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Neutrino masses

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Neutrino oscillation experiments have provided convincing evidence that neutrinos have non-zero masses and non-trivial mixing. Unfortunately they cannot tell us anything about the absolute neutrino mass scale, which is very important for understanding the nuclear and particle physics beyond the Standard Model as well as the evolution and structure formation of our universe.
Two methods for determining the neutrino mass scale in the laboratory are currently pursued: the search for neutrinoless double β-decay ($\beta\beta(0\nu)$) and the kinematic measurements, investigating single β-decays or electron captures. The former is also a unique probe for the Majorana character of neutrinos and provides a very sensitive test of lepton number violation.
Very sensitive, though strongly model dependent, results are provided also by cosmological observations.
These three methods represent the core of the present experimental strategy, which aims at gathering complementary informations to complete our understanding of neutrino properties.
A number of experiments based on different techniques are presently being constructed, commissioned or are even running. They aim at sensitivities on the neutrino mass of O(100) meV. A large number of proposals implementing ingenuous methods to approach the O(10) meV region have also been discussed.

The principle methods of these experiments will be discussed together with the most relevant results.

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1. Introduction

Precision measurements from atmospheric, solar, accelerator and reactor neutrinos have unambiguously demonstrated that neutrino flavor states are non-trivial superpositions of neutrino mass eigenstates. As a consequence neutrinos oscillate from one flavor state into another during their flight and details of the neutrino mixing matrix U as well as the differences between the squares of neutrino masses can be determined [1].

Neutrino oscillation experiments cannot however determine absolute neutrino masses.

Neutrino masses are very important for nuclear and particle physics, since they are a very sensitive probe for physics beyond the Standard Model of particle physics. Moreover, since neutrinos carry no conserved charge apart from lepton number, they provide a unique possibility for self-conjugate fermions. In other words they could be their own antiparticles giving rise to intriguing Majorana mass terms [2].

Neutrino masses are very important also for astrophysics and cosmology. Actually, although very light, neutrinos may contribute significantly to the mass density of the universe, playing a relevant role in its evolution. Indeed, with 336 neutrinos per cm^{3}left over from the big bang they are about a billion times more abundant than atoms. The direct observation of these low energy relic neutrinos is actually one of the most striking open challenges.

Since oscillation experiments cannot determine the absolute value of the neutrino masses, other methods are needed. Three experimental techniques have been so far devised:

- Kinematic (also known as “direct”) measurements, based on the investigation of the final part of the single β or electron capture decay spectra ($\rightarrow m_\beta = \sqrt{\sum_k m^2_{\nu k}|U_{ek}|^2}$).
- Neutrinoless Double beta decay (ββ(0ν) or DBD, $\rightarrow m_{ee} \sum_k m_{\nu k} U^2_{ek}$).
- Cosmological measurements ($\rightarrow m_\Sigma = \sum_k m_{\nu k}$)

Each of these methods is sensitive to a different combination of the mass eigenvalues weighted on the mixing matrix elements (indicated in parenthesis in the previous list by an arrow) and provides therefore important complementary informations.

Currently available neutrino oscillation results allow to put important constraints on these combinations [1] providing important informations about the available parameter space and the required sensitivities. In particular cosmological measurements m_Σ have a nearly full correlation to the kinematic parameter m_β, while the structure of the effective neutrino mass m_{ee} measured in ββ(0ν) is complicated by the presence of the unknown CP and Majorana phases which can give rise to cancellations.

It should be noticed that ββ(0ν) could also be mediated by exotic mechanisms (e.g. the exchange of exotic SUSY particles) that would spoil most of the information on the neutrino mass. Nevertheless, ββ(0ν) is still the only way to probe the Majorana character of neutrinos providing also a unique experimental handle on the Majorana phases.

Model-independent measurements can be provided only by kinematical methods which however have presently sensitivities still far from the region of interest for the neutrino mass inverted hierarchy (10-50 meV). On the other hand, ββ(0ν) and cosmological measurements are characterized by much more stringent sensitivities though they suffer from strong model dependencies.

Moreover, as already pointed out above, the three techniques provide complementary informations that could help disentangling the missing parameters from the few available experimental results. A global approach gathering results from all of the three available techniques looks therefore the only reasonable strategy.

