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Searching for the Dirac Nature of Neutrinos: Combining Neutrinoless Double Beta Decay and Neutrino Mass Measurements

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Abstract

We studied the neutrinoless double beta decay process to tackle the issue about the nature of neutrino. Establishing the nature of neutrinos, whether they are Dirac or Majorana particles is one of the fundamental questions we need to answer in particle physics, and is related to the conservation of lepton number. Neutrinoless double beta decay ($(\beta\beta)_{0\nu}$) is the tool of choice for testing the Majorana nature of neutrinos. However, up to now, this process has not been observed, but a wide experimental effort is taking place worldwide and soon new results will become available.

Different mechanisms can induce $(\beta\beta)_{0\nu}$-decay and might interfere with each other, potentially leading to suppressed contributions to the decay rate. This possibility would become of great interest if upcoming neutrino mass measurements from KATRIN and cosmological observations found that $m_\nu > 0.2$ eV but no positive signal was observed in $(\beta\beta)_{0\nu}$-decay experiments. We focus on the possible interference between light Majorana neutrino exchange with other mechanisms, such as heavy sterile neutrinos and R-parity violating supersymmetric models. We show that in some cases the use of different nuclei would allow to disentangle the different contributions and allow to test the hypothesis of destructive interference. Finally, we present a model in which such interference can emerge and we discuss the range of parameters which would lead to a significant suppression of the decay rate.

Keywords: Majorana Neutrino, Double Beta Decay, Neutrino Mass

1. Introduction

After the discovery of neutrino oscillation, the search of nature of neutrino has gained new momentum. The most sensitive search is provided by $(\beta\beta)_{0\nu}$-decay which plays an important role in neutrino physics. This process also implies the Lepton Number Violation (LNV) and put Seesaw Mechanism in favor. Thus the study of $(\beta\beta)_{0\nu}$-decay plays an important role in neutrino physics. However, up to now, this process has not been seen experimentally yet. The underlying mechanism of the process cannot be identified either.

In the past 10 years, efforts have been put to determination of the dominant mechanism for $(\beta\beta)_{0\nu}$-decay. To determine the leading mechanism, various techniques have been discussed, e.g. analysis of the angular distribution [1], and comparison of the nuclear matrix elements between different nuclei ([2], [3]).

However, it is also possible that the contributions from different mechanisms are **of the same order**. For instance, the light neutrino and heavy neutrino exchange mechanism may destructively interfere each other, reducing the decay rate of the process, as first considered in Ref. [4]. This may explain why the detection of neutrinoless double beta decay is still absent, and give a hint that even neutrino is Majorana, we may still fail to detect the signal of $(\beta\beta)_{0\nu}$-decay in some nuclei.

We are interested in studying the case in which a future neutrino mass measurements from KATRIN [5, 6] and cosmological observations [7, 8] turn out to be incompatible with null results in neutrinoless double beta

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decay experiments, but might be reconciled if destructive interference is allowed between different mechanisms. Therefore, we study if it is possible to test the presence of destructive interference by combining the searches in different nuclei.

2. Different Mechanisms for $(\beta\beta)_{0\nu}$-decay

Neutrinoless double decay can be induced by various lepton-number violating mechanisms, including: (a) light Majorana neutrinos exchange [9, 10, 11]; (b) heavy Majorana neutrinos exchange [12, 13]; (c) R-parity violation (RPV) with short-range exchange [14, 15] and long-range exchange [16]; (d) right-handed leptonic and hadronic currents coupling [17]; (e) Kaluza-Klein neutrino exchange via extra dimension [18] and others.

From a theoretical perspective, the contributions from (b) - (e), the "new-physics" mechanisms, are generically expected to be subdominant, as the couplings of the "new-physics" particles will be small. Recently, the possibility of large contributions from these mechanisms have been explored with interesting implications for $(\beta\beta)_{0\nu}$-decay [19, 20, 21, 22]. Thus it is worthy to study these "new-physics" mechanisms and estimate the possible ranges of their magnitudes.

