Numerical estimate of minimal active-sterile neutrino mixing

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Abstract. Seesaw mechanism constrains from below mixing between active and sterile neutrinos for fixed sterile neutrino masses. Signal events associated with sterile neutrino decays inside a detector at fixed target experiment are suppressed by the mixing angle to the power of four. Therefore sensitivity of experiments such as SHiP and DUNE should take into account minimal possible values of the mixing angles. We extend the previous study of this subject [1] to a more general case of non-zero CP-violating phases in the neutrino sector. Namely, we provide numerical estimate of minimal value of mixing angles between active neutrinos and two sterile neutrinos with the third sterile neutrino playing no noticeable role in the mixing. Thus we obtain a sensitivity needed to fully explore the seesaw type I mechanism for sterile neutrinos with masses below 2 GeV, and one undetectable sterile neutrino that is relevant for the fixed-target experiments. Remarkably, we observe a strong dependence of this result on the lightest active neutrino mass and the neutrino mass hierarchy, not only on the values of CP-violating phases themselves. All these effects sum up to push the limit of experimental confirmation of sterile-active neutrino mixing by several orders of magnitude below the results of [1] from 10^{-10} – 10^{-11} down to 10^{-12} and even to 10^{-20} in parts of parameter space; non-zero CP-violating phases are responsible for that.

1 Introduction

Neutrino oscillations clearly call for an extension of the Standard Model of particle physics (SM). Sterile neutrino models can provide a simple theoretical framework explaining this phenomenon, which makes them popular among many candidates for physics beyond SM. In this framework one commonly introduces three Majorana fermions $N_I, I = 1, 2, 3$, sterile with respect to SM gauge interactions $SU(3)_c \times SU(2)_W \times U(1)_Y$.

One can write down the most general renormalizable sterile neutrino Lagrangian as:

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

where M_I are the Majorana masses, and $Y_{\alpha I}$ stand for the Yukawa couplings with lepton doublets $L_\alpha, \alpha = e, \mu, \tau$ and SM Higgs doublet ($\tilde{H}_a = \epsilon_{ab}H_b^*$).

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When the Higgs field gains vacuum expectation value $v = 246$ GeV, the 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. If active-sterile mixing angles are small, then active neutrino masses are double suppressed, $m \sim U^2 M$. This is the standard seesaw type I mechanism, for more details one can address [2].

The seesaw mechanism implies non-zero mixing between sterile and active neutrinos. But sterile neutrino mass scale is not fixed by this mechanism. If sufficiently light, sterile neutrinos can be produced in weak processes and directly studied in particle physics experiments, for recent results see Troitsk νMass [3], OKA [4], LHCb [5, 6], Belle [6], E949 [7], NA62 [8].

The authors of Ref. [9] suggest that in upcoming particle physics experiments sterile neutrinos of GeV scale may appear in heavy hadron decays and can be detected as they decay into light SM particles. In proposed fixed target experiments such as SHiP [10] or DUNE [11] the main source of sterile neutrinos are D-mesons decays, so mostly only sterile neutrinos with masses below 2 GeV are produced. We note that in a part of parameter space such sterile neutrinos can be responsible for leptogenesis in the early Universe which allows for direct laboratory tests of early time cosmology [12].

The minimal values of mixing between sterile and active neutrinos, consistent with the type I seesaw mechanism, have been estimated in [1] for the case when some of sterile neutrinos are lighter than 2 GeV and CP-violating phases are set to zero. Our estimates (and that of Ref. [1] as well) are performed for mixing with only two sterile neutrinos: the third sterile neutrino is considered to be unobservable in the discussed experiments. One scenario is that the third sterile neutrino can be too heavy to be produced in the mentioned experiments. It can also be too light to be kinematically recognizable there. Or it can be of interesting mass range, but very feebly interacting, i.e. practically decoupled.

For $M_I = 500$ MeV, widely discussed in this paper, current upper limit on active-sterile mixing angles come from CHARM experiment [15] at $|U_e|^2, |U_\mu|^2 \sim 10^{-6}$. It can be improved in the near future by SHiP experiment [10], whose limit is expected to be as low as $|U_e|^2, |U_\mu|^2 \sim 10^{-9}$. In more detail present bounds and expected sensitivities of some future experiments one can found, for example, in Ref. [10].

