XIV International Conference on Topics in Astroparticle and Underground Physics (TAUP 2015) IOP Publishing
Journal of Physics: Conference Series **718** (2016) 022006 doi:10.1088/1742-6596/718/2/022006

Neutrinoless Double Beta Decay

Oliviero Cremonesi
INFN Sez. Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
E-mail: oliviero.cremonesi@mib.infn.it

Abstract. After more than 3/4 of century from its proposal, Neutrinoless Double Beta Decay (NLDBD) is still missing observation and continues to represent the only practical method for investigating the Dirac/Majorana nature of neutrinos. In case neutrinos would be Majorana particles, NLDBD would provide unique informations on their properties (absolute mass scale and Majorana phases). Boosted by the discovery of neutrino oscillations, a number of experiments with improved sensitivity have been proposed in the past decade. Some of them have recently started operation and others are ready to start. They will push the experimental sensitivity on the decay halflife beyond 10^{26} year, starting to analyze the region of the inverted mass hierarchy. The status and perspectives of the ongoing experimental effort are reviewed. Uncertainties coming from the calculation othe decay nuclear matrix elements (NME) as well as the recently suggested possibility of a relevant quenching of the axial coupling constant are also discussed.

1. Introduction

Proposed in 1939 by Furry[1], just two years after the Majorana description for neutral fermions [2], Neutrinoless Double Beta Decay is a very rare nuclear decay in which a nucleus (A,Z) transforms in its isobar (A,Z+2) with the only emission of two electrons: $(A, Z) \rightarrow (A, Z + 2) + 2e^-$ $(0\nu\beta\beta)$. Although characterized by lower experimental sensitivities, the equivalent decay modes in which the electrons are replaced by positrons or by an electron capture are also possible. Of particular relevance is also the 2ν mode $(2\nu\beta\beta)$ ${}^A_Z X \rightarrow {}^A_{Z+2} X + 2e^- + 2\overline{\nu}$, which observes the lepton number conservation and is allowed by the Standard Model (SM) of electro-weak interactions. The distinctive feature of neutrinoless double beta decay is the explicit violation of the lepton number L, which supports the exciting possibility that neutrinos played an important role in the creation of the matter-antimatter asymmetry in the universe. In addition, $0\nu\beta\beta$ can proceed only if neutrinos are Majorana fermions, i.e. if they coincide with their anti-particles. In particular $0\nu\beta\beta$ observation would imply that neutrinos are Majorana massive particles and would provide important constraints on their mass scale. On the other hand, complementary informations on the absolute mass scale of neutrinos can come also from direct and cosmologicakl measurements[3]. Given the progress in these areas it is extremely important to combine the experimental constraints coming from all of them. Unfortunately the different measurements are affected by very different systematics which makes the comparison a complicated task which asks for a careful and critical approach.

By demonstrating that neutrinos have a finite mass, neutrino oscillation experiments have strengthened the case of light massive neutrinos as the dominant mechanism for $0\nu\beta\beta$ and have boosted a revived interest for $0\nu\beta\beta$ experimental searches. In particular, the possibility that neutrino masses have an Inverted Hierarchy (IH) is very appealing and most of the future

experiments have been designed with half-life sensitivities in the range 10^{26-28} y just to be able to probe this region of neutrino masses.

Several papers and reviews on NLDBD are available in the literature; each of them tends to cover specific aspects of the process but globally they provide a very comprehensive and up-to-date picture of the present status of the research and witness the strong interest in this topic. We refer the reader to them [4, 5, 6, 7] for a detailed treatment of the subject while we intend to focus here just on few aspects and issues that characterize the present status of the experimental investigation and its future perspectives.

2. Theoretical framework

The laws of conservation of lepton (L) and baryon (B) numbers are only of phenomenological nature and support the fact that specific elementary processes have not been observed yet. Having no deep justification for these laws, it is possible to suspect that their validity is just approximate and limited to the range of energies investigated by present experiments. While B and L are strictly conserved within the Standard Model of particle physics (SM), they are not in the framework of Grand Unified Theories (GUTs), most of which exhibit a L/R symmetry and can accomodate Majorana neutrinos. Unfortunately the possibilities to test these theories are limited and their major manifestations could be just rare processes in which L and B are violated. In fact, Majorana mass terma could be a natural manifestations of lepton number violating phenomena and $0\nu\beta\beta$ would have unique features for the experimental investigation. A particularly attractive theoretical possibility is that Majorana neutrinos produced some leptonic asymmetry in the original Universe which has then originated the corresponding presently observed matter-antimatter asymmetry (Leptogenesis[8]). Unfortunately GUT's are still unable to link in a convincing way the fermion masses to new phenomena such as $0\nu\beta\beta$ and additional effort is still needed.

