LUCIFER: a New Technique for Double Beta Decay

F. Ferroni([1])

([1]) *Sapienza University & INFN Roma, P.za A. Moro 2, Roma, Italy*

Summary. — LUCIFER (Low-background Underground Cryogenic Installation For Elusive Rates) is a new project aiming to study the neutrinoless Double Beta Decay. It will be based on the technology of the scintillating bolometers. These devices shall have a great power in distinguishing signals from α's and β/γ's promising a background-free experiment, provided that the Q value of the candidate isotope is higher than the ^{208}Tl line. The baseline candidate for LUCIFER is ^{82}Se. Here the LUCIFER concept will be introduced and the prospects related to this project will be discussed.

PACS 14.60.Pq – Neutrino mass and mixing..
PACS 23.40.-s – β decay; double β decay; electron and muon capture....

1. – Introduction

In the field of fundamental particle physics the neutrino has become more and more important in the last few years, since the discovery of its mass. In particular, the ultimate nature of the neutrino (if it is a Dirac or a Majorana particle) plays a crucial role not only in neutrino physics, but in the overall framework of fundamental particle interactions and in cosmology. The only way to disentangle its ultimate nature is to search for the so-called Neutrinoless Double Beta Decay ($0\nu2\beta$) [1]. One of the best technology for studying this extremely challenging problem is the bolometric one. Bolometers are low-temperature-operated particle detectors which provide better energy resolution, lower energy thresholds and broader material choice than conventional devices. They can be thought as perfect calorimeters, able to thermalize fully the energy released by a particle. One of the best technology for studying this extremely challenging problem is the bolometric one. Bolometers [2] are low-temperature-operated particle detectors which provide better energy resolution, lower energy thresholds and broader material choice than conventional devices. They can be thought as perfect calorimeters, able to thermalize fully the energy released by a particle. The best features of bolometric detectors are:

- They can contain the candidate nuclei with a favorable mass ratio and be massive

- They exhibit good energy resolution. This parameter is crucial since the signal is a peak in the energy spectrum of the detector positioned exactly at the Q-value of the reaction. This peak must be discriminated over the background and therefore has to be narrow.
- They can be built in a way to be characterized by low intrinsic background.

Up to now, the choice for bolometers as $0\nu2\beta$ detectors has fallen on natural TeO_2 that has very good mechanical and thermal properties together with a very large (27% in mass) content of the candidate ^{130}Te. The success of CUORICINO [3] and the excellent prospects for CUORE [4] are based on this approach. Bolometer-based $0\nu2\beta$ searches require however extremely low levels of background. Even if you reduce drastically that arising from radioactive contaminants in the bolometers themselves, you still have the problem of the surrounding materials. Surface contamination is of particular concern. In fact, alpha particles arising from radioactive contaminations 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 signal event. A realistic possibility to improve substantially the background rejection capability is to join the bolometric technique proposed for the CUORE experiment with the bolometric light detection technique used in cryogenic dark matter experiments. The bolometric technique allows an extremely good energy resolution while its combination with the scintillation detection offers an ultimate tool for background rejection. Preliminary tests on several double-beta-decay detectors have clearly demonstrated the excellent background rejection capabilities that arise from the simultaneous, independent, double readout (heat + scintillation). Indeed a demonstrator for this technique (LUCIFER) will be constructed in the next couple of here with ERC funding.

