LUCIFER: Neutrinoless Double Beta decay search with scintillating bolometers

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Abstract. One of the fundamental open questions in elementary particle physics is the value of the neutrino mass and its nature of Dirac or Majorana particle. Neutrinoless double beta decay (DBD0ν) is a key tool for investigating these neutrino properties and for finding answers to the open questions concerning mass hierarchy and absolute scale. Experimental techniques based on the calorimetric approach with cryogenic particle detectors are proved to be suitable for the search of this rare decay, thanks to high energy resolution and large mass of the detectors. One of the main issues to access an increase of the experimental sensitivity is strictly related to background reduction, trying to perform possibly a zero background experiment.

The LUCIFER (Low-background Underground Cryogenic Installation For Elusive Rates) project, funded by the European Research Council, aims at building a background-free DBD0ν experiment, with a discovery potential comparable with the present generation experiments. The idea of LUCIFER is to measure, simultaneously, heat and scintillation light with ZnSe bolometers. Detector features and operational procedures are reviewed. The expected performances and sensitivity are also discussed.

1. Introduction
Interest in double-beta decay (DBD) has seen a significant renewal in recent years after evidences for neutrino oscillations were obtained from the results of solar, atmospheric, nuclear reactor and accelerator neutrino experiments [1, 2, 3, 4, 5, 6]. These results are an impressive proof that neutrinos have a non-zero mass. However, the experiments studying neutrino oscillations are not sensitive to the nature of the neutrino (Dirac or Majorana) and provide no information on the absolute scale of the neutrino masses, since they are sensitive only to the difference of the masses, ∆m². The search for DBD0ν is an important experimental technique for understanding the inclusion of the massive neutrino in the Standard Model of Particle Physics.

Double beta decay is a rare nuclear process that can occur in certain even-even nuclei. It is the dominant decay mode when the single beta decay is energetically forbidden. Two-neutrino double beta decay (DBD2ν) is allowed by the Standard Model and has been observed in the laboratory for several isotopes. In the Standard Model, which does not include a neutrino mass term, DBD0ν is a forbidden decay. However, for a massive Majorana neutrino, the decay is allowed.
The double beta decay without emission of neutrinos 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.

2. Double beta decay

Double beta decay is a second order nuclear weak process and it corresponds to the transition from a nucleus \((A, Z)\) to its isobar \((A, Z + 2)\) with the emission of two electrons. The transition may occur via a Standard Model allowed process in which two electron antineutrinos are emitted along with the electrons: \((A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e\). This decay mode, known as two-neutrino double beta decay, can be thought of as two simultaneous beta decays. The expected rate for \(\text{DBD}^{2\nu}\) decay was first calculated by Goeppert-Mayer in 1935 [7], and the decay has now been observed in various nuclides. Double beta decay half-lives for nuclei that undergo the process are very long, on the order of \(10^{19}\) y, since the decay is second order in the weak interaction. In principle, a nucleus \((A, Z)\) can decay by double beta decay as long as the nucleus \((A, Z + 2)\) is lighter. However, if the nucleus can also decay by single beta decay, \((A, Z + 1)\), the branching ratio for the DBD will be too difficult to be observed due to the overwhelming background rate from the single beta decay. Therefore, candidate isotopes for detecting double beta decay are even-even nuclei that, due to the nuclear pairing force, are lighter than the odd-odd \((A, Z + 1)\) nucleus, making single beta decay kinematically forbidden (see Figure 1).

If neutrinos are Majorana fermions, there is an additional double beta decay mode, \((A, Z) \rightarrow (A, Z + 2) + 2e^-,\) with no (anti)neutrinos in the final state. This decay mode is known as neutrinoless double beta decay and has never been observed (except for one controversial claim [9]). The first calculations of the rate for \(\text{DBD}^{0\nu}\), performed by Furry [10], yielded a much faster rate than for \(\text{DBD}^{2\nu}\) decay, which prompted initial interest in experimental detection of the decay. However, at that time the chiral nature of the weak interaction was not yet known so a severe suppression of the \(\text{DBD}^{0\nu}\) rate was not incorporated in the calculations.

