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Neutrino masses and neutrinoless double-beta decay

Maura Pavan
Dipartimento di Fisica dell'Università di Milano,
Bicocca and sezione INFN di Milano Bicocca, Italy.

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The potentialities of Double Beta Decay experiments in the field of neutrino study are here discussed. Sensitivity and results are compared with the information coming from oscillation, cosmology and beta decay measurements.

Keywords: Double-beta decay; neutrino masses; Majorana neutrino.

Se discuten las potencialidades de experimentos decaimiento doble-beta en el área de física de neutrinos. Se comparen las sensibilidades y los resultados con la información de oscilaciones de neutrinos, cosmología y mediciones de decaimiento beta.

Descriptores: Decaimiento doble-beta; masas de neutrinos; neutrino de Majorana.

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1. Introduction

After 78 years since the first guess on its existence, neutrino still escapes our insight: the mass and the true nature (Majorana or Dirac) of this particle is still unknown. From experimental results, we know there are three generations of neutrinos, according to their leptonic flavor. These are the only not-sterile neutrinos with masses lower than the Z_0 mass. The related phenomenology [1,2] is described in the framework of three distinguishable particles provided with their leptonic number, flavor and mass eigenvalue. As it is in the quark sector, a not diagonal matrix - the Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS) - describes the mixing of neutrinos. The PMNS matrix is parametrized by 3 angles (θ_{12}, θ_{23} and θ_{13}) and 3 CP-violating phases for a total of 6 parameters to be added to the 3 unknown values of the neutrino masses (m_i). The results on solar [3], atmospheric [4], reactor [5] neutrinos and those from neutrinos beams [6] constrain neutrino mass differences and most of the PMNS mixing parameters within rather narrow bands (Table I). The unespected LSND [7] result was accommodated in this framework by an additional *sterile* neutrino. MiniBooNE [8], not confirming LSND, weakened this hypothesis; even if in a two sterile neutrinos scenario [9] all the oscillation experiment results (including LSND and MiniBooNE) can still survive.

The square mass differences (Δm^2_{12} and $|\Delta m^2_{23}|$) measured by the oscillation experiments open to the possibility of three different scenarios regarding mass spread: direct hierarchy, inverted hierarchy and degenerate hierarchy (see Table I).This because while in the case of Δm^2_{12} the sign of the square mass difference is known, in the case of $|\Delta m^2_{23}|$ it is not. To measure the sign of Δm^2_{23}, it is necessary to be able to measure oscillation *matter* effects, something that hopefully will become possible in the next future. Most of the information we have today about neutrino properties come from oscillation experiments. However in the case of the neutrino Majorana/Dirac character and of the absolute mass scale, Neutrinoless Double Beta Decay ($\beta\beta(0\nu)$) appears the more promising tool of investigation.

2. Neutrino absolute mass scale

The absolute scale of neutrino masses is presently constrained by experimental measurements of the following three parameters:

1. from Cosmology $\Sigma = \sum m_i$;
2. from Beta Decay $m_{\nu e} = \sum |U_{ei}|^2 m_i^2$
3. from Neutrinoless Double Beta Decay

   $|\langle m_\nu \rangle| = |\sum m_i U^2_{ei}|$

Either of these three parameters can be expressed in terms of Δm^2_{12} , $|\Delta m^2_{23}|$ and of the lightest neutrino mass eigenstate. Consequently, oscillation experiments provide constraints on the values that these parameters can assume according to the possible the neutrino hierarchy [10]. In particular in the case of Σ and of $m_{\nu e}$ lower bounds of $\sim$0.05 and of $\sim$0.005 eV are obtained. In the case of $|\langle m_\nu \rangle|$ (also called neutrino *Majorana mass*) no lower bound is present since cancellation are possible, yielding a null value.