2. Direct neutrino mass experiments

As recognized since the beginning of the neutrino history, a non-zero value of the neutrino mass would imply a tiny modification of the spectrum of the β-electrons near its endpoint. Such a weak signature requires that electron energies are measured with very high precision. Moreover, in order to maximize the effect, β emitters with very low endpoint energy (e.g. E0(^{187}Re) = 2.47 keV, E0(^{3}H) = 18.57 keV) are favored. Similar effects are also induced on the X-ray spectra accompanying electron capture (EC) or internal bremsstrahlung (IB) decays [3]. They have been recently proposed as sensitive probes for future direct neutrino mass measurements [4].

In principle also time-of-flight measurements are a possible mean to get direct information on the neutrino mass. However, they require very long baselines and therefore very strong sources, which only cataclysmic astrophysical events like a core-collapse supernova could provide. Moreover, results depend somewhat on the underlying supernova model and nearby supernova explosions are too rare to really compete with the laboratory direct neutrino mass experiments.

Experimental methods are generally classified in homogeneous (or calorimetric, “source=detector”) and inhomogeneous (or “source$\neq$detector”). In the former case the decay source is dispersed inside the detector volume. This method can provide precise measurements characterized by high efficiency and a low dependence on systematic effects. On the other hand, the main limitation is given by pile-up effects.

Inhomogeneous detectors are mainly based on the use of very large mass spectrometers to measure the energy of a small fraction (close to the endpoint) of the β spectrum. They are mainly limited by background rates and are affected by a number of systematic effects. They have provided so far the best available results.

Tritium is the standard isotope for the inhomogeneous approach. Actually, its low endpoint energy (18.6 keV), its rather short half-life of (12.3 y), its super-allowed β transition, and its simple electronic structure make it an ideal candidate for this kind of research. Tritium β-decay experiments using a tritium source and a separated electron mass spectrometer have been performed for more than 60 years reaching a sensitivity of 2 eV [5, 6].

The improvement of these experiments by an order of magnitude in the final sensitivity as well as in solving the most relevant systematic effects (at the origin of the âĂIJnegative m_ν^2âĂIJ problem) is mainly based on a new design of the spectrometer as well as a very careful study of the systematics.

KATRIN [7] (KArlsruhe TRItium Neutrino experiment), the huge experiment aiming at a sensitivity to the neutrino mass down to 200 meV currently being set up at the Karlsruhe Institute of Technology KIT, is the last effort in this direction.

The KATRIN design is based on the successful MAC-E-Filter ((Magnetic Adiabatic Collimation and Electrostatic)) spectrometer technique combined with a very strong windowless gaseous molecular tritium source. The whole setup is 70 m long.

The decay electrons are guided by strong magnetic fields (up to 6 T) from the source, through the transport section towards the spectrometer section of the experiment, which is responsible for the energy analysis. Since only a fraction of 10^{13} of all the decay electrons is emitted with energies in the interesting region, the background rate B has to be kept sufficiently low. The expected sensitivity of 200 meV on the neutrino mass depends essentially on the ability to reach the background design value of 10^2 counts per second (cps).

Most of the effort in KATRIN development has been devoted to develop appropriate countermeasures for each of several sources of background identified in the MAC-E filter design. These are mainly μ- or γ-induced secondary electrons from the wall and radon- or tritium-induced electrons stored in the volume of the spectrometer. Secondary electrons are largely suppressed (10^{-5}) by an external air coil and inner electrode systems. Cryo-cooled baffles prevent the radon from entering the spectrometer, while the application of a proper electric dipole field gets rid of the stored primary electrons.

The KATRIN main spectrometer has been successfully commissioned during summer 2013. The start of data taking is expected in 2015.

Calorimetric measurements have been so far proposed to investigate the β-decay of ^{187}Re and/or EC-decay of ^{163}Ho [4]. Compared to tritium, ^{187}Re has a lower endpoint energy (2.47 keV) and a correspondingly higher (by a factor $\sim$350) useful fraction of the β-spectrum. Unfortunately ^{187}Re exhibits a very complicated electronic structure and a very long half life ($4.3 \cdot 10^{10}$ y). Low temperature calorimeters (LTD's), which measure the entire energy released in the detector (except that of the neutrino), can somehow compensate this disadvantage and get rid of the corresponding systematics. LTD's can however only apply an integral approach (i.e. they can only measure the whole energy spectrum) and random pile-up of events is the limiting factor. Very small detector masses (O(mg)) are therefore the only way out. Large arrays of low temperature bolometers are then required [8] to suppress pile-up effects and reach the necessary sensitivity to the neutrino mass. Energy resolution is another possible issue. Indeed, although highly performing LTD's have been produced (ΔE of the order of few eV), this is not yet the case with rhenium.