Despite the large number of possibe exotic contributions, the exchange of light Majorana neutrinos is still the most appealing mechanism for $0\nu\beta\beta$. This is essentially due to the fact that experiments point out the existence of three light massive neutrinos. However it is also expected on theoretical grounds if one assumes that the scale of new physics is much higher than the electroweak scale,

Among the alternative mechanisms, of particular interest is the case of a heavy RH neutrino in which the mass of the exchanged neutrino is expected to be of the order of 10 GeV[9, 10]. On the other hand, if the mass of the heavy neurtrino approaches the one of the light neutrinos their contributions can cancel each other[11].

Another class of models of great interest are those that include RH currents and intermediate bosons, specially if the masses of the RH gauge bosons are accessible to direct experimental investigation.

In this respect, of particular relevance are the searches for exotic particles at the accelerators since thy could reveal new physics relevant for $0\nu\beta\beta$. Among the numerous possibilities, this is the case of the minimal supersymmetric extension of the SM as well as the hypothesized extra-dimensions at the TeV scale which could both be connected to new L-violating operators[6, 12].

3. Phenomenology

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

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

where $G^{0\nu}$ is the 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 (named "effective neutrino mass")

$$\langle m_\nu \rangle \equiv \sum_{k=1}^{3} |U_{ek}^L|^2 m_k e^{i\phi_k} \simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3 \quad (2)$$

The last equality holds for small neutrino masses. α_1 and α_2 are the so-called neutrino Majorana phases and their presence in (2) implies that cancellations are possible. It is worth to notice that $0\nu\beta\beta$ represents a unique possibility to measure the neutrino Majorana phases.

The observation of $0\nu\beta\beta$ would establish definitely that neutrinos are Majorana particles. The accurate determination of the $\langle m_\nu \rangle$ would then fix their absolute mass scale. It should be stressed however that even in the case that forthcoming $0\nu\beta\beta$ experiments would not observe any decay, important constraints can be obtained. 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. On the other hand, if future oscillation experiments would demonstrate the inverted ordering of the neutrino masses, a failure in observing $0\nu\beta\beta$ at a sensitivity of 20-30 meV would show that neutrinos are Dirac particles. The case of the normal neutrino mass hierarchy (NH, weakly suggested by recent results on neutrino ocillations) is often considered to spoil the interest for $0\nu\beta\beta$ searches since there would be no lower bounds on $\langle m_\nu \rangle$. However, even disregarding the possibile contribution of sterile neutrinos which would produce a very similar behaviour of $\langle m_\nu \rangle$ in the two hierarchies[13], the lowest values of $\langle m_\nu \rangle$ would be in any case strongly disfavoured[14] maintanining the interest for $0\nu\beta\beta$ searches down to the O(10^{-3} eV) range.

In the case of a heavy neutrino exchange (m$\gtrsim$100 MeV) the neutrino mass parameter $\langle m_\nu \rangle$ /m$_e$ appearing in (1) must be replaced by $m_p \langle M_H^{-1} \rangle = m_p | \sum k \frac{U_{ek}^2}{M_k} |$ where m_p is the proton mass and the sum is over the heavy neutrino mass eigenstates.

4. Nuclear calculations

Eq. (1) clearly indicates that a precise knowledge of the Phase Space Integrals G$^{0\nu}$ (PSI) and of the Nuclear Matrix Elements M$^{0\nu}$ (NME) is needed in order to extract the effective neutrino mass $\langle m_\nu \rangle$ from the experimental values of the $0\nu\beta\beta$ half-lives. Unfortunately they can only be calculated.

PSI factors can be precisely calculated and new accurate descriptions with less approximations are now available[15, 16, 17]. On the contrary, the different approaches adopted for NMEs calculations have produced a vaste literature of often conflicting evaluations. The calculation of the $0\nu\beta\beta$ NMEs is actually a difficult task involving the ground states and a number of excited states of open-shell nuclei with complicated nuclear structure. Many different approaches have been used to compute NMEs: Interacting Shell Model (ISM)[18, 19], Quasiparticle Random Phase Approximation (QRPA)[20, 21], Interacting Boson Model (IBM2)[22], Projected Hartree-Fock Bogoliubov Method (PHFB)[23] and Energy Density Functional Method (EDF)[24]. All of them have pro and cons and use approximations that limit the reliability of the calculations. Significant improvements have been obtained recently in reducing the spread among the different methods[25], although ISM calculations are still systematically smaller than the others.

Of course the relative agreement between the different calculations does not guarantee by itself their correctness, however the convergence of the results from very different methods can hardly be a chance. Nevertheless the estimate of the uncertainties both on G$^{0\nu}$ and M$^{0\nu}$ is of crucial importance and is still an open issue.

