On the minimal active-sterile neutrino mixing in seesaw type I mechanism with sterile neutrinos at GeV scale

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Abstract

Renewed interest in GeV-scale sterile neutrinos capable of explaining active neutrino oscillations via see-saw 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 D-meson.

1. Neutrino oscillations definitely ask for some extension of the Standard Model of particle physics (SM), and may be 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

$$L = i\bar{N}_I\gamma^n\partial_n N_I - \frac{1}{2}M_I\bar{N}_I^c N_I - Y_{\alpha I}\bar{L}_\alpha\tilde{H}N_I + h.c.$$  \hspace{1cm} (1)

where $M_I$ are the Majorana masses and $Y_{\alpha I}$ stand for Yukawa couplings with lepton doublets $L_{\alpha}$, $\alpha = e, \mu, \tau$ 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 $\nu_\alpha$ 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 $Y^2/M$. 

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Then it is tempting to consider a variant of type I seesaw model, where some of 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 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 $\nu$MSM (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 has 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 E494 experiment [7] at BNL, and is suggested for 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], HiResM$\nu$ [11].

Recently, an idea has been put forward [12] to construct a dedicated experiment and fully explore a part of $\nu$MSM parameter space, where heavier sterile neutrinos responsible for leptogenesis are light enough to emerge in $D$-meson decays. Later the idea has got a support and motivated a realistic proposal [13] of a beam-target experiment at CERN based on high-intensity 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 type I seesaw mechanism, if some of 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.

2. It is convenient to adopt the bottom-up parametrization for the $3 \times 3$ Yukawa coupling matrix $Y_\nu$, firstly proposed in [14],

$$Y_\nu \equiv \frac{i\sqrt{2}}{v} \sqrt{M_R} R \sqrt{m_\nu} U_{\text{PMNS}}^\dagger,$$

where $M_R \equiv \text{diag}\{M_1, M_2, M_3\}$, $m_\nu \equiv \text{diag}\{m_1, m_2, m_3\}$, $U_{\text{PMNS}}$ is the unitary Pontecorvo–Maki–Nakagawa–Sakata matrix and $R$ is a complex orthogonal matrix, $R^TR = 1$. 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,
\[ m_{\text{atm}} = 5.01 \times 10^{-2} \text{ eV}, \]
\[ m_{\text{sol}} = 8.73 \times 10^{-3} \text{ eV}, \]
\[ \theta_{12} = 34.45^\circ, \]
\[ \theta_{23} = 51.53^\circ, \]
\[ \theta_{13} = 9.02^\circ, \]
\[ \delta = \alpha_1 = \alpha_2 = 0. \]

Matrix \( R \) can be parametrized as
\[
R = \text{diag}\{\pm 1, \pm 1, \pm 1\} \times \begin{pmatrix}
  c_2 c_1 & c_2 s_1 & s_2 \\
- c_3 s_1 - s_3 s_2 c_1 & c_3 c_1 - s_3 s_2 s_1 & s_3 c_2 \\
 s_3 s_1 - c_3 s_2 c_1 & - s_3 c_1 - c_3 s_2 s_1 & c_3 c_2
\end{pmatrix},
\]
where \( c_i = \cos z_i \), \( s_i = \sin z_i \) and \( z_i \) are three complex angles. Thus, the matrix of Yukawa couplings \( Y_\nu \) depends on six dimensionless extra parameters, which do not enter the active neutrino sector. Three other model parameters from sterile neutrino sector are the three Majorana masses \( M_I \). One can introduce the matrix of mixing angles between active and sterile neutrinos by
\[
U = \frac{v}{\sqrt{2}} M_R^{-1} Y_\nu.
\]

In a fixed-target experiment the sterile neutrinos are produced due to mixing (5) in weak decays of hadrons (if kinematically allowed, \( M_I < 2 \text{ GeV} \)). 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 \( \tau \)-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 \( |U_{I\tau}|^2 \) and \( |U_{I\mu}|^2 \), which determine the maximal sensitivity of an experiment required to fully explore type I seesaw model.