The persisting difficulties with rhenium absorbers (either metallic or compounds) have triggered an increasing interest for the EC-capture of ^{163}Ho . The very upper end of the electromagnetic de-excitation spectrum of the ^{163}Ho daughter ^{163}Dy resembles the endpoint spectrum of a β-decay and is similarly sensitive to the neutrino mass [3]. Indeed, the isotope ^{163}Ho could be implanted into properly designed LTD's and actually two independent programs based on the use of different low temperature techniques have been started: EcHo and HOLMES [4]. First ^{163}Ho spectra with test detectors have been presented and large efforts are been undertaken to develop a multiplexing read-out technology to allow the run of very large large (10^4) arrays.

3. Cosmological measurements

Relic neutrinos would have affected cosmological data at various extents depending on their masses. The most distinct signature is on Cosmic Microwave Background (CMB) anisotropies, whose various measurements have been traditionally combined to put very stringent limits on the sum of the three neutrino mass states m_Σ. Limits in the range $m_\Sigma < 0.21$-1.11 eV have been obtained from different combinations of Planck, WMAP, HST and BAO data [9]. These limits are still strongly model and analysis dependent but cover a parameter space comparable with terrestrial experiments.

4. Neutrinoless double beta decay

Double Beta Decay (DBD) is a rare spontaneous nuclear transition in which an initial nucleus (A,Z) decays to a daughter (A,Z+2) with the simultaneous emission of two electrons. Various decay modes have been devised in which the two electrons are accompanied by a variety of more or less exotic particles. However, from the point of view of Particle Physics, the neutrinoless mode $\beta\beta(0\nu)$ in which no other particle is emitted apart from the electrons is the most interesting for its important theoretical implications. In fact, after 80 years from its introduction, $\beta\beta(0\nu)$ is still the only practical way to probe experimentally the Majorana nature of neutrinos while providing important information on their masses. Indeed, $\beta\beta(0\nu)$ can exist only if neutrinos are Majorana particles and its observation would unambiguously prove that total lepton number is not conserved in Nature.

Apart from a theoretical prejudice in favor of Majorana neutrinos, neutrino oscillation results suggest that favorable conditions for $\beta\beta(0\nu)$ observation may be realized in Nature.

It should also be stressed that $\beta\beta(0\nu)$ could have been already observed. Indeed, an extremely intriguing and debated claim (KHDK) for $\beta\beta(0\nu)$ observation in ^{76}Ge has been announced in 2001 and confirmed to various extents in the following years [10]. The original claim looks however hardly compatible with the recent results from the GERDA experiment, specially when combined with other available results [11].

The important implications of massive Majorana neutrinos and the possible experimental observation of $\beta\beta(0\nu)$ have triggered a whole generation of new experiments spanning a variety of candidate isotopes with different experimental techniques, all aiming at reaching a sensitivity allowing to test the region of neutrino masses indicated by neutrino oscillation experiments.

Experimental techniques range from the well-established germanium calorimeters, to xenon time projection chambers and low temperature calorimeters. Some of the experiments are already running or will run very soon. Others are still in their R&D phase, trying to reach the limit of their experimental technique.

When mediated by the exchange of a light virtual neutrino, the $\beta\beta(0\nu)$ rate is expressed as: $[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}\ |M^{0\nu}|^2\ |\langle m_{\rm ee}\rangle|^2/m_{\rm e}^2$, where $G^{0\nu}$ is the phase space integral, $M^{0\nu}$ is the nuclear matrix element, $m_{\rm e}$ is the electron mass, and $\langle m_{\rm ee}\rangle$ (the so called *Majorana mass*) is the already mentioned combination of neutrino mass eigenstates measured in $\beta\beta(0\nu)$. In terms of the PNMS matrix elements it can be expressed as: $\langle m_{\rm ee}\rangle = c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}e^{i\alpha_1}m_2 + s^2_{13}e^{i\alpha_2}m_3$ where the Majorana phases α_k appear explicitly. In the inverted hierarchy (IH) case, oscillation results constrain $|\langle m_{\rm ee}\rangle|$ in the range 20-50 meV.