Independent checks for $0\nu\beta\beta$ NME's calculations are obviously impossible. However, indirect informations from a number of measurable processes can be used to test the reliability of the calculations. This is the case of single beta decay, electron capture and $2\nu\beta\beta$. Significant

deviations from measured half lives have then been observed[26, 27], in clear disagreement with available estimates on the NMEs uncertainties which amount to 15-20%[28, 22].

The problem of assessing the uncertainties in the NMEs is therefore far from being solved. In this respect, let us emphasized the role of the axial and vector coupling constants g_A and g_V by parameterising the $0\nu\beta\beta$ NME as $M^{0\nu} \equiv g_A^2\, M^{0\nu\prime} = g_A^2 \left(M_{GT}^{0\nu} - (g_V/g_A)^2\, M_F^{0\nu} + M_T^{0\nu} \right)$, where $M_{F/GT/T}^{(0\nu)}$ are the Fermi (F), Gamow-Teller (GT) and tensor (T) terms. It is then evident that a small variation of g_A translates in a significant change of $M^{0\nu}$.

By interpreting the discrepancies between calculations and experimental results in terms of a significant quenching of the coupling constant g_A a consistent picture has been obtained[29], where however a weak dependence of g_A on A has also been observed[26]. Since it is evident that the quenching of g_A could have a dramatic impact on experimental searches, a lively discussion has recently started to assess if an alternative origin for the discrepancy is possible: limited model space[30], contributions from non-nucleonic degrees of freedom[31], renormalization of the GT operator[31, 32]. An equally relevant question is if the g_A quenching is the same for $2\nu\beta\beta$ and $0\nu\beta\beta$. In fact, a difference between the two decay modes is not unreasonable noting that $2\nu\beta\beta$ can only occur through 1+ (GT) intermediate states while there is no limitation for $0\nu\beta\beta$[19, 33]. However the dominant multipole in $0\nu\beta\beta$ is GT, which makes the hypothesis rather weak[22]. A possible way out is the study of the g_A quenching in non GT transitions. The experimental study of double charge exchange (DCE) nuclear transitions (a process analogous to $0\nu\beta\beta$) could also provide important information. Indeed, despite DCE transitions and $0\nu\beta\beta$ are mediated by a different interaction, the analogy between the two processes could help assessing the reliability of $0\nu\beta\beta$ NME calculations. In this framework a new experimental investigation has been proposed at Laboratori Nazionali del Sud (INFN, Italy)[34].

Missing new insight (experimental and/or theoretical) on the subject of the g_A quenching, the obvious conclusion is that g_A in the nuclear medium cannot be regarded as a reliable quantity. This is currently the largest source of uncertainty in the derivation on neutrino mass properties from $0\nu\beta\beta$ results.

Given the reasonable relative agreement between the different NME calculations and in order to preserve correlations and allow a (relative) comparison between the sensitivities of $0\nu\beta\beta$ experiments, we will refer in the following to a single calculation. To this end we have chosen the IBM2 calculations which have the advantage of being available for all the nuclei of interest[22].

A peculiar inverse correlation between the PSIs and the square of the NMEs has been observed recently in a survey of the nuclear calculations for $0\nu\beta\beta$ [35]. No physical motivation for this behaviour has yet been provided. However, this strengthens the impression that no isotope seems to be either favored or disfavored for $0\nu\beta\beta$ searches.

The neutrinoless decay mediated by the exchange of a heavy neutrino asks for specific NME calculations. These have been evaluated in the framework of the IBM2[22] and QRPA[36] models. The values obtained within the QRPA model are larger than those obtained with the IBM2. Also in this case, we will refer in the following to the IBM2 calculations.

5. Experimental appoaches and sensitivity

A large number of experiments has been and is presently involved in the search for $0\nu\beta\beta$ processes.

TFrom the experimental point of view, the observation of a $0\nu\beta\beta$ signal relies just on the detection of the two emitted electrons. The signature is therefore quite poor and consists in the obsevation of an energy release equal to the Q-value of the transition. Indeed, being the energy of the recoiling nucleus negligible, the two electrons share all the available energy. A monochromatic peak at the Q-value in the sum energy of the two emitted electrons is therefore the distinctive

feature of the decay. Unfortunately, a number of natural processes (e.g. radioactive decays) can give rise to a similar signal and the background reduction or identification is generally the true experimental challenge. However, even in the ideal case in which all the external source of background could be eliminated, $2\nu\beta\beta$ would represent an unavoidable disturbance. Indeed, because of the finite energy resolution of the detectors, a finite fraction of the two neutrino decays would extend beyond the Q-value overlapping to the $0\nu\beta\beta$ peak. The releveance of this intrinsic source of background depends on the choice of the isotope ($2\nu\beta\beta$ lifetime) and on the detector resolutions. For some of the current generation detectors it is already close to be the limiting factor.

