Minimal active-sterile neutrino mixing in seesaw type I mechanism with sterile neutrinos at GeV scale

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Renewed interest in GeV-scale sterile neutrinos capable of explaining active neutrino oscillations via a seesaw type I mechanism has been expressed in several proposals of direct searches. Given this activity we estimate the minimal values of sterile-active mixing angles provided one, two, or three sterile neutrinos are lighter than the D meson.

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I. INTRODUCTION

Neutrino oscillations definitely ask for some extension of the standard model (SM) of particle physics, and maybe the simplest, yet complete and renormalizable, version is introducing three new Majorana massive fermions, N_I, $I = 1, 2, 3$, sterile with respect to all SM gauge interactions. One can write down the most general renormalizable Lagrangian,

$$\mathcal{L} = i\bar{N}_I\gamma^\mu\partial_\mu N_I - \frac{1}{2}M_I\bar{N}^c{}_I N_I - Y_{\alpha I}\bar{L}_\alpha\tilde{H}N_I + \text{H.c.}, \quad (1)$$

where M_I are the Majorana masses and $Y_{\alpha I}$ stand for Yukawa couplings with lepton doublets L_α, $\alpha = e, \mu, \tau$ and SM Higgs doublet H ($\tilde{H}_a = \epsilon_{ab}H_b^*$, $a = 1, 2$). When the Higgs field gains vacuum expectation value $v = 246$ GeV, Yukawa couplings in (1) yield mixing between sterile N_I and active ν_α neutrino states. Diagonalization of the neutral fermion mass matrix provides active neutrinos with masses m_i and mixing which are responsible for neutrino oscillation phenomena.

With some hierarchy between model parameters $Y_{\alpha I}$ and M_I/v, when the Dirac mass scale Yv is well below the Majorana mass scale M, active-sterile neutrino mixing angles are small, $U \sim Yv/M \ll 1$, and active neutrino masses are double suppressed, $m \sim U^2M$. This is a type I seesaw mechanism (for a review see e.g., Ref. [1]) which explains naturally why active neutrino mass scale is much lower than masses of other SM particles. However, the Dirac mass scale and hence the size of Yukawa couplings are not fixed from this reasoning: the seesaw mechanism determines not Y and M but ratio Y^2/M.

Then it is tempting to consider a variant of the type I seesaw model, where some of the sterile neutrinos are at GeV scale. The variant can be directly tested in particle physics experiments, where sterile neutrinos appear in heavy hadron decays and subsequently decay in light SM particles. Quite remarkably, in a part of parameter space this model can explain not only neutrino oscillations but also baryon asymmetry of the Universe via lepton number generation (leptogenesis) in primordial plasma [2]. In addition, it can even provide with a dark matter candidate as light sterile neutrino of 1–50 keV mass; then, independently of the dark matter production mechanism, the successful leptogenesis requires two heavier sterile neutrinos to be degenerate in mass. This pattern of seesaw type I is known as νMSM (for neutrino minimal extension of the SM, see details in e.g., [3]).

In the past century several dedicated searches for GeV-scale sterile neutrinos were performed in fixed target experiments with negative results [4]. Recently, searches for the sterile neutrino signal have been done by Belle Collaboration [5] in e^+e^--collisions at KEK, similar studies are planned for LHCb [6] at CERN. Special investigation of sterile neutrinos from kaon decays is undertaken in the E494 experiment [7] at BNL, and is suggested for the T2K experiment [8]. GeV-scale sterile neutrinos are considered in physical programs of proposed next generation long-base line neutrino oscillation experiments: near detectors in LBNE [9], NuSOnG [10], HiResMν [11].

Recently, an idea has been put forward [12] to construct a dedicated experiment and fully explore a part of νMSM parameter space, where heavier sterile neutrinos responsible for leptogenesis are light enough to emerge in D-meson decays. Later the idea has gotten support and motivated a realistic proposal [13] of a beam-target experiment at CERN based on high-intensity super proton synchrotron (SPS) beam of 400 GeV protons.