Neutrinoless double beta decay is forbidden in the Standard Model since it breaks lepton number conservation. Of course lepton number conservation is broken anyway if neutrinos are Majorana particles. Feynman diagrams for \(\text{DBD}^{2\nu}\) and \(\text{DBD}^{0\nu}\) modes are shown in Figure 2. The \(\text{DBD}^{2\nu}\) diagram contains only Standard Model interactions, while the \(\text{DBD}^{0\nu}\) diagram requires only a massive Majorana neutrino. One can think of the virtual neutrino in the Feynman diagram as an antineutrino (equal to a neutrino since it is Majorana particle) at one vertex which is absorbed as a neutrino at the other vertex. In addition to the Majorana equivalence of neutrino
Figure 2. Double beta decay diagrams for the DBD2$\nu$ (left) and the DBD0$\nu$ (right) decay modes. The DBD0$\nu$ diagram assumes that the process is mediated by the exchange of a Majorana neutrino.

and antineutrino, a non-zero neutrino mass is required to flip the helicity since antineutrinos are right-handed and neutrinos are left-handed. The helicity flip and the smallness of the neutrino mass cause the rate of DBD0$\nu$ decay to have a smaller rate compare to the DBD2$\nu$.

The DBD0$\nu$ rate is given, to a good approximation [11] by:

$$\frac{1}{T_{1/2}^{DBD\nu}} = G_{0\nu}(Q, Z) \left| M^{0\nu} \right|^2 \langle m_{\beta\beta} \rangle^2 \quad (1)$$

where $G_{0\nu}(Q, Z)$ is the phase-space factor including coupling constants, $|M^{0\nu}|$ is the nuclear matrix element of the transition and $\langle m_{\beta\beta} \rangle$ is the effective Majorana mass, defined as:

$$\langle m_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right| \quad (2)$$

where $U_{ei}$ represents the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix that describes the mixing between the neutrino mass eigenstates and the neutrino flavor eigenstates, and $m_i$ are the different mass eigenvalues. The information concerning the neutrino mass is contained in $m_{\beta\beta}$. The phase-space factor $G_{0\nu}(Q, Z)$ is calculable but the evaluation of the nuclear matrix element is a challenging problem in nuclear theory, and it is the main source of uncertainty in the evaluation of the neutrino mass.

3. Sensitivity for DBD0$\nu$ experiments

It is now analyzed the concept of sensitivity in the case of an experiment with background. Defining the sensitivity as the average upper limit that would be obtained by an ensemble of identical replicas of such an experiment, each one with the same mean expected background and no true signal. Translating in mathematical formulas this concept [12], we define the number of background events, $B$, can be written as:

$$B = b \cdot \Delta E \cdot M \cdot t, \quad (3)$$

where $b$ is the background rate in counts·keV$^{-1}$·kg$^{-1}$·y$^{-1}$, $M$ is the mass of the $\beta\beta$ emitter in kg, $t$ is the experimental running time in years and $\Delta E$ is the width of the region of interest (ROI) in keV and is proportional to the energy resolution of the detector. In this case, we assume that
the background in our ROI is approximately constant over the interval $\Delta E$. In the case that $\Delta E$ is very large, this approximation is less valid because events from DBD$2\nu$ decay can fall into the interval $\Delta E$.

The number of DBD$0\nu$ events ($N_{\beta\beta}$) can be expressed in terms of the decay rate ($\Gamma_{\beta\beta}$) as follows:

$$N_{\beta\beta} = \Gamma_{\beta\beta} \cdot n \cdot \epsilon \cdot t \propto \Gamma_{\beta\beta} \cdot a \cdot M \cdot \epsilon \cdot t,$$  \hspace{1cm} (4)

where $n$ is the total number of nuclide that can DBD$0\nu$ decay, $a$ the isotopic abundance of the nuclide candidate and $\epsilon$ the detection efficiency for DBD$0\nu$ events.

It is convenient to define a general criterion for discovery potential for a DBD$0\nu$ experiment in terms of $\sigma$ of the Poisson distribution. If we require $N_{\beta\beta}$ to be equal to $\sqrt{B}$ (68% C.L.), then we will have:

$$k \cdot \Gamma_{\beta\beta} \cdot a \cdot \epsilon \cdot M \cdot t = \sqrt{b \cdot \Delta E \cdot M \cdot t}$$  \hspace{1cm} (5)

$k$ is a constant that includes the Avogadro's number and the atomic mass of the nuclide candidate. The equation 5 results in the following expression for the sensitivity:

$$T_{1/2}^{DBD0\nu} = k \cdot a \cdot \epsilon \cdot \sqrt{M \cdot t \over b \cdot \Delta E}.$$  \hspace{1cm} (6)

Once the technique for detecting the decay products and the isotopic abundance of the candidates are chosen, the only parameters on which experimentalists can play are: $b$, $M$ and $t$. They are related to the neutrino mass value by the fourth root law, therefore big efforts are required to improve the sensitivity. Since the variable time will never improve fast enough, the search for the DBD$0\nu$ must be carried out increasing the source mass and reducing the background as much as possible.

