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Neutrinoless double beta decay, nuclear environment and structure

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A novel effect in neutrinoless double beta decay ($0\nu\beta\beta$-decay), namely a generation of in-medium Majorana neutrino masses due to non-standard neutrino interaction with quarks, is discussed. The modified rate of the $0\nu\beta\beta$-decay can lead to the apparent incompatibility of observations of the $0\nu\beta\beta$-decay with the value of the neutrino mass determined or restricted by the β-decay and cosmological data. Further, an impact of the quenching of the axial-vector coupling constant on the $0\nu\beta\beta$-decay processes is discussed. It is maintained that if two-body currents are behind most of the quenching, their impact on the $0\nu\beta\beta$-decay rate is mild.

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1. Introduction

The discovery of neutrino oscillations, and hence, non-zero neutrino masses and mixing implies physics beyond the standard model of particle physics. Currently, one of the most important open questions in neutrino physics is the question of whether neutrinos are Majorana (particles and anti-particles are identical except for their helicities) or Dirac particles (particles are distinct from anti-particles).

The most sensitive probe for Majorana neutrinos is a nuclear process known as neutrinoless double-beta decay ($0\nu\beta\beta$-decay) [1],

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-}, \tag{1.1}$$

whereby a nucleus decays by emitting only two electrons, while changing its charge by two units. The $0\nu\beta\beta$-decay breaks the total lepton number conservation and is forbidden in the standard model. Observation of the $0\nu\beta\beta$-decay, a spontaneous transition, may occur in several candidate nuclei.

The $0\nu\beta\beta$-decay has not been observed yet. The main aim of experiments on the search for $0\nu\beta\beta$-decay is the measurement of the effective Majorana mass $m_{\beta\beta}$. If the $0\nu\beta\beta$-decay is governed by the exchange of light neutrinos interacting with nucleons via standard model V-A interaction, the inverse value of the $0\nu\beta\beta$-decay half-life can be written as [1]

$$\left(T^{0\nu}_{1/2}\right)^{-1} = m^2_{\beta\beta}\; g^4_A\; \left|M'^{0\nu}\right|^2\; G^{0\nu}(E_0,Z). \tag{1.2}$$

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.

In this contribution the possible effect of the nuclear environment on $m_{\beta\beta}$ is addressed and the effect of quenching of g_A is discussed.

2. The effective Majorana mass in vacuum and in nuclear environment

The neutrino oscillation data, accumulated over many years, converge towards a minimal three-neutrino framework, where known flavor states ($\nu_e,\ \nu_\mu,\ \nu_\tau$) are expressed as a quantum superpositions of three massive states ν_i (i=1,2,3) with masses m_i. We have

$$|\nu_\alpha\rangle = \sum_{j=1}^{3} U^*_{\alpha j}|\nu_j\rangle \quad (\alpha = e,\ \mu,\tau). \tag{2.1}$$

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.

Neutrino oscillation experiments cannot tell us about the overall scale of neutrino masses. The measured two neutrino mass squared differences suggest two scenarios for neutrino mass pattern: i) *Normal Spectrum*: $m_1 < m_2 < m_3$; ii) *Inverted Spectrum*, $m_3 < m_1 < m_2$. The inverted hierarchy ($m_3 \ll m_1 < m_2$) corresponds to the case where the lightest neutrino is dominated by muon and tau

