LUCIFER: A Scintillating Bolometer Array for the Search of Neutrinoless Double Beta Decay

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Abstract. One of the main limitations in the study of $0\nu$DBD is the presence of a radioactive background in the energy region of interest. This limit can be overcome by the technological approach of the LUCIFER project, which is based the double read-out of the heat and scintillation light produced by ZnSe scintillating bolometers. This experiment aims at a background lower than $10^{-3}$ counts/keV/kg/y in the energy region of the $0\nu$DBD of $^{82}$Se. Such a low background level will provide a sensitivity on the effective neutrino mass of the order of 100 meV. In the following, the results of the recent R&D activity are discussed, the single module for the LUCIFER detector is described, and the process for the production of $^{82}$Se-enriched ZnSe crystals is presented.

1. Introduction
The Neutrinoless Double Beta Decay ($0\nu$DBD) is, at present, the most sensitive process to investigate the neutrino properties. The observation of this very rare decay, indeed, would demonstrate the Majorana nature of neutrinos and give an insight on the absolute mass scale of these particles.

The purpose of the $0\nu$DBD next generation experiments [1, 2, 3, 4] is to approach the region of the inverse mass hierarchy, reaching a sensitivity on the mass of the neutrino of the order of 50 meV. In order to achieve this goal, the development of innovative detectors with high efficiency and energy resolution, low background and large source mass is mandatory.

So far, bolometers and Ge diodes are the detectors that showed the best results under this point of view. The most massive bolometric experiment ever realized, Cuoricino, demonstrated that this technique provides a resolution of 0.2–0.5% above 2615 keV, an efficiency of the order of 85% and a very low background in the energy region of interest ($\sim 10^{-1}$ counts/keV/kg/y) [5]. CUORE [2], the natural evolution of Cuoricino, will scale the mass of the detector up to $\sim 1$ ton and achieve a background level of the order of $10^{-2}$ counts/keV/kg/y.

It is clear that a further improvement can not rely on the mass increase, and we can not expect significant changes in the resolution, which for bolometers is already excellent. The parameter that gives more room for improving the sensitivity is thus the background.

In the following we describe a new technological approach, based on scintillating bolometers, that will allow to reduce the background of at least one order of magnitude with respect to other bolometric experiments.
Table 1. Main features of the analyzed crystals. The LY is defined as the ratio between the measured light (in keV) and the nominal energy of the event (in MeV). The QF for α particles (QF$_\alpha$) is defined as the ratio of Light Yield of α’s to that of electrons of the same energy.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Crystal</th>
<th>Q–value</th>
<th>Isotopic Abundance</th>
<th>LY [keV/MeV]</th>
<th>QF$_\alpha$</th>
<th>Enrichment cost [euro/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{116}$Cd</td>
<td>CdWO$_4$</td>
<td>2809</td>
<td>7.5%</td>
<td>17.6 [8]</td>
<td>0.19</td>
<td>&gt;150-200</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>ZnMoO$_4$</td>
<td>3034</td>
<td>9.6%</td>
<td>1.1 [9]</td>
<td>0.16</td>
<td>50–80</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>ZnSe</td>
<td>2996</td>
<td>8.7%</td>
<td>7.4 [10]</td>
<td>4.2</td>
<td>50–80</td>
</tr>
</tbody>
</table>

2. Scintillating Bolometers
A bolometer is a cryogenic particle detector that can be sketched as a crystal in thermal contact with a heat sink plus a proper thermometer. The energy $E$ deposited by a particle interaction in the crystal gives rise to a temperature increase $\Delta T = \frac{E}{C}$, where $C$ is the thermal capacitance of the crystal. Small values of $C$ can be obtained by operating dielectric and diamagnetic crystals at cryogenic temperatures (~10 mK), as for these materials $C$ scales as $T^3$. The thermal pulse can be converted into a readable voltage signal by means of the thermometer.

The main advantage of the bolometric technique is that dielectric and diamagnetic crystals can be grown with almost all the isotopes of interest for the $0\nu$DBD, providing a certain degree of freedom in the choice of the candidate. Other important advantages of bolometers are the excellent energy resolution and efficiency and the radio–purity that can be obtained in the growth of the crystals, that is particularly appealing for a low–background experiment. Important physics results were obtained by the Cuoricino experiment, which provided also a detailed analysis of the background sources for a bolometric detector. Cuoricino demonstrated that the most important contribution to the background in the energy region above 2615 keV comes from $\alpha$ contaminations that can not be eliminated in spite of the recent efforts in this direction.

The lack of an active background suppression in Cuoricino can be overcome by using scintillating crystals as absorbers [6]. In this way, thanks to the different Light Yield (LY) of $\alpha$ and $\beta/\gamma$ events, the background due to $\alpha$’s can be easily disentangled and rejected. The read–out of the light is performed by means of a second bolometer as this is the easiest device to operate at cryogenic temperatures [7].

