Neutrinoless double beta decay and nuclear environment

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Abstract. We show that the presence in the nuclear medium of lepton number violating four-fermion interactions of neutrinos with quarks from a decaying nucleus could account for an apparent incompatibility among the 0$\nu$ββ searches in the laboratory, the direct neutrino mass measurement with the nuclear $\beta$-decay and cosmological data.

1. Introduction
The most sensitive probe for Majorana neutrinos mass is the neutrinoless double-beta decay (0$\nu$ββ-decay) \cite{1},
\[ (A, Z) \rightarrow (A, Z + 2) + 2e^-, \] (1)
whereby a nucleus decays by emitting only two electrons, while changing its charge by two units.

The 0$\nu$ββ-decay has not been observed yet. The main aim of experiments on the search for 0$\nu$ββ-decay is the measurement of the effective Majorana mass $m_{\beta\beta}$. The inverse value of the 0$\nu$ββ-decay half-life can be written as \cite{1}
\[ (T_{1/2}^{0\nu})^{-1} = m_{\beta\beta}^2 g_A^4 |M_{0\nu}|^2 G_{0\nu}(E_0, Z). \] (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. $g_A$ is the axial vector coupling constant.

2. The effect of nuclear environment on $m_{\beta\beta}$
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 $\nu_i$ (i=1,2,3) with masses $m_i$. We have
\[ |\nu_\alpha\rangle = \sum_{j=1}^{3} U_{\alpha j}^* |\nu_j\rangle \quad (\alpha = e, \mu, \tau). \] (3)
The Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix $U$ is represented by six parameters: three lepton mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), CP-violating Dirac phase $\delta$, and two CP-violating Majorana phases $\alpha_1, \alpha_2$.

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, $m_3 < m_1 < m_2$.

Absolute neutrino masses in vacuum are probed via three main methods:

i) The first one is provided by tritium $\beta$-decay, sensitive to so-called effective electron neutrino mass $m_\beta$, 

$$m_\beta = \left[ \sum_{i=1}^{3} |U_{e i}|^2 m_i^2 \right]^{1/2} = \left[ c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \right]^{1/2}.$$  \hspace{1cm} (4)

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, 

$$m_{\beta\beta} = \left| \sum_{k=1}^{3} U_{e k}^2 m_k \right| = \left| c_{13}^2 c_{12}^2 m_1 e^{i\alpha_1} + c_{13}^2 s_{12}^2 m_2 e^{i\alpha_2} + s_{13}^2 m_3 \right|,$$  \hspace{1cm} (5)

which enters the $0\nu\beta\beta$-decay half-life in Eq. (2). The current $0\nu\beta\beta$-decay data imply $|m_{\beta\beta}| \lesssim (0.20 - 0.3)$ eV [1]. In future experiments a sensitivity $m_{\beta\beta} \lesssim$ a few meV is planned to be reached.

iii) The third observable is the cosmological mass $\Sigma$, 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, 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 [2].

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

$$L_{eff} = \frac{1}{\Lambda^2_{LNV}} \sum_{i,j,q} \left( g^{\nu L}_{ij} \bar{\nu}_{Li} \nu_{Lj} \bar{q} q + H.c. \right),$$  \hspace{1cm} (6)

where the fields $\nu_{Lj}$ are the active neutrino left-handed flavor states, $g^{\nu L}_{ij}$ 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 $\hat{g} = U^\dagger g^2 U$ In this case the effective Majorana mass (5) is 

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} (U_{ei})^2 \xi_i |m_i - \langle qq \rangle g| \right|.$$  \hspace{1cm} (7)

The Majorana phase factor $\xi_i$ is given in [2].

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. (7) 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 $m_\beta$ and $\Sigma$. The best-fit values of vacuum mixing angles and the neutrino mass squared differences are taken from [3]. In upper and lower panels green, blue and red bands refer to values $\langle qq \rangle g = 0$ (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 ($g = 0$).
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 $m_\beta$ (left panels) and sum of neutrino masses $\Sigma$ (right panels). The upper and lower panels correspond to the cases of the inverted and normal spectrum of neutrino masses. In panels yellow, blue and red bands refer to $\langle \bar{q}q \rangle g = 0$ (vacuum), 0.1, and $-0.05$ eV, respectively.

3. Conclusion
In summary, if in the future gradually improving limits on $m_\beta$ and $\Sigma$ 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.

References
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