2. – The physics case

The oscillation experiments has proven that neutrinos are massive and do mix. They have measured with precision the mass difference squared between the neutrino species and two out of the three parameters of the P-MNS mixing matrix. These values allow to express the composition of the three flavour neutrino states $(\nu_e, \nu_\mu, \nu_\tau)$ in terms of their mass eigenstates (ν_1, ν_2, ν_3). One shall notice that the ambiguity inherent to the measurement of squared mass differences in the oscillation process leaves two possibilities for the hierarchical mass arrangements of neutrinos. There could also be a common baseline. The measured values of the neutrino mass differences are indeed tiny. Many orders of magnitude smaller than the mass of the lightest of charged leptons, the electron. Long ago E. Majorana formulated an elegant and minimal description of the neutrino field. The question is whether Nature makes use of this simplicity. Seventy years after, Majorana neutrinos are still an exciting possibility, indeed the best description we can find for the physical neutrinos. Majorana neutrino may explain the dominance of matter over antimatter in our Universe, from which asymmetry our very same existence depends. Until the discovery of the massive nature of neutrinos no much attention was paid to the issue of Majorana neutrino: if neutrinos are massless, as everybody believed, it did not matter. The Standard Theory changed the situation and it came (slowly) to be realized that the chiral symmetry is broken, so that there is no reason a priori to expect massless neutrinos and that a Dirac neutrino mass requires a right-handed (sterile, i.e. not interacting) neutrino, but then why neutrinos are so much lighter than the charged leptons or quarks ? Majorana mass and weak isospin selection rules make it possible to find a natural explanation to the smallness of neutrino mass. The pattern of neutrino masses and mixing admit an elegant solution, the so-called see-saw mechanism. Although the possibility for this process was pointed out far in the past, the experimental search looked just impossible. The key element for the process to occur is in fact in the helicity flip needed. As long as the neutrino was thought to be massless this could just not happen. Nowadays we know that this is indeed possible. The DBD are extremely rare processes. In the two neutrino decay mode their half- lives range from $T_{1/2} \simeq 10^{18} y$ to $10^{25} y$. The rate for this process will go as

$$1/\tau = G(Q,Z)|M_{nucl}|^2 m_{\beta\beta}^2$$

The first factor (phase space) that goes like Q^5 is easily calculated. The second (nuclear matrix element) is hard to compute. Several calculation made under different approaches exist and the agreement is getting better and better with time.

The experimental investigation of these phenomena requires a large amount of DBD emitter, in low-background detectors with the capability for selecting reliably the signal from the background. The sensitivity of an experiment will go as

$$S^{0\nu} \propto a(\frac{MT}{b\Delta E})^{1/2}\epsilon$$

Isotopic abundance (a) and efficiency (ϵ) will end up in a linear gain, while mass (M) and time (T) only as the square root. Also background level (b) and energy resolution (ΔE) behaves as a square root. In the case of the neutrinoless decay searches, the detectors should have a sharp energy resolution, or good tracking of particles, or other discriminating mechanisms. The choice of the emitters should be made also according to its two-neutrino half-life (which could limit the ultimate sensitivity of the neutrinoless decay), according also to its nuclear factor-of-merit and according to the experimental sensitivity that the detector can achieve.

3. – The experimental challenge

There are three regions of neutrino mass that well separate the possible experiment on $0\nu2\beta$. The degenerate already attained by experiments like HdM [**?**] and Cuoricino characterized by a need for sensitivity to masses in excess of 100 meV, the inverted hyerarchy confined between 20 and 100 meV and the direct one with masse in the meV range and below. The sensitivity to neutrino mass requested for probing the entire region of the inverted hyerarchy requires a factor 10 with respect to what achieved so far. As the sensitivity goes with the square root of neutrino mass, this unpleasant feature calls for a factor 100 difference in any (or o combination of) parameter regulating the game: mass, live-time, energy resolution and background rate. Todate performance of the most advanced bolometric project, CUORE, already foresees a mass of 1 Ton, a running time of 5 years and an energy resolution of 5 keV. As easily seen there is not much to gain from any of these parameters. Conversely the background index so far achieved with this technique is the 0.18 counts/keV/Kg/y from Cuoricino (see Fig. 1).

CUORE aims to 0.01 and so far has demonstrated a plausible 0.04. The following figure shows the request to experiment performance in term of background called by the inverted hyerarchy region search.