Here we focus on the first three mechanisms in order to highlight the impact of destructive interference between multiple mechanisms [22]. Similar considerations also apply in other cases. The inverse half-life of $(\beta\beta)_{0\nu}$-decay is

$$\begin{aligned}\Gamma_i &\equiv [T^{0\nu}_{1/2}]^{-1}_i \\ &= G_i \mid \eta_\nu \mathcal{M}_{\nu,i} + \eta_N \mathcal{M}_{N,i} + \eta_\lambda \mathcal{M}_{\lambda,i} \\ &\quad + \eta_q \mathcal{M}_{q,i} \mid^2, \end{aligned} \tag{1}$$

where G_i is the common phase space factor. Here, i indicates the nuclear species. $\mathcal{M}_{\nu,i}$, $\mathcal{M}_{N,i}$, $\mathcal{M}_{\lambda,i}$, $\mathcal{M}_{q,i}$ are the corresponding nuclear matrix elements (NME), which describe the nuclear effects in $(\beta\beta)_{0\nu}$-decay. The subscripts ν, N, λ, q refer to light neutrino, heavy neutrino, short-range and long-range RPV mechanisms respectively.

η_ν, η_N and η_λ, η_q are the lepton number violating (LNV) parameters respectively, defined as,

$$\eta_\nu = \frac{1}{m_e} \sum_k^{\text{light}} (U_{ek})^2 m_k \equiv \frac{< m_\nu >}{m_e} \equiv \frac{m_{\beta\beta}}{m_e}, \tag{2}$$

$$\eta_N = m_p \sum_j^{\text{heavy}} (V^L_{ej})^2 \frac{1}{M_j}, \tag{3}$$

$$\eta_\lambda \simeq \frac{\pi \alpha_s}{6} \frac{\lambda'^2_{111}}{G_F^2 m^4_{\tilde{d}_R}} \frac{m_p}{m_{\tilde{g}}} \cdot [1 + (\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}})^2]^2, \tag{4}$$

$$\eta_q = \sum_k \frac{\lambda'_{11k}\lambda'_{1k1}}{2\sqrt{2}G_F} [\sin 2\theta^d_{(k)} (\frac{1}{m^2_{\tilde{d}_1(k)}} - \frac{1}{m^2_{\tilde{d}_2(k)}})]. \tag{5}$$

All the LNV parameters in the equations above are independent of nuclear structure.

In Eq. (2), m_e is the electron mass, m_k, U^L_{ek} are the light ν masses and the elements of mixing matrix between light ν mass and flavor state, respectively.

Sterile neutrinos with masses M_j much higher than the average propagating momentum, $M_j \gg 100$ MeV, give the contribution in Eq. (3). We indicate with V^L_{ej} the mixing between the heavy mass states and electron neutrinos.

In Eq. (4 - 5), G_F is the Fermi constant, α_s is the SU(3) gauge coupling constant, λ'_{ijk} is the trilinear coupling constant in the R-parity violation superpotential. $m_{\tilde{u}_L}$, $m_{\tilde{d}_R}$ and $m_{\tilde{g}}$ are the masses of u-squark, d-squark and gluino, respectively. The definitions of $m_{\tilde{d}_1(k)}$, $m_{\tilde{d}_2(k)}$ and $\sin 2\theta^d_{(k)}$ can be referred to Ref. [16]. The physical meaning or more detailed explanations of these SUSY parameters can be referred to Ref. [23].

Given the evidence for light ν masses, the corresponding mechanism for neutrinoless double beta decay is the most discussed one. Its Feynman diagram is given in Fig. 1.

As shown in Eq. (2), the predictions for the decay rate of $(\beta\beta)_{0\nu}$-decay depends critically on $|\langle m_\nu \rangle|$, which is related to the neutrino masses and the CP-violating phases. Future information on the value of ν mass, from e.g. tritium β decay experiments and cosmology, on the type of ν mass ordering and on the mixing angles will allow to obtain new predictions for $|\langle m_\nu \rangle|$ and consequently for $T^{0\nu}_{1/2}$.

For the exchange neutrino mass larger than 100 MeV, the process becomes 'short-range' and the inter-nucleon

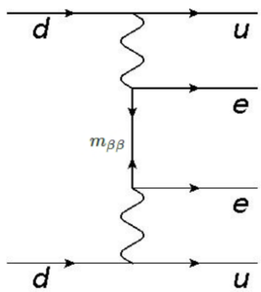

Figure 1: Feynman diagram giving rise to the standard light ν mechanism contribution to $(\beta\beta)_{0\nu}$-decay.