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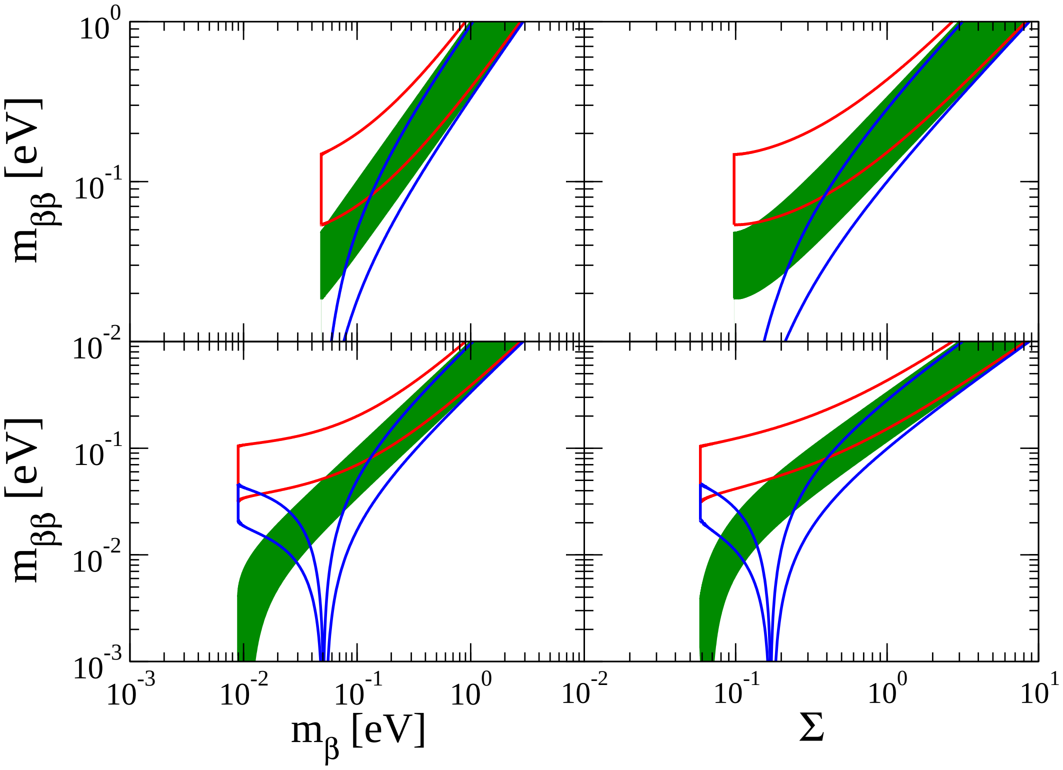

Figure 1: (Color online) The allowed range of values for effective Majorana mass $m_{\beta\beta}$ as a function of the effective electron neutrino mass m_β (left panels) and sum of neutrino masses Σ (right panels). The upper and lower panels correspond to the cases of the inverted and normal spectrum of neutrino masses. In panels green, red and blue bands refer to to values $\langle\bar{q}q\rangle g = 0$ (vacuum), 0.1, and -0.05 eV, respectively.

neutrino flavors, rather than the alternative normal hierarchy ($m_1 \ll m_2 \ll m_3$), where the lightest neutrino has a major electron neutrino component.

Absolute neutrino masses can be probed via three main methods:

i) The first one is provided by tritium β-decay, sensitive to so-called *effective electron neutrino mass* m_β,

$$m_\beta = \left[\sum_{i=1}^{3} |U_{ek}|^2 m_k^2\right]^{1/2} = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{1/2}. \tag{2.2}$$

Currently, from the Mainz and Troitsk experiments we have $m_\beta < 2.1$ eV. The KATRIN experiment in construction aims at reaching a sensitivity of $m_\beta = 0.2$ eV^2 [1].

ii) The second observable is the *effective Majorana mass*,

$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| = \left|c_{13}^2 c_{12}^2 m_1 e^{i\alpha_1} + c_{13}^2 s_{12}^2 m_2 e^{i\alpha_2} + s_{13}^2 m_3\right|, \tag{2.3}$$

which enters the $0\nu\beta\beta$-decay half-life in Eq. (1.2). The current $0\nu\beta\beta$-decay data imply $|m_{\beta\beta}| \leq (0.20 - 0.3)$ eV [1]. In future experiments a sensitivity $m_{\beta\beta} \simeq$ a few meV is planned to be reached.

iii) The third observable is the *cosmological mass* Σ, which is the sum of three active neutrino masses ($\Sigma = m_1 + m_2 + m_3$). The combination of several cosmological data sets allows to put an upper bound $\Sigma\ <\ 0.18$ eV [1].

Recently, the possible effect of nuclear medium on the $0\nu\beta\beta$-decay was considered [3]. It was proposed that the neutrino mixing and masses in nucleus can differ significantly from those in vacuum, if there are exotic particles, preferably scalars, which do interact with neutrinos. The nuclear matter effect on the $0\nu\beta\beta$-decay rate can be calculated in the mean field approach [3].