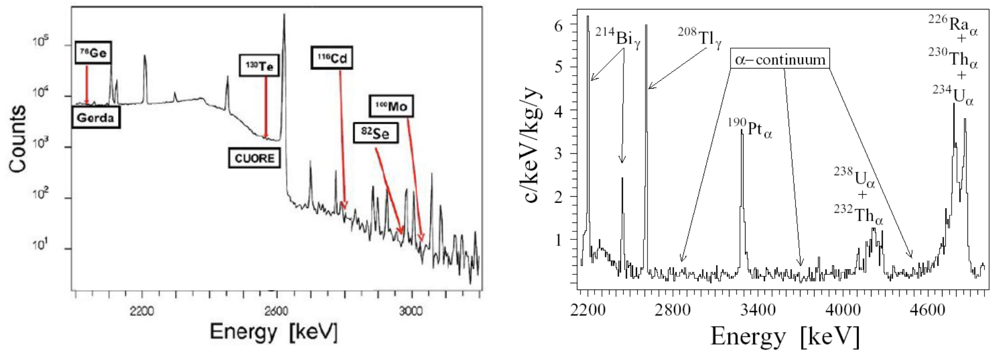

Fig. 1. – Left: Cuoricino background in the DBD region and above. It clearly shows the dominance of degraded α's. Right: Radiative nuclear transitions. It clearly shows that above the ^{208}Tl this contribution to the DBD background becomes negligible.

It is clear that a breaktrough is achieved only by going below 10^{-3} counts/keV/Kg/y. The experience of Cuoricino 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. Therefore, the ability to tag α particles would be a formidable asset. 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 radioactivity, i.e. the ^{208}Tl 2615 keV line. 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 virtual zero background experiment.

4. – Scintillating bolometers

Bolometers represent the generalization of the Ge diode technique to the majority of the interesting candidates. Bolometers consist of two main parts.

- Energy absorber:It is the main detector part. The energy deposited by a single quantum into this element determines an increase of its temperature. This temperature variation corresponds to the ratio between the energy released by the particle and the heat capacity of the absorber. Therefore, the main requirement is to operate the device at low temperatures (usually less than 0.1 K and sometimes even less than 0.015 K) in order to make its heat capacity low enough. Another requirement is that the absorber material is dielectric and diamagnetic, assuring a very low specific heat at low temperatures

- Thermometer: It is thermally coupled to the energy absorber and measures its temperature. The thermometer is usually a resistive element with a strong dependence of the resistance on the temperature. For large mass bolometers a reliable and simple thermistor technology consists of the use of neutron transmutation doped (NTD) Ge thermistors.

Scintillating bolometers to the search for $0\nu2\beta$ bring in an enormous added value, by allowing the use of high Q-value candidates first, and second by providing a substantial α/β discrimination power. 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 is a very powerful tool to identify the nature of the interacting particle. In particular, alpha particles can be discriminated (see Fig. 2) with respect to beta and gamma interaction because of the different quenching factor (QF).

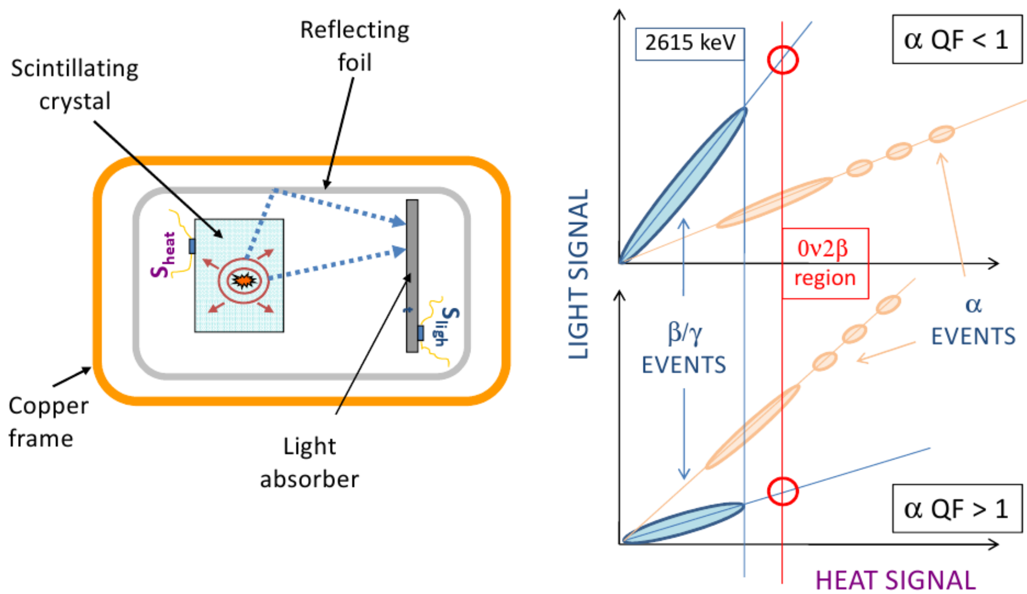

Fig. 2. – Left: schematic structure of a double read-out scintillating bolometer. All the basic elements of the detector are shown. Right: schematic scatter plots of light signals vs. heat signals corresponding to events occurring in the scintillating bolometer. Cases with QF larger or smaller than 1 are illustrated. In both circumstances α events can be efficiently rejected and the $0\nu2\beta$ signal region is background free.