The lower limit on mixing is usually associated with seesaw mechanism, Big Bang Nucleosynthesis (BBN) and some limits that are specific to concrete model. The seesaw limit is a plain mathematical limitations imbued on model (1) to make it consistent with current central values for active neutrino parameters. If sterile neutrino decays during BBN, products of decay would change light element abundances. Observation of these abundances gives us limit on contribution of non-standard BBN scenarios.

This work is based on the talk given at the XXth International Seminar “Quarks-2018”, which was based on my part of work in yet unpublished paper [16], written in co-authorship with Timofey Grigorin-Ryabov. The goal of this paper is to study the dependence of minimal mixing, consistent with the seesaw mechanism, on CP-violating phases, unaccounted before in Ref. [1]. During this research it also became obvious that the role of lightest active neutrino mass can be essential. The obtained results can be used to estimate the sensitivity of future experiments required to fully explore the parameter space of type I seesaw models with sterile neutrinos in the interesting mass range.

2 Matrix of mixing angles

The main subject of this work is the matrix of mixing angles between active and sterile neutrinos [1, 17, 19]

$$U = \frac{v}{\sqrt{2}} M_R^{-1} Y = i M_R^{-\frac{1}{2}} R m_\nu^{\frac{1}{2}} U_{PMNS}^\dagger \quad (2)$$

It depends on three complex angles z_i in matrix R and three yet unknown CP-violating phases of U_{PMNS} matrix. Also we know to a certain extent three U_{PMNS} matrix angles $\theta_{12}, \theta_{13}, \theta_{23}$ and two differences in active neutrino masses squared $\Delta m_{21}^2, |\Delta m^2|$, but neither mass of the lightest neutrino $m_{lightest}$ nor the hierarchy of masses.

We consider sterile neutrino production in a fixed-target experiment due to mixing (2) in weak decays of hadrons. As D-meson decays are the main source of sterile neutrinos in the mentioned fixed target experiments, sterile neutrinos with $M_I > 2$ GeV are too heavy to be produced. Sterile neutrino main signature is a weak decay into SM particles due to the same mixing. The number of signal events depends on the values of $|U_{I\alpha}|^2, I = 1, 2, 3; \alpha = e, \mu, \tau$. We should note that due to kinematics, mixing $|U_{I\tau}|^2$ doesn't play any role in the decays[1] of sterile neutrino emerged in decays of charmed hadrons. Hence we study the minimal values of $|U_{Ie}|^2$ and $|U_{I\mu}|^2$ in order to determine what maximal sensitivity the coming experiments should achieve to fully explore the type I seesaw model.

The case of one sterile neutrino being lighter than 2 GeV (e.g. $M_1 > 2$ GeV, $M_2 > 2$ GeV, $M_3 < 2$ GeV) is of little interest as sterile neutrinos N_1, N_2 can't be observed in the discussed experiments in this case. During the scan of possible values of unrestricted parameters $z_1, z_2, z_3, \alpha_1, \alpha_2$, there always can be found such a set of these parameters, that $|U_{3e}|^2 = 0, |U_{3\mu}|^2 = 0$. Because of that we can't rule out this model even if a fixed-target experiment doesn't detect sterile neutrinos with ultimately high precision. In this paper we only consider the case when one of sterile neutrinos doesn't have significant contribution to the mixing with active sector. If $M_1, M_2, M_3 \lesssim 2$ GeV all three sterile neutrinos kinematically can be born in D-meson decays. Although we don't specifically restrict this mixing in such a way, it would include also the special case where this sterile neutrino can play a role of warm dark matter [13], from cosmological constraints its mass is restricted to be in keV range and from experimental point of view not kinematically recognizable in fixed-target experiments. It was shown [14] that in that case when the two heavier sterile neutrinos are strongly degenerate in mass they can provide explanation for leptogenesis. This model is called neutrino minimal extension of the SM or just νMSM. It was suggested, though, that leptogenesis could be successful even with arbitrary masses of sterile neutrino, given that they are at the same scale, including GeV region, and mix to the active neutrino with comparable strength [20]. It is estimated in [6] for $M_I < 5$ GeV case that mixing $U_{\mu I}^2 \lesssim 10^{-10}$ is consistent with the leptogenesis scenario. The lower limits on mixing for $M_1, M_2, M_3 < 2$ GeV considered in [6] are $|U_{\mu I}|^2 \sim 10^{-13}$ for $m_{lightest} = 0.23$ eV and $|U_{\mu I}|^2 \sim 10^{-12}$ for $m_{lightest} = 0$. Study of the case of all three masses below 2 GeV scale, $M_1, M_2, M_3 < 2$ GeV, can be a subject for further research.

