LUCIFER: A NEW TECHNIQUE FOR DOUBLE BETA DECAY

F. FERRONI

Dipartimento di Fisica, Università La Sapienza & INFN-Roma,
Rome, I-00185, Italy

* E-mail: fernando.ferroni@roma1.infn.it

LUCIFER (Low-background Underground Cryogenic Installation For Elusive Rates) is a 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 $\alpha$’s and $\beta/\gamma$’s. This feature might lead to an almost background-free experiment, provided that the Q value of the candidate isotope is higher than the energy of the $^{208}$Tl line. The baseline isotope for LUCIFER is $^{82}$Se. Here the LUCIFER concept will be introduced and the prospects related to this project will be discussed.

Keywords: Neutrino Physics; Majorana Neutrino; Double Beta Decay

1. Introduction

Mysteries about neutrinos are several and of different nature. We know that they are neutral particles with an extraordinary little mass compared to the one of all the other particles. Although they are massive we have not succeeded yet in measuring their mass. We do not know if the neutrino is a particle different from its antiparticle or rather as hypothesized by Majorana they are the same particle. Majorana observed that the minimal description of spin 1/2 particles involves only two degrees of freedom and that such a particle, absolutely neutral, coincides with its antiparticle. If the Majorana conjecture holds then it will be possible to observe an extremely fascinating and rare process that takes the name of Neutrinoless Double Beta Decay (0$\nu$2$\beta$). The net effect of this ultra rare process will be to transform two neutrons in a nucleus into two protons and simultaneously to emit two electrons. Since no neutrinos will be present in the final state the sum of the energy of the two electrons will be a monochromatic line. The rate of this, so far, unobserved phenomenon will also allow a determination, although not precise, of the neutrino mass. Neutrinoless double-beta decay is an old subject. What is new is the fact that, recently, neutrino oscillation experiments have unequivocally demonstrated that neutrinos do have a non zero mass and that the neutrino mass eigenstates do mix. Indeed the massive nature of neutrinos is a key element in resurrecting the interest for the Majorana conjecture.
2. Physics and Challenges

The difference between Dirac neutrinos and Majorana ones is shown in Fig. 1.

![Diagram of Dirac and Majorana neutrinos](image1)

Fig. 1. Dirac and Majorana neutrinos.

The practical possibility to test the Majorana nature of neutrinos is indeed in detecting the process shown in Fig. 2, the Double Beta Decay (DBD) without emission of neutrinos.

![Diagram of Neutrinoless Double Beta Decay](image2)

Fig. 2. Neutrinoless Double Beta Decay diagram.
In the two neutrino decay mode the measured (predicted) half-lives range from \(T_{1/2} \simeq 10^{18} \text{y} \) to \(10^{25} \text{y}\). The rate for the \((0\nu2\beta)\) process will go as
\[
1/\tau = G(Q, Z)|M_{\text{nucl}}|^2m_{\beta\beta}^2
\]
where \(G\) is the easily calculable phase space factor and \(M\) is the challenging nuclear matrix element that is known\(^3\) with still large uncertainties. The effective neutrino mass \((m_{\beta\beta}^2)\) is a combination of neutrino masses, mixing angles and Majorana phases. The experimental investigation of this process definitely requires a large amount of DBD emitter, in low-background detectors with the capability of selecting reliably the signal from the background. The sensitivity of an experiment will go as
\[
S^{0\nu} \propto a\rho(MTb\Delta E)^{1/2}\epsilon
\]
From this formula it is clear that isotopic abundance \((a)\) and efficiency \((\epsilon)\) 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 \((\Delta E)\) behaves as a square root. In the case of the neutrinoless decay searches, the detectors should therefore 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. The element has to be chosen amongst the one in the following figure 3.

The challenge is in the very fact that the sensitivity of this kind of experiment, as previously seen, improves only with the square root of the selected isotope mass, running time, decrease of background index and improvement of energy resolution. Not much choice is left for deciding where to go for designing a superior experiment. Once you have reached the practical limit (say one ton of mass, five years running time and a few keV energy resolution) there is nothing else left than to work hard on background reduction.

3. The two experimental lines
Double beta decay experiments can be divided into two main categories (see Fig. 4): measurement with source separate from the detector and measurement with a detector that also acts as the source.

When the source is the same as the detector (calorimetric type), source mass is maximized, as well as detection efficiency, while materials that could potentially contribute to the background is minimized. Also energy resolution can be optimized. However the absence of topological signature does not allow to reject on the event-by-event basis the background coming from photons. Conversely the other type of detectors (spectrometer type) can optimize the background rejection although at the cost of a reduced mass, modest efficiency, a complicate geometry and a definitely
worse energy resolution. Possibly the best detector of the calorimetric type is based on the bolometric technique.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$Q_{\beta\beta}$ (MeV)</th>
<th>Isotopic abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}$Ca</td>
<td>4.271</td>
<td>0.0035</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2.039</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{90}$Zr</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>0.868</td>
<td>31.7</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Fig. 3. Candidate elements for $0\nu$ DBD.