The choice for the best isotope is the starting point of any experiment. It impacts the choice (and performance) of the detector and the influence of background sources ($2\nu\beta\beta$ rate and transition energy). Furthermore it determines the number of nuclei under observation per unit mass (atomic weight and isotopic abundance). Apart from few exceptions (essentially the tellurium isotopes), most $0\nu\beta\beta$ candidates are charaterized by more or less poor isotopic abundances ($\lesssim$10%) and isotopic enrichment is rarely an option. A number of other parameters affects the experimental sensitivity which is therefore a complex item ruling the success of the various proposed experiments.

An extremely useful experimental factor of merit can be obtained under the very simple assumption that the minimum detectable signal is determined by the statistical fluctuations of the background events. For a constant background rate and a given energy integration interval (usually chosen as a FWHM) the background contribution amounts to $n_B=\sqrt{BTM\Delta}$, where B is the background level per unit mass and energy, M is the detector mass, T is the measure time, Δ is the FWHM energy resolution. At 1σ the background fluctuations are then given by the suare root of n_B and one can define a corresponding experimental factor of merit (sensitivity) as :

$$F_{0\nu}^{NB} = \tau_{1/2}^{Back.Fluct.} = \ln 2 \; N_{\beta\beta}\epsilon\frac{T}{n_B} = \; = \ln 2 \times \frac{x \; \eta \; \epsilon \; N_A}{A}\sqrt{\frac{M \; T}{B \; \Delta}} \; (68\%CL) \tag{3}$$

where $N_{\beta\beta}$ is the number of $\beta\beta$ decaying nuclei under observation, η their isotopic abundance, N_A the Avogadro number, A the compound molecular mass, x the number of $\beta\beta$ atoms per molecule, and ϵ the detection efficiency. Actually B never scales exactly with the detector mass but this approximation is usually reasonable and in many cases has also a physical justification.

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 or less than unity (B ·M·T ·$\Delta\lesssim$ O(1)) deserves particular attention. In these case one generally speaks of "zero background" (ZB) experiments, a condition met by a number of upcoming projects. In these conditions, eq. (3) can no more be used and a good approximation to the sensitivity is given by

$$F_{0\nu}^{ZB} = \ln 2 \; N_{\beta\beta}\epsilon\frac{T}{n_L} = \ln 2 \times \frac{x \; \eta \; \epsilon \; N_A}{A}\frac{M \; T}{n_L} \tag{4}$$

where n_L is a constant depending on the chosen CL and on the actual number of observed events.

The most relevant feature of equation (4) is that $F_{0\nu}^{ZB}$ 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 Δ is fixed by the experimental technique, the ZB condition translates to $B\cdot M \lesssim O(1)/\Delta\cdot T$). The equality marks the transition to the new regime and underlines that for any given mass M there is always a threshold value B^{ZB} 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 $B \cdot M \lesssim 1/\Delta \cdot T$. For most of

the next generation high resolution calorimeters this corresponds to $B^{ZB} \simeq \frac{1}{10 \cdot M}$ or $B^{ZB} \simeq 10^{-4}$ for a O(1 ton) experiment.

Despite its simplicity, equations (3) and (4) have the unique advantage of emphasizing the role of the essential experimental parameters: mass, measuring time, isotopic abundance, background level and detection efficiency. Actually most of the criteria to be considered when optimizing the design of a new $0\nu\beta\beta$ experiment follow directly from the above equations: 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. These criteria are actually being pursued by all the next generation experiments. Unfortunately, they are often conflicting and their simultaneous optimisation is rarely possible.

A strong limitation of eq. (3) and (4) is that they don't take into account important details like the shape of the expected signal or of the background. Furthermore they can't be used to analyze the case of very low statistics. In these cases a more sophisticated Monte Carlo approach is needed.

Given the dependence of the $F^{0\nu}$'s on many experimental parameters it is difficult to rely on them for a direct comparison of the proposed experiments potential. Many authors chose a pair of parameters (usually the most suitable or convenient for their analysis) and proceed to the comparison of the experiment performance forgetting the others. This approach risks to forget important contributions to the sensitivity and should be avoided. On the other hand, as shown in [37], under reasonable hypotheses and with a proper redefinition of the experimental parameters it is possible to express the $F^{0\nu}$'s in terms of only two normalized parameters (Scale and Performance) and exploit the simplicity of eq. (3) and (4) for a global comparison of the experimental approaches.

6. Experiments

The relevannce of the question about the neutrino Dirac/Majorana nature has motivated a continuous effort to search for $0\nu\beta\beta$. When associated to the considerable technological progress that has caracterized the past decades, this translates in an impressive list of results in which the experimental sensitivity has increased by several orders of magnitude for a number of isotopes. A phased approach has been generally adopted, in which safer steps in the experimental sensitivity have been preferred to big leaps of faith. The result is a variety of approaches that have focused on one or two experimental parameters which characterize the adopted technique. However, irrespective of technique, all experiments face the common challenge of getting the lowest possible background level. Material assay, deep underground laboratories and effective shields are then the key ingredients.