Lastly, the third neutrino can be heavy $M_1 < 2$ GeV, $M_2 < 2$ GeV, $M_3 > 2$ GeV. Naturally, in this case N_3 kinematically can not be produced in D-meson decays and has no effect in these experiments. We don't consider any specific way to test obtained mixing values in this paper. Basically all these values correspond to a concrete values of active and sterile neutrino parameters, some of which can't be observed in any experiments in the near future. The mixing itself can be constrained from heavy meson decays as we discussed earlier.

So for our setup the relevant observables are mixing angels between N_1, N_2 and ν_e, ν_μ. Our aim is to find the lowest sensitivity enough to rule out the seesaw mechanism. It implies

[1] Here we count only observable decay modes; $|U_{I\tau}|^2$ governs decay into unrecognisable τ-neutrino

the absence of any signal of either of sterile neutrinos. Hence the relevant combinations to constrain are:

$$U_e \equiv |U_{1e}|^2 + |U_{2e}|^2$$
$$U_\mu \equiv |U_{1\mu}|^2 + |U_{2\mu}|^2 \quad (3)$$

Thus we search for minimal values of U_e, U_μ, which, at a given M_1, M_2 guarantee full exploration of the seesaw mechanism for such case. It can be seen that U_e and U_μ don't depend on M_3 in this particular case. In our numerical studies, unless stated otherwise, we set $M_1 = 500$ MeV, $M_2 = 600$ MeV.

3 BBN constraint

We should note, that for sterile neutrinos at GeV scale we have constraints from the Big Bang Nucleosynthesis. They follow from the fact that sterile neutrino decay products would change light element abundances originating from BBN. Sterile neutrinos can be born in the early Universe, although we don't consider any specific mechanism in this paper. They are not stable due to mixings with active neutrino, and may decay during BBN. SM products of sterile neutrino decays are very energetic and can destroy atoms that has already been produced, thus changing chemical composition of the Universe. Direct observations imply limits on how much new physics can affect these abundances. These limitations are mainly independent from the seesaw constraint, and can significantly change with the introduction of some new physics affecting active-sterile neutrino mixing in the early Universe.

In our analysis [16] we come to a conclusion, that at least all values $10^{-23} < |U|^2 < 2 \times 10^{-11}$ are excluded by BBN.

We note, that BBN excludes only mixing $|U|^2$ above a certain, although significantly small, value. We show in this paper that such straightforward limitation can be a stronger constraint than seesaw mechanism constraint. BBN constraint is independent from seesaw mechanism constraint and can be avoided with introduction of the new physics. On side note, BBN doesn't constrain too weak mixings, which we show might also be allowed by seesaw constraint. As we discuss in Sec. 4.2.3, this scenario can't be tested in any experiments in the near future, so we don't study it in details. We state that our numerical estimate can't recognise values of mixing below $|U|^2 \sim 10^{-20}$, that lays in the zone still excluded by BBN. This qualitative estimate is correct for the interesting sterile neutrino mass range $100\,\text{MeV} < M_I < 2\,\text{GeV}$.

4 Numerical part

For our numerical simulations we take the observable parameters θ_{12}, θ_{13}, θ_{23}, Δm^2_{21}, $|\Delta m^2|$ from experimental data analysis [17], and not yet observed quantities $\delta, m_{lightest}, M_1, M_2$ as external parameters. After specifying these parameters we minimize functions U_μ and U_e using downhill simplex method taking $z_1, z_2, z_3, \alpha_1, \alpha_2$ as variables.