If the $\alpha$ contaminations are rejected, one has to deal only with the background from $\beta/\gamma$ interactions. However, this contribution can be suppressed by choosing emitters whose Q–value lies well above the 2615 keV $^{208}$Tl line, which is the highest peak of the natural $\gamma$ radioactivity (apart from extremely rare high-energy $\gamma$-rays like the one from $^{214}$Bi). Examples of interesting isotopes under this point of view are $^{116}$Cd ($Q = 2809$ keV), $^{82}$Se ($Q = 2996$ keV) and $^{100}$Mo ($Q = 3034$ keV).

3. The possible candidates
In the last years an extensive R&D activity was performed on several samples containing $^{116}$Cd, $^{82}$Se or $^{100}$Mo. All these isotopes show a large Q–value and a relatively low isotopic abundance (see Table 1), so the candidate for a large mass experiment must be chosen according to the enrichment feasibility and the bolometric performances.

Among the several candidates, three crystals were chosen because of the good bolometric and scintillating properties: CdWO$_4$, ZnSe and ZnMoO$_4$. The features of these compounds are reported in Table 1.
Several large CdWO$_4$ crystals were successfully tested in the last years [8]. In spite of the absence of procedures dedicated to the reduction of the contaminations during the crystal growth, the measured samples showed an extremely high radio-purity. In addition, CdWO$_4$ is a well known scintillator and shows a rather large LY (~17 keV/MeV for a 0.51 kg crystal). The only concern about CdWO$_4$ is the presence of $^{113}$Cd, that is a $\beta$-emitter and has an extremely large cross section for neutron capture. However, a competitive experiment with CdWO$_4$ requires the isotopic enrichment in $^{116}$Cd, which would suppress the background due to $^{113}$Cd.

Another very interesting candidate is ZnMoO$_4$ [9], as this compound is very radio-pure and an excellent background rejection can be obtained through the pulse shape analysis. We want to stress that suppressing the background without the need of a LD would simplify the experimental set-up and reduce the cost of the detector. Unfortunately, the excellent results reported in [9] were obtained on very small samples (~30 g). An accurate study on larger crystals is mandatory.

ZnSe shows very peculiar features. We report in Figure 1 a light vs heat scatter plot obtained with a 337 g ZnSe scintillating bolometer, in order to describe the main characteristics of this detector.

**Figure 1.** Light vs heat scatter plot for a ZnSe crystal (calibration run).

In Figure 1 one can see that the events produced by a degraded uranium $\alpha$ source (blue points) can be easily discriminated by the $\gamma$'s emitted by an AmBe neutron source (red points) by means of the read-out of the scintillation light. As reported in Table 1, the QF$_{\alpha}$ is larger than 1, which is opposite to what happens in a “standard” scintillator. A lot of effort was made in order to understand this behavior and we can now exclude effects due to ZnSe self-absorption, inefficient light collection or transparency of the LD to certain wavelengths [10]. Other tests are planned to better understand this feature which, however, does not constitute a serious problem for the background rejection. In addition, all the ZnSe crystals show extremely low internal contaminations, a rather large LY and a good discrimination capability. The discrimination, in particular, can be improved thanks to the pulse shape analysis (Figure 2), providing an $\alpha$ background rejection larger than 99% with a signal efficiency of more than 98%.

Finally, encouraging results were obtained in terms of energy resolution: with a large crystal (337 g) we obtained 9.5 keV at 2615 keV. There is still room for improvement considering that the optimization of the crystal growth is now under study.

Due to the summarized features, ZnSe was chosen as the baseline for the LUCIFER project.
4. The development of the LUCIFER detector

The LUCIFER detector will consist in a closely packed array of tens of ZnSe scintillating bolometers, each equipped with a light detector. The detector will be operated in a cryostat in the underground Laboratori Nazionali del Gran Sasso (L’Aquila, Italy).

4.1. ZnSe crystals

At the moment, the most delicate issue is the growth of ZnSe crystals. The procedure must guarantee a large yield, a very high radio-chemical purity and it must be easily reproducible.

The first step is the Se enrichment in $^{82}$Se at 95%. The elemental Se, whose radio-chemical purity is carefully checked, is enriched (by URENCO) and converted into Se beads with chemical processes optimized in order to avoid re-contaminations. The enriched Se is further purified up to a level of 6N by means of the zone refining technique. ZnSe powder is then synthesized and the crystals are grown with particular care in avoiding twining and in ensuring the reproducibility of the bolometric and scintillation properties.

4.2. Light Detector

The scintillation light emitted by ZnSe bolometers is detected by thin Ge disks operated as bolometers. Several dimensions and surface treatments have been tested in order to optimize the performances of the germanium detectors, as well as guarantee their reproducibility.

As an example of the interesting results obtained during the R&D activity, we report the first detection of the Cerenkov light emitted by a TeO$_2$ bolometer [11], that was made possible also by the development of a new algorithm to lower the threshold of the LD [12].

5. The LUCIFER Perspectives

Even if the project aims at a feasibility study of a new technological approach in the search of 0$\nu$DBD, we want to underline that a good sensitivity on this rare process will be achieved. Indeed, assuming 10 kg of 95% enriched $^{82}$Se, a live time of 5 years, a background counting rate of $10^{-3}$ counts/keV/kg/y and an energy resolution of 5 keV in the energy region of interest, we can expect a sensitivity on the effective neutrino mass $m_{\nu}$ of the order of 100 meV.

Acknowledgments

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References

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