

# Neutrinoless Double Beta Decay Searches

**Oliviero Cremonesi**

INFN, Sezione di Milano Bicocca  
Piazza della Scienza,3 - I-20126 Milano

E-mail: [oliviero.cremonesi@mib.infn.it](mailto:oliviero.cremonesi@mib.infn.it)

**Abstract.** The oscillation experiments have demonstrated that neutrinos are massive particles and have provided most of the neutrino mixing matrix elements. However, two very important neutrino properties are still missing: their nature and the absolute scale of their masses. Neutrinoless double beta decay ( $\beta\beta(0\nu)$ ) is presently the only practical tool for probing the character of neutrinos. In case neutrinos are Majorana particles  $\beta\beta(0\nu)$  can moreover provide fundamental informations on their absolute mass scale. The present status of experiments searching for  $\beta\beta(0\nu)$  is reviewed and the most relevant results discussed. The possibility to observe  $\beta\beta(0\nu)$  at a neutrino mass scale in the range 10-50 meV is attracting a lot of interest for  $\beta\beta(0\nu)$  searches. The achievement of the required experimental sensitivity is a real challenge faced by a number of new proposed projects. A review of the most relevant projects proposed for the future is given and the most relevant parameters contributing to the experimental sensitivity are finally outlined.

## 1. Introduction

During the past decade, the results on neutrino oscillations from atmospheric, solar, reactor and accelerator experiments have shown that neutrinos are massive particles and the three neutrino mass eigenstates are related to the three neutrino mass flavor eigenstates through the PMNS mixing matrix. This is a very strong demonstration that the Standard Model of electroweak interactions is incomplete and that new Physics beyond it must exist.

Being sensitive only to the mixing matrix parameters and to the squared mass differences between the neutrino species, the experiments on neutrino oscillations can't provide however any insight into the problems of the neutrino nature and their mass scale. Indeed, two possible hierarchical mass arrangements (Direct and Inverted) are allowed by present data[1, 2]. The obvious quasi-degenerate option describing the situation in which the neutrino masses are all comparable and much larger than their differences is also still possible.

Two most outstanding questions are therefore still puzzling the world of neutrino Physics: the possible Majorana nature of neutrinos and their absolute mass scale. Neutrinos are the only fermions for which the Majorana formulation[3] is possible (assuming a violation of the Lepton Number). The smallness of their masses complicates however the situation and the problem of the neutrino character and absolute mass scale get mixed. Indeed the distinction between the Majorana and the Dirac formulation tends to vanish as the neutrino mass tends to zero. Although present techniques for direct measurements of the electron antineutrino mass guarantee a model-independent approach, at present they can only probe the quasi-degenerate region. On the other hand, the much more sensitive cosmological inferences and neutrinoless double-beta decay experiments could probe the inverted hierarchy but suffer from a heavy model dependence.

All these experimental approaches provide complementary pieces of information and a common effort is compulsory. Before the discovery that neutrinos are massive little attention was actually dedicated to the issue of Majorana neutrinos. On the other hand the situation has dramatically changed after 1998 and presently there is a common consensus that the Majorana picture is indeed the best for the physical neutrinos.

## 2. Neutrinoless Double Beta Decay

First suggested by M.Goeppert-Mayer in 1935[4], Double Beta Decay (DBD) is a rare nuclear process in which an initial nucleus  $(A,Z)$  decays to a member  $(A,Z+2)$  of the same isobaric multiplet with the simultaneous emission of two electrons. Given the natural trend of the nuclear masses, such a transition is possible for a number of nuclei. However, in order to avoid (or at least inhibit) the occurrence of the equivalent sequence of two single beta decays, it is generally required that both the parent and the daughter nuclei be more bound than the intermediate one. Because of the pairing term, such a condition is fulfilled in nature for a number of even-even nuclei. The decay can then proceed both to the ground state or to the excited states of the daughter nucleus. Double beta transitions accompanied by positron emission or electron capture are also possible. However they are usually characterized by lower transition energies and have correspondingly poorer experimental sensitivities. They will not be discussed in the following. We refer to the most recent reviews on  $\beta\beta$  for a more complete treatment on the subject[5, 6]. Among the possible  $\beta\beta$  modes two are of particular interest, the  $2\nu$  mode  $(\beta\beta(2\nu)) \frac{A}{Z}X \rightarrow \frac{A}{Z+2}X + 2e^- + 2\bar{\nu}$ , which observes the lepton number conservation and it is allowed in the framework of the Standard Model (SM) of electro-weak interactions, and the  $0\nu$  mode  $(\beta\beta(0\nu)) \frac{A}{Z}X \rightarrow \frac{A}{Z+2}X + 2e^-$  which violates the lepton number by two units and occurs if neutrinos are their own antiparticles. A third decay mode  $(\beta\beta(0\nu,\chi))$  in which one or more neutral bosons  $\chi$  (Majorons) are emitted  $\frac{A}{Z}X \rightarrow \frac{A}{Z+2}X + 2e^- + N\chi$  is also often considered. The interest in this decay is mainly related to the existence of Majorons, massless Goldstone bosons that arise upon a global breakdown of B-L symmetry and could play a significant role in the history of the early Universe and in the evolution of stars. Several models of the Majoron have been so far proposed in the framework of the supersymmetric and other extended theories[7]. Present bounds on the Majoron-neutrino coupling constant from  $\beta\beta(0\nu,\chi)$  are in the range  $0.35-1.9 \cdot 10^{-4}$ [8].