Note that possible values $\delta \in [0, 2\pi)$ can be restricted to $\delta \in [0, \pi)$, as (3) can't distinguish between some points of this area.

4.1 Zero phases

Firstly we study the dependence of minimal U_μ on U_e with zero CP-violating phases for a set of values of $m_{lightest}$ and two hierarchies of masses. This work was done in [1]. Obtained graphs have been almost identical to those of Ref. [1], but for the slight differences due to the usage of different values of experimentally observed variables.

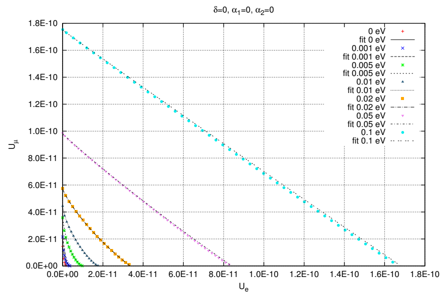

Figure 1. Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \alpha_1 = \alpha_2 = 0$. Different curves correspond to different $m_{lightest}$ values.

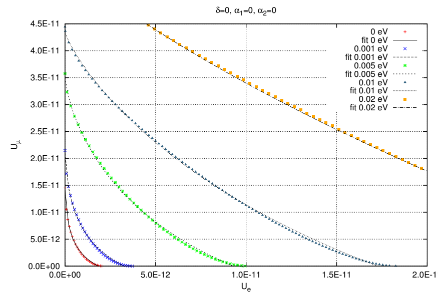

Figure 2. Zoom in the small scale area of Fig 1.

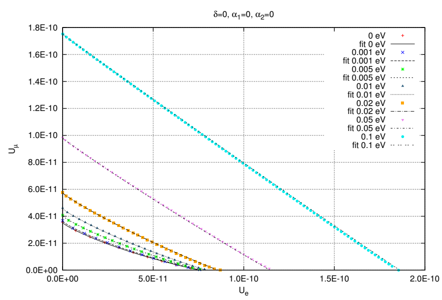

Figure 3. Dependence of minimal U_μ on minimal U_e for the inverted hierarchy and $\delta = \alpha_1 = \alpha_2 = 0$. Different curves correspond to different $m_{lightest}$ values.

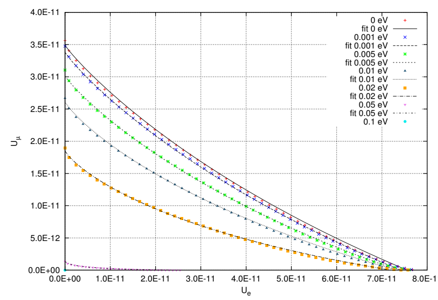

Figure 4. Dependence of minimal U_μ on minimal U_e for the inverted hierarchy. Different curves correspond to different $m_{lightest}$ values, $\delta, \alpha_1, \alpha_2$ are minimization variables.

In Figs. 1 – 3 we present the results calculated with presently accepted central values of neutrino parameters [17] for both hierarchies and we use only these values from now on as well.

We plot dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \alpha_1 = \alpha_2 = 0$ and different values of $m_{lightest}$ on Fig. 1. Fig. 2 is a zoom in a small scale area of Fig. 1, studied in [1]. On Fig. 3 we plot the same dependence for the inverted hierarchy.

To make further descriptions more tangible, we take for each specific curve the value of U_μ when $U_e = 0$ and the value of U_e when $U_\mu = 0$ and call them characteristic values of U_μ and U_e for this curve correspondingly. Usually we present only the smallest characteristic values. Thus for the normal hierarchy defined in that way the characteristic values of the seesaw mixing are $U_\mu \approx 1.5 \times 10^{-11}$, $U_e \approx 2 \times 10^{-12}$. For the inverted hierarchy they are $U_\mu \approx 3.5 \times 10^{-11}$, $U_e \approx 7.5 \times 10^{-11}$.

