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A REVIEW ON NEUTRINOLESS DOUBLE BETA DECAY

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Abstract

The current status of the neutrinoless double beta decay ($0\nu\beta\beta$) search is summarized, exploiting the up-to-date knowledge of the oscillation parameters and of the recent theoretical developments in the understanding of the $0\nu\beta\beta$ process, especially those concerning the nuclear description and its limitations. This also allows to infer expectations and uncertainties for the experimental search for the $0\nu\beta\beta$. Looking ahead at the future of the search for $0\nu\beta\beta$, the challenges that the next generation of experiments will face in order to further improve the sensitivity are discussed, focusing in particular on the background abatement.

1 Introduction

In 1937, Majorana proposed a new way to represent fermions in a relativistic quantum field theory ?). This formalism could be especially useful for neutral particles, since a single Majorana quantum field characterizes the situation in which particles and antiparticles coincide and, in particular, it could be fully applied to the description of massive neutrinos. Within this theoretical framework, a new a new process was proposed ?): the double beta decay without neutrino emission, or *neutrinoless double beta decay* ($0\nu\beta\beta$), namely

$$(A, Z) \to (A, Z+2) + 2\mathrm{e}^{-}. \tag{1}$$

The main and evident feature of $0\nu\beta\beta$ is the explicit violation of the number of leptons, with the creation of an electron pair. The discovery of $0\nu\beta\beta$ would thus demonstrate that lepton number L is not a symmetry of nature. This, in turn, could support the exciting picture that leptons played a part in the creation of the matter-antimatter asymmetry in the universe.

The experimental observable in the search for $0\nu\beta\beta$ is the half-life time of the decaying isotope, whose theoretical expression is:

$$\left[t^{1/2}\right]^{-1} = G_{0\nu}\, g_{\mathrm{A}}^{4}\, |\mathcal{M}|^{2}\, \frac{m_{\beta\beta}^{2}}{m_{\mathrm{e}}^{2}} \tag{2}$$

where $G_{0\nu}$ is the phase space factor (PSF), g_{A} is the axial coupling constant, $\mathcal{M}$ is the nuclear matrix element (NME), while $m_{\beta\beta}$ is the *Majorana effective mass*, the key parameter that regulates the $0\nu\beta\beta$ rate (the electron mass m_{e} is conventionally taken as a reference).

The Majorana effective mass represents the absolute value of the ee-entry of the neutrino mass matrix and its expression takes the form

$$m_{\beta\beta} \equiv \left| \mathrm{e}^{i\alpha_1} |U_{ei}^2| m_1 + \mathrm{e}^{i\alpha_2} |U_{e2}^2| m_2 + |U_{e3}^2| m_3 \right| \tag{3}$$

where m_i are the masses of the individual neutrinos ν_i, $\alpha_{1,2}$ are the Majorana phases and U_{ei} are the elements of the mixing matrix that define the composition of the electron neutrino: $|\nu_{\mathrm{e}}\rangle = \sum_{i=1}^{3} U_{ei}^{*} |\nu_i\rangle$.

The knowledge of the oscillation parameters ?), allows to set a first series of constraints on $m_{\beta\beta}$. The result is shown in Fig. 1, where the representation $m_{\beta\beta}$ as a function of the mass of the lightest neutrino ?, ?) ha been adopted. It has to be noted that, since the complex phases $\alpha_{1,2}$ in Eq. (3) cannot be probed by oscillations and are unknown, the allowed regions for $m_{\beta\beta}$ are actually bands.

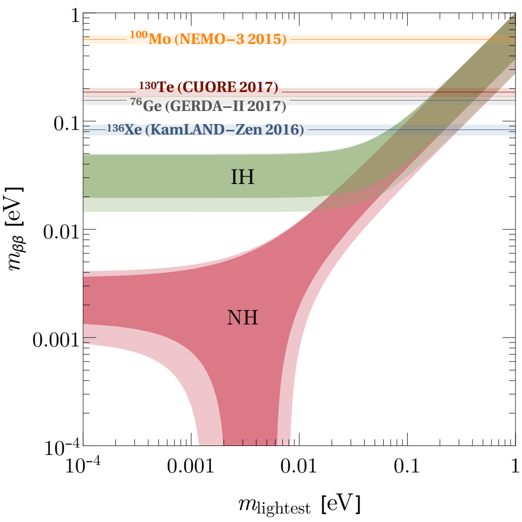

Figure 1: Majorana effective mass as a function of the lightest neutrino (3σ uncertainty regions). The horizontal lines show the current experimental limits from the searches for $0\nu\beta\beta$ of ^{76}Ge, ^{100}Mo, ^{130}Te and ^{136}Xe (see the text for the related references).

