Sterile neutrinos in neutrinoless double beta decay

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(Received 26 February 2005; published 7 April 2005)

We study possible contribution of the Majorana neutrino mass eigenstate ν_h, dominated by a sterile neutrino component, to neutrinoless double beta ($0\nu\beta\beta$) decay. A special emphasis is made on accurate calculation of the corresponding nuclear matrix elements. From the current experimental lower bound on the $0\nu\beta\beta$-decay half-life of 76 Ge we derive stringent constraints on the $\nu_h - \nu_e$ mixing in a wide region of the values of ν_h mass. We discuss cosmological and astrophysical status of ν_h in this mass region.

The sterile right-handed neutrinos ν_R, not participating in the electroweak interactions, are natural candidates for the extension of the standard model (SM) field contents. They are very typical for various scenarios of the physics beyond the SM. It has long been recognized that the sterile neutrinos may have plenty of phenomenological implications. One of the celebrated examples is the seesaw generation of tiny Majorana neutrino masses for the three observable very light neutrinos via a very large Majorana mass term of the right-handed neutrinos. In this case together with the very light neutrinos there also appear very heavy Majorana neutrino mass states with the typical masses of $\sim 10^{12}$ GeV. However, in a more general case of the sterile-active neutrino mixing there may also appear additional neutrino states ν_h with arbitrary masses m_h. The neutrino mass eigenstates ν_h, dominated by the sterile ν_R neutrino weak eigenstates, contain some admixture of the active $\nu_{e,\mu,\tau}$ neutrino species that allows the ν_h to contribute to various processes, in particular, to those which are forbidden in the SM by the Lepton Number or Lepton Flavor Violation (LNV or LFV). They may also modify the interpretation of cosmological and astrophysical observations. Therefore, the masses m_h of ν_h neutrino states and their mixing with the active neutrinos are subject to various experimental as well as cosmological and astrophysical constraints. Various implications of the sterile neutrinos have been extensively studied in the literature within different scenarios of neutrino mass generation [1,2].

Experimentally, the ν_h neutrino states can be searched for as peaks in differential rates of various processes and by direct production of ν_h followed by their decays in detector

(for summary see Ref. [3]). The ν_h can also give rise to a significant enhancement of the total rates of certain processes if their masses, m_h, have the values in appropriate regions specific for each of these processes [4,5]. This effect would be especially pronounced in reactions that are forbidden in the SM. The LNV and/or LFV processes belong to this category. Many of them are stringently restricted by experiment and allow one to derive stringent limits on the ν_h contribution. Unprecedented sensitivities have been reached in the experiments searching for neutrinoless nuclear double beta decay ($0\nu\beta\beta$-decay) [6]. The current limits on the half-life of $0\nu\beta\beta$-decay are known to stringently constrain various parameters of the LNV physics, in particular, those which correspond to the Majorana neutrino contributions.

The sterile neutrino contribution to $0\nu\beta\beta$-decay has been first studied in the pioneer work Ref. [2] within a specific model with the two sterile neutrinos mixed only with the ν_e flavor state. In the present paper we develop this analysis by a more careful treatment of the nuclear $0\nu\beta\beta$-decay matrix elements on the basis of a well motivated nuclear structure approach known as the renormalized proton-neutron Quasiparticle Random Phase Approximation(QRPA) [7]. Also, we adopt a general phenomenological approach to the neutrino mass generation without referring to a specific model. We consider an extension of the SM with the three left-handed weak doublet neutrinos $\nu'_{Li} = (\nu'_{Le}, \nu'_{L\mu}, \nu'_{L\tau})$ mixed with n species of the SM singlet right-handed neutrinos $\nu'_{Ri} = (\nu'_{R1}, \ldots \nu'_{Rn})$. In general, in this scenario there appear $n + 3$ Majorana neutrino mass eigenstates $\nu_i = U^*_{ki}\nu'_k$, where U_{ki} is the corresponding mixing matrix. For simplicity, we assume that in addition to the three conventional light neutrinos there exists only one Majorana neutrino mass eigenstate ν_h, dominated by the sterile neutrino species, with an arbitrary mass m_h, which may mix with all the active neutrino weak eigenstates, $\nu_{e,\mu,\tau}$. We study possible contribution of this ν_h neutrino state to $0\nu\beta\beta$-decay via a nonzero admixture of ν_e weak eigenstate. From the non-observation of this LNV process we derive stringent limits

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on the $\nu_h - \nu_e$ mixing matrix element U_{eh} in a wide region of the values of m_h.

