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NEUTRINOLESS DOUBLE BETA DECAY: AN EXTREME CHALLENGE

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Abstract. Neutrino-less Double Beta Decay is the only known way to possibly resolve the nature of neutrino mass. The chances to cover the mass region predicted by the inverted hierarchy require a step forward in detector capability. A possibility is to make use of scintillating bolometers. These devices shall have a great power in distinguishing signals from alfa particles from those induced by electrons. This feature might lead to an almost background-free experiment. Here the Lucifer concept will be introduced and the prospects related to this project will be discussed.

Keywords: neutrino physics, Majorana mass, bolometers.

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 by Majorana [1] 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 ($0\nu2\beta$). 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 well discussed for example by Avignone, Elliot & Engel [2]. 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. The physics

The practical possibility to test the Majorana nature of neutrinos is indeed in detecting the process shown in Fig. 1, the Double Beta Decay (DBD) without emission of neutrinos. The rate for $0\nu2\beta$ process will go as $1/\tau = G(Q,Z)|M^2|m^2_{\beta\beta}$ where G is the easily calculable phase space factor and M is the challenging nuclear matrix element that is known, Ref. [3], with still large uncertainties. The effective neutrino mass ($m_{\beta\beta}$) 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

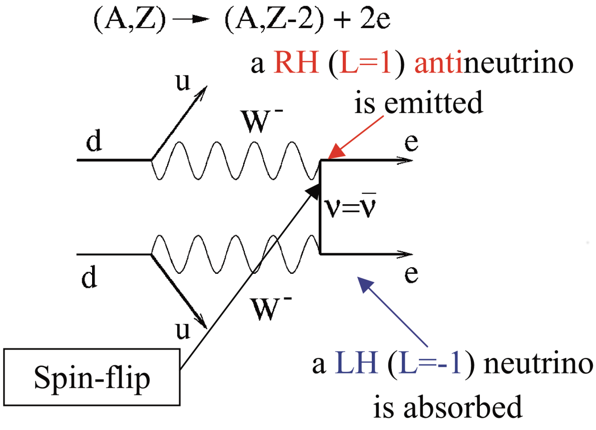

Figure 1. Neutrino-less double beta decay process.

$$S^{0\nu} = a\sqrt{\frac{Mt}{b\Delta E}}\varepsilon.$$

From this formula it is clear that 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 therefore have at least very sharp energy resolution and possibly other discriminating mechanisms. The key however is in the background index value (b).

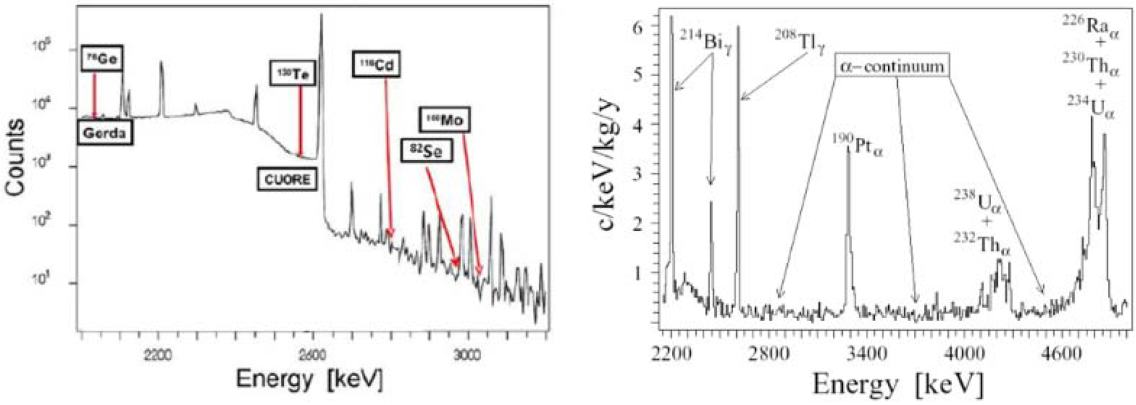

Figure 2. Radiative nuclear transitions. It clearly shows (left) that above the ^{208}Tl this contribution to the DBD background becomes negligible. Right: Cuoricino background in the DBD region and above. It clearly shows the dominance of degraded α's. The two components are the natural radiation and the degraded α's. Cuoricino experiment (in Ref. [4]) has been a clear cornerstone for identifying the nature of the problem.

3. The problem

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. In Fig. 2 the main problem with background, at least for the calorimetric experiments, is elucidated.

4. The future

One (high)way open for at least getting to the possibility of testing the entire region allowed by the inverted hyerarchy case is to combine the superior energy resolution of the bolometric technique, moreover applicable to almost all of the isotopes suited for the search, with the information provided by scintillation light in a way to use the different yield generated by α particles with respect to electrons.