A perfect tool, for the search of this rare decay, able to scale to big masses (tens of kg) \[13,14\] and potentially have an extremely small background are the scintillating bolometer detectors.

4. Scintillating bolometer 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. Almost the total released energy can be detected in this device.

The energy deposited by a single particle into an energy absorber (connected to a heat sink) produces an increase of the temperature $T$ of the absorber. This variation corresponds to the ratio between the energy released by the interacting particle and the heat capacity of the absorber. The only requirements needed for running this type of devices are therefore to operate the detector at low temperatures (mK scales), in order to reduce the value of the heat capacity (large temperature variations), and to have a sensitive thermometer coupled to the absorber. The thermometer is usually a thermistor, a resistive device with a strong dependence of the resistance to the temperature.

When the bolometer crystal is an efficient scintillator at low temperatures, a small but significant fraction of the deposited energy (up to a few percentage) is converted into scintillation while the remaining part is detected in the form of heat. The emitted light can be measured by a light detector facing the scintillating bolometer \[15\] (see Figure 3). The idea to use a bolometer as light detector was first developed by Bobin \[16\] and then optimized for Dark Matter (DM) searches. Now, it is evident that the best way to detect the scintillating light is to developed an independent detector opaque to the emitted light and equiped with its own thermal sensor. The size and the relative position to the scintillating bolometer must be chosen in a way to maximize the light collection.

The idea to use these detectors for DBD$0\nu$ purposes was born in 1998 \[17\].
5. Background sources
The experimental signature of the DBD0ν is in principle very clear: a peak (at the Q_{ββ} value) in the two-electron summed energy spectrum. In spite of such characteristics, the rarity of the process makes the identification very difficult. Such a signal has to be disentangled from a background produced by natural radioactive decay chains, cosmogenic-induced activity, and artificial radioactivity. All of these background sources can release energy in the region of interest for the DBD, unfortunately at a higher rate. Thus, the main task in DBD0ν searches is to suppress the natural background using state-of-the-art ultralow background techniques and, hopefully, identifying the signal.

Among the various background sources (external γ background, neutrons, surface contaminations and 238U and 232Th internal contaminations) surface contaminations represent the main source of background for bolometric detectors, such as CUORICINO [18]. This source of background plays a role in almost all detectors but turns out to be crucial for fully active detectors, as in the case of bolometers: a radioactive nucleus located within a few μm of a surface facing the detector can emit an α particle (whose energy is roughly between 4 and 9 MeV). Those particles can lose part, or even all, of their energy in the few microns of dead layer before reaching the bolometer. The energy spectra read by the bolometer, therefore, will result in a continuum between 0 and 9 MeV, covering, unfortunately all the possible Q_{ββ} values (see Figure 4). Furthermore, the same mechanism holds in the case of surface contaminations on the bolometer itself. The use of scintillating crystals as absorbers can overcome these background limitations,

Figure 3. Pictorial view of a scintillating bolometer.

Figure 4. Natural abundances and Q-value for several DBD0ν isotopes. The dashed lines represents the 2615 keV γ line, one of the highest natural γ emission.
Table 1. Sensitivity of three experimental options for a scintillating bolometer experiment on neutrinoless double beta decay (isotope candidate enriched at 98% level). The value $m_{\beta\beta}$ is the $1\sigma$ sensitivity calculated with the Feldman Cousin approach for 5 years running, considering a background level of 0.001 counts·keV$^{-1}$·kg$^{-1}$·y$^{-1}$, an energy resolution of 5 keV and the matrix elements described in [22, 23, 24, 25].

| Crystal   | Mass  | Useful material | Sensitivity to $m_{\beta\beta}$ [meV] |
|-----------|-------|-----------------|---------------------------------------|
| CdWO$_4$  | $^{116}$Cd 15.1 kg | 32 % | 65 –80 |
| ZnMoO$_4$ | $^{110}$Mo 11.3 kg | 44 % | 67 –73 |
| ZnSe      | $^{82}$Se 17.6 kg | 56 % | 52 –65 |

providing a powerful tool to improve the experimental DBD0ν sensitivities. In fact, by means of the various scintillation yield of various particle interactions (namely $\beta/\gamma$, $\alpha$ and neutrons) they can be very different.