Cosmology: the fraction of mass density stored in cosmological relic neutrinos has an influence on the Cosmic Microwave Background power spectrum (CMB) and on the Large Scale Structures (LSS) formation. The recent precise measurements of CMB, when compared with cosmological model predictions, allows to extract upper bounds on Σ of the order of $\sim$2 eV [11]. The LSS matter power spectrum is traced through the galaxy luminous matter distribution or through measurements of the "forest" of absorption lines at Ly-α frequencies (LyαF) in far quasars. Once again the comparison of recent experimental results with cosmological

TABLE I. Summary table of ν properties [2]. We assume $m_2 > m_1$, m_3 being the most split state.

NPMS elements	$0.25 < sin^2\theta_{12} < 0.39$; $0.34 < sin^2\theta_{23} < 0.68$; $sin^2\theta_{13} < 0.004$
mass eigenstates	m_1, m_2, m_3
normal hierarchy	$m_1 \lesssim m_2 \ll m_3$
inverted hierarchy	$m_3 \ll m_1 \lesssim m_2$
degenerate hierarchy	$m_1 \approx m_2 \approx m_3$
Δm^2 solar	Δm^2_{12} = (m_1^2 - m_2^2)$\sim$ (7.2-9.2) 10^{-5} [eV^2]
Δm^2 atmospheric	$\|\Delta m^2_{23}\|$ = $\|m_1^2$ - $m_3^2\|$ $\sim$(2.0-3.2) 10^{-3} [eV^2]

models predictions, provides constraints on Σ. When a combination of CMB, LSS and Ly-α data is considered the upper bound on Σ becomes even lower than 1 eV [11]. Despite their increasing sensitivity - in the next future sensitivities of the order (or below) $\sim$0.1 eV will be reached - cosmological bounds on neutrino mass are considered with caution since they are (strongly) model dependent.

Beta Decay: the study of the end point in the beta decay Kurie plot provides a straightforward and direct technique to measure the electronic antineutrino mass. Present experimental results come from Tritium experiments providing an upper bound on $m_{\nu e}$ of 2 eV at 95% C.L. [12]. This bound will be improved in the next future by the KATRIN spectrometer [13] that aims at reaching a sensitivity of the order of $\sim$0.2 eV. The ultimate limit to sensitivity in spectrometers comes from the correct evaluation of the apparatus response function and from the evaluation of the effects of final excited states. To overcome this problems and to be able to reach a sensitivity beyond the degenerate mass scale, it has been proposed the use of low temperature calorimeters (bolometers) [14]. These, measuring the whole energy produced in the decay, will have a definitely less dramatic dependence from the final state. Bolometers have not jet reached the performances required to surpass KATRIN sensitivity, but the situation is in rather fast evolution. While for Tritium - an allowed transition - there is no problem in the analytical determination of the beta spectrum, in bolometric experiments other nuclei are studied. Presently the attention is focused on beta decay of ^{187}Re, a forbidden transition for which the analytical solution is not available, this is a possible source of systematic errors whose impact has to be carefully evaluated.

Double Beta Decay: this transition - in which a (A, Z) nucleus decays into its (A, Z+2) isobar - is the main decay channel for a group of isotopes whose single beta decay is forbidden. The *standard* decay channel is the one in which 2 neutrinos and 2 electrons are emitted. Not standard decay channels are open whenever a Majorana character for the neutrino is assumed. In this case the lepton number is not conserved and neutrinoless decay modes are possible. $\beta\beta(0\nu)$ can proceed via different mechanisms but the dominant one is that in which a Majorana massive neutrino is exchanged between the two nucleons involved in the decay [15]. The half-life ($T^{0\nu}_{1/2}$) is in this case proportional to the square of $|\langle m_\nu \rangle|$:

$$\frac{1}{T^{0\nu}_{1/2}} = |\langle m_\nu \rangle|^2 F_N = |\langle m_\nu \rangle|^2 G^{0\nu} |M^{0\nu}|^2 \qquad (1)$$

Here $G^{0\nu}$ is the two-body phase-space factor and $M^{0\nu}$ is the $\beta\beta(0\nu)$ Nuclear Matrix Element (NME), their product F_N being called *nuclear factor of merit*. Present experimental bounds on $|\langle m_\nu \rangle|$ are of the order of $\sim$0.5 eV. As in the case of cosmological bounds, even here the extraction of $|\langle m_\nu \rangle|$ values from experimentally measured rates is model dependent. Indeed it implies the use of nuclear models for NME evaluation.