Given the interest to the subject we estimate in this paper the minimal values of mixings between sterile and active neutrinos, allowed by the type I seesaw mechanism, if some of the sterile neutrinos are lighter than 2 GeV. One can argue that most sensitive to this model is a fixed-target experiment, where produced by a proton beam hadrons decay into sterile neutrinos. The obtained results are needed to estimate the sensitivity of the future experiments required *to fully explore the parameter space of type I seesaw models with sterile neutrinos* in the interesting mass range.

II. PARAMETRIZATION

It is convenient to adopt the bottom-up parametrization for the 3×3 Yukawa coupling matrix Y_ν, first proposed in [14],

$$Y_\nu \equiv \frac{i\sqrt{2}}{v}\sqrt{M_R}R\sqrt{m_\nu}U^\dagger_{\rm PMNS}, \tag{2}$$

where $M_R \equiv \mathrm{diag}\{M_1, M_2, M_3\}$, $m_\nu \equiv \mathrm{diag}\{m_1, m_2, m_3\}$, $U_{\rm PMNS}$ is the unitary Pontecorvo-Maki-Nakagawa-Sakata matrix and R is a complex orthogonal matrix, $R^T R = \mathbb{1}$. We take for the active neutrino sector the central values of the combined fit [15] to neutrino oscillation data and all (still unknown) complex phases set to zero,

$$m_{\rm atm} = 5.01\times 10^{-2}\ \mathrm{eV}, \tag{3a}$$

$$m_{\rm sol} = 8.73\times 10^{-3}\ \mathrm{eV}, \tag{3b}$$

$$\theta_{12} = 34.45°, \tag{3c}$$

$$\theta_{23} = 51.53°, \tag{3d}$$

$$\theta_{13} = 9.02°, \tag{3e}$$

$$\delta = \alpha_1 = \alpha_2 = 0. \tag{3f}$$

Matrix R can be parametrized as

$$R = \mathrm{diag}\{\pm 1, \pm 1, \pm 1\} \times \begin{pmatrix} c_2 c_1 & c_2 s_1 & s_2 \\ -c_3 s_1 - s_3 s_2 c_1 & c_3 c_1 - s_3 s_2 s_1 & s_3 c_2 \\ s_3 s_1 - c_3 s_2 c_1 & -s_3 c_1 - c_3 s_2 s_1 & c_3 c_2 \end{pmatrix}, \tag{4}$$

where $c_i = \cos z_i$, $s_i = \sin z_i$ and z_i are three complex angles. Thus, the matrix of Yukawa couplings Y_ν depends on six dimensionless extra parameters, which do not enter the active neutrino sector. Three other model parameters from the sterile neutrino sector are the three Majorana masses M_I. One can introduce the matrix of mixing angles between active and sterile neutrinos by

$$U = \frac{v}{\sqrt{2}} M_R^{-1} Y_\nu. \tag{5}$$

In a fixed-target experiment the sterile neutrinos are produced due to mixing (5) in weak decays of hadrons (if kinematically allowed, $M_I < 2$ GeV). The same mixing is responsible for sterile neutrino weak decays into SM particles, that is the main signature accepted in sterile-neutrinos hunting. Therefore the number of signal events depends on the values of $|U_{I\alpha}|^2$. For charmed hadrons as the main source of sterile neutrinos, $|U_{I\tau}|^2$ may contribute to production only (via decays of τ leptons from D_s mesons), and is irrelevant for subsequent sterile neutrino decays due to kinematics. Thus, to be conservative, below we are interested in minimal values of $|U_{Ie}|^2$ and $|U_{I\mu}|^2$, which determine the maximal sensitivity of an experiment required to fully explore the type I seesaw model.

III. RESULTS

We begin with a special situation, when two sterile neutrinos are degenerate in mass, $M_1 = M_2 \equiv \mathcal{M}$, while mass of the third sterile neutrino M_3 varies independently. If $M_3 < 2$ GeV but $\mathcal{M} > 2$ GeV, the interesting values are $|U_{3e}|^2$ and $|U_{3\mu}|^2$, however they both can take zero values. It happens when N_3 mixes only with ν_τ or does not mix at all with active neutrinos (then one of the active neutrinos is massless).