The effective lepton number violating four-fermion neutrino-quark Lagrangian with the operators of the lowest dimension can be written as

$$\mathscr{L}_{eff} = \frac{1}{\Lambda^2_{LNV}} \sum_{i,j,q} \left(g^q_{ij} \overline{\nu^C_{Li}} \nu_{Lj}\ \bar{q}q + \text{H.c.} \right), \tag{2.4}$$

where the fields ν_{Li} are the active neutrino left-handed flavor states, g^q_{ij} are their dimensionless couplings to the scalar quark currents with $i,j = e,\mu,\tau$.

For sake of simplicity we consider case of scalar coupling such that $2\hat{g}_{ij}/\Lambda^2_{LNV} = \delta_{ij}g$, where $\hat{g} = U^\dagger\ g^q\ U$ In this case the effective Majorana mass (2.3) is

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} (U_{ei})^2\ \xi_i |m_i - \langle \bar{q}q \rangle g| \right|. \tag{2.5}$$

The Majorana phase factor ξ_i is given in [3].

With the above simplification the quantity $m_{\beta\beta}$ in nuclear medium in comparison with the one in vacuum depends on the new unknown parameter g. The unknown phases in Eq. (2.5) are varied in the interval $[0, 2\pi]$. In Figure 1 $m_{\beta\beta}$ is expressed as a function of a directly observable parameters, namely m_β and Σ. The best-fit values of vacuum mixing angles and the neutrino mass squared differences are taken from [2]. In upper and lower panels green, red and blue bands refer to values $\langle \bar{q}q \rangle g = 0$ (vacuum), 0.1, and -0.05 eV, respectively. We see that in-medium ($g \neq 0$) values of $m_{\beta\beta}$ differ significantly from those for a vacuum ($g = 0$). If in the future gradually improving limits on m_β and Σ will come into conflict with the possible evidence of the $0\nu\beta\beta$-decay represented by $m_{\beta\beta}$ in vacuum, new physics would be mandatory. A possible explanation could be a generation of in-medium Majorana neutrino mass due to nonstandard interactions of neutrinos with nuclear matter of decaying nuclei.

3. Nuclear matrix elements and effective weak 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 $M'^{0\nu}$.

The important source of uncertainty in $M'^{0\nu}$ is the renormalized or quenched value of axial-vector coupling constant g_A^{eff}, which includes the nuclear medium effects. If only one-body nucleon currents are considered, we have $M'^{0\nu} = (g_A^{eff}/g_A)^2 M^{0\nu}$. Here, $M^{0\nu}$ depends mainly on the nuclear structure of the particular isotopes (A,Z), $(A,Z+1)$ and $(A,Z+2)$ under study and weakly on g_A^{eff}.

Many different nuclear models were used for the calculation of $M^{0\nu}$ in the literature, namely the quasiparticle random phase approximation (QRPA), interacting shell model, interacting boson