Basically, curves have the behaviour of “the greater the mass the higher the curves lay”. One can see that, for zero CP-violating phases, “$m_{lightest} = 0$” curve corresponds to the lower limit that the values of mixing can achieve. To fully explore type I seesaw model with corresponding sterile neutrino masses for zero CP-violating phases one just has to reach the sensitivity corresponding to that lower limit.

4.2 Non-zero phases

In this section we study the dependence of minimal U_μ on U_e, but with non-zero phases. We only lay out here some of the more characteristic graphs.

4.2.1 Inverted hierarchy

We plot dependence of minimal U_μ on minimal U_e for the inverted hierarchy and different values of $m_{lightest}$ on Fig. 4. The difference between graphs calculated using different values of δ can't be observed with naked eye. As dependence on δ doesn't play much role for these graphs, we only include graph for minimization on $\delta, \alpha_1, \alpha_2$.

For the inverted hierarchy and minimization on $\delta, \alpha_1, \alpha_2$ (Fig. 4) a significant difference can be seen as compared with zero phases case (Fig. 3). First of all while the curve corresponding to $m_{lightest} = 0$ practically doesn't change its position, other curves change their behaviour of "the greater the mass the higher the curves lay" to the opposite one of "the greater the mass the lower the curves lay". In this way, in case of non-zero CP-violating phases the lower limit corresponds to the curve with the highest possible mass. From graphs in Fig. 4 one can see that with growth of $m_{lightest}$ characteristic values of U_μ, U_e lose as much as several orders of magnitude. Here we define the characteristic values in the same way as we did it in 4.1. $m_{lightest} = 0$ curve keeps these values at $U_\mu \approx 3.5 \times 10^{-11}$, $U_e \approx 7.5 \times 10^{-11}$, not differing much from $\delta = \alpha_1 = \alpha_2 = 0$ case. For "$m_{lightest} = 0.05$ eV" curve characteristic values are estimated to be $U_\mu \approx 1.4 \times 10^{-12}, U_e \approx 2.7 \times 10^{-11}$. Characteristic values diminish even more rapidly with further growth of $m_{lightest}$, and for "$m_{lightest} = 0.1$ eV" curve these values are indistinguishable from the point of origin, $U_\mu \sim U_e \sim 10^{-20}$. This behaviour exceeds our expectation and we study dependence on the $m_{lightest}$ in more detail in Sec. 4.2.3. Nevertheless, this result shows that the estimation of the upper limit of $m_{lightest}$ can become the leading factor in determining the theoretical lower limit on the mixing angles. Non-zero values of minimized α_1, α_2 are responsible for the difference with results of Sec. 4.1.

4.2.2 Normal hierarchy

For the normal hierarchy the difference with zero phases case takes more complex shape.

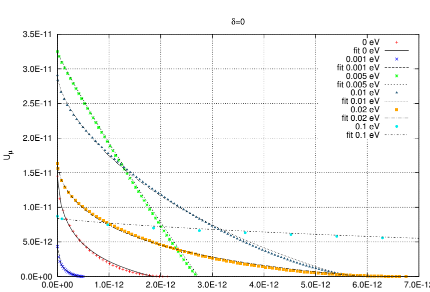

Figure 5. Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = 0$. Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.

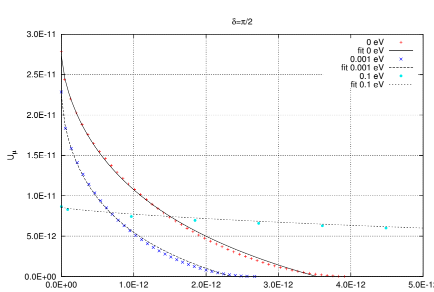

Figure 6. Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \frac{\pi}{2}$. Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.

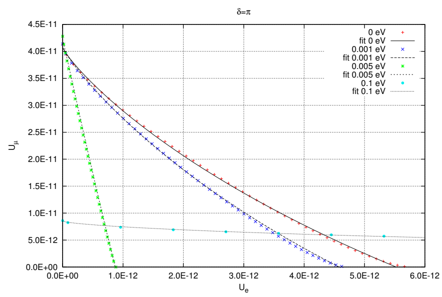

Figure 7. Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \pi$. Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.