In the opposite case, $M_3 > 2$ GeV but $\mathcal{M} < 2$ GeV, our goal is to calculate minimal possible values of the sums:

$$\mathcal{U}_e = |U_{1e}|^2 + |U_{2e}|^2, \tag{6a}$$

$$\mathcal{U}_\mu = |U_{1\mu}|^2 + |U_{2\mu}|^2. \tag{6b}$$

For $\mathcal{M} = 500$ MeV the numerical results are presented in Fig. 1 for two different hierarchies in active neutrinos masses. They are obtained by scanning over parameters of matrix R [see Eq. (4)] for a set of values of the lightest active neutrino mass $m_{\rm lightest}$. The values of $\mathcal{U}_{e,\mu}$ change with $\mathcal{M}$ as $\mathcal{U}_{e,\mu} \propto \mathcal{M}^{-1}$, and are independent of the heaviest sterile neutrino mass M_3, in agreement with Eqs. (2) and (5). Actually, these formulas imply that the minimal values of $\mathcal{U}_{e,\mu}$ remain the same even for the third sterile neutrino lighter than 2 GeV. This third neutrino may either show up or be unobservable in the beam-target experiment (for example, due to kinematics if M_3 is in keV region, or because when both $\mathcal{M} < 2$ GeV and $M_3 < 2$ GeV, $|U_{3e}|^2$ and $|U_{3\mu}|^2$ can take zero values). With additional constraints on the model parameters, minimal $\mathcal{U}_e$ and $\mathcal{U}_\mu$ generally grow and certainly never drop below the lines presented in Fig. 1. In particular, for the νMSM [3] (where the lightest sterile neutrino is dark matter and almost decoupled from active neutrinos) the parameters are so constrained that $\mathcal{U}_e$ and $\mathcal{U}_\mu$ for the two heavier (almost) degenerate neutrinos [16] are proportional to each other as indicated in Fig. 1. Minimal ($\mathcal{U}_e$, $\mathcal{U}_\mu$), marked by a point in Fig. 1, is well above the lower limit calculated for the unconstrained case with $m_{\rm lightest} = 0$, relevant for νMSM.

Now we turn to a more general case and split N_1 and N_2, so that $M_1 < M_2 < 2$ GeV. We found numerically that lower limits on both $\mathcal{U}_e$ and $\mathcal{U}_\mu$ scale from the numbers given in Fig. 1 as $\propto M_2^{-1}$. Note however that, when

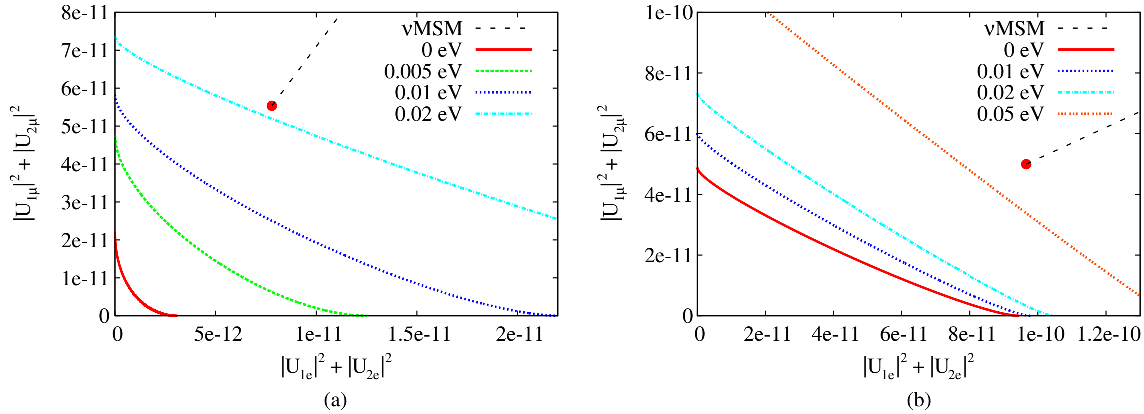

FIG. 1 (color online). The minimal values of mixings for $M_1 = M_2 = 500$ MeV and (a) normal hierarchy, (b) inverted hierarchy of active neutrino masses. The different lines correspond to different values of the lightest active neutrino mass m_{lightest}. On both plots the dashed line refers to the mixing in νMSM [3,16] as explained in the main text.

