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Majorana Neutrinos

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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 others. 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 [1] by Majorana in 1937 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 measure an extremely fascinating and rare process that takes the name of Neutrinoless Double Beta Decay (0ν DBD). 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 line. The rate of this yet unobserved phenomenon will also allow a determination, although not precise, of the neutrino mass. A set of pioneering experiments [2] has been performed for this search. With the exception of one, all of them resulted into a negative observation. The one claiming a positive evidence [3] (about 4σ) has not fully convinced the community and it is waiting for a possible confirmation. A new generation of experiments is in preparation [4] for challenging this difficult problem. In this paper, one of them will be described in some detail. It is CUORE [5], a concept extrapolated from a running prototype (CUORICINO [6]) that will be functional around 2010 with a sensitivity such to be able to probe the inverted hierarchy region as described by the most recent analyses [8] of the global neutrino data.

2 Majorana Neutrinos and Double Beta Decay

Neutrinoless double-beta decay is an old subject. What is new is the fact that, recently, neutrino oscillation experiments have unequivocally demonstrated that neutrinos have mass and that the neutrino mass eigenstates mix. Indeed the massive nature of neutrinos is a key element in resurrecting the interest for the Majorana conjecture. The difference between Dirac neutrinos and Majorana ones is shown in Fig. 1. The practical possibility to test the Majorana nature of neutrinos is indeed

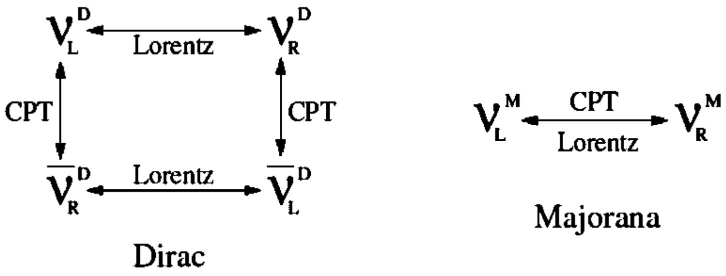

Figure 1: Dirac and Majorana neutrinos

in detecting the process shown in Fig. 2, the Double Beta Decay (DBD) without emission of neutrinos.

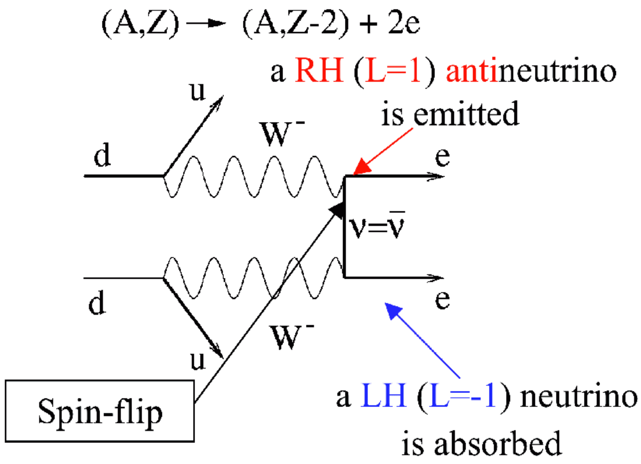

Figure 2: Neutrinoless Double Beta Decay diagram

Although the possibility [7] for this process was pointed out by W. Furry 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 discriminant between Dirac and Majorana neutrinos is in the lepton flavour conservation, required by Dirac and violated by Majorana. So that the observation of neutrinoless DBD would be the proof of the Majorana conjecture. The oscillation experiments have yielded valuable information on the mixing angles and on the mass differences of the three eigenstates. They cannot, however, determine the scale of the neutrino mass, which is fixed by the lightest neutrino mass eigenvalue. This can only be directly determined by beta decay end point spectral shape measurements, or in the case of Majorana neutrinos, by the observation and measurement of the neutrinoless double-beta decay half-life. The oscillation experiments yield values for the mixing angles and mass differences accurate enough to allow the prediction of a range of values of the effective mass of the Majorana electron neutrino. As a function of the oscillation parameters indeed we find that

$$m_{\beta\beta} = \Sigma m_{\nu_k} U_{ek}^2 = cos^2\theta_{13}(m_1 cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 e^{2i\beta} sin^2\theta_{13}$$

According to most theoretical analyses of of present neutrino experiment results, next-generation DBD experiments with mass sensitivities of the order of 10 meV may find the Majorana neutrino if its mass spectrum is of the quasi- degenerate type or it exhibits inverted hierarchy.