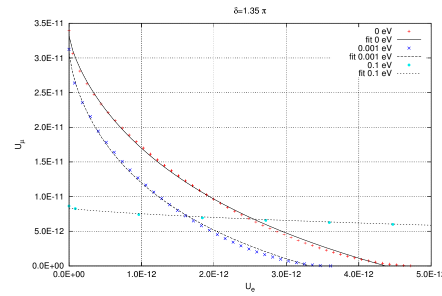

Figure 8. Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = 1.35\pi$ (the best fit value for the normal hierarchy). Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.

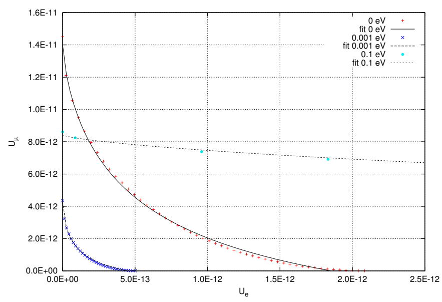

Figure 9. Dependence of minimal U_μ on minimal U_e for the normal hierarchy. Different curves correspond to different $m_{lightest}$ values, $\delta, \alpha_1, \alpha_2$ are minimization variables.

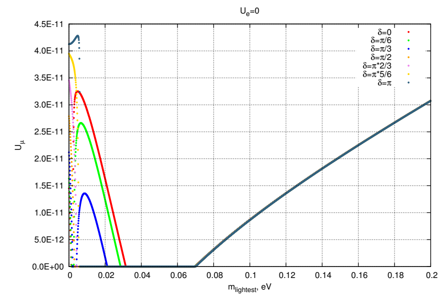

Figure 10. Dependence of minimal U_μ on $m_{lightest}$ at $U_e = 0$ for the normal hierarchy. Different curves correspond to different δ values.

We plot dependence of minimal U_μ on minimal U_e for the normal hierarchy and different values of $m_{lightest}$ for $\delta = 0, \frac{\pi}{2}, \pi, \delta = 1.35\pi$, on Figs. 5, 6, 7, 8 respectfully. α_1, α_2 are minimization variables. On Fig. 9 δ is also a minimization variable.

For zero phases (Figs. 1, 2) we have the "the greater the mass the higher the curves lay" behaviour. It changes completely, as curves start to cross each other, behave differently in areas with big values of $m_{lightest}$ compared to the areas of small values. For some masses the mixing angle takes such minuscule values, that the corresponding curves become indistinguishable from the point of origin (they lose several orders of magnitude up to $U_\mu \sim U_e \sim 10^{-20}$). Moreover, for different values of δ the graphs differ significantly from each other.

We study more closely the dependence of graphs on $m_{lightest}$ and δ to understand such behaviour in the next Sec. 4.2.3.

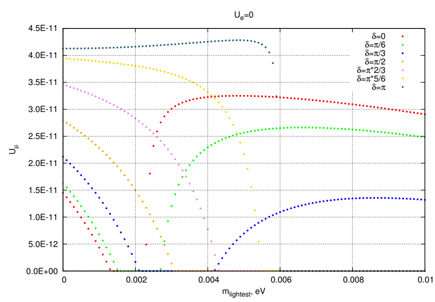

Figure 11. Zoom in the small scale area of Fig 10.

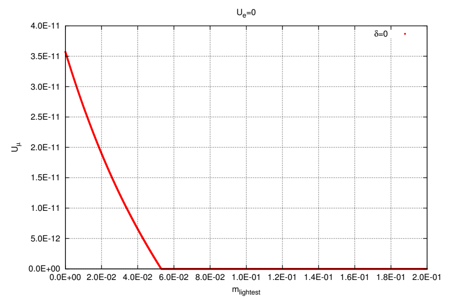

Figure 12. Dependence of minimal U_μ on $m_{lightest}$ at $U_e = 0$ and $\delta = 0$ for the inverted hierarchy.

