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Neutrinoless double beta decay: Theoretical challenges

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Abstract

The recent progress in theoretical description of the neutrinoless double beta decay ($0\nu\beta\beta$-decay) is briefly reviewed. A possible effect of nuclear medium on exchange of three light neutrinos is addressed. It is shown that non-standard neutrino interaction generates in-medium Majorana neutrino masses, which influences the $0\nu\beta\beta$-decay rate. A subject of interest is also a problem of reliable calculation of the $0\nu\beta\beta$-decay nuclear matrix elements. An impact of the quenching of the axial-vector coupling constant on double beta decay processes is discussed. A connection between two-neutrino and neutrinoless double beta decay nuclear matrix elements is analyzed.

1. Introduction

There are two types of double-beta decay processes depending on whether (anti)neutrinos are emitted or not [1]. The former one is referred to two-neutrino double-beta decay ($2\nu\beta\beta$-decay),

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}, \tag{1}$$

and the latter one to neutrinoless double beta decay ($0\nu\beta\beta$-decay),

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

The $2\nu\beta\beta$-decay, which conserves lepton number, has been recorded for eleven nuclei. Only this type of the double-beta decay is admissible if the neutrino is a Dirac particle (i.e,. is different from its antiparticle). The $0\nu\beta\beta$-decay has not been observed yet. This total lepton number violating process can take place if the neutrino is a Majorana particle (i.e., identical to its own antiparticle). Majorana nature of neutrinos would have far-reaching consequences of our understanding of the Early Universe. The presently best lower bound on the $0\nu\beta\beta$-decay half-life has been achieved in GERDA ($T^{0\nu}_{1/2}(^{76}Ge) \geq 3.0\ 10^{25}$ yrs) [2], EXO and KamLAND-ZEN experiments ($T^{0\nu-exp}_{1/2}(^{136}Xe) \geq 3.4\ 10^{25}$ yrs) [3].

The main aim of experiments on the search for $0\nu\beta\beta$-decay is the measurement of the effective Majorana neutrino mass $m_{\beta\beta}$. The inverse value of the $0\nu\beta\beta$-decay half-life for a given isotope (A,Z) can be written as [1]

$$\frac{1}{T^{0\nu}_{1/2}} = \left|m_{\beta\beta}\right|^2 g_A^4 \left|M'^{0\nu}\right|^2 G^{0\nu}(E_0,Z). \tag{3}$$

Here, $G^{0\nu}(E_0,Z)$ and $M'^{0\nu}$ are, respectively, the known phase-space factor (E_0 is the energy release) and the nuclear matrix element (NME). g_A is the axial-vector coupling constant. While $0\nu\beta\beta$-decay addresses a set of important questions, the interpretation of the results of $0\nu\beta\beta$-decay experiments will depend upon the theoretical calculations of the nuclear matrix elements.

This contribution gives a brief description of some theoretical challenges concerning the theory of the $0\nu\beta\beta$-decay.

2. The effective Majorana neutrino mass

The observation of neutrino oscillations established fact that neutrinos posses small masses and that leptonic

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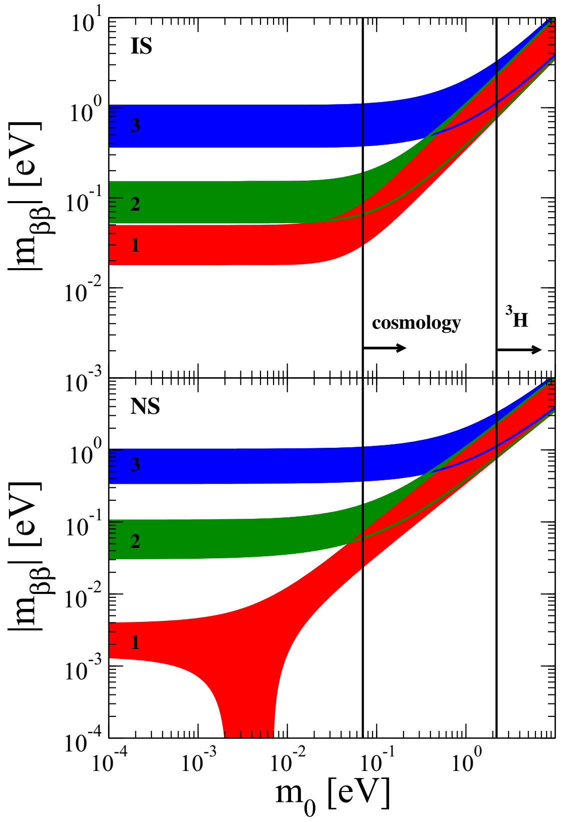