In conclusion, the three techniques appear to be - in some way - complementary. Either of them is affected by a different systematic, that could become however less relevant if the combination of their results is considered. However, a rather special role is played by $\beta\beta(0\nu)$: the simple observation of the existence of this decay will prove that - as predicted by most theories beyond the Standard Model - the neutrino is a Majorana particle. This piece of information is so relevant for today-physics that justifies by itself the huge experimental efforts done in this direction. In the next section the $\beta\beta(0\nu)$ technique and its future experimental development will be discussed in detail.

3. Neutrinoless double Beta Decay present and future

The decay is detected on the basis of the two electrons signal: given the negligible energy of the recoiling nucleus the sum kinetic energy of the two electrons is equal to the Q-value of the $\beta\beta(0\nu)$ transition. This almost monochromatic signal is the main signature used by all the experiments. Depending on the detector type and set-up features, other characteristic information can be used (as it is in tracking experiments) to discriminate background, thus improving the sensitivity. The sensitivity is measured in terms of the number of $\beta\beta$ emitters ($N_{\beta\beta}$), the detection efficiency (ϵ), the live-time (T), the energy resolution (Γ) and the background counting rate (B):

$$S_{0\nu\beta\beta} = ln2 \times N_{\beta\beta} \times \epsilon \times \sqrt{\frac{mass \times T}{\Gamma \times B}} \qquad (2)$$

and have to be converted into a $|\langle m_\nu \rangle|$ sensitivity by Eq. (1).

Given the signature is not so strong, it is only if the decay will be observed in more than one isotope that we will be sure that the detected events truly belong to a $\beta\beta(0\nu)$ decay and are not spurious background effects. The combined observation of the decay in different nuclei could also help on the side of the effects of uncertainty on $|\langle m_\nu \rangle|$ coming from NME evaluations.

The Q-value, the predicted Nuclear Factor of Merit, the natural isotopic abundance and the available detection techniques bias the choice of the $\beta\beta$ emitters used in experiments. High abundances (or isotopes with a viable enrichment) imply high $N_{\beta\beta}$. High Q-values imply low background (B) coming from environmental radioactive emissions. Finally the detection technique defines ϵ and Γ and, in most cases, also restricts the number of isotopes that can be investigated.

3.1. NME problem

There are mainly two different approaches used for the evaluation on the NME so far. These are the *Quasi Random Particle Approximation* (QRPA) and the *Shell Model* (SM). Both the models imply approximations and uncertainties, both are still in development and evolution.

Most of the results reported in literature refer to QRPA based calculations. These evaluations differ from each other in the way the authors deal with approximations, correlations, and parameter fine tuning. In particular QRPA based models appear to be particularly sensitive to the g_{pp} parameter (particle-particle coupling parameter). The value of this parameter has to be fixed *ad hoc* and two possible approaches have been proposed: infer its value from $T^{0\nu}_{1/2}$ (measured for several $\beta\beta(0\nu)$ emitters) [16] or from β^+ data (available only for few isotopes) [17]. In the two cases different results for the $\beta\beta(0\nu)$ NME are obtained. SM calculation are in principle much better than QRPA since they could provide information (and comparisons) with any spectroscopic observable. However, because of their higher complexity, very few calculation have been performed so far [18].

A question arise from this picture: what is the impact of NME uncertainties on $\beta\beta(0\nu)$ physics?