3 Experimental techniques

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 they differ as much as two order of magnitude. 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 make you gain linearly, 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. There are several natural and enriched isotopes that have been used in experiments with tens of kilograms. Some of them could be produced in amounts large enough to be good candidates for next generation experiments. 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 table 3.

Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic abundance (%)
^{48}Ca	4.271	0.0035
^{76}Ge	2.039	7.8
^{82}Se	2.995	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{116}Cd	2.802	7.5
^{128}Te	0.868	31.7
^{130}Te	2.533	34.5
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

Figure 3: Candidate elements for 0ν DBD

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

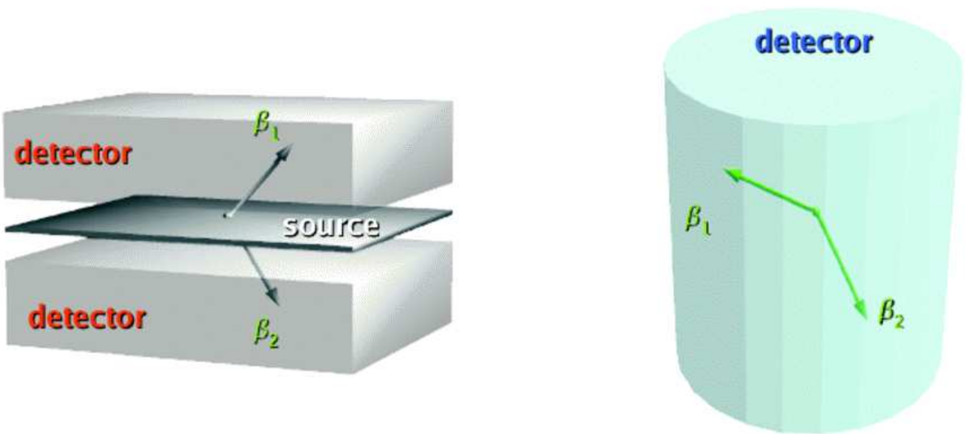

Figure 4: Schematics of main DBD detector types

When the source is the same as the detector (calorimetric type) , source mass is maximized 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, a complicate geometry and a comparatively worse energy resolution. Bolometers belong to the calorimetric category. At low temperatures (the operating temperature for CUORICINO is 8 mK), the heat capacity of crystals is proportional to the cube of the ratio of the operating and Debye temperatures. The energy released in a single particle interaction within the crystal is clearly measurable as change in temperature of the entire crystal by using neutron transmutation doped (NTD) germanium thermistors which are optimized to operate at these temperatures.

A number of experiments are currently at various stages of development to probe the degenerate and into the inverted mass hierarchy region of the neutrino mass spectrum.

All of them are needed since it is imperative to carry out double beta decay searches in multiple isotopes, both to improve the nuclear matrix calculations necessary to extract the effective neutrino mass, and to ensure that the observation of a line at the expected energy is not a result of a yet unknown radioactivity line.