From the point of view of Particle Physics  $\beta\beta(0\nu)$  is of course the most interesting of the  $\beta\beta$  decay modes. In fact, after 70 years from its introduction by W.H. Furry[9],  $\beta\beta(0\nu)$  is still one of the most powerful tools to test neutrino properties: it can exist only if neutrinos are Majorana particles and it allows then to fix important constraints on the neutrino mass scale.

When mediated by the exchange of a light virtual Majorana neutrino, the  $\beta\beta(0\nu)$  rate can be expressed as

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 |\langle m_\nu \rangle|^2 \quad (1)$$

where  $G^{0\nu}$  is the (exactly calculable) phase space integral,  $|M^{0\nu}|^2$  is the nuclear matrix element and  $\langle m_\nu \rangle$  is a (coherent) linear combination of the neutrino masses

$$\langle m_\nu \rangle \equiv \sum_{k=1}^3 |U_{ek}^L|^2 m_k e^{i\phi_k} \quad (2)$$

or, explicitly for small neutrino masses

$$\langle m_\nu \rangle = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3 \quad (3)$$

where  $\alpha_1$  and  $\alpha_2$  are the neutrino Majorana phases. Unfortunately, the presence of these phases in the  $\langle m_\nu \rangle$  expression implies that cancellations are possible. In particular, these cancellations are complete for a Dirac neutrino since it is equivalent to two degenerate Majorana neutrinos

with opposite CP phases. This stresses once more the fact that  $\beta\beta(0\nu)$  can occur only through the exchange of Majorana neutrinos. On the other hand  $\beta\beta(0\nu)$  represents a unique possibility to measure the neutrino Majorana phases.

Altogether, the observation of  $\beta\beta(0\nu)$  and the accurate determination of the  $\langle m_\nu \rangle$  would definitely establish that neutrinos are Majorana particles, fixing their mass scale and providing a crucial contribution to the determination of the absolute neutrino mass scale.

It should be stressed that important constraints could be obtained even in the case that forthcoming  $\beta\beta(0\nu)$  experiments would not observe any decay. Indeed, assuming that neutrinos are Majorana particles, a negative result in the 20-30 meV range for  $\langle m_\nu \rangle$  would definitely rule out the inverse ordering thus fixing the neutrino hierarchy problem[1, 2].

### 3. $\beta\beta(0\nu)$ Nuclear Matrix Elements

As can be easily deduced from eq. (1),  $\langle m_\nu \rangle$  is the only  $\beta\beta(0\nu)$  measurable parameter containing direct information on the neutrino mass scale. Its derivation from the experimental  $\beta\beta(0\nu)$  results requires a precise knowledge of the transition Nuclear Matrix Elements  $M^{0\nu}(\text{NME})$  for which many (unfortunately often conflicting) evaluations are available in the literature. The disagreement among available calculations has led to large uncertainty ranges for  $\langle m_\nu \rangle$ . This has been recognized as a critical problem by the  $\beta\beta$  community and a strong effort aiming at more stable and reliable calculations has been started since few years.

The calculation of  $\beta\beta(0\nu)$  nuclear matrix elements (NME) has been carried out in the last decades by many authors using different methods: Quasiparticle Random Phase Approximation (QPRPA, RQPRPA, pnQPRPA etc.), the Shell Model (SM), the Projected Hartree-Fock-Bogoliubov (PHFB) and the Interacting Boson Model (IBM2).

The different methods have complementary virtues. Indeed, QRPA calculations include many single-particle levels outside a relatively small inert core but they can hardly manage correlations. On the other hand, the shell model can include arbitrarily complicated correlations, but is limited to a few single-particle orbitals outside the inert core.

Significative improvements have been obtained recently. SM calculations are still systematically smaller than the others but NME calculations presently agree within a factor 2-3[10]. Such an agreement does not guarantee by itself the correctness of the calculations but the convergence of the results from very different methods can hardly be by chance and their comparison can help to identify the important effects responsible for the observed disagreement.

The careful check of the models in order to account for the omitted physics or the important missing informations seems the only way out of the problem. A systematic analysis of the calculation methods and their basic hypotheses have been therefore started.

A statistical analysis of the different NME calculations (comparison of different methods and model parameters) has also been recently considered[11]. Besides providing useful recipes for the comparison of the experimental results on different isotopes this approach could help in identifying systematic effects in the different calculations.

