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Status of the search for neutrinoless double beta decay, circa 2015

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Following [Phys. Rev. D **90**, 033005 (2014)], we review the present status and the future perspectives on the search for neutrinoless double beta decay ($0\nu\beta\beta$) within the hypothesis that its rate is dominated by the Majorana mass of ordinary neutrinos. We show updated predictions on $0\nu\beta\beta$ coming from neutrino oscillations, we assess the sensitivity of present and future experiments and we focus on the effects of the uncertainties coming from nuclear physics. In particular, the impact of the quenching of the axial vector coupling constant in the nuclear medium is analyzed. Finally, we stress the important interplay between $0\nu\beta\beta$ and cosmology. In fact, taking into account the most recent indications on neutrino masses coming from cosmology, we discuss whether it could be possible to measure the Majorana phases and/or discriminate the two neutrino mass hierarchies.

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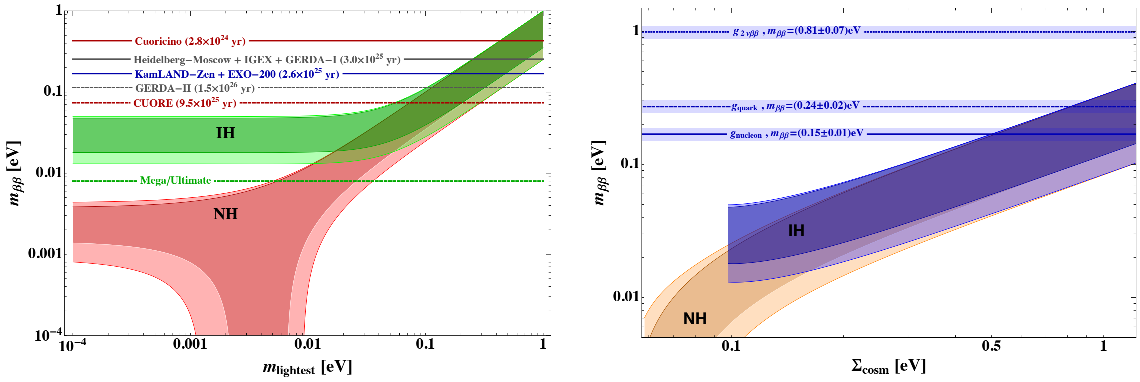


(a) **(b)**

Figure 1: Predictions on $m_{\beta\beta}$ from oscillations as a function of the lightest neutrino mass and of the cosmological mass. The shaded areas correspond to the 3σ regions due to error propagation of the uncertainties on the oscillation parameters. (Left) The various lines represent the sensitivity on $m_{\beta\beta}$ for different experiments. In particular, the Mega/Ultimate line refers to hypothetical future experiments, as clarified in the text. (Right) The bands indicate the Xe combined limit [6] in the three quenching scenarios considered. The (1σ) bands come from the uncertainties on the NMEs and on the PSFs. See Ref. [1] for references and details.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is a key tool to address some of the major outstanding issues in neutrino physics, such as the lepton number conservation and the Majorana nature of the neutrino. Furthermore, an eventual discovery of $0\nu\beta\beta$ would provide precious information on the neutrino mass scale and ordering.

The decay half-life can be factorized as:

$$\left[t_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\,|\mathscr{M}_{0\nu}|^2\,|f|^2 \tag{1.1}$$

where $G_{0\nu}$ is the phase-space factor (PSF), $M_{0\nu}$ is the nuclear matrix element (NME) and f contains the physics beyond the Standard Model that could explain the decay. From the theoretical point of view, there can be different mechanisms describing the $0\nu\beta\beta$ decay. If ordinary neutrinos dominate the transition, it is convenient to define the so called "Majorana mass":

$$m_{\beta\beta} = m_e\,|f| \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|. \tag{1.2}$$

Here, U_{ei} are the elements of the mixing matrix defining the electron neutrino composition and m_i are the masses of the individual ν_i. The electron mass m_e is taken as a reference.

2. Bounds on the Majorana mass

Thanks to the knowledge of the oscillation parameters [2], it is possible to constrain $m_{\beta\beta}$. However, since the complex phases cannot be probed by oscillations and are unknown, the allowed region for $m_{\beta\beta}$ is obtained letting them vary freely. A possible graphical representation foresees

$m_{\beta\beta}$ as a function of the lightest neutrino mass (see e. g. Ref. [1]). The result is shown in the left panel of Fig. 1.

An experimental limit on the half-life can be translated into a limit on the mass parameter by reversing Eq. 1.1 and by using the appropriate PSFs [3] and NMEs [4]. At present, the most recent and competitive bounds on $0\nu\beta\beta$ come from ^{76}Ge and ^{136}Xe and are of the order of 10^{25} yr [5, 6].

The parameter $m_{\beta\beta}$ can also be expressed as a function of a directly observable parameter. A natural choice is the cosmological mass Σ, defined as the sum of the three active neutrino masses: $\Sigma \equiv m_1 + m_2 + m_3$. This representation is shown in the right panel of Fig. 1.

2.1 The role of nuclear physics

As recently pointed out in Ref. [4], the theoretical uncertainty on the NMEs is huge. This is due to the possible renormalization (i. e. reduction) of the value of the axial vector coupling constant g_A, due to the presence of the nuclear medium. This issue is known as the "g_A quenching". Since the dependence of the $0\nu\beta\beta$ half life time on g_A turns out to be quartic, a little change in g_A results in a huge change in $t^{0\nu}_{1/2}$ and, consequently, on the corresponding value of $m_{\beta\beta}$. In a conservative approach, we discuss the three following scenarios:

$$g_A = \begin{cases} 1.269 & \text{for free nucleons} \\ 1 & \text{for quarks, [7]} \\ 1.269 \cdot A^{-0.18} & \text{in } 2\nu\beta\beta\text{, [8, 4]} \end{cases} \tag{2.1}$$

where A is the atomic number of the nuclear species considered.