Figure 1: (Color online) The allowed range of values for $|m_{\beta\beta}|$ as a function of the lowest mass eigenstate m_0 for the cases of normal (lower panel) and inverted (upper panel) spectrum of neutrino masses. In panels the red (1), green (2) and blue (3) bands correspond to values $\langle \bar{q}q\rangle g$ = 0, 0.1, and 1 eV, respectively. Regions to the right from the vertical solid lines are excluded by the tritium β-decay [6] and by the cosmological data [5].

flavors are not symmetries of the Nature. The results converge towards a minimal three-neutrino framework, where known flavor states (ν_e, ν_μ, ν_τ) are expressed as a quantum superpositions of three massive states ν_i (i=1,2,3) with masses m_i. We have

$$|\nu_\alpha\rangle = \sum_{j=1}^{3} U^*_{\alpha j}|\nu_j\rangle \quad (\alpha = e,\ \mu, \tau). \qquad (4)$$

The Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix U is represented by six parameters: three lepton mixing angles (θ_{12}, θ_{23}, θ_{13}), CP-violating Dirac phase δ, and two CP-violating Majorana phases α_1, α_2. These α_1 and α_2 are the degrees of freedom of phase which come from the assumption that neutrinos are Majorana fermions.

2.1. $m_{\beta\beta}$ in vacuum

Neutrino oscillation experiments are sensitive to three mixing angles (θ_{12}, θ_{13} and θ_{23}) the CP phase δ and the two independent mass-squared differences, which can be chosen as follows: $\delta m^2 = m_2^2 - m_1^2$ and $\Delta m^2 = m_3^2 - (m_1^2+m_2^2)/2$ [4]. Two neutrino mass spectra are possible:

- Normal Spectrum (NS): $m_1 < m_2 < m_3$: $\Delta m^2 > 0$. In this case $m_2 = \sqrt{\delta m^2 + m_0^2}$, $m_3 = \sqrt{\Delta m^2 + \delta m^2/2 + m_0^2}$ with $m_0 = m_1$.
- Inverted Spectrum (IS), $m_3 < m_1 < m_2$: $\Delta m^2 < 0$. We have $m_1 = \sqrt{-\Delta m^2 - \delta m^2/2 + m_0^2}$, $m_2 = \sqrt{-\Delta m^2 + \delta m^2/2 + m_0^2}$ with $m_0 = m_3$

Here, $m_0 = m_1(m_3)$ is the lightest neutrino mass. Given the type of neutrino mass spectrum, m_0 fully determines the absolute neutrino mass scale.

The recent updated set of six neutrino oscillation parameters (δm^2, Δm^2, θ_{12}, θ_{13}, θ_{23}, δ) obtained by a global fit of results coming from experiments using neutrinos from solar, atmospheric, accelerator and reactor sources is presented in [4]. Currently, this combined analysis allows to constrain the previously unknown CP phase δ. Concerning the type of spectrum (sign(Δm^2)), there is no indication in favor of normal or inverted mass ordering yet.

In order to fix completely the three light neutrino masses, there is just one parameter left to be measured, namely absolute neutrino mass scale. No current experiment has sufficient sensitivity to measure it. There exist 3 different approaches to the absolute neutrino mass scale:

- The absolute neutrino mass scale determines the impact of cosmic neutrinos on the formation of matter structure in the early universe. The combination of several cosmological data sets allows to put an upper bound for the sum of neutrino masses [5],

  $$\sum_{k=1}^{3} m_k < 0.18 \text{ eV}, \qquad (5)$$

  which implies $m_0 \leq 0.07$ eV.
- Terrestrial experiments such as tritium β-decay gives a further constraint on the absolute neutrino