From a purely experimental point of view, the spread in the available NME calculations causes a lot of confusion in the comparison of the results and sensitivities of the different experiments. Indeed different authors tend to report  $\langle m_\nu \rangle$  intervals obtained using different set of calculations thus spoiling the relevance of any comparison. Such a problem has been once more recognized recently in [6], where a practical solution consisting in referring to a Physics Motivated Average (PMA) set of NME values is suggested when comparing results or sensitivities referring to different nuclei. A different approach, consisting in disentangling the uncertainty intervals according to the different NME used calculations[12], has been also suggested recently. Such an approach has the advantage of allowing a separate comparison between different calculation methods but does not solve completely the confusion of the NME intervals.

#### 4. Experimental approach

The only experimentally available information in  $\beta\beta(0\nu)$  is carried by the daughter nucleus and the two emitted electrons. Only few experimental parameters are therefore available: sum of the electron energies, single electron energy and angular distributions, identification and/or counting of the daughter nucleus. Two main general approaches have been followed so far for  $\beta\beta$  experimental investigation: i) indirect or inclusive methods, and ii) direct or counter methods. Inclusive methods are based on the measurement of anomalous concentrations of the daughter nuclei in properly selected samples, characterized by very long accumulation times. They include Geochemical and Radiochemical methods which, being completely insensitive to different  $\beta\beta$  modes, can only give indirect evaluations of the  $\beta\beta(0\nu)$  and  $\beta\beta(2\nu)$  lifetimes. They have played a crucial role in  $\beta\beta$  searches especially in the past.

Counter methods are based instead on the direct observation of the two electrons emitted in the decay. Different experimental parameters (energies and momenta of the emitted electrons, topology, etc) can then be registered according to the different capabilities of the employed detectors, which characterize also the accuracy with which the available information is collected. These methods are further classified in *inhomogeneous* (when the observed electrons originate in an external sample) and *homogeneous* experiments (when the source of  $\beta\beta$  's serves also as detector).

In most cases the various  $\beta\beta$  modes are separated simply on the basis of the different distribution expected for the electron sum energies: a continuous bell distribution for  $\beta\beta(2\nu)$  and  $\beta\beta(0\nu,\chi)$ , and a sharp line at the transition energy for  $\beta\beta(0\nu)$ . In these cases, a good energy resolution is the most attractive experimental feature. Indeed, direct counting experiments with very good energy resolution, providing so far the best experimental results, are still the most attractive approach for  $\beta\beta(0\nu)$  searches.

**Table 1.** Best reported results on  $\beta\beta(2\nu)$  and  $\beta\beta(0\nu)$  processes and most relevant  $\beta\beta$  parameters. Limits are at 90% CL.  $F_N^{0\nu}$  are  $\beta\beta(0\nu)$  nuclear factor of merit computed using, for the NME, the PMA suggested in [6].

Isotope	$T_{1/2}^{2\nu}$ [13] ( $10^{19}$ y)	$T_{1/2}^{0\nu}$ ( $10^{24}$ y)	Q (keV)	nat. ab. (%)	$F_N^{0\nu}$ ( $10^{-25}y^{-1}eV^{-2}$ )
$^{48}\text{Ca}$	$(4.4^{+0.6}_{-0.5})$	$> 0.0014$ [14]	4271	0.19	
$^{76}\text{Ge}$	$(150 \pm 10)$	$> 19$ [15] $22.3^{+4.4}_{-3.1}$ [17] $> 15.7$ [18]	2040	7.8	22.6
$^{82}\text{Se}$	$(9.2 \pm 0.7)$	$> 0.36$ [19]	2995	9.2	15.1
$^{96}\text{Zr}$	$(2.3 \pm 0.2)$	$> 0.0092$ [19]	3350	2.8	
$^{100}\text{Mo}$	$(0.71 \pm 0.04)$	$> 1.1$ [19]	3034	9.6	
$^{116}\text{Cd}$	$(2.8 \pm 0.2)$	$> 0.17$ [20]	2802	7.5	
$^{130}\text{Te}$	$(68^{+12}_{-11})$	$> 2.8$ [21]	2527	34.5	22.6
$^{136}\text{Xe}$	$> 81$ [22]	$> 0.45$ [23]	2479	8.9	15.8
$^{150}\text{Nd}$	$(13.3^{+4.5}_{-2.6})$	$> 0.0036$ [24]	3367	5.6	26.7
$^{238}\text{U}$	$(220 \pm 50)$	$> 0.0036$ [24]			

Experimental evidence for several  $\beta\beta(2\nu)$  decays has been provided using the measured two-electron sum energy spectra, the single electron energy distributions and the event topology[13].

