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Developments on double beta decay search

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Despite the success of the oscillation experiments in demonstrating that neutrinos are mixing massive particles, 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 still the only practical tool for probing the character of neutrinos and, if neutrinos are Majorana particles, can provide fundamental informations on their absolute mass scale. 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 ongoing experiments and of the projects proposed for the future is given. The most relevant parameters contributing to the experimental sensitivity are outlined.

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1. Introduction

During the past decade, the results on neutrino oscillations have shown that neutrinos are massive particles that mix through the PMNS matrix to give rise to the flavor eigenstates. Recent results from reactor experiments[1] have shown that all the three ming angles are different from zero, opening a new window on the search for CP violations on the leptonic sector. This is a very strong demonstration that the Standard Model of electroweak interactions is incomplete and that new Physics beyond it must exist.

Neutrino oscillations can't provide however any insight into the problems of the neutrino nature and their mass scale which stands therefore as two most outstanding questions still puzzling the world of neutrino Physics. Moreover, two possibile hierarchical mass arrangements (Direct and Inverted) are allowed by present data. . Neutrinos are the only fermions for which the Majorana formulation[2] is possible (assuming a violation of the Lepton Number). 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 (δm « m). On the other hand, the much more sensitive consmological inferences suffer from a heavy model dependance. All these experimental approaches provide however complementary pieces of information and a common effort is compulsory.

2. Neutrinoless Double Beta Decay

First suggested by M.Goeppert-Mayer in 1935[3], Double Beta Decay (DBD) is a rare nuclear process in which a parent 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. 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, a condition met in nature by 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. They are usually characterized by lower transition energies and have correspondingly poorer experimental sensitivities. They will not be discussed in the following while we refer to the most recent reviews on $\beta\beta$ for a more complete treatment on the subject[4, 5].

Among the possible $\beta\beta$ modes two are of particular interest, the 2ν mode ($\beta\beta(2\nu)$) ${}^{A}_{Z}X \rightarrow^{A}_{Z+2} X + 2e^{-} + 2\overline{\nu}$, which observes the lepton number conservation and it is allowed by the Standard Model (SM) of electro-weak interactions, and the 0ν mode ($\beta\beta(0\nu)$) ${}^{A}_{Z}X \rightarrow^{A}_{Z+2} X + 2e^{-}$ which violates the lepton number by two units and occurs only if neutrinos are their own antiparticles.

In fact, after 70 years from its introduction by W.H. Furry[6], $\beta\beta(0\nu)$ 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

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M^{0\nu}|^{2}|\langle m_{\nu}\rangle|^{2}/m_{e}^{2} \tag{2.1}$$

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

$$\langle m_\nu \rangle \equiv \sum_{k=1}^{3} |U_{ek}^L|^2 m_k e^{i\phi_k} \simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3 \tag{2.2}$$

The last equality holds for small neutrino masses and α_1 and α_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 establish definitely 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. On the other hand, if future oscillation experiments would demonstrate the inverted ordering of the neutrino masses, a failure in observing $\beta\beta(0\nu)$ at a sensitivity of 20-30 meV would show that neutrinos are Dirac particles.

As can be easily deduced from eq. (2.1), $\langle m_\nu \rangle$ 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 $\mathrm{M}^{0\nu}$(NME) for which many (unfortunately often conflicting) evaluations are available in the literature. Significative improvements have however been obtained recently. SM calculations are still systematically smaller than the others but NME calculations presently agree within a factor 2-3[7]. 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 a chance and their comparison can help to identify the important effects responsible for the observed disagreement.

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 significance of any comparison. Such a problem has been once more recognized recently in [5], 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[9], 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. In order to preserve correlations and allow a (relative) comparison between $\beta\beta(0\nu)$ experiment sensitivities free of the uncertainties arising from different calculations we will refer here to a single calculation [10] which has the advantage of being available for all the nuclei of interest.

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. $\langle m_\nu \rangle$ are computed using NME and phase space factors from [10] and [11] respectively.