After a long period in which the use of isotopically enriched HPGe diodes has been the dominant approach, we have recently entered a very exciting period in which new experimental approaches have shown competitive sensitivities and have started to produce results in the range of 10^{24-25} y for the $0\nu\beta\beta$ half lifetime. This is the case of EXO-200[38] (liquid Xenon TPC), KamLAND-Zen[39] (large organic scintillator loaded with Xenon) and CUORE-0[40] (bolometer).

Even more exciting is the fact that new improved experiments with design sensitivities in the range of 10^{26} y have just started (GERDA-II and MJD) or are going to start operation shortly (CUORE, SNO+ and SuperNEMO). These experiments will pave the way to the next generation experiments whose ideas are presently at an R&D stage and aim to tread the boards of the next decade.

Most of these experiments implement the calorimetric approach (source and detector coincide)

Table 1. Best reported results on $2\nu\beta\beta$ and limits (90% CL) on $0\nu\beta\beta$ processes from direct experiments, and most relevant $\beta\beta$ parameters. $\langle m_\nu \rangle$ are computed using NME and phase space factors from [22] and [15] respectively.

Isotope	$T^{2\nu}_{1/2}$ (10^{19}y)	$T^{0\nu}_{1/2}$ (10^{24}y)	Experiment	$\langle m_\nu \rangle$ (eV)	Q (MeV)
^{48}Ca	$(4.4^{+0.5}_{-0.4} \pm 0.4)$[41]	> 0.058	CANDLES[42]	6.7	4.27
^{76}Ge	(184^{+14}_{-10})[43]	> 21	GERDA[44]	0.4	2.04
^{82}Se	$(9.6 \pm 0.3 \pm 10)$[45]	> 0.36	NEMO3[41]	1.9	2.995
^{96}Zr	$(2.35 \pm 0.14 \pm 0.16)$[46]	> 0.0092	NEMO3[46]	13.1	3.35
^{100}Mo	$(0.71 \pm 0.002 \pm 0.05)$[45]	> 1.1	NEMO3[47]	1.0	3.034
^{116}Cd	$(2.8 \pm 0.05 \pm 0.4)$[48]	> 0.17	Solotvina[49]	3.5	2.802
^{130}Te	$(70 \pm 9 \pm 11)$[50]	> 4.0	CUORE0[40]	0.5	2.527
^{136}Xe	> 81[51]	> 19	KamLAND-Zen[39]	0.3	2.479
^{150}Nd	$(0.911 \pm 0.025 \pm 0.063)$[52]	> 0.018	NEMO3[52]	6.5	3.367

and have obtained noteworthy results in the reduction of background contributions. A selected list of the most recent and stringent results is summarized in Tab. 1.

In general, three broad classes of experiments can generally 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).

MAJORANA[53] and GERDA[54] 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}Ge $0\nu\beta\beta$. Background control is based upon a careful choice of the setup materials and of very effective (passive and/or active) radiation shields. Active background reduction techniques are based on a new detector design capable to isolate the $0\nu\beta\beta$ events (pulse shape analysis). The GERDA-I programa (based on pre-existing detectors) has been comleted in 2013[44]. Both GERDA-II and the Majorana Demonstrator (MJD) have started operation at the end of 2015.

CUORE[55] is a very large extension of the TeO_2 bolometric array concept pioneered by the Milano group at the Gran Sasso Laboratory since the eighties. It consists of a rather compact cylindrical structure of 988 cubic natural TeO_2 crystals of 5 cm side (750 g) operated at a temperature of 10 mK. A single tower of CUORE (named CUORE0) has been operated at LNGS in the same cryostat that hosted Cuoricino, from 2013 to 2015. It demonstrated the all the design parameters of the CUORE detector have been met[40]. On the other hand, CUORE has successfully completed the commissioning of the cryogenic setup and is going to install and commission the detector during the summer 2016.

Thanks to the bolometer's versatility, alternative options with respect to TeO_2 are also possible. In particular, hybrid detectors exploiting scintillation or Cerenkov light to get rid of the dominant surface contributions have already produced very promising results. A large group of interest has formed around these ideas to propose a ton-scale bolometric experiment with an unprecedented sensitivity (CUPID: CUORE Upgrade with Particle IDentification)[56].

Gas and liquid TPC's represent another powerful approach to $0\nu\beta\beta$. The limited resolution is the most relevant limitation while scalability and geometrical reconstruction are the most evident advantages. EXO-200 (*Enriched Xenon Observatory*) is a challenging project based on a large mass ($\sim$ 1–10 tons) of isotopically enriched (85% in ^{136}Xe) Xenon, whose medium size prototype (200 kg enriched at 80% in ^{136}Xe) has been deployed at WIPP since summer

2009[38]. The success of EXO-200 has triggered the proposal of a lerger scale version (nEXO) characterized by further improvements on energy resolution and background[57].