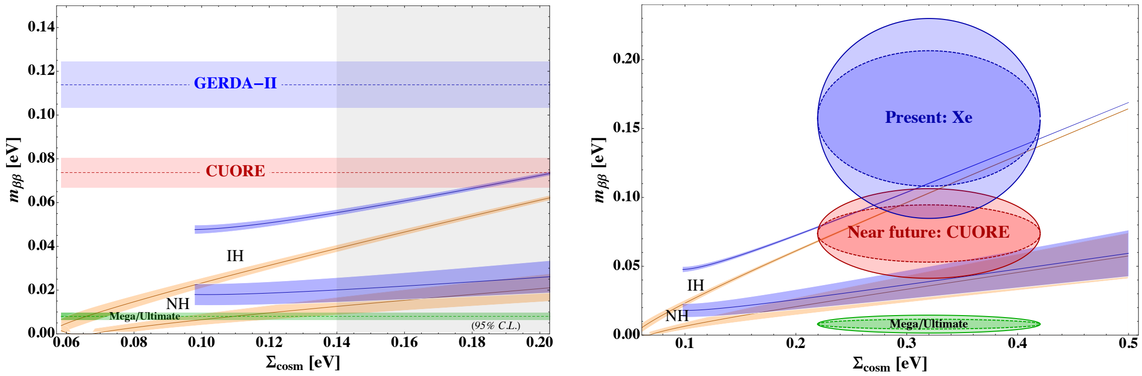
The impact of the quenching appears evident from the right panel of Fig. 1. The current limit on ^{136}Xe almost worsens of a factor 6 if g_A is assumed to be the same as for the $2\nu\beta\beta$.

3. Future experiments

Let us consider a next generation experiment (call it a *Mega* experiment) and a next-to-next generation one (an "Ultimate" experiment) with sensitivity able to exclude the Inverted Hierachy case for the neutrino mass spectrum: $m_{\beta\beta} \lesssim 8\,\text{meV}$ (left panel of Fig. 1). In particular, the "mega" experiment satisfies this requirement in the most favorable case, namely when the quenching of g_A is absent. Instead, the "ultimate" experiment assumes that g_A is maximally quenched. By referring to the calculations from Ref. [1], it can be seen that in the former case a few ton $\cdot$ yr exposure is necessary while, in the latter, almost 100 ton $\cdot$ yr of exposure are required to reach the expected sensitivity. The implication is that, if the true value of g_A is quenched, the goal of excluding the Inverted Hierarchy will be out of the reach of the next generation of experiment. This stresses even more the importance of the issue.

4. The interplay between $0\nu\beta\beta$ and cosmology

Recently, a very tight limit on Σ has been set by the work of Palanque-Delabrouille *et al.*: 0.14 eV at 95% C. L. [9]. The analysis exclude the Inverted Hierarchy case at 1σ C. L., thus disfavoring an observation by the near future experiments, as shown in Fig. 2. On the other side, an observation of a $0\nu\beta\beta$ signal is likely to be due to new physics!



(a) (b)

Figure 2: Allowed regions for $m_{\beta\beta}$ as a function of the neutrino cosmological mass Σ. The colored bands correspond to the 3σ regions for the extremal values of $m_{\beta\beta}$ as a function of the neutrino cosmological mass Σ. (Left) The horizontal bands represent the sensitivity for examples of future experiments [5, 11]. The vertical band shows the 95% C. L. region excluded by cosmology [9]. (Right) The big (small) ellipses show the 90% C. L. regions in which a positive observation of $0\nu\beta\beta$ could be contained, according to the experimental uncertainties and 5 (20) actually observed events. See the text and Ref. [1] for a more detailed discussion.

4.1 Any hint on the Majorana phases?

Interestingly, different studies have emphasized some tension between different cosmological data sets. Their combination suggests a nonzero best fit value of the mass, in the range $(0.3-0.4)$ eV (see e. g. [10]).

If we assume that both Σ and $m_{\beta\beta}$ are measured with nonzero values, the situation depicted in the right panel of Fig. 2 is obtained. In this case, particular attention has to be paid on the evaluation of the error on $m_{\beta\beta}$. In fact, both the theoretical and the statistical contribution have to be considered (see [1] for a detailed discussion). Is it is possible to infer something on the values of Majorana phases? Let us discuss about the possibility of distinguishing the maximum and the minimum values of $m_{\beta\beta}$. From the right plot of Fig. 2, one can see that in the "near future" case only by considering the small ellipses (which means if the number of observed event is extremely high) no firm conclusion either on the mass hierarchy or on the Majorana phases could be reached.

Interestingly, if $0\nu\beta\beta$ were instead discovered with a $m_{\beta\beta}$ a little bit below the current best limit on Xe [6], this could allow us to make some inference on the Majorana phases even with a reasonable number of observed events. Finally, in the case of "far future" experiments, an observation would imply either some cosmological assumption is not correct, or other mechanisms than the light neutrino exchange mediate the $0\nu\beta\beta$ transition.

As a final remark, in order to state anything precise about $m_{\beta\beta}$ and the Majorana phases, the issue of the value of the quenching of the axial coupling constant has to be solved or, at least, the present uncertainty has to be dramatically decreased.

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