Isotope	$T^{2\nu}_{1/2}$[12]	$T^{0\nu}_{1/2}$	Q	nat. ab.	$\langle m_\nu \rangle$
	(10^{19}y)	(10^{24}y)	(keV)	(%)	eV
^{48}Ca	$(4.4^{+0.6}_{-0.5})$	> 0.0014[13]	4271	0.19	14
^{76}Ge	(150 ± 10)	> 19[14]	2040	7.8	0.44
		$22.3^{+4.4}_{-3.1}$[15]		0.4	
		> 15.7[16]		0.5	
^{82}Se	(9.2 ± 0.7)	> 0.36 [17]	2995	9.2	1.9
^{96}Zr	(2.3 ± 0.2)	> 0.0092[17]	3350	2.8	15
^{100}Mo	(0.71 ± 0.04)	> 1.1[17]	3034	9.6	1.0
^{116}Cd	(2.8 ± 0.2)	> 0.17[18]	2802	7.5	3.5
^{130}Te	(68^{+12}_{-11})	> 2.8[19]	2527	34.5	0.6
^{136}Xe	> 81[20]	> 0.45[21]	2479	8.9	0.3
^{150}Nd	$(13.3^{+4.5}_{-2.6})$	> 0.0018[22]	3367	5.6	21
^{238}U	(220 ± 50)	> 0.0036[22]			

3. Past experiments

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.

Counter methods based on the direct observation of the two electrons emitted in the decay have provided so far the best experimental sensitivities. 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 provided so far the best experimental results are still the most attractive approach for $\beta\beta(0\nu)$ searches.

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[12, 21, 23].

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 experiments based on the use of isotopically enriched HPGe diodes (Heidelberg-Moscow[14] and IGEX[16]) but two other experiments reached comparable sensitivities: NEMO3[17, 24] at LSM and CUORICINO at LNGS[25].

The evidence for a $\beta\beta(0\nu)$ signal has also been claimed[26] (and later confirmed [15]) by a small subset (KHDK) of the HDM collaboration at LNGS with $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ 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 whlile 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.

4. Present and next generation experiments

The performance of a $\beta\beta(0\nu)$ experiment is usually expressed in terms of a detector *factor of merit* (or sensitivity), 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 C.L. At 1σ level (n$_B$=$\sqrt{BTM\Delta}$), one obtains:

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

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, 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 has a physical justification.

Despite its simplicity, equation (4.1) 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. In these cases a more sophisticated Monte Carlo approach is needed.

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 ·M·T ·$\Delta\sim$O(1)) deserves particular attention. In these case one generally speaks of "zero background" (0B) experiments, a condition met by a number of upcoming projects. In these conditions, eq. (4.1) can no more be used and a good approximation to the sensitivity is given by

$$F^{0B}_{0\nu} = \ln 2 \, N_{\beta\beta} \varepsilon \frac{T}{n_L} = \ln 2 \times \frac{x \, \eta \, \varepsilon \, N_A}{A} \frac{M \, T}{n_L}$$

where n_L is a constant depending on the chosen CL and on the actual number of observed events. The most relevant feature of equation (4.1) is that F$^{0B}_{0\nu}$ does not depend on the background level or the energy resolution and scales linearly with the sensitive mass M and the measure time T.

Most of the criteria to be considered when optimizing the design of a new $\beta\beta(0\nu)$ experiment follow directly from eq. (4.1): 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 by all the next generation experiments. Unfortunately, they are often conflicting and simultaneous optimisation is rarely possible.

Since T is usually limited to a few years and Δ is usually fixed (meaning that for a given experimental technique is usually difficult to get sizable improvements), the 0B condition translates to B·M ∼O(1)/Δ·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 $B \cdot M \simeq\gtrsim 1/\Delta \cdot T$. 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 ($\langle m_\nu \rangle$ ∼10-50 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[27, 28].

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 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).

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. Here the measured values (“Measured”) are distinguished from realistic projections (“Reference”) and most optimistic expectations (“Improved”). Experiments entering the 0B regime are also indicated . 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.

Three “second generation” experiments (EXO, KAMLAND-Zen and GERDA) have started data taking in the past year. Their recently presented first results are summarized in Tab. 2 and in the

Table 2: List of some of the most developed $\beta\beta(0\nu)$ projects. 5 years sensitivity at 90% C.L. Experimental phases are indicated as running (R), progress (P) or development (D). $\langle m_\nu \rangle$ values are calculated using NME and phase space factors from [10] and [11] respectively. Asterisk signals 0B condition.