The contribution of ν_h neutrino state to the $0\nu\beta\beta$-decay amplitude is described by the standard Majorana neutrino exchange between the two β-decaying neutrons. The corresponding half-life formula for a transition to the ground state of final nucleus is given by the expression

$$[T_{1/2}^{0\nu}]^{-1} = G_{01} \left| U_{eh}^2 \frac{m_h}{m_e} M^{0\nu}(m_h) \right|^2. \qquad (1)$$

Here, m_e is the mass of electron and G_{01} is the integrated kinematical factor (for its numerical values see e.g. Ref. [7]). The nuclear matrix element $M^{0\nu}(m_h)$ we write in the form

$$M^{0\nu}(m_h) = \langle H_F(m_h, r_{12})\mathbf{1} + H_{GT}(m_h, r_{12})\sigma_{12}$$
$$+ H_T(m_h, r_{12})\mathbf{S}_{12}\rangle \qquad (2)$$

with the three terms corresponding to the Fermi, Gamow-Teller, and tensor contributions, which depend on the neutrino mass m_h and on the relative coordinates defined as $\mathbf{r}_{12} = \mathbf{r}_1 - \mathbf{r}_2$, $r_{12} = |\mathbf{r}_{12}|$, $\hat{\mathbf{r}}_{12} = \mathbf{r}_{12}/r_{12}$, where $\mathbf{r}_1$ and $\mathbf{r}_2$ are the coordinates of beta decaying nucleons. We also introduced the operators: $S_{12} = 3(\vec{\sigma}_1 \cdot \hat{\mathbf{r}}_{12}) \times (\vec{\sigma}_2 \cdot \hat{\mathbf{r}}_{12}) - \sigma_{12}, \sigma_{12} = \vec{\sigma}_1 \cdot \vec{\sigma}_2$.

The neutrino-exchange potentials $H_K(m_h, r_{12})$, with $K = F, GT, T$, have the following form:

$$H_K(m_h, r_{12}) = \frac{2}{\pi g_A^2} R \int_0^\infty f_K(qr_{12}) \frac{h_K(q^2)q^2}{\sqrt{q^2 + m_h^2}(\sqrt{q^2 + m_h^2} + E_J^m - (E_{g.s.}^i + E_{g.s.}^f)/2)} dq. \qquad (3)$$

where $f_K(qr_{12}) = j_0(qr_{12})$, $j_0(qr_{12})$ and $j_2(qr_{12})$ for $K = F$, GT and T, respectively, (j_0 and j_2 are spherical bessel functions). $E_{g.s.}^i$, $E_{g.s.}^f$, and E_J^m are the energies of initial, final, and intermediate nuclear states, respectively. The mean nuclear radius is given by $R = r_0 A^{1/3}$ with $r_0 = 1.1 \, fm$, and $g_A = 1.25$ is the axial nucleon constant. The functions $h_K(q^2)$ are

$$h_F(q^2) = -g_V^2(q^2),$$
$$h_T(q^2) = \frac{2}{3} \frac{g_A(q^2)g_P(q^2)q^2}{2m_p} - \frac{1}{3} \frac{g_P^2(q^2)q^4}{4m_p^2}$$
$$+ \frac{1}{3} \frac{g_M^2(q^2)q^2}{4m_p^2}, \qquad (4)$$
$$h_{GT}(q^2) = g_A^2(q^2) - \frac{2}{3} \frac{g_A(q^2)g_P(q^2)q^2}{2m_p} + \frac{1}{3} \frac{g_P^2(q^2)q^4}{4m_p^2}$$
$$+ \frac{2}{3} \frac{g_M^2(q^2)q^2}{4m_p^2}.$$

For the nucleon form factors we use the standard parametrizations: $g_V(q^2) = (1 + q^2/\Lambda_V^2)^{-2}$, $g_A(q^2) = g_A(1 + q^2/\Lambda_A^2)^{-2}$, $g_M(q^2) = (\mu_p - \mu_n)g_V(q^2)$, $g_P(q^2) = 2m_p g_A(q^2)(q^2 + m_\pi^2)^{-1}$, where $(\mu_p - \mu_n) = 3.70$, $\Lambda_V = 0.84$ GeV, $\Lambda_A = 1.09$ GeV, and m_π is the pion mass.

We calculated the nuclear matrix element in Eq. (2) for the transition ^{76}Ge$(0_{g.s.}^+) \rightarrow ^{76}Se(0_{g.s.}^+)$ within the proton-neutron renormalized QRPA [7]. We analyzed the single-particle model space which involves the full $2 - 4\hbar\omega$ major shells both for protons and neutrons. The single-particle energies were obtained using the Coulomb-corrected Woods-Saxon potential. We calculated the two-body G-matrix elements from the Bonn one-boson exchange potential on the basis of the Brueckner theory. Since the considered model space is finite the pairing

interactions have been adjusted to fit the empirical pairing gaps. In addition, we renormalized the particle-particle and particle-hole channels of the G-matrix interaction of the nuclear Hamiltonian following the procedure outlined in Ref. [8]. In this way we obtained the nuclear matrix element with a weak dependence on the nuclear structure parameter space. Finally, in order to take into account the two-nucleon correlations we multiplied the transition operators by the square of the correlation Jastrow-like function [9].