2 Considerations on the nuclear physics

The $0\nu\beta\beta$ transition is a nuclear process – it takes place inside the nuclei – and the momentum of the virtual nucleon is large, of the order $O(100\,\text{MeV})$, i. e. the inverse of the nucleonic size, therefore much larger than the neutrino mass. At the same time, the axial coupling of the nucleons is very importance, since the decay rate scales as g_A^4. Theory thus plays a fundamental role in extracting the information on the neutrino mass and, in a conservative approach, it is important to discuss the uncertainties of the quantities involved in Eq. (2) while passing from $t^{1/2}$ to $m_{\beta\beta}$.

The PSFs are known with accurate precision, about 7% for all the nuclei of interest [?], while the situation is more complicated for the NMEs. In fact, despite a relatively small intrinsic error of less than $\sim$ 20% is assessed for the latter parameters by the most recent calculations [?, ?], the disagreement between the results from different models is actually larger, up to a factor

~ 3. Moreover, when other processes than the $0\nu\beta\beta$ are considered (single β decay, electron capture, $2\nu\beta\beta$) and the calculations from the same models are compared to the measured rates, the actual differences are much larger than 20%.

The value of g_A remains an open issue: that actually measured in weak interactions and decays of nucleons ($g_{A,nucl} \simeq 1.27$) could be indeed renormalized to the one appropriate for quarks inside the nuclear medium ($g_{A,quark} = 1$). Or, even, the possibility of a further reduction (quenching) has been argued based on the systematic over-prediction of the β and $2\nu\beta\beta$ NMEs (worst scenario: $g_{A,phen} \simeq g_{A,nucl} \cdot A^{-0.18}$, where A is the mass number ?, ?)).

An experimental limit on $t^{1/2}$ thus translates into a range of values for $m_{\beta\beta}$. Referring to Fig. 1, the broadness of the horizontal bands depends on the adopted approach in discussing these theoretical uncertainties.

Looking ahead in the future of the $0\nu\beta\beta$ search, a large effort has to be put in the nuclear studies (NMEs and effective value of g_A) in order to maximize the information that can be extracted from the experimental searches.

3 Experimental search for $0\nu\beta\beta$

The experimental search for a $0\nu\beta\beta$ signal relies on the detection of the two emitted electrons. Being the energy of the recoiling nucleus negligible, the sum of the kinetic energy of the two electrons is equal to the Q-value of the transition. Therefore, we expect to observe a monochromatic peak at $Q_{\beta\beta}$.

Despite the very clear signature, due to the rarity of the process, the detection of the two electrons is complicated by the occurrence of background events within the region of interest than can actually mask the $0\nu\beta\beta$ signal. Any event producing an energy deposition similar to that of $0\nu\beta\beta$ increases the background level, and hence spoils the experiment sensitivity. The main contributions to the background come from the environmental radioactivity, the cosmic rays, and the $2\nu\beta\beta$ itself. In particular, the latter one is unavoidable in presence of finite energy resolution, since it originates from the same isotope which is expected to undergo $0\nu\beta\beta$.

The choice for the best isotope to look for $0\nu\beta\beta$ is the first issue to deal with. A high $Q_{\beta\beta}$ is important, since it directly influences the background, the actual suitability depending on the detector resolution and rejection capabilities. A large isotopic abundance for either the natural or the enriched material is needed in order to achieve a sufficient large mass. Finally, the isotope of interest has to be integrated in a working detector. These requirements result in a group of "commonly" studied isotopes among all the candidate $0\nu\beta\beta$ emitters: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe and ^{150}Nd.

Regarding the detector, a good energy resolution is the first requirement, crucial to identify the sharp $0\nu\beta\beta$ peak and to protect against the (intrinsic) $2\nu\beta\beta$ induced events. Fundamental as well is a very low background. An underground location, a careful material selection for the detector and the surrounding parts, and the presence of passive and/or active shielding are therefore mandatory. The employed technique has also to guarantee the scalability to large masses, since tonnes of isotope of interest will be needed for the next generation of experiments.