4 CUORICINO and CUORE

Cryogenic bolometers, with their excellent energy resolution, flexibility in material, and availability in high purity of material of interest, are excellent detectors for search for neutrinoless double beta decay. Kilogram-size single crystals (cubic crystals of 5cm side) for TeO_2 are now available and utilized in CUORICINO in an array for a total detector mass of 40 kg. CUORICINO results from a total exposure of 8.38 kg-yr of

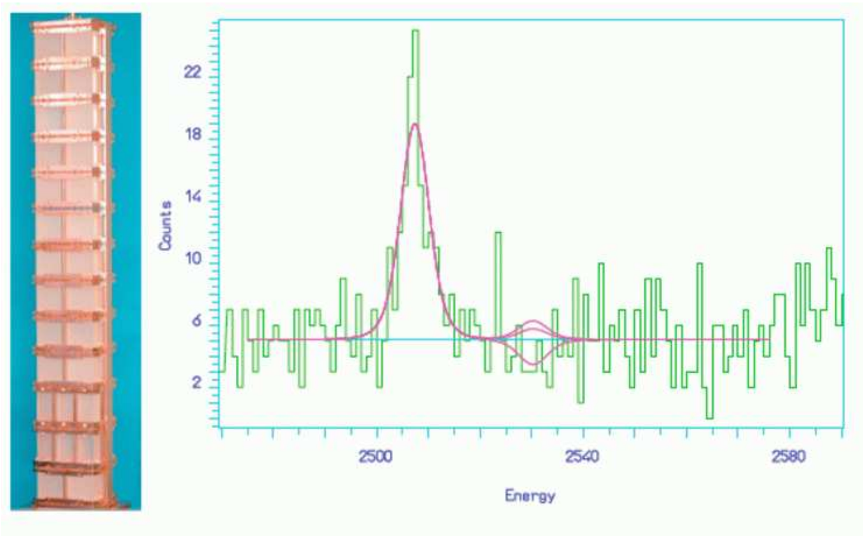

Figure 5: CUORICINO sketch (left) and results (right)

^{130}Te (Fig. 5) show no evidence for a peak at 2530 keV, the expected Q-value for for

^{130}Te. The absence of any excess events above backgrounds in the region of interest gives a limit of $T_{1/2} \geq 2.4 \times 10^{24}$ yr(90%) C.L. on the 0ν decay rate of ^{130}Te. This corresponds to an effective neutrino mass of $m_{\beta\beta} \leq 0.18-0.94$ eV, the range reflecting the spread in nuclear matrix element calculations. The background measured in the region of interest is 0.18 ± 0.01 counts/keV/kg/yr. CUORE (Cryogenic Underground Observatory for Rare Events), to be located at the Gran Sasso National Laboratory of INFN (LNGS) , at a depth of 3400 m.w.e., will consist of 988 bolometers of TeO_2 crystals, with a total mass of 740 kg. Because of the high isotopic abundance (34%), 204 kg of ^{130}Te will be available for the relevant process without isotopic enrichment, a virtue that eliminates the requirement for the very expensive process needed in all of the other proposed next generation experiments, making CUORE both timely and significantly less expensive than other experiments. CUOREs modular design (see Fig. 6) and flexibility of cryogenic detector will also allow future searches in other isotopes of interest.

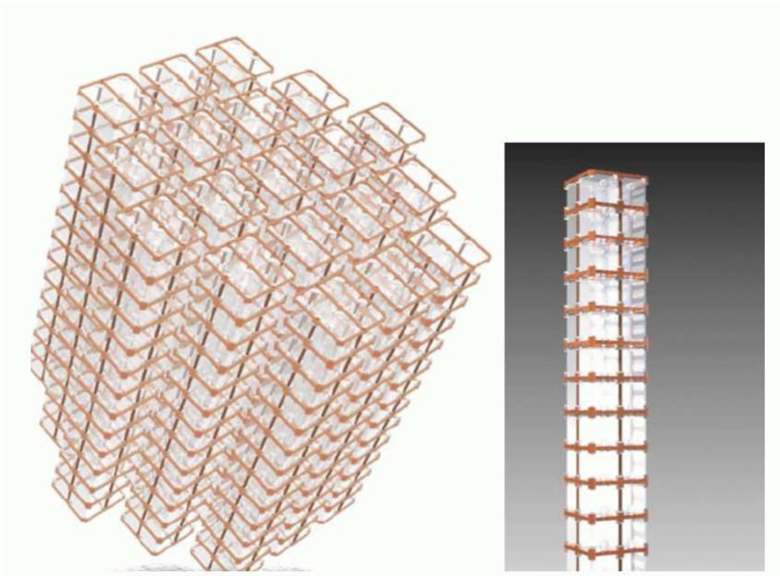

Figure 6: CUORE design

The extrapolation from CUORICINO results to CUORE expectation is based on the following facts:

- a total mass 20 times larger
- a running time 10 times longer
- an energy resolution 50% better

- a background 20 times smaller

The major challenge in obtaining the desired sensitivity is the reduction of the background rate. This task can be accomplished in three main ways: 1) By reducing the amount of material (Cu in our case) surrounding the crystals. 2) By a proper cleaning procedure of all the materials that will be in contact or will see the crystals. 3) By finding a veto procedure to eliminate unwanted signals coming from outside the bolometer. The results so far available from the CUORICINO understanding, the dedicated *R&D* performed in a dedicated cryogenic facility running at LNGS and the MonteCarlo simulations indicate that a factor 10 has been already secured. The sensitivity, in term of neutrino mass and taking into account the entire set of matrix elements calculation available, is $m_{\beta\beta} \approx 19 - 100$ meV.

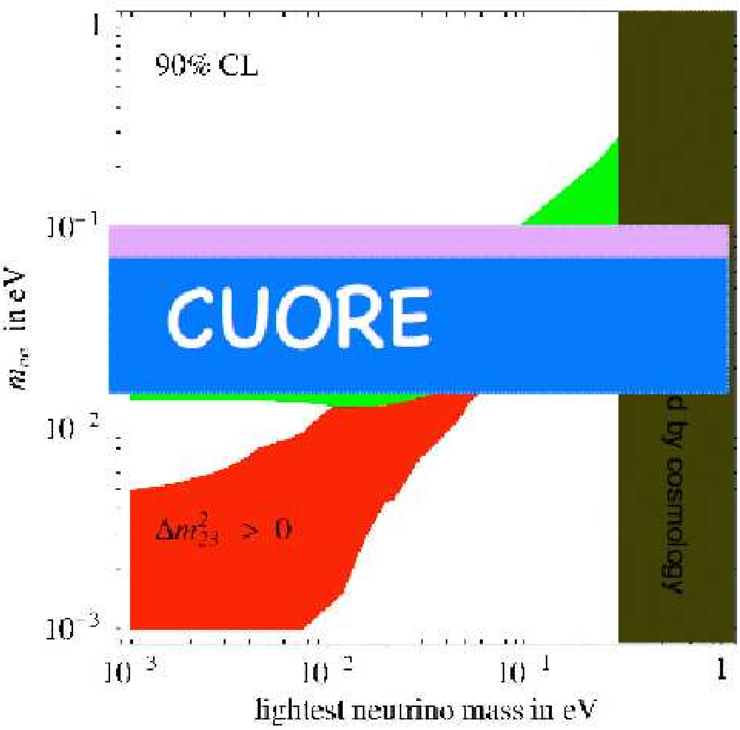

Figure 7: CUORE projected sensitivity to $m_{\beta\beta}$

5 Conclusion

Neutrino physics is one of the leading field of the high energy research today. One of the top question that has to be answered is about the Dirac or Majorana nature of neutrino mass. The neutrino-less double beta decay search is the only experimental line that can answer this fundamental question and that might possibly be the sole chance to provide a measure of neutrino mass. Cryogenic bolometer, with its flexibility in material choice and the ability to scale up to the ton- scale makes it an ideal technology for large-scale detector for double-beta physics experiments. CUORICINO is currently running as the most sensitive experiment. Much of the technology has been tested for CUORE that will start taking data in 2010 with much a larger mass. The sensitivity of CUORE will allow probing a good portion of the mass region predicted in case of inverted hierarchy. The proof of the Majorana nature of the neutrinos might be achieved by CUORE together with a determination of the neutrino mass scale.

6 Acknowledgments

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