On the other hand, impressive progress has been obtained during the last years also in improving  $\beta\beta(0\nu)$  half-life limits for a number of isotopes (Tab.1). The best results are still

maintained by the use of isotopically enriched HPGe diodes for the experimental investigation of  $^{76}\text{Ge}$  (Heidelberg-Moscow[15] and IGEX[18]) but two other experiments have recently reached comparable sensitivities: NEMO3[19, 25] at LSM and CUORICINO at LNGS[26]. The former is a large inhomogeneous detector aiming at overcoming the intrinsic limits of the technique (relatively small active masses) by expanding the setup dimensions. The big advantage of the NEMO3 technique is the possibility to access single electron informations. CUORICINO is, on the other hand, a  $\text{TeO}_2$  granular calorimeter based on the bolometric technique. The most attractive features of this approach are an excellent performance of the bolometers and the possibility to build large mass homogeneous detectors with any material of practical interest[27, 28]. A scan of the most interesting  $\beta\beta(0\nu)$  active isotopes is thus possible. NEMO3 data taking continued until the end of 2010 while CUORICINO was stopped in June 2008 to be substituted by CUORE-0 (the first tower of CUORE) which is presently under construction at LNGS to start data taking at the end of 2011.

The evidence for a  $\beta\beta(0\nu)$  signal has also been claimed[16] (and later confirmed [17]) by a small subset (KHDK) of the HDM collaboration at LNGS with  $T_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25}$  y. The result is based on a sophisticated re-analysis of the HDM data heavily relying on pulse shape analysis and artificial neural network algorithms aiming to identify the  $\beta\beta(0\nu)$  signal while reducing the background contributions. Such a claim has raised a lot of criticism but cannot be dismissed out of hand. On the other hand, none of the existing experiments can rule out it, and the only certain way to confirm or refute it is with additional sensitive experiments. In particular, next generation experiments should easily achieve this goal.

## 5. Future experiments

The performance of the different  $\beta\beta(0\nu)$  experiments is usually expressed in terms of an experimental *sensitivity* or detector *factor of merit*, defined as the process half-life corresponding to the maximum signal  $n_B$  that could be hidden by the background fluctuations at a given statistical CL. At  $1\sigma$  level ( $n_B = \sqrt{BTM\Delta}$ ), one obtains:

$$F_{0\nu} = \tau_{1/2}^{Back.Fluct.} = \ln 2 N_{\beta\beta} \epsilon \frac{T}{n_B} = \ln 2 \times \frac{x \eta \epsilon N_A}{A} \sqrt{\frac{M T}{B \Delta}} \quad (68\%CL)$$

where B is the background level per unit mass and energy, M is the detector mass, T is the measure time,  $\Delta$  is the FWHM energy resolution,  $N_{\beta\beta}$  is the number of  $\beta\beta$  decaying nuclei under observation,  $\eta$  their isotopic abundance,  $N_A$  the Avogadro number, A the compound molecular mass,  $x$  the number of  $\beta\beta$  atoms per molecule, and  $\epsilon$  the detection efficiency.

Actually B never scales exactly with the detector mass but this approximation is usually reasonable and has a physical justification. Despite its simplicity, equation (4) has the unique advantage of emphasizing the role of the essential experimental parameters: mass, measuring time, isotopic abundance, background level and detection efficiency. On the other hand, it does not take into account important details like the shape of the expected signal or of the background and can't be used to analyze the case of very low statistics (discussed in the following). In these cases a more sophisticated Monte Carlo approach is needed. However, most of the criteria to be considered when optimizing the design of a new  $\beta\beta(0\nu)$  experiment follow directly from eq. (4): i) a well performing detector (e.g. good energy resolution and time stability) giving the maximum number of informations (e.g. electron energies and event topology); ii) a reliable and easy to operate detector technology requiring a minimum level of maintenance (long underground running times); iii) a very large (possibly isotopically enriched) mass, of the order of one ton or larger; iv) an effective background suppression strategy. They are actually being pursued with great determination by all the next generation experiments. Unfortunately, they are often conflicting and simultaneous optimisation is rarely possible.

The case when the background level  $B$  is so low that the expected number of background events in the region of interest along the experiment life is of order of unity ( $B \cdot M \cdot T \cdot \Delta \simeq O(1)$ ) deserves particular attention. In this case one generally speaks of “zero background” (0B) experiments, a condition met by a number of future projects. In such conditions, eq. (4) can no more be used and a good approximation to the sensitivity is given by

$$F_{0\nu}^{0B} = \ln 2 N_{\beta\beta} \epsilon \frac{T}{n_L} = \ln 2 \times \frac{x \eta \epsilon N_A M T}{A n_L}$$

where  $n_L$  is a constant depending on the chosen CL and on the actual number of observed events. The most relevant feature of the previous equation is that  $F_{0\nu}^{0B}$  does not depend on the background level or the energy resolution and scales linearly with the sensitive mass  $M$  and the measure time  $T$ . Since  $T$  is usually limited to a few years and  $\Delta$  is usually fixed (meaning that for a given experimental technique is usually difficult to get sizable improvements), the 0B condition translates to  $B \cdot M \simeq O(1/\Delta \cdot T)$ . This means that for a given mass  $M$  there always exists a threshold for  $B$  below which no further improvement of the sensitivity is obtained or, alternatively, that it can be useless to reduce at will the background level without a corresponding increase of the experimental mass. A well designed experiment has therefore to match the condition  $B \cdot M \gtrsim 1/\Delta \cdot T$ . For most of the next generation high resolution calorimeters  $B_T \simeq \frac{1}{10 \cdot M}$  or  $B_T \simeq 10^{-4}$  for a O(1t) experiment.