Expected to operate at LSC, NEXT is a mainly Spanish project based on the use of a high pressure Xe gas TPC for a better energy resolution and topological signature for a powerful background rejection[58]. It aims at a phased program starting with a 100 kg prototype in 2016. Smaller scale prototypes have been already built and operated successfully providing excellent results on energy resolution[59].

New developments have also been proposed to exploit the low background environments of SNO and KamLAND for $0\nu\beta\beta$ searches. After an initial interest for a large mass scintillator loaded with ^{150}Nd, SNO+ is pursuing the goal of studying ^{130}Te with about 780 ktons of liquid scitillator loaded with 0.3% natural tellurium[60]. Start of operation is expected in 2017.

In KAMLAND-Zen, 320 kg of 90% isotopically enriched ^{136}Xe are dispersed inside a smaller balloon embedded in the original KamLAND liquid scintillator. The program has started operation in in September 2011. The first results, characterized by an unexpected large background level in the ROI, have been presented in 2013[39]. After a strong effort to identify and suppress the unexpected background and a technical stop in 2016, operation is expected to resume in 2017 with a larger mass.

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}Se foils spread among 20 detector modules. The expected energy resolution is 7% FWHM (12% in NEMO-3) to improve the signal detection efficiency from 8% to 40% and reduce the $2\nu\beta\beta$ contribution. The projected background is $\sim 3.5 \times 10^{-4}$ c/keV/kg. A demonstrator (single module) is expected to start operation at LSM in 2016.

In order to sound the IH region of neutrino masses the next generation experiments will need tons of $\beta\beta$ isotope and background rates below 0.1 c/(keV·ton). This is a challenge that has already been accepted by most of the existing experiments which have already proposed major extensions of the running experiments (e.g. nEXO, Majorana/GERDA, CUPID, MAGIX and next phases of SNO+ and Kamland-Zen).

In all cases, the goal is to increase the $0\nu\beta\beta$ sensitivity by improving the detector mass, energy resolution, background discrimination technique, granularity and track reconstruction, etc.

Apart from the technical challenge, each of the proposed programs represents a significant investment in terms of resources and asks for big international collaborations. It is therefore already clear that only few of them will be likely funded. Indeed, the downselection process has already started[61]. In this respect, if one assumes that all the proposed programs can actually maintain the expected performance, then time and cost could become relevant factors.

Given that in all cases isotopic enrichment is irremissible, the procurement of tons of $\beta\beta$ isotope is likely to require a lot of time and dominate the experiment costs. The choice of the isotope can therefore become a critical issue. A natural question could then be:"what sensitivity can you reach with a fixed budget"? Of course the final answer depends the actual ability to optimize all the sensitivity parameters but a significant exercise can be carried out assuming that the cost of the next generation experiments is of the order of 100 million USD and that half of the cost is required for enrichment. The result is summarized in table 2 where it has been assumed that each technology aims at meeting the ZB condition (i.e. a background of the order or less than B^{ZB}). It is evident that the choice of the isotope can make the difference and that in the discussion for the future experiment(s) the cost will play a relevant role. Of course an equivalent analysis would consist in comparing the cost of experiments with similar sensitivity based on different isotopes. The conclusions would be however very similar.

Before concluding, we would like to underline once more the crucial role played by the energy resolution. Indeed, apart from the obvious importance in identifying the $0\nu\beta\beta$ peak

Table 2. Sensitivity estimate for next generation experiments with an expected cost of the order of ∼100 M USD. The different technologies have been indicated with suffixes: D for diodes, B for bolometers, T for TPCs and S for scintillators. The adopted units are 10^{27} y for $T^{0\nu}_{1/2}$, 10^{-3} c/(keV·ton·y) for B, keV for Δ, ton/y for the prodution rate R and ton for the masses M_{tot} and M_{iso}. C and C' are the estimated costs (USD/g) for the natural and enriched material. Material data are taken from[62] while energy resolutions are typical values from current experiments. $\langle m_\nu \rangle$ values are evaluated using NMEs from [22] and PSIs from [15].