As can be easily deduced from $\beta\beta(0\nu)$ rate formula, the derivation of the only neutrino relevant parameter $\langle m_{\rm ee}\rangle$ from the experimental $\beta\beta(0\nu)$ results requires a precise knowledge of the transition Nuclear Matrix Elements M$^{0\nu}$(NME). Many (unfortunately often conflicting) evaluations are available in the literature[12]. In fact, the spread in the available NME calculations causes a lot of confusion in the comparison of the experimental results and sensitivities on $|\langle m_{\rm ee}\rangle|$. Instead of using spread intervals, a possible way out is to refer to a single calculation (or a proper average).

In fact, the agreement between different calculations has greatly improved in the last years. Recent QRPA, IBM-2 and GCM calculations seem to agree within a 25%, while ISM still produce estimates which are lower by a factor of about 2. The reason for this disagreement is still unknown and matter of discussion. A further possible problem with NME calculations is the renormalization of the g_A coupling constant in nuclei, which could affect in a sizable way calculation results. An estimate from know processes like $\beta\beta(2\nu)$ or single β transitions is now under investigation [12].

It's maybe worth noting that in a recent work [13], hints of a possible anti-correlation between nuclear matrix elements and phase space integrals of the same nucleus, have been suggested. If confirmed, this would imply that, from the nuclear point of view, all ββ(0ν) isotopes are almost equivalent or, said differently, that no super-element exists.

From an experimental point of view, the strongest decay signature is the fact that the energies of the two emitted electrons add to Q, the transition energy (the nuclear recoil is negligible). Such a signature is essentially exploited by all the proposed experiments which all aim at an excellent energy resolutions. Unfortunately a lot of sources can produce background counts in this same energy region and their fluctuations can easily hide very faint peaks like the ββ(0ν) one.

Additional information (e.g. single electron energies and angular correlations, identification and/or counting of the daughter nucleus) can result in an improvement of the signal to background ratio. Complementary signatures have however a price and a compromise has to be reached.

The performance of the different ββ(0ν) experiments is usually expressed in terms of an experimental *sensitivity* or detector *factor of merit*, defined as the process half-lifetime ($\tau_{1/2}^{Back.Fluct.}$) corresponding to the maximum signal n_B that can be hidden by the background fluctuations (68% CL): $F_{0\nu} = \tau_{1/2}^{Back.Fluct.} = \ln 2 \times \frac{x\ \eta\ \varepsilon\ N_A}{A} \sqrt{\frac{M_{\beta\beta}\ T}{b\ \Delta}}$ where ε is the detection efficiency, T is the measure time, $M_{\beta\beta}$is the mass of the isotope, b is the specific background rate per unit $M_{\beta\beta}$, time and energy and Δ is the FWHM resolution, x is the number of $\beta\beta$ atoms in the molecule, η is the $\beta\beta$ isotopic abundance, N_A is the Avogadro number and A is the molecular weight.

Despite its simplicity, $F_{0\nu}$ has the unique advantage of emphasizing the role of the essential experimental parameters: mass, measuring time, isotopic abundance, background level and detection efficiency.

Of particular interest is the case when the background rate B is so low that the expected number of background events in the region of interest along the experiment life is close to zero. In such cases, one generally speaks of *zero background* (ZB) experiments, a condition sought by a number of future projects. In such conditions the sensitivity reads: $F_{0\nu}^{ZB} = \ln 2\ N_{\beta\beta}\ \varepsilon\ \frac{T}{n_L} = \ln 2 \times \frac{x\ \eta\ \varepsilon\ N_A}{A} \frac{M\ T}{n_L} = \ln 2 \times \frac{\varepsilon\ N_A}{A_{\beta\beta}} \frac{M_{\beta\beta}\ T}{n_L}$ which does not depend anymore on the background level or the energy resolution and scales linearly with the sensitive mass $M_{\beta\beta}$and the measure time T. The dramatic effect of background is therefore not only to limit the sensitivity but even to change its dependence on the other experimental parameters.