6. The LUCIFER experiment

LUCIFER (Low-background Underground Cryogenic Installation For Elusive Rates) is a Double Beta Decay pilot project based on scintillating bolometers and it is funded by the European Community.

6.1. Isotope candidate

Practical scintillators for DBD searches can be built out Mo, Cd and Se [19, 20]. These three nuclides contain isotopes that can potentially decay through DBD0ν channel: $^{100}$Mo, $^{116}$Cd and $^{82}$Se, with a $Q_{\beta\beta}$ value higher than the characteristic gamma emission of $^{208}$Tl (2.6 MeV) (see Figure 4), which is one of the most energetic natural gamma line. This feature implies that the gamma background will be significantly reduced.

If we still look at Figure 4, the three mentioned candidates have a small isotopic abundance, compare to $^{130}$Te, so if these isotopes are used for a DBD0ν experiment they will require a large mass (difficult to handle) or an isotopic enrichment.

The candidates crystals are CdWO$_4$, ZnMoO$_4$, ZnSe. In Table 1, we compare these nuclei with respect to physics sensitivity for a given detector mass, relative amount of DBD emitter in the crystal (48 crystals of 125 cm$^3$), background rejection factor (Quenching Factor [21]). The Quenching Factor is usually defined as the ratio between the amplitude of light pulses corresponding to alpha and $\beta/\gamma$ particles of the same energies.

Looking at Table 1 the ZnSe choice seems to be the best for what concerns the mass source and the useful material. But if we consider the quenching factor (Q.F.) values for these scintillating crystals (Table 2), ZnSe has a non-standard value: it is larger than 1. This implies that alpha particles scintillate more compare to the $\beta/\gamma$ in the crystal (see Figure 5). This behavior is supposed to be caused by the energy distribution in radiative (detectable) and non-radiative or long-living metastable (non-detectable) channels.

Discrimination problems may arise in these crystals, in fact if there is an inefficient light collection, we can have a leak of alpha events in the $\beta/\gamma$ region, producing a background in our region of interest. Anyway it should be stressed that the Q.F. for ZnSe crystals is quite large, and the particle discrimination is still efficient (see Figure 6). In the specific, preliminary studies reveal the capability of an $\alpha$ power rejection larger than 99% [26].
Table 2. Alpha quenching factor for three different scintillating crystals [19, 29]

| Crystal  | Q.F. (α/β) |
|----------|-------------|
| CdWO₄    | 0.19        |
| ZnMoO₄   | 0.16        |
| ZnSe     | 4.2         |

Figure 5. Scatter plot for heat-light events, for a scintillating crystal with Q.F. smaller (top) and greater (bottom) than 1.

Figure 6. Comparison between α events from $^{234}$U and $^{238}$U sources (in blue) and γ events generated by neutrons from AmBe source (in red).

6.2. The detector structure
As every large mass bolometric detector, 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 to achieve large masses (~ 50 kg) keeping the single crystal mass reasonable (hundreds of grams) and providing a rough granularity, very helpful for background identification and rejection. The array will be composed by a set of identical elementary modules (see Figure 7).

The proposed structure of each single module exploits the experience gathered during the development of past and present DBD bolometric experiments. The configuration resembles
Figure 7. Elementary module equipped with four ZnSe scintillating crystals read out by a single light detector (left), and the whole LUCIFER detector inside the cryostat (right).

closely the one selected and extensively tested for CUORE [27], with an additional light detector, designed and developed during the scintillating-bolometer R&D [28]. 12 single modules will be assembled one above the other. The total tower height will be about 85 cm, exploiting the available space in the CUORICINO cryostat in the present internal shielding arrangement. The total bolometric mass will be 31.7 kg, and the corresponding mass of the enriched material 17.6 kg.

7. Conclusions
The project LUCIFER aims to unveil the nature of the neutrino mass. A positive result of the experiment would give an answer to one of the fundamental open questions in Nature, that neutrino is a Majorana particle. Beside this fundamental assessment, it would constitute a proof of existence of New Physics and it would give a scale to the absolute neutrino mass. This project will have the merit of indicating the way to go for next generation experiments, by setting a limit (or hopefully a value) on the DBD$^{0}\nu$ half-life, using such a detector mass 30 kg. The technology demonstrated by this project is indeed fully scalable.

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