	Isotope	Mass [kg]	Lab	Status	Start	$S_5^{0\nu}$ [10^{26}y]	$\langle m_\nu \rangle$ [meV]
CUORE[29]	^{130}Te	200	LNGS	P	2014	2.1	73
GERDA I[30]	^{76}Ge	18	LNGS	R	2012	1.1	184
GERDA II		40		D		2.1*	133
MJD[31]		30	SUSEL	P	2014	2.6*	67
EXO[21]	^{136}Xe	200	WIPP	R	2011	1.2	115
		1000		D	2015	7	30
SuperNEMO[32]	^{82}Se	100-200	LSM	D	2013-2015	0.8	90
KamLAND-Zen[23]	^{116}Cd	400	Kamioka	R	2011	0.33	220
		1000		D	2013-2015	0.59	164
SNO+[33]	^{150}Nd	44	Sudbury	D	2013	0.08	310
NEXT[34]		100	Canfranc	D	2014	5	56

following sections. In all cases the effort to lower the background level is apparent. On the other hand, the effects of unexpected contributions in enetring new background regimes also appear.

4.1 High resolution calorimeters

MAJORANA and GERDA belong to the class of the high energy resolutions calorimeters and are both phased programs representing large scale extensions of past successful experiments on ^{76}Ge $\beta\beta(0\nu)$. Background control is based upon a careful choice of the setup materials and of very effective radiation shields. Active reduction based on new detector design for single site event identification represent the new frontier and are presently gathering most of the experimental efforts. In both cases this is accomplished by means of p-type “Broad Energy” isotopically enriched germanium diodes (or “BEGe”).

Evolved from the HM experiment, GERDA[30] aims at implementing the concept of Ge diodes immersed in a LAr bath[35] for a radical background suppression. The GERDA setup construction was completed in Gran Sasso during 2010. Two experimental phases are foreseen. GERDA-I is intended to scrutinize the KHDK claim and has recently started (November 2011) with 18 kg of enriched detectors ($\sim$85%) inherited from previous experiments. With an exposure of 6.1 kg ·y they have measured the ^{76}Ge $\beta\beta(2\nu)$ halflife $T_{1/2}^{2\nu}$ = (1.88 ± 0.10) 10^{21} yr and a detailed analysis of the BBz background contributions leading to a background index of $0.020^{+0.006}_{-0.004}$ cts/(keVk̃gỹr)[38]. The average energy resolution at the $\beta\beta(0\nu)$ energy (2039 keV)is 4.5 keV FWHM. 40 kg of germanium isotopically enriched in ^{76}Ge are already available for GERDA-II. A large part of the efforts are presently directed to develop the detectors with background reduction capability crucial for the targeted 10^{-3} c/keV/kg background level. 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 whole assembly is enclosed in a low-background passive shield and active veto and be located deep underground. The choice of an extremely pure conventional cryostat for hosting the BeGe detectors represents the most relevant difference with respect to GERDA. A 30 kg detector (Majorana Demonstrator or MJD) is presently under construction in the Homestake mine to demonstrate the viability of the technique. A very low background rate, of the order of $2-3\times10^{-4}$ c/keV/kg, is the distinctive and ambitious target of this project. The completion of this phase is expected in 2014.

CUORE[29] (*Cryogenic Underground Observatory for Rare Events*) 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. CUORE consists of a rather compact cylindrical structure of 988 cubic natural 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 ∼5 keV FWHM at the $\beta\beta(0\nu)$ transition energy (∼2.53 MeV). A background level of of the order of ∼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 2.1×10^{26} y allowing a close look at the IH region of neutrino masses. CUORE is presently under construction at LNGS. Setup completion and data taking start are expected in 2014. A test tower fully assembled following the CUORE protocol has been recently built at LNGS as a full scale test of the procedure. It will soon operate in the cryogenic system used for CUORICINO and act as an independent experiment (CUORE-0) with intermediate sensitivity. Thanks to the high natural abundance of ^{130}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 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[36]. The use of hybrid scintillating bolometers could allow to study in the future new $\beta\beta(0\nu)$ active isotopes with improved sensitivity. A ∼30 kg demonstrator (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.