A series of new proposals has been boosted in recent years by the renewed interest in  $\beta\beta(0\nu)$  following neutrino oscillation results. The ultimate goal is to reach sensitivities such to allow an investigation of the inverted hierarchy (IH) of neutrino masses ( $\langle m_\nu \rangle \sim 10\text{-}50$  meV). From an experimental point of view this corresponds however to active masses of the order of 1 ton with background levels of the order of 1 c/keV/ton/y. A challenge that can hardly be faced by the current technology. Phased programs have been therefore proposed in USA and Europe[29, 30].

Next generation experiments are all characterized by hundred kg detectors and 1-10 c/keV/ton background rates. Their goal is to select the best technology and approach the IH region.

A restricted list of some of the most advanced forthcoming  $\beta\beta(0\nu)$  projects is given in Table 2. Very different classification schemes can of course be adopted for them. They are usually based on the different strategies adopted to improve the  $\beta\beta(0\nu)$  sensitivity: experimental approach, mass, energy resolution, background discrimination technique, granularity and track reconstruction, etc. In general, three broad classes can be identified: i) arrays of calorimeters with excellent energy resolution and improved background suppression methods (e.g. GERDA, MAJORANA) or based on unconventional techniques (e.g. CUORE); ii) detectors with generally poor energy resolution but topology reconstruction (e.g. EXO, SuperNEMO); iii) experiments based on suitable modifications of an existing setup aiming at a different search (e.g. SNO+, KAMLAND). In some cases technical feasibility tests are required, but the crucial issue is still the capability of each project to pursue the expected background suppression. Different estimates of the expected  $B$  levels are usually based on the extrapolation of real measurements to the final experimental conditions or on the Monte Carlo simulations based on more or less realistic expectations. The former are usually more reliable especially when based on the results of medium size detectors. The expected sensitivities are listed in Tab.2. On the other hand, the projected backgrounds are compared in Fig.1 as a function of the expected energy resolution to point out the role of the product  $B \cdot \Delta$  in the comparison of the  $\beta\beta(0\nu)$  sensitivities. The more realistic projections (“Reference”) are here distinguished from the most optimistic expectations (“Improved”). The same holds for Fig.2 where the plotted line identifies the transition to the 0B regime. Although all proposed projects show interesting features for a second generation experiment, only few of them are characterized by a reasonable technical feasibility within the next few years.

**Table 2.** List of some of the most developed  $\beta\beta(0\nu)$  projects. Sensitivity at 90% CL (duration as explicitly indicated). Experimental phases are indicated as preparation (P=Progress) or development (D=R&D).  $\langle m_\nu \rangle$  values are calculated using PMA NME and phase space factors from [6] and [31] respectively.