The best features of bolometric detectors are that they can contain the candidate nuclei with a favorable mass ratio and be massive and 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. Beside, they can be built in a way to be characterized by low intrinsic background.

Scintillating bolometers bring in an enormous added value by providing a substantial α/β discrimination power (by difference of quenching factor). Further there is some flexibility in the choice of crystal type which allows the use of most of the high Q-value candidates. A first demonstration is given in [5]. 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 percent) 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.

The principle of operation of a scintillating bolometer is shown in Fig. 3.

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. A lot of pro and cons have been evaluated for the three materials, without going into details we say that the final decision has favoured Se in form of 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 (see in [6]) 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 as seen in Fig. [4].

The detector configuration proposed for Lucifer [7] resembles closely the one selected and extensively tested for CUORE [8] 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. In Tab. 1 we give a rough indication of a merit factor of experiments ongoing (GERDA [9]) and EXO [10] and in preparation (CUORE and Lucifer). The merit refers only to the capability (real or claimed) of background discrimination through energy resolution and background

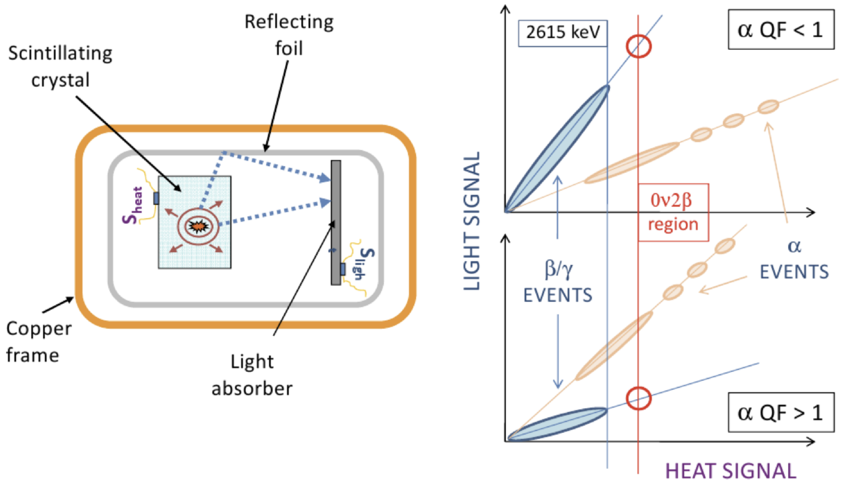

FIGURE 3. Schematic structure of a double read-out scintillating bolometer. Right: schematic scatter plots of light signals vs. heat signals corresponding to events occurring in the scintillating bolometer. In both circumstances (positive/negative QF) α induced events can be efficiently rejected.

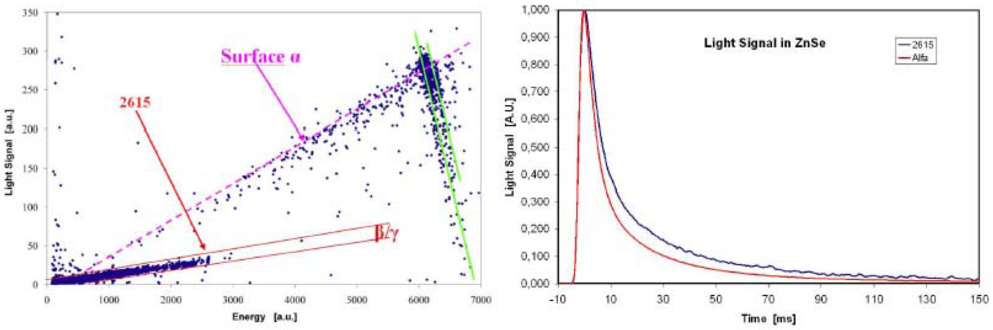

FIGURE 4. Results from a run on a ZnSe crystal with double (heat and light) readout exposed to radiactive sources. Left: scatter plot light vs. heat. Right: Decay time of the scintillation light from α and electrons ^{208}Tl line.

exp	ΔE keV	b count/(keV kg y)	$b\,\Delta E$ count/(ton y)
GERDA	4.5	0.02	90
EXO	80	0.0015	120
CUORE	5	0.02	100
Lucifer	10	0.001	10

TABLE 1. Merit factors due to background rejection for some experiment running or in preparation.

rejection. A realistic projection shall of course include Nuclear Matrix Elements, tonnage and, helas, cost.

5. CONCLUSIONS

The search for understanding the nature of neutrino mass is undergoing. Experiments of the actual generation are unable to explore the entire region allowed by the inverted mass hierarchy hypothesis. One of the possible breakthrough for a future generation experiment is the use of scintillating crystals bolometrically exploited. A conclusive demonstration of the validity of this approach is still missing. Lucifer experiment will be a cornerstone in this respect.

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