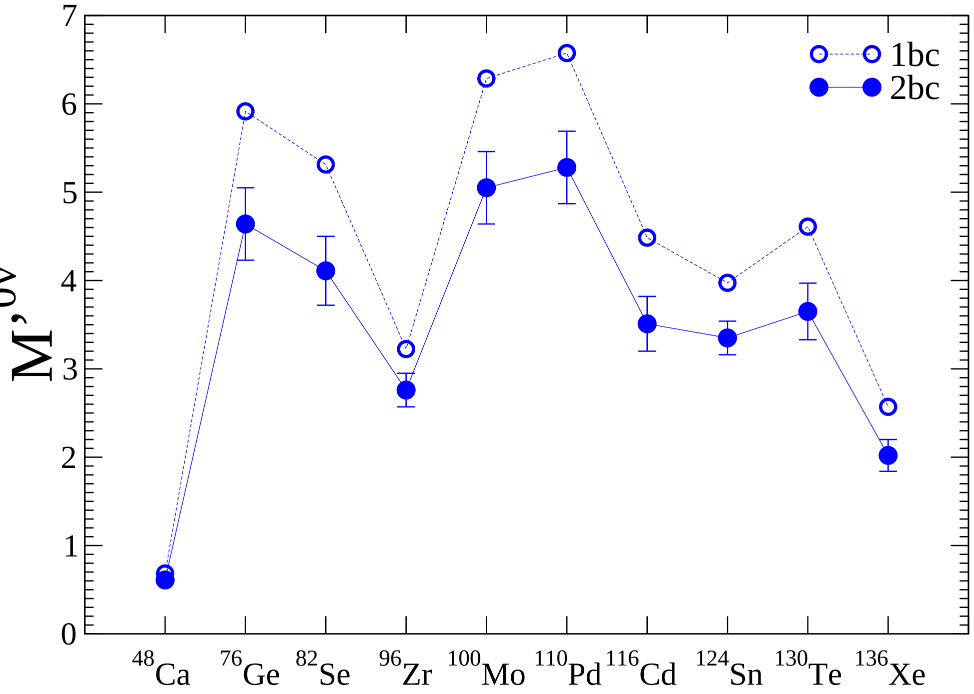

Figure 2: (Color online) Nuclear matrix element $M'^{0\nu}$. The empty circles represent the results with the one-body current (1bc) only, and the solid circles the average of the results with two-body currents (2bc) included. The error bars represent the dispersion in those values.

model, energy density functional method and projected Hartree-Fock-Bogoliubov model etc (see references given in [1]). The results for $M^{0\nu}$ differ up to factor 2-3 for a given nucleus.

Quenching of axial-vector coupling constant is very important for the double beta decay because g_A^{eff} appears to the fourth power in the decay rate. A modern value of axial-vector coupling constant measured in the weak interactions and decays of free nucleons is g_A=1.269 (previously, $g_A = 1.254$ was considered). It is well known that the calculated strengths of Gamow-Teller β-decay transitions to individual final states are significantly larger than the experimental ones. To account for this, it is customary to quench the calculated Gamow-Teller matrix elements. Formally, this is accomplished by replacing the true value of the coupling constant $g_A = 1.269$ by a quenched value g_A^{eff}= 1.0. The shell model, which describes qualitatively well energy spectra, does reproduce measured values of two-neutrino double beta decay ($2\nu\beta\beta$-decay) half-life only by consideration of significant quenching of the $2\nu\beta\beta$-decay NMEs, typically by 60-70%. In the IBM-2 that number is more like 80 % suggesting $g_A^{eff} = 1.269\ A^{-0.18}$ [4]. In [5] g_A^{eff} was treated as a completely free parameter alongside particle-particle interaction parameter g_{pp} by performing calculations within the QRPA. It was found that a least-squares fit of g_A^{eff} and g_{pp}, where possible, to the β-decay rate and β^+/EC rate of the $J^\pi = 1^+$ ground state in the intermediate nuclei involved in double-beta decay in addition to the $2\nu\beta\beta$ rates of the initial nuclei, leads to an effective g_A^{eff} of about 0.7 or 0.8.

We see that the uncertainty due to quenching might be up to about factor $(A^{0.18})^4$ ≈30 (for A = 100) what would be a disaster for the $0\nu\beta\beta$-decay experiments. The origin of the quenching is not completely known. The $0\nu\beta\beta$-decay matrix element has a different form than does the $2\nu\beta\beta$-decay matrix element, and it may be that whatever structure is quenching $2\nu\beta\beta$-decay has no effect on $0\nu\beta\beta$-decay. In [6, 7] this issue was discussed within the effective field theory by assuming that the quenching is related to two-body currents. The effects of the two-body currents decrease as the momentum transfer increases, and so such currents will quench $2\nu\beta\beta$-decay, for which the momentum transfer is essentially zero, more than $0\nu\beta\beta$-decay, for which an intermediate neutrino can transfer several hundred MeV of momentum from one decaying nucleon to the other. Thus, if most of the quenching is due to two-body currents, as effective field theory suggests, the $0\nu\beta\beta$-matrix elements will be quenched by a factor on the order of 30% [6, 7]. The nuclear matrix element $M'^{0\nu}$ calculated for nuclei of experimental interest by consideration both one- and two-body currents within the QRPA [7] are displayed in Figure 2.

4. Conclusion

In summary, it was shown that non-standard neutrino interaction generates in-medium Majorana neutrino masses, which might affect the $0\nu\beta\beta$-decay rate. As a result a compatibility of observations of the $0\nu\beta\beta$-decay, the measurement of the tritium β-decay and cosmological measurements can be spoiled. Further, we stressed the importance of better understanding the quenching of weak axial-vector coupling constant in nuclear medium. It was pointed out that if origin of quenching is related with two-body currents, it affects only slightly the $0\nu\beta\beta$-decay unlike the $2\nu\beta\beta$-decay half-life.

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