A scintillating bolometer for $0\nu2\beta$ is no new concept in the field and was proposed more than one decade ago for ^{48}Ca with CaF_2 crystals [6]. Nature has kindly provided us with a few isotope 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. The most suited are based on Cd, Mo and Se with the drawback of a need for an isotopic enrichment that brings their natural abundances (less than 10%) to a much higher value. This means in practice that although results [7] obtained by using $CdWO_4$ have basically proven (see Fig. 3) the power of this approach the final choice for a practical experiment cannot make use of this crystal. Cd is difficult to enrich, the process is extremely costly and the residual, unavoidable presence of ^{109}Cd and ^{113}Cd too much of a nuisance. Mo does not offer at this point any convincing cristalline compound and it is an element heavily contaminated by the presence of U, Th. When applying different materials to this scheme and considering all the relevant elements (scientific, technical, economical), the final balance is in favour of ^{82}Se (ZnSe crystals).

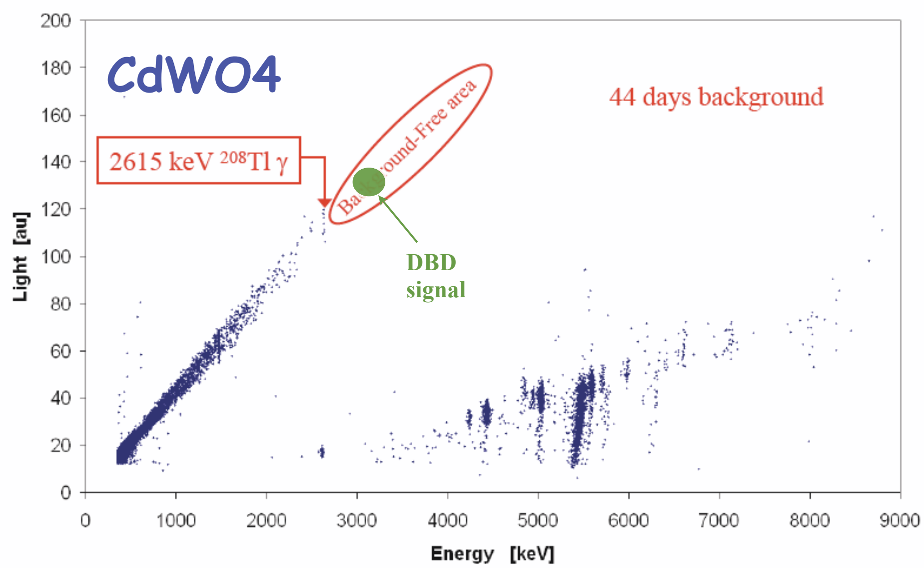

Fig. 3. – Results from a run on a $CdWO_4$ crystal with double (heat and light) readout exposed to radiactive sources

5. – LUCIFER demonstrator

One of the most striking features of ZnSe is the abnormal QF, higher than 1 unlike all the other studied compounds. 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 (see Fig. 4).

The detector configuration proposed for LUCIFER resembles closely the one selected and extensively tested for CUORE, with an additional light detector, designed according to the recipes developed during the scintillating-bolometer R&D and consisting of an auxiliary bolometer, opaque to the light emitted by the ZnSe crystals (see Fig. 5). A preliminary version of the LUCIFER structure consists of an array of 48 crystals, divided in 12 elementary modules with 4 crystals each arranged in a tower, which would fit exactly the experimental volume of the Cuoricino cryostat. This structure assumes that a single light detector, quite large in order to monitor four scintillating crystals simultaneously, is sensitive enough to perform efficiently the α/β discrimination. The total detector mass would be 25 kg, with about 14 kg of enriched material assuming an enrichment level of