It has to be noted that it is impossible to simultaneously optimize all these features in a single detector. Therefore, it is up to the experimentalists to choose which aspect to privilege in order to get the best sensitivity. Among the most successful examples of detectors, we find Ge-diodes, bolometers, Xe liquid and gaseous TPC, liquid scintillators loaded with the $0\nu\beta\beta$ isotope, tracker + calorimeter (external $0\nu\beta\beta$ source), ...

The sensitivity of a $0\nu\beta\beta$ experiment can be defined as the process half-life corresponding to the maximum signal that could be hidden by the background fluctuations n_B (at a given statistical C. L. n_σ) and can be parametrized as:

$$S^{0\nu} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{n_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{1}{n_\sigma} \cdot \frac{x\,\eta\,N_A}{\mathscr{M}_A} \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta}} \tag{4}$$

where B is the background level per unit mass, energy, and time, M is the detector mass, Δ is the FWHM energy resolution, x is the stoichiometric multiplicity of the element containing the $\beta\beta$ candidate, η is the $\beta\beta$ candidate isotopic abundance, N_A is the Avogadro number and, finally, $\mathscr{M}_A$ is the compound molecular mass. Despite its simplicity, Eq. (4) has the advantage of emphasizing the role of the essential experimental parameters.

3.1 Constraints on $m_{\beta\beta}$

Once the experimental sensitivities are known in terms of $S^{0\nu}$, it is possible to correspondingly find the lower bounds on $m_{\beta\beta}$ by inverting Eq. (2).

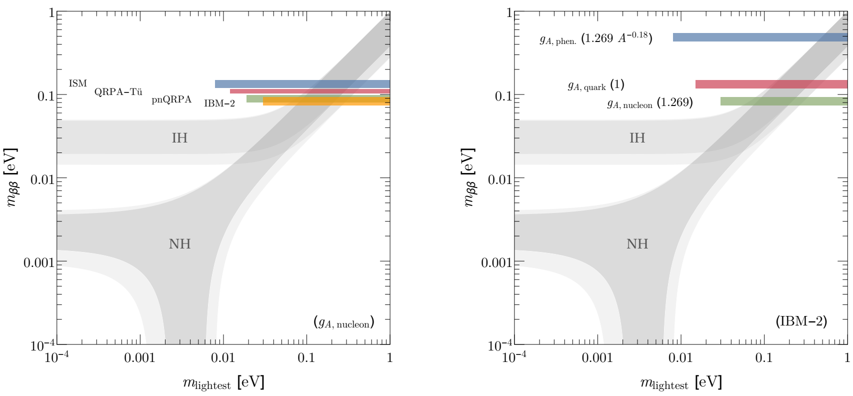

Figure 2: Uncertainty of the current $m_{\beta\beta}$ bound from ^{136}Xe. (Left) Dependence on the NME. (Right) Dependence on the value of the axial vector coupling constant. See the text for more details and references.

In the left panel of Fig. 1, the most stringent limits up to date are shown. They come from ^{76}Ge, ^{100}Mo, ^{130}Te and ^{136}Xe: $t^{1/2}_{\mathrm{Ge}} > 8.0 \cdot 10^{25}$ yr ?), $t^{1/2}_{\mathrm{Mo}} > 1.1 \cdot 10^{24}$ yr ?), $t^{1/2}_{\mathrm{Te}} > 1.5 \cdot 10^{25}$ yr ?), $t^{1/2}_{\mathrm{Xe}} > 1.1 \cdot 10^{26}$ yr ?) at 90% C. L..

In the figure, the case $g_A = g_{\mathrm{nucleon}}$ (unquenched value) is assumed. The error propagation on the NME (fixed to an arbitrarily chosen model) ?) and on the PSF ?) results in the broadening of the lines describing the limits. As the plot shows, the current generation of experiments is probing the quasi-degenerate part of the neutrino mass spectrum, down to a value for $m_{\beta\beta}$ of $\sim$ 85 meV.

The effect of the uncertainties is shown in Fig. 2, both for the choice of different NMEs (left panel) and different values of g_A (right panel). In particular, in the latter case it can be seen that the sensitivity for the same limit (that on ^{136}Xe ?)), in the two cases of g_{nucleon} and $g_{\mathrm{phen.}}$ differs of a factor $\gtrsim 5$. It is clear from the figure that this is the biggest uncertainty, with respect to all the other theoretical ones.