The impact is on two opposite sides: the NME bias the experimental choices so that if large errors on NME exist some experiment could be under or overestimate, some isotope could have been erroneously rejected as a *bad* candidate, loosing an important opportunity. On the other side the $\beta\beta(0\nu)$ result could be given, by the scientific community, a less relevant importance because of the $|\langle m_\nu \rangle|$ uncertainty derived from the NME problem. If only recent and complete QRPA calculation are considered, the NME spread is restricted to a factor $\sim$5 (for example this is what is obtained considering the NME values of different authors reported in Table II of Ref. 16) and if the recent SM calculations [18] are compared to QRPA calculations the NME values appear to be consistent. This seems to indicate that results are proceeding in the same direction and hopefully in the long term even better results and a more reliable comparison with experimental data will be provided.

3.2. Present experiments

Several experiments searching for $\beta\beta(0\nu)$ decay of different isotopes have been realized so far [15]. A comparison between experiments studying different isotopes is made difficult by the uncertainty in the NME. In the following the $|\langle m_\nu \rangle|$ mass range corresponding to the different bounds on $T^{0\nu}_{1/2}$ will be extracted using the the NME elements listed in Table II of Ref. 16 for different authors.

The use of Germanium diodes to search for $\beta\beta(0\nu)$ decay of ^{76}Ge was started as early as in 1967, the best results have been obtained by the Heidelberg-Moscow [19] (HM) and the IGEX [15] collaborations employing respectively five (11 kg total mass) and three (6 kg total mass) isotopically enriched (86%) HPGe diodes, and resulting in a lower limit on $T^{0\nu}_{1/2}$ (^{76}Ge) of respectively 1.9 10^{25} years and 1.57 10^{25} years (both limits are at 90% C.L.). In both experiments a Pulse Shape Discrimination (PSD) technique is used to reject multi-site events (typical of non-$\beta\beta$ interactions), that are a consistent fraction of the measured background in the $\beta\beta(0\nu)$ decay region of the spectrum. The HM result corresponds to a $|\langle m_\nu \rangle|$ mass range of 0.2-1 eV. In year 2001 a part of the HM collaboration published a reanalysis of the entire statistics collected during more than 10 years, reporting a positive result on $\beta\beta(0\nu)$ decay of ^{76}Ge[20]. This positive result corresponds to a mass range between 0.14 and 1.7 eV.

The analysis technique of [20] has been repeatedly criticized[21] and the two high sensitivity experiments presently running, CUORICINO and NEMO3, are investigating this same mass range but with different isotopes. However, given the large spread in the NME values, it is very likely that only next generation experiments will give the final answer on this result.

Low temperature calorimeters (bolometers) are used by the CUORICINO experiment to search for $\beta\beta(0\nu)$ of ^{130}Te. The detector consists in a 62 detector array (40.7 kg of total mass) of TeO_2 natural crystals operated as bolometers in a low temperature refrigerator. The bolometric technique do not allow any kind of discrimination between background and $\beta\beta(0\nu)$ events from pulse shape information (as it is for Ge diodes), but the segmentation of the detector allows the rejection of background by operating the 62 devices in anticoincidence. $\beta\beta(0\nu)$ decay is completely contained within a single detector in $\sim$85% of cases, while background events are often the result of multiples interaction in the array. The result on $T^{0\nu}_{1/2}$ is of 3.1 10^{24} years at 90% C.L. corresponding to $|\langle m_\nu \rangle|$ mass range of 0.2-0.7 eV [23].

A completely different approach is that of the NEMO3 collaboration [22]. In this case the source is external to the detector and a device consisting in a tracking detector plus a calorimeter is used. The source is introduced in the form of thin foils and different isotopes (^{100}Mo, ^{82}Se, ^{130}Te, ^{116}Cd, ^{96}Zr, ^{48}Ca, ^{150}Nd) are studied at the same time. This technique bases its competitiveness on the high background rejection efficiency obtained through the events tracking, at the price of a more complex apparatus. The result reported on

$\beta\beta(0\nu)$ are: $T^{0\nu}_{1/2}$ (^{100}Mo)> 5.8 10^{23} years at 90% C.L and $T^{0\nu}_{1/2}$ (^{82}Se)> 2.1 10^{23} years at 90% C.L. Once converted in a mass range these limits produce upper bound on $|\langle m_\nu \rangle|$ in the range 0.5-2.6 eV and 1.0-5.9 eV respectively.