Isotope	Mat.	$T^{0\nu}_{1/2}$	$B(ZB)$	Δ	M_{iso}	$\langle m_\nu \rangle$	i.a.	C'	R	C	M_{tot}
^{76}Ge	$Ge^{(D)}$	6.99	84	3	0.71	19	7.8	70	165	1.2	0.79
^{82}Se	$ZnSe^{(B)}$	6.32	15.6	10	0.71	12	9.2	70	2275	0.8	1.28
^{100}Mo	$ZnMO_4^{(B)}$	3.63	19.4	9	0.5	15	7.6	100	266000	0.02	1.15
^{116}Cd	$CdWO_4^{(B)}$	2.09	31.9	6	0.33	26	9.6	150	22200	0.06	1.05
^{130}Te	$TeO_2^{(B)}$	23.4	8.35	5	3.85	6	34.2	13	150	0.03	4.79
	$Te^{(S)}$	5.37	0.19	270	3.85	12	34.2	13	150	0.03	3.85
^{136}Xe	$LXe^{(T)}$	20.9	0.55	58	6.25	7	8.9	8	50	1.2	6.25
	$Xe^{(S)}$	12.5	0.13	250	6.25	9	8.9	8	50	1.2	6.25
	$Xe^{(T)}$	12.5	2.13	15	6.25	9	8.9	8	50	1.2	6.25

and protecting against the $2\nu\beta\beta$ background contribution, a good energy resolution can make the difference when discussing about the discovery potential. Most of the considerations leading to eq. (3) and (**??**) do not take into account the peak shape and refer to the FWHM simply as the energy interval over which signal and background are integrated. However the peak shape is very important in disentangling the signal from the background, a very hard task with a poor energy resolution[63].

7. Conclusions

Neutrinoless double beta decay is a crucial test of lepton number conservation still representing a unique opportunity to determine the nature of neutrinos and to probe their mass scale.

After a long preparation phase we have now entered a very exciting period in which a number of new experiments have started to study $0\nu\beta\beta$ with improved sensitivity. Furthermore, others are very close to start operation. The result is a vivid interest for $0\nu\beta\beta$ searches which, when coupled to the promising results from a number of ongoing R&D's, is paving the road to a rich program of future ton-scale experiments characterized by sensitivities in the range 10^{27-28} years on $0\nu\beta\beta$ half-lifetime. While it has already been pointed out that only few of them will survive the present proposal phase it is important to point out that, given the still large uncertainty affecting NME calculations, the experimental investigation on the largest possible number of $\beta\beta$ isotopes is of crucial importance. On the other hand, if the quenching of g_A would result to affect also $0\nu\beta\beta$ calculations, then the effect on the experimental program would be dramatic and could even spoil the sensitivity on $\langle m_\nu \rangle$ [5]. Useless to say this is a question that deserves an urgent answer.

References

[1] Furry W H 1939 *Phys. Rev.* **56** 1184
[2] Majorana E 1937 *Nuovo Cim.* **14** 322
[3] Dell'Oro S, Marcocci S, Viel M and Vissani F 2015 (*Preprint* `hep-ph/1505.02722`)
[4] Cremonesi O and Pavan M 2013 *Adv. High Energy Phys.* **2014** 951432
[5] DellOro S, Marcocci S, Viel M and Vissani F 2015 *J. Cosm. Astropart. Phys.* **1512** 023
[6] HPas and Rodejohann W 2015 *New J. Phys.* **17** 115010 (*Preprint* `hep-ph/1507.00170`)

