to form a tower. The sequence will start from below with an isolated light detector. Then, 12 elementary modules will be assembled one above the other.

The above structure assumes that a single light detector is sensitive enough to perform efficiently the α/β discrimination. So big light detectors have not been realized yet in the R&D activity which has preceeded LUCIFER. In case one should encounter problems in fabricating those large devices, each crystal will be coupled individually to a small light detector with 5 cm diameter, similar to existing devices. This alternative is fully viable and implies only a larger number of read-out channels, anyway available in the Cuoricino refrigerator.

A preliminary evaluation of the LUCIFER sensitivity can be made on the basis of the structure discussed above and of the background expectations after α/β rejection. Assuming 5 year live time, a conservative energy window of 20 keV and a specific background coefficient of 10^{-4} counts/keV/kg/y, less than 1 background count is expected in the region of interest (the transition energy for ^{82}Se is 2995 keV). This corresponds to a sensitivity to the Majorana neutrino mass of the order of 100 meV, enough to scrutinize the ^{76}Ge claim[8,9] with another nuclide. Apart from being a sensitive experiment *per se*, LUCIFER can be considered a demonstrator of the scintillating bolometer technology, with a significant mass and a full test of all the critical elements of this approach (large size crystals, large scale enrichment, final radiopurity of the detectors, background rejection investigated in many modules simultaneously operated).

4. Acknowledgements

The project LUCIFER has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement n. 247115.

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