3.3. Next generation and beyond

The renewed interest in DBD of these years, strongly supported by the recent results on neutrino physics, lead to a proliferation of proposed next generation experiments. These experiments are projected in order to reach a sensitivity of about 50 meV on $|\langle m_\nu \rangle|$, to be capable of distinguishing between the different neutrino mass hierarchies. This $|\langle m_\nu \rangle|$ sensitivity corresponds to a $T^{0\nu}_{1/2}$ range between 10^{26} and 10^{28} years for the most commonly studied isotopes. To accomplish these results, huge masses of $\beta\beta$ candidates (1 or more tons) and extremely low backgrounds are required. Of course the choice of a *favorite* candidate from the point of view of the nuclear factor of merit (F_N) could help although within the limits imposed by the NME uncertainties.

The SuperNEMO [22] project will apply the NEMO3 technique to planar structure detectors where the energy resolution and the efficiency will be improved in order to guarantee, together with the increased isotope mass, a sensitivity on $T^{0\nu}_{1/2}$ of the order of 10^{26} y. The isotope to be investigated is not yet fixed (more likely Se or Nd) and also the location of the experiment is under discussion. MOON aims at the detection of ^{100}Mo decay with plastic scintillators sandwiched with Mo foils. GERDA [24] and Majorana [25] are the next generation Ge calorimetric experiments. Both will use arrays of HPGe diodes, made with ^{76}Ge enriched material. In both cases segmented HPGe devices will be used to guarantee a high efficiency to reject multi-site events (*i.e.* most gamma background). The main differences between the two experiments rely in the set-up design that is much more traditional in the case of Majorana (with groups of Ge diodes placed together in a heavy radiopure lead shield and surrounded by thick n-shield) and innovative in the case of GERDA (the naked diodes will be immersed in a LAr filled tank surrounded by a water Cerehkov muon veto). GERDA, presently under construction at LNGS, will use in phase I the HM and IGEX detectors (18 kg of ^{76}Ge) aiming at confirm/disclaim the reported Ge positive result with high statistic significance. In phase II the mass will be increased to $\sim$100 kg adding segmented HPGe and pushing therefore the sensitivity to the 100 meV scale. This same sensitivity is the one at which Majorana aims. CUORE [26] is a tightly packed array of 988 TeO_2 bolometers. The project is based on the experience of CUORICINO and foresees the realization of the largest array ever projected to work at 10 mK. The designed array, heavily shielded and mounted in a specially designed dilution refrigerator, forms a highly segmented detector with a good efficiency in rejecting multicrystal events. The total mass will be of 740 kg corresponding to $\sim$200 kg of ^{130}Te. Like GERDA the experiment is under construction at the LNGS. According to the present $T^{0\nu}_{1/2}$ projections and construction time schedules, CUORE will be probably the first experiment entering significantly the inverted hierarchy region.

Novel techniques, yet never used to produce $\beta\beta(0\nu)$ results, are presently under study. The EXO [27] collaboration is currently developing a LXe TPC that will have a quite effective background rejection capability. Indeed whenever a candidate $\beta\beta(0\nu)$ event will be recorded by the TPC a laser excitation of the daughter nucleus will be used to identify (from the atomic de-excitation light) whether this is really the Ba atom produced by the $\beta\beta(0\nu)$ of ^{136}Xe. The BOLUX project of the INFN aims at the development of composite bolometers where the thermal read-out will be accomplished with a scintillation signal read-out [28]. The double read-out allows to reject one of the most pernicious sources of background presently observed in bolometer $\beta\beta(0\nu)$ experiments: degraded alpha particles. Scintillating bolometers made of Ca, Mo and Cd composite have been already successfully tested. ^{48}Ca, ^{100}Mo and ^{116}Cd are double beta emitters characterized by a high Q value, far above the typical environmental gamma energies. Extremely low counting rates are consequently expected for these devices since the alpha background can be rejected on the basis of the double read-out and environmental gammas are too low in energy to be a problem.

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