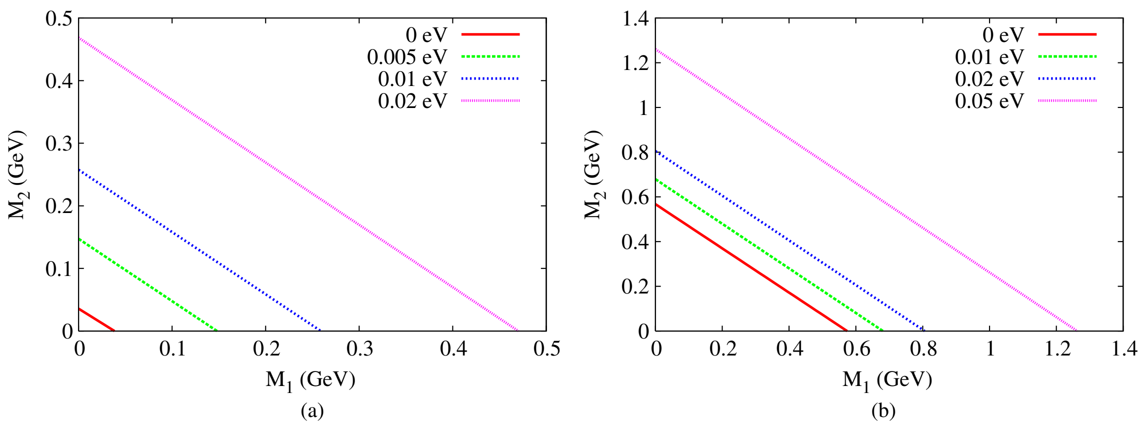

FIG. 2 (color online). The regions below the lines will be excluded by an experiment achieving the sensitivity to mixing parameters of $U_c^2 = 2.5 \times 10^{-11}$ for (a) normal hierarchy and (b) inverted hierarchy of active neutrino masses. The different lines correspond to different values of the lightest active neutrino mass m_{lightest}.

neutrinos are of different masses, the signals are expected at different masses (i.e. invariant masses of outcoming charged pion and lepton) and strengths in e, μ channels. They are shared by the two sterile neutrinos in some proportions. For example, it may happen that the signal in the e channel is saturated by the first sterile neutrino, while the signal in the μ channel is mostly due to the second neutrino, and thus happens at different mass. The generalization to the case of three neutrinos of similar masses at (sub)GeV scale observable at beam-target experiment is straightforward.

To illustrate the dependence on the sterile neutrino masses we outline in Fig. 2 the regions in (M_1, M_2) space, where at least one of the squared mixing values $|U_{I\alpha}|^2$, $I = 1, 2$, $\alpha = e, \mu$, exceeds a given value U_c^2. Reaching the sensitivity U_c^2, an experiment rules out the seesaw model with sterile neutrino masses in the corresponding region. The exclusion regions are separated by lines $M_1 + M_2 = f(m_{\mathrm{lightest}})/U_c^2$.

Finally, we have checked that switching on complex phases in active neutrino sector (3) may change the obtained estimates of *minimal mixing values* $\mathcal{U}_e, \mathcal{U}_\mu$ by some tense of percents. This is due to suppression of one of the mixings $|U_{I\alpha}|^2$, $I = 1, 2$, $\alpha = e, \mu$ occurring for particular sets of angles and complex phases of U_{PMNS} (see e.g., [17]). This consideration completes the discussion.

IV. CONCLUSION

To conclude, we found minimal values of active-sterile neutrino mixing for the seesaw type I model for those sterile neutrinos which are lighter than 2 GeV. Present experimental upper limits on the mixing can be found in Ref. [18].

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