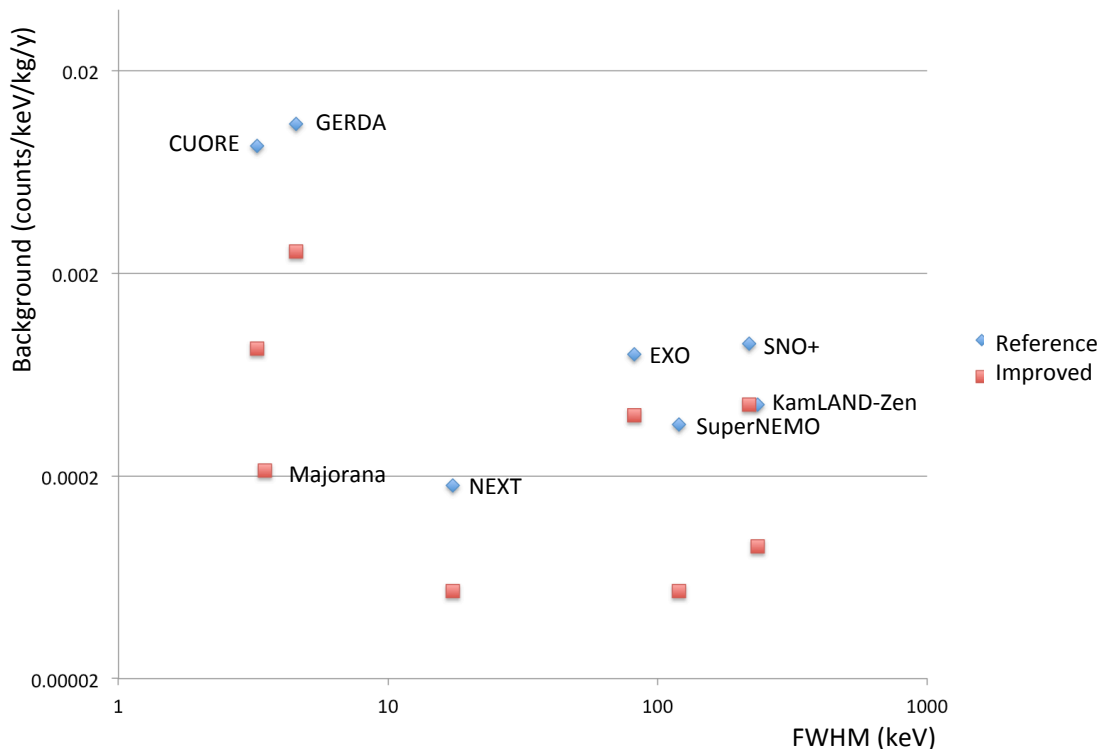
	Isotope	Mass [kg]	Lab	Status	Start	$T_{1/2}^{0\nu}$ [ $10^{26}$ y]	$\langle m_\nu \rangle$ [meV]
CUORE[32]	$^{130}\text{Te}$	200	LNGS	P	2014	2.1	45
GERDA[33]	$^{76}\text{Ge}$	18	LNGS	P	2012	2	100
		40		D		5	56
MAJORANA[34]	$^{136}\text{Xe}$	30	SUSEL	P	2013	5	67
EXO[35]		200	WIPP	P	2011	2.2	54
		1000		D	2015	7	30
SuperNEMO[36]	$^{82}\text{Se}$	100-200	LSM	D	2013-2015	0.8	90
KamLAND-Zen[37]	$^{116}\text{Cd}$	400	Kamioka	P	2011	3.1	45
		1000		D		2013-2015	11
SNO+[38]	$^{150}\text{Nd}$	56	Sudbury	P	2012	0.5	87
		1000		D		2015	2.2

### 5.1. High resolution calorimeters

MAJORANA and GERDA belong to the class of the high energy-resolution calorimeters and are both phased programs representing large scale extensions of past successful experiments on  $^{76}\text{Ge}$   $\beta\beta(0\nu)$ . Background control is based upon a careful choice of the setup materials and of very effective radiation shields. Active background reduction based on new detector design for single site event identification represents the new frontier and is presently gathering most of the experimental efforts. Evolved from the HM experiment, GERDA[33] aims at implementing the concept of Ge diodes immersed in a LAr bath[39] for a radical background suppression. The GERDA setup construction was completed in Gran Sasso during 2010. Since then, pre-operation with natural abundance Germanium crystals is ongoing. Two experimental phases are foreseen. GERDA-I is going to scrutinize the KHDK claim starting in 2011 with 18 kg of enriched detectors ( $\sim 85\%$ ) inherited from previous experiments and an expected background level of the order of  $10^{-3}$  c/keV/kg. 40 kg of germanium isotopically enriched in  $^{76}\text{Ge}$  are already available for GERDA-II. One of the most attractive features of the Germanium diodes is the excellent energy resolution, of the order of 3.5 keV FWHM in the region of interest (ROI). A large part of the efforts is presently directed to develop the detectors with background reduction capability crucial for the targeted  $10^{-3}$  c/keV/kg background level. The expected 5y sensitivity is  $\sim 2.3 \times 10^{26}$  and  $1.1 \times 10^{27}$ y for the phase I and II respectively. Depending on the actual physics results of the two experimental phases, a third phase using 500 to 1000 kg of enriched germanium detectors is planned, merging GERDA with the US lead Majorana collaboration.

MAJORANA, a mainly USA proposal with important Canadian, Japanese, and Russian contributions, is an evolution of the IGEX experiment. The proposed configuration[34] is based on segmented n-type germanium crystals distributed inside ultra-clean electro-formed conventional cryostats (57 crystals each). The whole assembly would be enclosed in a low-background passive shield and active veto and be located deep underground. A 30 to 60 kg demonstrator (single cryostat) is presently being developed to demonstrate the viability of the technique. The detector performance is comparable to GERDA but a very low background rate, of the order of  $2 \times 10^{-4}$  c/keV/kg, is the distinctive and ambitious target of this project. The

**Figure 1.** Projected background rates as a function of the expected energy resolution for the  $\beta\beta(0\nu)$  projects listed in table 2.