Common goal of all the next generation experiments is to reach a sensitivity on $|\langle m_{ee} \rangle|$ of the order of 10-50 meV.

This corresponds to active masses of the order 1 ton (or larger) with background levels as low as $\sim$ 1 c/keV/ton/y, a challenge that can hardly be faced by the current technology and has triggered a number of phased programs whose first step are detector with sensitive masses of 10-100 kilograms ("demonstrators") .

Table 1: A selected list of the next generation $\beta\beta(0\nu)$ experiments.

Experiment	Isotope	$M_{\beta\beta}$ (kg)	Technique	Location	Start date
^{130}Te	CUORE0/CUORE	11/206	Bolometric	LNGS	2012/2015
^{76}Ge	GERDA I/II	11/30	Ionization	LNGS	2012/2014
^{82}Se	LUCIFER	9	Bolometric	LNGS	2014
	MJD	26	Ionization	SUSEL	2014
^{130}Te	SNO+	163	Scintillation	SNOlab	2014
^{82}Se or ^{150}Nd	SND/SuperNEMO	6/100	Tracko-calo	LSM	2014/2015
^{136}Xe	EXO-200	79	Liquid TPC	WIPP	2012
^{136}Xe	KamLAND-ZEN	179	Scintillation	Kamioka	2012
^{136}Xe	NEXT-100	90	Gas TPC	Canfranc	2014

The primary goal of “demonstrators” is to select the best technology to approach the neutrino mass region around 10 meV.

A restricted list of some of the most advanced forthcoming $\beta\beta(0\nu)$ projects is given in Table 1.

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-Zen).

In all cases the crucial issue is the capability of each project to pursue the design background suppression.

Different estimates of the expected background 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 (prototypes). Although all proposed projects show interesting features, it is likely that only few of them will be characterized by a reasonable technical feasibility in the next future. The expected sensitivities are listed in Table 2.

While we refer the reader to the literature (e.g. [14]) for details on the future $\beta\beta(0\nu)$ projects, we would like to summarize here just the concept and status of few of the most advanced experimental programs.

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 on a new detector design for single site event identification. In both cases this is accomplished by means

Table 2: Half-lifetime sensitivities (68% CL, 5 y running time, in units of 10^{25} yr) of some of the most advanced ββ(0ν) projects [14]. B_{iso} is the background per ton of isotope mass in units of counts/(keV·ton·yr). The status of the experiment, R (running), C (construction), D (development) is also shown. $|\langle m_{ee}\rangle|$ values (meV) are calculated using NME and phase space factors from [12]. Asterisks label ZB conditions.

	Isotope	B_{iso}	FWHM (keV)	*Status*	$F^{0\nu}_{68\%C.L.}$ (5 yr)	$\|\langle m_{ee}\rangle\|$
CUORE0	^{130}Te	266	5.6	R	1.5	224
CUORE	^{130}Te	36	5	C	21	60
GERDA I	^{76}Ge	21	4.8	R	9.4	165
GERDA II	^{76}Ge	20/1.1	3.2	C	22/60*	107/65*
LUCIFER	^{82}Se	1.9	13	D	16*	76*
MJD	^{76}Ge	0.9	4	C	44*	77*
SNO+	^{130}Te	0.9	240	D	20	62
EXO	^{136}Xe	1.9	96	R	12	97
SND	^{82}Se	0.6	120	D	3.3	166
SuperNEMO	^{82}Se	0.6	130	D	13	85
KamLAND-Zen	^{136}Xe	7.4	243	R	6.9	127
NEXT	^{136}Xe	0.8	13	D	16	82

of p-type "Broad Energy" isotopically enriched germanium diodes (or "BEGe"). GERDA phase I started operation in 2012 and has recently published interesting results on the background and the detector performance, as well as a lower limit of 2.1 $\times 10^{25}$ (90% C.L.) on the ^{76}Ge ββ(0ν) half-lifetime. Very interesting conclusions are also drawn about the KDHK claim, which would be strongly disfavored by the GERDA null result. Indeed, assuming the KDHK result, the probability of observing a null result in GERDA would be only 0.01, further reduced to 2×10^{-4} when HDM and IGEX spectra are properly taken into account (and even worse when including also EXO and Kamland-Zen results). It is worth to note that the GERDA collaboration decided to consider only the 2004 KDHK publication [10] (where a 4.2σ ββ(0ν) evidence was reported with a half-life of $T^{0\nu}_{1/2} = 1.19 \times 10^{25}$ yr) while neglecting later papers.