Fig. 4. Schematics of main DBD detector types.
4. Bolometric technique

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. The best features of bolometric detectors are:

- they can contain the candidate nuclei with a favorable mass ratio and be massive
- they exhibit spectacular 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 the narrower the better.
- they can be built in a way to be characterized by low intrinsic background.

Up to now, the choice for bolometers as $0\nu$2$\beta$ detectors has fallen on natural TeO$_2$ crystals that have very good mechanical and thermal properties together with a very large (27% in mass) content of the candidate isotope $^{130}$Te. The success of CUORICINO$^4$ and the excellent prospects for CUORE$^5$ are based on this approach.

As said, the performances are striking in terms of their energy resolution (Fig. 5).

![Energy response of a TeO$_2$ crystal of the CUORE experiment at the $^{210}$Po $\alpha$ line.](image)

Fig. 5. Energy response of a TeO$_2$ crystal of the CUORE experiment at the $^{210}$Po $\alpha$ line.
Bolometer-based $0\nu 2\beta$ searches require however extremely low levels of background. Even if you reduce drastically the one 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. Although TeO$_2$ crystals are extremely good bolometers there are two problems that cannot be avoided when making a DBD search with them. The first is that the transition energy, the so-called Q-value is below the last important photon line coming from the U, Th chains, the $^{208}$Tl. The second and most important is that the shape of the bolometric response does not allow any discrimination of $\alpha$ particle signals with respect to $\beta/\gamma$’s ones. The problem is best elucidated in Fig. 6.

![Fig. 6](image)

It is clearly seen that the two main sources of background are:

- the $\gamma$ radioactivity that in the near perfect experiment could be reduced to a negligible contribution by selecting as DB emitter one of the element having their Q-value around or in excess of 3 MeV ($^{82}$Se, $^{100}$Mo, $^{116}$Cd)
- the degraded $\alpha$’s coming from the surface of the crystal themselves or from the material holding the detector (Cu mainly) that leave a fraction of their energy and then disappear in a non sensitive region.

The only way to reduce this second (and likely dominant) contribution is to build an experiment capable of distinguishing the energy deposits of an $\alpha$ from those of $\gamma/\beta$’s.

Scintillating bolometers to the search for $0\nu 2\beta$ bring in an enormous added value, by allowing the use of high Q-value candidates first, and second by providing
a substantial $\alpha/\beta$ 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. 7) with respect to beta and gamma interaction because of the different quenching factor (QF).

A scintillating bolometer for $0\nu 2\beta$ is no new concept in the field and was proposed more than one decade ago for $^{48}\text{Ca}$ with CaF$_2$ crystals. 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.

An example of the power of the method is given in Fig. 8. That reports the results achieved with a 430 g CdWO$_4$ bolometer operated in the Gran Sasso laboratory. The figure shows, without need of additional comments, that the combination of a high Q-value candidate with a scintillating bolometer represents at the moment the best approximation to a zero-background experiment with high energy resolution and almost 100% efficiency, due to the coincidence of the source with the detector.
5. LUCIFER: a prototype of a double read-out bolometric device

The most suited scintillating crystals are based on Cd, Mo and Se with the serious drawback of the need for an isotopic enrichment that brings their natural abundances (less than 10%) to a much higher value. In practice, coming to the choice for an experiment, although the results obtained by using CdWO\(_4\) have proven the concept, the final choice is not in favour of this crystal. Cd presents indeed the drawback of the unavoidable presence of isotopes that could be too much of a nuisance, even after enrichment, for their radioactivity and the extremely high neutron absorption cross section. Mo does not offer at this point any convincing crystalline compound and it is an element often heavily contaminated by the presence of U, Th. It presents however very interesting properties when crystallized in the form of zinc molybdate and certainly deserves more studies. When applying different considerations to this problem and considering all the relevant elements (scientific, technical, economical), the final balance is in favour of \(^{82}\)Se (ZnSe crystals).

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\(^8\) 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 \(\alpha/\beta\) discrimination on the basis of the temporal structure of the signals, both in the heat and light channel (see Fig. 9).

The detector configuration proposed for LUCIFER resembles closely the one

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Fig. 8. Results from a run on a CdWO\(_4\) crystal with double (heat and light) readout.
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. 10). 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 $\alpha/\beta$ discrimination. The total detector mass would be 25 kg, with about 14 kg of enriched material assuming an enrichment level of 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 $\alpha/\beta$ 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 $^{82}$Se is 2995 keV). The most important goal for LUCIFER is however 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 ($70$/gr) material
- background rejection investigated in many modules simultaneously operated.
Fig. 10. 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

At this point, the contract for producing the isotope has been signed and the work assigned to URENCO (Almelo) company. The requirement for chemical purity are still under investigation and we are considering either the process to be carried in house with a dedicated chemistry line or assigned to whoever will synthetize the ZnSe powder. The crystal production shall happen at ISMA (Kharkov) where a vigourous R&D is being pursued.

This demonstrator module has the ambition to indicate the way to the experiment of future generation for a search of \(0\nu2\beta\) able to span over the whole inverted hierarchy region.

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References