4.2.3 Dependence on $m_{lightest}$

As each curve in Figs. 5 – 9 monotonously declines with growth of U_e, for convenience we choose the case of $U_e = 0$, representing the highest value of U_μ, as the characteristic point for each curve and study the dependence of U_μ on $m_{lightest}$.

Firstly, we plot dependence of minimal U_μ on $m_{lightest}$ for the normal mass hierarchy and U_e set to zero for a set of δ-phases (Figs. 10, 11). Starting from the $m_{lightest} = 0$ point on the graph, where values of all curves lay at the same magnitude of 10^{-11}, the curves start to decline as $m_{lightest}$ grows. The only exception is $\delta = \pi$ curve, which exhibits a short growth before it reaches a local maximum and starts to decline like every other curve. At this point all curves on this plot show a common behaviour: they decline swiftly, their values lose several orders of magnitude over minuscule increase in $m_{lightest}$. For linear scale it seems as if values of U_μ swiftly decline to almost zero values[2] and stay this way for a wide range of values of $m_{lightest}$, before they start to increase just as swiftly as they have declined earlier. Due to its distinguished form we call this problematic area the "plateau". Another point of interest is that the curves no longer depend on delta for all values of $m_{lightest}$ grater when "plateau" area, uniting into one curve, as can be seen on Fig. 10.

In the "plateau" area our estimate shows that values of U_μ can become as small as $U_\mu \sim 10^{-20}$, but we didn't estimate it exactly beyond that limit. What we mean is that the values certainly are no higher than the ones we provide, but in the "plateau" area they can be even lower than $U_\mu \sim 10^{-20}$. That is of low interest to us, given the fact that mixing $|U_{I\alpha}|^2 \sim 10^{-20}$ can't be tested by experiments in the foreseeable future. The reason why a small increment in the values of $m_{lightest}$ brings such drastic drop in the values of U_e, U_μ turns out to be a mutual subtraction. As we minimize α_1, α_2 in plateau area they can be chosen in such a way that both $U_{\mu 1}, U_{\mu 2}$ can loose their leading orders, their absolute values dropping drastically. On a side note, the mixing with third sterile neutrino in such case can be more intense than mixing with other two, but it won't be observable in considered experiments if $M_3 > 2$ GeV.

We plot dependence of minimal U_μ on $m_{lightest}$ for the inverted mass hierarchy and U_e set to zero for $\delta = 0$ on Fig. 12. For inverted hierarchy there is no significant dependence on δ for all values of $m_{lightest}$ and so we don't include graphs with other values of δ. Starting from the $m_{lightest} = 0$ point on the graph, where values of the curve lay at the magnitude of 10^{-11}, the curves start to decline as $m_{lightest}$ grows. If one looks in linear scale, curve simply reaches

[2]We should note, that U_μ and U_e can't reach zero values simultaneously. It's rather obvious, as one can't obtain matrix with three eigenvalues (active neutrino mass matrix) while using rotational matrix with only two non-zero eigenvalues.

“zero” value and after that stays in the “plateau”. At $m_{lightest} = 0.1$ eV curve still doesn’t leave “plateau”.

5 Conclusion

In this paper we study minimal possible mixing angles between sterile and active neutrinos $|U_{I\alpha}|^2$ for the specific case of two sterile neutrinos with masses less than 2 GeV. These angles provide us with information on sensitivity which experiments such as SHiP or DUNE or their successors should achieve to fully explore type I seesaw model. To that end we study the dependence of mixing matrix on model parameters $(\delta, \alpha_1, \alpha_2)$, that hasn’t been considered in work [1]. Characteristic values for zero phases are $|U_{I\alpha}|^2 \sim 10^{-11}$. Introducing the dependence on CP-violating phases, we observe strong dependence on the lightest neutrino mass $m_{lightest}$ and these phases. For both hierarchies minimal mixing $|U_{I\alpha}|^2$ could be lowered depending on $m_{lightest}$ and $(\delta, \alpha_1, \alpha_2)$ to the values of 10^{-20} at least. To summarize we conclude that still unknown parameters of active neutrino $m_{lightest}, \delta, \alpha_1, \alpha_2$ may significantly change the mixing pattern and should be taken into account in future experiments.

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