CUORE 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) operated at a temperature of 10 mK. The expected energy resolution is ∼5 keV FWHM at the ββ(0ν) transition energy (∼2.53 MeV). The expected background level is of the order of ∼0.01 c/keV/kg/y. The expected 5y sensitivity is 2.1×10^{26} y allowing a close look at the IH region of neutrino masses. CUORE is an advanced stage of construction at LNGS. Very promising results from the CUORE0 prototype (the first tower of CUORE assembled strictly following the same procedures) have been recently presented. Extrapolations to CUORE seem to show that the experiment would be very close to the design goals both in terms of detector performance and background level.

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. These hybrid detectors look particularly effective in identifying the dangerous alpha background from the surface of the detector setup and could allow a sizable reduction of the background rate at the level of 10^{-3} counts/(keV·kg·yr).

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 ($\sim$ 1–10 tons) of isotopically enriched (85% in ^{136}Xe) Xenon. A sizable prototype experiment with a Xe mass of 200 kg (80% ^{136}Xe), has been deployed at WIPP since summer 2009 and has recently published a lower limit of 1.6 10^{25} yr on the ^{136}Xe $\beta\beta(0\nu)$ half-life. Further improvements on energy resolution and background are still expected while the experiment is approved to run for 4 more years. 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. It aims at a phased program starting with a 100 kg, presently under construction. Smaller scale prototypes have been already built and operated successfully providing excellent results on energy resolution.

New developments have been proposed in recent years in order to exploit two successful experiments on neutrino oscillations: SNO and KamLAND. SNO+ is pursuing the goal of studying ^{130}Te with 2.34 tons of natural Tellurium dispersed (0.3%) in a balloon filled with a liquid scintillator. The projected half-life sensitivity is of the order of 2 $\times 10^{26}$ y. A second phase characterized by a possible increase by an order of magnitude of the Tellurium concentration is also scheduled.

The same concept is applied by KAMLAND-Zen, in which a large masses of ^{136}Xe is dispersed in the liquid scintillator. Proposed in 2009, the program has started in September 2011 with 320 kg of 90% enriched ^{136}Xe. Also this experiment has recently published a lower limit of 1.9×10^{25} y. The measured spectrum is characterized by an unexpected large background level in the ROI which dominates the $\beta\beta(0\nu)$ result. A strong effort to identify its origin and reduce its effects is presently ongoing.

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 $\beta\beta(2\nu)$ contribution. The projected background is $\sim 3.5 \times 10^{-4}$ c/keV/kg. A demonstrator (single module) is presently fully funded to be operated in the current NEMO3 site.

The dependence of the sensitivity formulas on many different experimental parameters (and different powers of them) has represented since a long time a serious obstacle to a global comparison of the projected sensitivities of the proposed experiments. However, by observing that the relevant parameters appear always in the same combinations and by properly re-defining some of the experimental parameters, it has been recently shown that such a comparison is possible [15]. When combined with the above mentioned conclusions about the (almost constant) nuclear factor of merit [13], this translates directly in a general comparison of the $|\langle m_{ee}\rangle|$ sensitivities. It turns out that all upcoming $\beta\beta(0\nu)$ experiments (Table 2) cluster more or less close to a sensitivity of $\sim 10^{26}$ y on the $\beta\beta(0\nu)$ half-lifetime. In terms of $|\langle m_{ee}\rangle|$ this means that none of them will cover the IH region of the neutrino masses and new experimental efforts will be needed.

5. Conclusions

Neutrino oscillation results have stimulated a renewed interest in the experimental study of neutrino properties. In this framework, cosmological measurements provide the most stringent constraints on the neutrino masses, kinematic measurements guarantee the unique model independent measurement, and neutrinoless $\beta\beta$ decay offers a unique opportunity to verify the Majorana nature of the neutrino while providing important information on the neutrino mass scale and intrinsic phases. While the huge spectrometer of KATRIN is approaching the start of data taking, a number of R&D's is seeking on alternative method to improve the sensitivity on the value of the electron neutrino mass. On the other hand, 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.

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