4.2 Tracking detectors

Gas and liquid 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 (*Enriched Xenon Observatory*) is a challenging project based on a large mass (∼ 1–10 tons) of isotopically enriched (85% in ^{136}Xe) Xenon. An ingenuous tagging of the doubly charged Ba isotope produced in the decay ($^{136}Xe \rightarrow ^{136} Ba^{++} + 2e^{-}$) 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 and has triggered an R&D program to improve the energy resolution by exploting the contemporary measurement of ionization and scintillation light. A sizable prototype experiment with a Xe mass of 200 kg (80% ^{136}Xe), has been deployed at WIPP since summer 2009. No barium tagging is yet active. EXO-200 has started data taking in May 2011 and collected so far (June 2012) a useful exposure of 32.5 kg ·y. A very good energy resolution of about 100 keV FWHM at the 2615 ^{208}Tl line has been measured. When coupled with the measured ^{136}Xe $\beta\beta(2\nu)$ half-life of $T^{2\nu}_{1/2}$ = (2.23 ± 0.017 stat ± 0.22 syst) 10^{21} yr [21] (5 times less than the previous published limit), it makes $\beta\beta(2\nu)$ contribution less worrisome. With a fiducial mass of 79.4 kg of ^{136}Xe, a detection efficiency of ^{60}Co 75% and an excellent background level of 1.5 $\times 10^{-3}$ c/keV/kg/y the EXO-200 has so far provided a lower limit of 1.6 10^{25} yr on the ^{136}Xe $\beta\beta(0\nu)$ half-life[21]. Further improvements on energy resolution and background are still expected while the experiment is approved to run for 4 more years.

The use of a Time Projection Chamber (TPC) filled with high-pressure gaseous xenon, and with capabilities for calorimetry and tracking (following the experience of the past Gotthard experiment) has been proposed in 2009 by a mainly Spanish collaboration headed by the Valencia group [34]. Thanks to an excellent energy resolution (∼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.

4.3 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[37]. New developments have been proposed more recently in order to exploit two successful experiments on neutrino oscillation like SNO and KamLAND. SNO+ is pursuing the goal of studying ^{150}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}Xe are dispersed in a dedicated plastic bag filled with liquid scintillator at the center of the KAMLAND detector. Proposed in 2009, the program has started in September 2011 with 320 kg of 90% enriched ^{136}Xe. The goal is to reach 1 ton in 2013. The Xe concentration in the scintillator is 2.44% wt and the measured energy resolution ∼250 keV FHWM at 2615 keV. The fiducial mass is ∼125 kg of ^{136}Xe and the total exposure so far collected is 38.6 kg ·y of ^{136}Xe. The measured ^{136}Xe $\beta\beta(2\nu)$ half-life of $T^{2\nu}_{1/2}$ = (2.30 ± 0.02 stat ± 0.12 syst) 10^{21} yr confirms the EXO result. The measured $\beta\beta(0\nu)$ background level is 2.8 $\times 10^{-3}$ c/keV/kg(Xe)/y dominated by an unexpected contribution very close to the $\beta\beta(0\nu)$ Q value. The best fit suggests a ^{110m}Ag (or ^{208}Bi, ^{88}Y) contamination of the scintillator or the acrylic vessel. A part from the lower limit of 6.2 10^{24} yr on the ^{136}Xe $\beta\beta(0\nu)$ half-life, lower than expected, the presence of unexpected lines very close to the transition energy coupled to the poor energy resolution is worrysome for the possible systematic contribution. An extensive program to get rid of this contribution is ongoing (LS purification and vessel replacement).

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 ~100 kg of ^{82}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.

5. Conclusions

Neutrino oscillation results have stimulated a renewed interest in the experimental study of neutrino properties. In this framework, neutrinoless $\beta\beta$ decay is 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. An international effort is supporting a phased $\beta\beta(0\nu)$ program based on a number of newly proposed experiments aiming at reaching sensitivities to test the inverted neutrino mass hierarchy. Three next generation experiments have already started data taking while other will soon be ready. The success of the upcoming $\beta\beta(0\nu)$ program strongly depends on the true capability of the proposed projects to reach the required background levels in the ROI. 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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