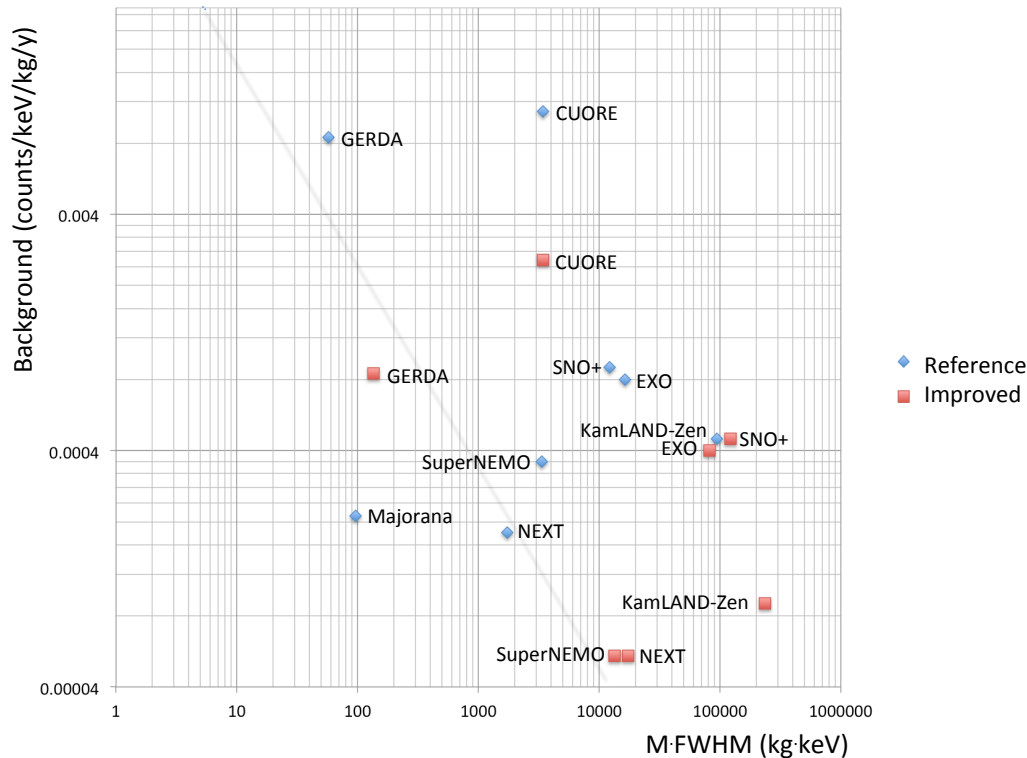


completion of this phase is expected in 2014.

CUORE[32] (*Cryogenic Underground Observatory for Rare Events*) is a very large extension of the  $\text{TeO}_2$  bolometric array concept pioneered by the Milano group at the Gran Sasso Laboratory since the eighties. CUORE consists of a rather compact cylindrical structure of 988 cubic natural  $\text{TeO}_2$  crystals of 5 cm side (750 g), arranged into 19 separated *towers* (13 *planes* of 4 crystals each) and operated at a temperature of 10 mK. The expected energy resolution is  $\sim 5$  keV FWHM at the  $\beta\beta(0\nu)$  transition energy ( $\sim 2.53$  MeV). A background level of the order of  $\sim 0.01$  c/keV/kg/y or better is expected by extrapolating the CUORICINO background results and the dedicated CUORE R&D measurements. The expected 5y sensitivity is  $2.1 \times 10^{26}$ y. CUORE will therefore allow a close look at the IH region of neutrino masses. CUORE is fully funded and presently under construction at LNGS. Setup completion is expected in 2013 followed by data taking start in 2014. Thanks to the high natural abundance of  $^{130}\text{Te}$ , CUORE is based on the use of natural tellurium even if an isotopically enriched version has been discussed as a future option. The most important limitation of this purely bolometric approach is presently represented by the difficulty to develop an active way of identify surface radioactivity contributions of the detector materials.

Thanks to the bolometer's versatility, alternative options with respect to  $\text{TeO}_2$  are also possible. In particular, promising results have been recently obtained with scintillating bolometers which are particularly effective in recognizing the dangerous alpha background from the surface of the detector setup[40]. The use of hybrid scintillating bolometers could allow to study in the future new  $\beta\beta(0\nu)$  active isotopes with improved sensitivity. A  $\sim 40$  kg demonstrator

**Figure 2.** Projected background rates as a function of the mass and expected energy resolution product for the  $\beta\beta(0\nu)$  projects listed in table 2.



(Lucifer) aiming at applying this hybrid technique to demonstrate the feasibility of a ZnSe experiment with a background level of the order of  $10^{-3}$  c/keV/kg was recently funded in the framework of an ERC research program. Results are expected in 2014.