[7] Gomez-Cadenas J, Martn-Albo J, Mezzetto M, Monrabal F and Sorel M 2012 *Riv. Nuovo Cim.* **35** 29
[8] Fukugita M and Yanagida T 1986 *Phys. Lett.* B **174** 45
[9] Atre A, Han T, Pascoli S and Zhang B 2009 *J. High Energy Phys.* **0905** 030
[10] Mitra M, Senjanovic G and Vissani F 2012 *Nucl. Phys.* B **856** 26
[11] Blennow M, Fernandez-Martinez E, Lopez-Pavon J and Menendez J 2010 *J. High Energy Phys.* **1007** 096 (*Preprint* `hep-ph/1005.3240`)
[12] Deppisch F, Hirsch M and Pas H 2012 *J. Phys.* G **39** 124007 (*Preprint* `hep-ph/1208.0727`)
[13] Giunti C and Zavanin E M 2015 (*Preprint* `hep-ph/1505.00978`)
[14] Benato G 2015 (*Preprint* `hep-ph/1510.01089`)
[15] Kotila J and Iachello F 2012 *Phys. Rev.* C **85** 034316
[16] Stoica S and Mirea M 2013 *Phys. Rev.* C **88** 037303
[17] Stefanik D, Dvornicky R, Simkovic F and Vogel P 2015 *Phys. Rev.* C **92** 055502
[18] Caurier E, Martinez-Pinedo G, Nowacki F, Poves A and Zuker A P 2005 *Rev. Mod. Phys.* **77** 427
[19] Menendez J, Poves A, Caurier E and Nowacki F 2009 *Nucl. Phys.* A **818** 139
[20] Simkovic F, Rodin V, Faessler A and Vogel P 2013 *Phys. Rev.* C **87** 045501
[21] Hyvarinen J and Suhonen J 2015 *Phys. Rev.* C **91** 024613
[22] Barea J, Kotila J and Iachello F 2015 *Phys. Rev.* C **91** 034304
[23] Rath P K, Chandra R, Chaturvedi K, Lohani P, Raina P K and Hirsch J G 2013 *Phys. Rev.* C **88** 064322
[24] Rodriguez T R and Martinez-Pinedo G 2010 *Phys. Rev. Lett.* **105** 252503 (*Preprint* `nucl-th/1008.5260`)
[25] Faessler A 2012 *J. Phys. (Conf. Ser.)* **337** 012065 (*Preprint* `nucl-th/1104.3700`)
[26] Barea J, Kotila J and Iachello F 2013 *Phys. Rev.* C **87** 014315
[27] Suhonen J and Civitarese O 2013 *Phys. Lett.* B **725** 153
[28] Rodin V A, Faessler A, Simkovic F and Vogel P 2006 *Nucl. Phys.* A **766** 107
[29] Faessler A, Fogli G L, Lisi E, Rodin V, Rotunno A M and Simkovic F 2008 *J. Phys.* G **35** 075104
[30] Fujita J I and Ikeda K 1965 *Nucl. Phys.* **67** 145
[31] Menendez J, Gazit D and Schwenk A 2011 *Phys. Rev. Lett.* **107** 062501
[32] Konieczka M, Baczyk P and Satula W 2015 Beta-decay study within multi-reference density functional theory and beyond (*Preprint* `nucl-th/1509.04480`)
[33] Engel J, Simkovic F and Vogel P 2014 *Phys. Rev.* C **89** 064308
[34] Cappuzzello F, Agodi C, Bond‘ M, Carbone D, Cavallaro M and Foti A 2015 *J. Phys. Conf. Ser.* **630** 012018
[35] Robertson R G H 2013 *Mod. Phys. Lett.* A **28** 1350021
[36] Faessler A, Gonzalez M, Kovalenko S and Simkovic F 2014 *Phys. Rev.* D **90** 096010
[37] Biassoni M, Cremonesi O and Gorla P 2013 (*Preprint* `hep-ph/1310.3870`)
[38] MAuger *et al.* (EXO-200) 2012 *Phys. Rev. Lett.* **109** 032505
[39] Gando A *et al.* (KamLAND-Zen) 2013 *Phys. Rev. Lett.* **110** 062502
[40] KAlfonso *et al.* (CUORE) 2015 *Phys. Rev. Lett.* **115** 102502
[41] Barabash A S and Brudanin V 2011 *Phys. Atom. Nucl.* **74** 312
[42] KAlfonso *et al.* (CUORE) 2008 *Phys. Rev.* C **78** 058501
[43] Agostini M *et al.* (GERDA) 2013 *J. Phys.* G **40** 035110
[44] Agostini M *et al.* (GERDA) 2013 *Phys. Rev. Lett.* **111** 122503
[45] Arnold R *et al.* (NEMO3) 2005 *Phys. Rev. Lett.* **95** 182302
[46] Argyriades J *et al.* 2010 *Nucl. Phys.* A **847** 168
[47] Arnold R *et al.* (NEMO3) 2014 *Phys. Rev.* D **89** 111101
[48] Poda D *et al.* 2014 *EPJ Web of Conf.* **65** 01005
[49] Danevich F *et al.* 2003 *Phys. Rev.* C **68** 035501
[50] Arnold R *et al.* 2011 *Phys. Rev. Lett.* **107** 062504
[51] Albert J B *et al.* (EXO-200) 2014 *Phys. Rev.* C **89** 015502
[52] Argyriades J *et al.* 2009 *Phys. Rev.* C **80** 032501
[53] Abgrall N *et al.* (Majorana) 2014 *Adv. High Energy Phys.* **2014** 365432
[54] Brugnera R and Garfagnini A 2013 *Adv. High Energy Phys.* **2013** 506186
[55] Ardito R *et al.* (CUORE) 2005 (*Preprint* `hep-ex/0501010`)
[56] Wang G and others (CUPID Group of Interest) 2015 (*Preprint* `physics.ins-det/1504.03599`)
[57] Ostrovskiy I 2015 This conference
[58] Gomez-Cadenas J *et al.* 2012 (*Preprint* `physics.ins-det/1210.0341`)
[59] Alvarez V *et al.* 2012 *JINS* T **7** 06001
[60] Andringa S *et al.* (SNO+) 2015 (*Preprint* `physics.ins-det/1508.05759`)
[61] RMcKeown *et al.* 2014 Report to the NSAC: Neutrinoless Double Beta Decay
[62] US Department of the Interior and US Geological Survey 2015 Usgs mineral commodity survey 2015
[63] Gomez-Cadenas J and Martn-Albo J 2014 *PoS (GSSI14)* 004