3.2 Towards the next generation of $0\nu\beta\beta$ experiments

The forthcoming generation of $0\nu\beta\beta$ experiments aims at sensitivities of the order of 10^{27} yr or more. This is crucial in order to begin to probe the Inverted Hierarchy region of neutrino mass spectrum (refer to Fig. 1), i. e. $m_{\beta\beta} \lesssim 50\,\text{meV}$.

All the experimental collaborations will be requested to demonstrate their capability to reach such a goal and the feasibility and effectiveness of the proposed technique will have to be tested by means of demonstrators and extensive R&D programs in order to stand a chance in continuing the challenge of the $0\nu\beta\beta$ search.

Unfortunately, the cost of the experiment will become even more a critical aspect and money, i. e. $/mole of detectable isotope, will have to be included in the sensitivity studies,taking into account the technological costs: procurement, enrichment/purification, infrastructures, . . . and projecting the efficiency of the detector at the tonne-scale. Politics will play a very central role in the experiment down-selection. From the experiment side, the possibility of merging of experiments sharing the same technology and that studying different nuclei with a specific setup should be considered.

A fundamental issue regards the background abatement. Referring to Eq. (4), 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, namely

$$M \cdot T \cdot B \cdot \Delta \lesssim 1, \tag{5}$$

the sensitivity begins to scale linearly with the exposure:

$$S_{0B}^{0\nu} = \ln 2 \cdot \varepsilon \cdot \frac{1}{N_{\text{events}}} \cdot \frac{x\,\eta\,N_A}{\mathscr{M}_A} \cdot M\,T. \tag{6}$$

It is called the "zero background" experimental condition and it is likely the experimental condition that next generation experiments will face. It is fair to notice that, up to now, the constraints on the background in Eq. (5) has been fulfilled for a 1-tonne experiment only for ^{76}Ge ?), but other experiments are on the way.

3.3 Future players

Despite the very hard challenge, the study and search for $0\nu\beta\beta$ is a very active field and many experiments promise to populate the near future scenario ?):

- AMoRE-II (bolometer, 200 kg of ^{100}Mo), the latest in the AMoRE program;

- CUPID (bolometer, $\sim 1\,\mathrm{t}$ of ^{100}Mo or ^{130}Te), the upgrade of the CUORE experiment;
- LEGEND (Ge-diode, $200\,\mathrm{kg} \rightarrow 1\,\mathrm{t}$ of ^{76}Ge) the upgrade of the joint GERDA + MAJORANA experiments;
- KamLAND2-Zen (Xe-loaded liquid scintillator, 1 t of ^{136}Xe), the next phase of the KamLAND-Zen program;
- nEXO (Xe liquid TPC, 5 t of ^{136}Xe), the upgrade of EXO-200;
- NEXT-tone (Xe gas TPC, 1 t of ^{136}Xe), the latest in the NEXT program;
- PANDA-X (Xe gas TPC, 1 t of ^{136}Xe), the $0\nu\beta\beta$ search with the PANDA program;
- SNO+ (Te-loaded liquid scintillator, 4 t of ^{130}Te);
- SuperNEMO (tracker+calorimeter, 100 kg of ^{82}Se), the upgrade of NEMO-3.

As it can be seen, each of these experiment is either the upgrade of an existing one or it the result of an R&D program: staring with smaller setups, the goal becomes to reach sensitivities larger to 10^{27} yr, with detector mass of hundreds of kilograms.

3.4 Summary and outlook

The study of $0\nu\beta\beta$ offers a unique tool to study lepton number violation and neutrino masses.

Today, sensitivities of the order of $(10^{25} - 10^{26})$ yr on the decay half-life time have been reached for multiple isotopes. The next generation of detectors aims at improving this values by more than one order of magnitude, starting to proble the Inverted Hierarchy region of the neutrino mass spectrum. The main challenge will be represented by the background abatement, and the cost and complexity of the setups will represent critical issues too.

On the theoretical side, a better understanding of the nuclear physics is needed in order to maximize the information that can be extracted from the experimental searches.

The field is very active, with ambitious experimental proposals and numerous R&D programs that will continue to guarantee excellent results.