3. We begin with a special situation, when two sterile neutrinos are degenerate in mass, \( M_1 = M_2 \equiv M \), while mass of the third sterile neutrino \( M_3 \) varies independently. If \( M_3 < 2 \text{ GeV} \) but \( M > 2 \text{ GeV} \), 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 \( \nu_\tau \) or does not mix at all with active neutrinos (then one of active neutrinos is massless).

In the opposite case, \( M_3 > 2 \text{ GeV} \) but \( M < 2 \text{ GeV} \), our goal is to calculate minimal possible values of the sums
\[
\mathcal{U}_e = |U_{1e}|^2 + |U_{2e}|^2,
\]
\[
\mathcal{U}_\mu = |U_{1\mu}|^2 + |U_{2\mu}|^2.
\]
For $M = 500 \text{ MeV}$ 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 $m_{\text{lightest}}$. The values of $U_{e,\mu}$ change with $M$ as $U_{e,\mu} \propto M^{-1}$, and are independent of the heaviest sterile neutrino mass $M_3$, in agreement with Eqs. (2), (5). Actually, these formulas imply that the minimal values of $U_{e,\mu}$ 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 $M < 2 \text{ GeV}$ and $M_3 < 2 \text{ GeV}$, $|U_{3e}|^2$ and $|U_{3\mu}|^2$ can take zero values). With additional constraints on the model parameters, minimal $U_e$ and $U_\mu$ generally grow and certainly never drop below the lines presented in Fig. 1. In particular, for the $\nu$MSM [3] (where the lightest sterile neutrino is dark matter and almost decoupled from active neutrinos) the parameters are so constrained that $U_e$ and $U_\mu$ for the two heavier (almost) degenerate neutrinos [16] are proportional to each other as indicated in Fig. 1. Minimal $(U_e, U_\mu)$, marked by point in Fig. 1, is well above the lower limit calculated for the unconstrained case with $m_{\text{lightest}} = 0$, relevant for $\nu$MSM.

Now we turn to more general case and split $N_1$ and $N_2$, so that $M_1 < M_2 < 2 \text{ GeV}$. We found numerically that lower limits on both $U_e$ and $U_\mu$ scale from the numbers given in Fig. 1 as $\propto M_2^{-1}$. Note however, that when 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 $e, \mu$ channels. They are shared by the two sterile neutrinos in some proportions. For example, it may happen, that the signal in $e$-channel is saturated by the first sterile neutrino, while the signal in $\mu$-channel is mostly due to the second neutrino, and thus

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

![Graph](image)

Figure 2: The regions below the lines will be excluded by an experiment achieving the sensitivity to mixing parameters of $U^2_{ec} = 2.5 \times 10^{-11}$ for: (a) normal hierarchy, (b) inverted hierarchy of active neutrino masses. The different lines correspond to different values of the lightest active neutrino mass $m_{\text{lightest}}$.

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 $U^2_{ec}$. Reaching the sensitivity $U^2_{ec}$, an experiment rules out the seesaw model with sterile neutrino masses in the corresponding region. The exclusion regions are separated by lines $M_1 + M_2 = f(m_{\text{lightest}})/U^2_{ec}$.

Finally, we have checked that switching on complex phases in active neutrino sector (3f) may change the obtained estimates of minimal mixing values $U_e, U_\mu$ by some tens percent. This is due to suppression of one of mixings $|U_{I\alpha}|^2$, $I = 1, 2$, $\alpha = e, \mu$ occurring for particular sets of angles and complex phases of $U_{\text{PMNS}}$ (see e.g. [18]). This consideration completes the discussion.

4. To conclude, we found minimal values of active-sterile neutrino mixing for 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. [17]. The authors are indebted to F. Bezrukov, O. Ruchayskiy and M. Shaposhnikov for useful discussions. The work is supported in part by the grant of the President of the Russian Federation NS-2835.2014.2. The work of D.G. is supported in part by RFBR grant 13-02-01127a. The work of A.P. is supported in part by the grant of the President of Russian Federation MK-1754.2013.2.
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