Having the nuclear matrix element $M^{0\nu}(m_h)$ calculated, we can derive the $0\nu\beta\beta$ decay limits on the mass m_h of the ν_h neutrino and its mixing U_{eh} with the ν_e neutrino weak eigenstate. Applying the presently best lower bound on the $0\nu\beta\beta$-decay half-life of ^{76}Ge [6]

$$T_{1/2}^{0\nu} \geq T_{1/2}^{0\nu-\exp} = 1.9 \times 10^{25} \text{ years} \qquad (5)$$

we derive from Eq. (1) the $|U_{eh}|^2 - m_h$ exclusion plot shown in Fig. 1. In Fig. 1 we also show typical domains excluded by some other experiments summarized in Ref. [3]. However, these domains are just indicative, because most of the previous bounds were obtained for some fixed values of m_h. For convenience, we interpolated this set of experimental points by continuous curves in different intervals of m_h. Let us also point out the following. The constraints listed in Ref. [3] are based on the searches for peaks in differential rates of various processes and the direct production of ν_h states followed by their decays in a detector. In Ref. [4] it was argued that in this case the results of data analysis depend on the ν_h total decay width, including the neutral current decay channels. The latter have not been properly taken into account in the derivation of the mentioned experimental constraints. However, the neutral current ν_h decay channels introduce the dependence of the final results on all of the mixing matrix
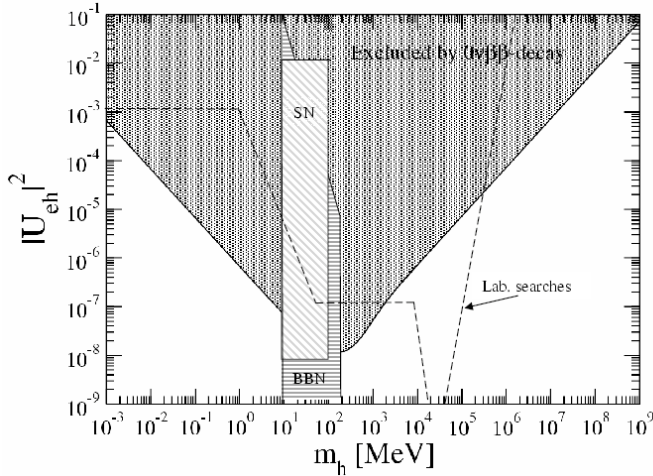
FIG. 1. Exclusion plots in the $|U_{eh}|^2 - m_h$ plane. The shaded regions are excluded by the $0\nu\beta\beta$-decay [present result], and by the big -bang nucleosynthesis and the SN 1987A neutrino observations. The dashed line mark typical upper limits from the laboratory searches for massive neutrinos.

elements U_{eh}, $U_{\mu h}$ and $U_{\tau h}$. In this situation one cannot extract individual limits for these matrix elements without some additional assumptions, introducing a significant uncertainty. In contrast, our $0\nu\beta\beta$-decay limits involve only U_{eh} mixing matrix element and, therefore, are free of the mentioned uncertainty. This is because in $0\nu\beta\beta$-decay intermediate Majorana neutrinos are always off-mass-shell states and their decay widths are irrelevant.

It is well known that massive neutrinos may have important cosmological and astrophysical implications. They are expected to contribute to the mass density of the universe, participate in cosmic structure formation, big-bang nucleosynthesis, supernova explosions, imprint themselves

in the cosmic microwave background etc. (see, for instance, Refs. [10–12] and references therein). This implies certain constrains on the neutrino masses and mixing, which, however, for unstable neutrinos, such as ν_h studied in the present paper, are quite weak and involve various uncertainties. The Big-bang nucleosynthesis(BBN) and the SN 1987A neutrino signal provide the most stringent and certain constraints [11] for this case. The corresponding constraints on ν_h parameters have been derived in Ref. [11] for the restricted mass regions: $10\text{ MeV} \leq m_h \leq 200\text{ MeV}$ for the BBN and $10\text{ MeV} \leq m_h \leq 100\text{ MeV}$ for the SN 1987A cases. We present the corresponding exclusion plots in Fig. 1 for comparison with our limits.

As seen from Fig. 1, our $0\nu\beta\beta$-decay limits cover much wider region of ν_h masses m_h and exclude the parts of the $|U_{eh}|^2 - m_h$ parameter space previously unconstrained by the laboratory experiments, and the cosmological and astrophysical observations.

In summary, we examined the possible contribution of the sterile neutrino dominated Majorana mass eigenstate ν_h to the $0\nu\beta\beta$ decay. From the currently most stringent lower bound on the $0\nu\beta\beta$-decay half-life of ^{76}Ge we derived upper limits on the $\nu_h - \nu_e$ neutrino mixing matrix element $|U_{eh}|^2$ in a wide region of the values of m_h, excluding previously unconstrained domains in the $|U_{eh}|^2 - m_h$ plane. Our constraints are free of the uncertainties, related to the assumptions on the values of the other neutrino mixing matrix elements $U_{\mu h}$ and $U_{\tau h}$, typical for the other laboratory constraints of this type.

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