### 5.2. Tracking detectors

Gas and liquid Time Projection Chambers (TPC's) represent another aspect of the homogeneous approach in which the limited resolution is the most relevant limitation while scalability and geometrical reconstruction are the most evident advantages. EXO[35] (*Enriched Xenon Observatory*) is a challenging project based on a large mass ( $\sim 1-10$  tons) of isotopically enriched (85% in  $^{136}\text{Xe}$ ) Xenon. An ingenious tagging of the doubly charged Ba isotope produced in the decay ( $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2e^-$ ) would allow an excellent background suppression. The technical feasibility of such an ambitious project aiming at a complete suppression of all the backgrounds requires a hard, still ongoing R&D phase. The unavoidable  $\beta\beta(2\nu)$  contribution is a serious concern due to the poor energy resolution of Xe detectors. A sizable prototype experiment with a Xe mass of 200 kg (80%  $^{136}\text{Xe}$ ), has been deployed at WIPP since summer 2009. The prototype has an expected energy resolution of  $\sim 80$  keV FWHM and no barium tagging. With a background level of  $\sim 10^{-3}$  c/keV/kg, the primary goal is to measure  $^{136}\text{Xe}$   $\beta\beta(2\nu)$  and to study  $\beta\beta(0\nu)$  with a sensitivity of  $\sim 10^{26}$  y in two years of data taking.

The use of a TPC filled with high-pressure gaseous xenon, and with capabilities for calorimetry and tracking (following the experience of the past Gotthard experiment) has been recently proposed by a mainly Spanish collaboration headed by the Valencia group [41].

Thanks to an excellent energy resolution ( $\sim 1\%$  at 2580 keV), together with a powerful background rejection provided by the distinct double-beta decay topological signature, the NEXT collaboration aims at a phased program starting with a 100 kg TPC capable of exploring the 100 meV region hence analysing the KHDH claim. Expected to operate in the Canfranc Underground Laboratory (LSC) and characterized by a projected background level of the order of few  $10^{-4}$  c/keV/kg/y, NEXT-100 will be large enough to prove the scalability of the technology up to a 1-ton detector. Smaller scale prototypes have been already built and operated successfully.

### 5.3. Large mass scintillators

The idea of exploiting large mass and very low background scintillators loaded with  $\beta\beta(0\nu)$  active materials dates back to the end of 90's[42]. New developments have been recently proposed in order to exploit two successful experiments on neutrino oscillation such as SNO and KamLAND. SNO+ is pursuing the goal of studying  $^{150}\text{Nd}$  with 50 to 500 kg of isotopically enriched Neodimium depending on the results of the currently ongoing R&D program. Difficulties in reaching a significant concentration of the  $\beta\beta(0\nu)$  element while maintaining a good detector performance are presently addressing most of the efforts.

A similar approach is proposed by KAMLAND-Zen, in which large masses of  $^{136}\text{Xe}$  are dispersed in a dedicated plastic bag filled with liquid scintillator at the center of the KAMLAND detector. The program is going to start in 2011 (first phase) with 200-400 kg of isotope and continue in 2013 with 1 ton of Xenon enriched to 90% in  $^{136}\text{Xe}$ . With a projected background of  $\sim 5 \times 10^{-4}$  c/keV/kg and an energy resolution of 240 keV FWHM, the preliminary estimate of the 5y sensitivity for phase I is in the range of few  $10^{26}$  y.

The proposed Super-NEMO experiment is the only project based on an inhomogeneous approach. It is an extension of the successful NEMO3 concept, properly scaled in order to accommodate  $\sim 100$  kg of  $^{82}\text{Se}$  foils spread among 20 detector modules. The proposed geometry is planar. The expected energy resolution is 7% FWHM (12% in NEMO-3) to improve the signal detection efficiency from 8% to 40% and reduce the  $\beta\beta(2\nu)$  contribution. The projected background is  $\sim 3.5 \times 10^{-4}$  c/keV/kg. The detector modules will have an active water shield to further reduce cosmic ray backgrounds. The proposed detector dimensions will require a larger hall than is currently available at Frejus and an expansion of the facility is therefore required and actively pursued. A demonstrator (single module) is presently fully funded to be completed in 2011 with a test run in the current NEMO3 site. If funded, Super-NEMO construction should immediately start.

## 6. Conclusions

Neutrino oscillation results have stimulated a renewed interest in the experimental study of neutrino properties. In this framework, neutrinoless  $\beta\beta$  decay is recognized as a unique tool to verify the Majorana nature of the neutrino providing moreover important informations on the neutrino mass scale and intrinsic phases, unavailable to the other neutrino experiments. Present  $\langle m_\nu \rangle$  sensitivities are still outside the range required to test the inverted neutrino mass hierarchy. An international effort is however supporting a phased  $\beta\beta(0\nu)$  program based on a number of newly proposed experiments aiming to pursue such a goal. The success of such a program strongly depends on the true capability of the proposed projects to reach the required background levels in the  $\beta\beta(0\nu)$  region. The claimed evidence for a  $\beta\beta(0\nu)$  signal in the HM data could be soon verified by the presently running experiments and in any case, by the forthcoming next generation experiments.

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