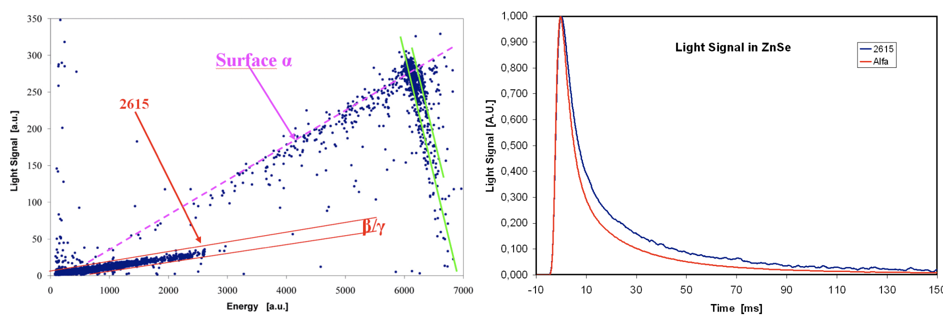

Fig. 4. – Results from a run on a ZnSe crystal with double (heat and light) readout exposed to radiactive sources. Left: scatter plot Light vs. Heat. Right: Decay time of the scintillation light for α's and ^{208}Tl line.

97% A preliminary evaluation of the LUCIFER sensitivity can be made on the basis of the structure discussed above and on the background expectations after α/β rejection. Assuming 5 year live time, an energy window of 20 keV and a specific background coefficient of 10^{-3} counts/keV/kg/y, less than a few background counts are expected in the region of interest (the transition energy for ^{8}2Se is 2995 keV). This corresponds to a sensitivity to the Majorana neutrino mass of the order of 100 meV. The most important goal for LUCIFER is to be a demonstrator of the scintillating bolometer technology, with a significant mass and a full test of all the critical elements of this approach:

- large scale enrichment
- efficient chemical purification meeting radioactive requirements
- large size crystals grown with high efficiency in using the precious (100$/gr) material
- background rejection invesigated in many modules simultaneously operated.

It has the ambition to indicate the way to the experiment for the search of $0\nu2\beta$ able to span over the whole inverted hierarchy region.

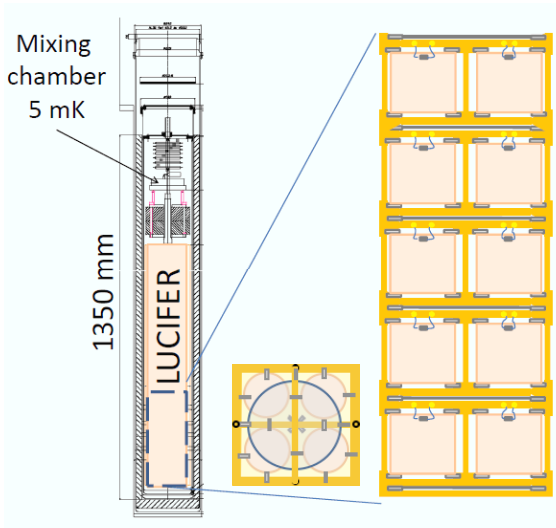

Fig. 5. – Schematics of Lucifer detector. Left: Cuoricino cryostat with Lucifer inserted. Center: Top view of 2×2 crystal plane with Ge light detector on top. Right: Side view of the detector array

* * *

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

REFERENCES

[1] Avignone F. T., Elliot R. S. and Engel J., *Rev. Mod. Phys.*, **80** (2008) 481.
[2] Fiorini E. and Niinikoski T. O., *Nucl. Instrum. Methods Phys. Res. A*, **224** (1984) 83.
[3] Arnaboldi C. and al., *Phys. Rew. C*, **78** (2008) 035502.
[4] Ardito R. and al., hep-ex/0501010 (2005).
[5] Klapdor-Kleingrothaus H. V.,, Proposal MPI-1987-V17 (1987).
[6] Alessandrello. A and al., *Phys. Lett. B*, **420** (1998) 109.
[7] Arnaboldi C. and al., nucl-ex/1005.1239 (2010).