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Bounds on heavy sterile neutrinos revisited

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Abstract: We revise the bounds on heavy sterile neutrinos, especially in the case of their mixing with muon neutrinos in the charged current. We summarize the present experimental limits and we reanalyze the existing data from accelerator neutrino experiments and from Super-Kamiokande to set new bounds on a heavy sterile neutrino in the range of masses from 8 MeV to 390 MeV. We also discuss how the future accelerator neutrino experiments can improve the present limits.

Keywords: Neutrino Physics, Beyond Standard Model.

Contents

1. Introduction

The existence of three active neutrinos and of the mass eigenstates ν_1, ν_2, ν_3 is well established, but the existence of a forth heavy mass eigenstate, ν_h, mainly in the direction of a sterile neutrino, remains an open question. Sterile neutrinos are $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ singlet fermions, which can mix with ordinary neutrinos.

There many reasons why one is interested in the limits on sterile neutrinos. Heavy mostly-sterile neutrinos have been investigated for their role in cosmology and astrophysics (see, e.g., ref. [1]). A keV sterile neutrino is a viable dark matter candidate [2, 3], which can also explain the origin of the pulsar kicks [4]. Sterile neutrinos provide a viable framework for baryogenesis [5, 6]. It was pointed out [7] that if such heavy neutrinos constitute a small but non-negligible fraction of dark matter, their decays into e^+-e^- pairs might produce the 511 keV gamma line observed by the INTEGRAL γ-ray observatory. Decays of heavier neutrinos have been proposed to explain the early ionization of the Universe [8]. If neutrinos are Majorana particles, they could mediate processes that violate the lepton number by two units, such as neutrinoless double beta decay, muon-positron conversion, and rare kaon decays [9]. In particular, for masses $245\,\mathrm{MeV} < m_h < 388\,\mathrm{MeV}$, the decay $K^+ \to \pi^- \mu^+ \mu^+$ could be strongly enhanced [10]. From the theoretical point of view, heavy sterile neutrinos with masses in this range arise naturally in extended technicolor models [11]. Because of these interesting possibilities, we want to map out the parameter space available for sterile neutrino masses and mixing parameters.

Here we consider the bounds on heavy neutrinos with masses $1\,\mathrm{MeV} \lesssim m_h \lesssim 400\,\mathrm{MeV}$, which are produced in pion, muon and kaon decays. We will review the existing limits on the mass and mixing of a heavy, mostly-sterile, neutrino [12 – 27]. We will then derive new bounds based on a re-analyses of the data from neutrino oscillations and accelerator neutrino experiments. In the 10–390 MeV mass range we use the data from accelerator experiments [24 − 27]. For masses $8\,\mathrm{MeV} \lesssim m_h \lesssim 105\,\mathrm{MeV}$, we use the Super-Kamiokande (Super-K) data [28]. We will also discuss ways in which the present and future neutrino oscillation experiments, such as MiniBOONE [29], K2K [30] and MINOS [31], can strengthen the present bounds. We also review the best current limits, based on big-bang nucleosynthesis (BBN) [32].

Let us characterize the mixing of the heavy neutrinos ν_h with the active neutrinos ν_a $(a = e, \mu, \tau)$ by the corresponding element in the mixing matrix U, which is the mixing matrix between the electroweak eigenstates and the mass eigenstates. The matrix U accounts for mixing in the neutral current (NC) interactions. In processes mediated by the lepton charged current (CC), the matrix U enters in combination with a unitary matrix V, which diagonalizes the charged lepton mass matrix. In principle, CC and NC interactions allow one to measure or constrain separately the elements of VU and U, respectively. If one takes $V = 1$, the elements of the matrix U can be interpreted as neutrino mixing angles. We will not make any assumptions about the matrix V and will present the constraints in full generality. We will assume, for simplicity, throughout our analysis that ν_h mixes mainly with ν_μ in the charged current, $(VU)_{eh}, (VU)_{\tau h} \sim 0$, while we allow for $U_{ah} \neq 0$, $a = e, \mu, \tau$, in the neutral current.

In section 2 we review the bounds coming from the analysis of the spectrum of muons in pion and kaon decays. In section 3 we study the case of mostly-sterile neutrino decays into visible decay products which would be observable in a detector. We discuss the limits on the mixing which can be obtained from accelerator neutrino and Superkamiokande data and the prospects for strengthening such bounds in present and future neutrino experiments. In section 4 we briefly review the bounds from big bang nucleosynthesis and supernovae. Finally, we summarize our results in the Conclusions.

2. Bounds on ν_h production

The different massive neutrinos ν_i, $i = 1, 2, 3, 4$, if they exist, are produced in meson decays, e.g. $\pi^\pm \to \mu^\pm \nu_i$, with probabilities that depend on the mixing in the charged current, VU. In our analysis we will assume that the heavy sterile neutrinos mix mainly with muon neutrinos in the charged current. We allow for mixing with all active neutrinos in the neutral current. The energy spectrum of muons in such decays would contain monochromatic lines [12] at

$$T_i = \frac{(m_\pi^2 + m_\mu^2 - 2m_\pi m_\mu - m_{\nu_i}^2)}{2m_\pi}\,, \tag{2.1}$$

as long as $T_i > 0$. Here T_i is the muon kinetic energy; m_π, m_μ, and m_{ν_i} are the masses of pion, muon and the ith neutrino mass eigenstate, respectively. The dominant line is obtained for nearly massless neutrinos, $\nu_{1,2,3}$, at $T_0 = 4.120\,\mathrm{MeV}$. Additional peaks in the muon energy spectrum would be present at a position related to the mass of the heavy neutrino, eq. (2.1), and with a branching ratio that depends on the mixing angle. The

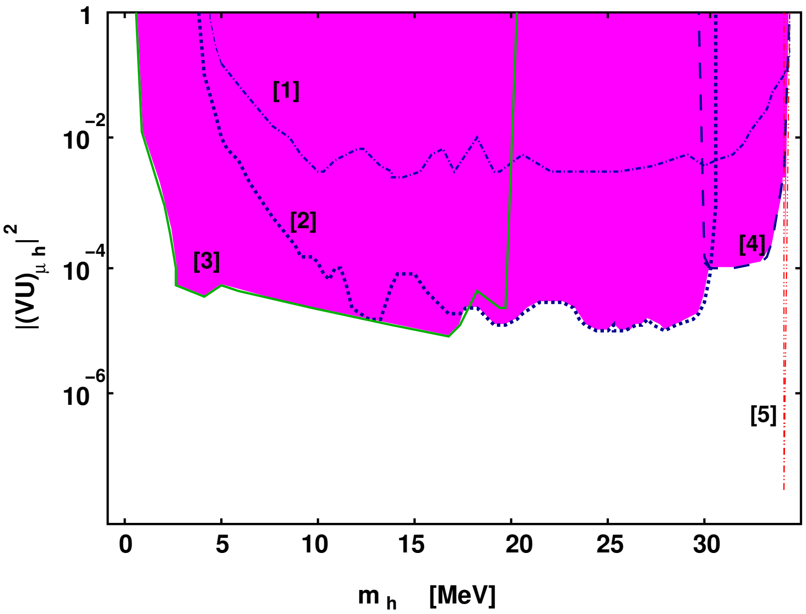

Figure 1: The exclusion plot for $|(VU)_{\mu h}|^2$ based on the energy spectrum of muons in pion decays. The excluded region is indicated in gray color (magenta color online). The bounds are taken from the analysis reported (i) in ref. [14] for the dash-dotted line indicated as "[1]"; (ii) in ref. [13] for the dotted line "[2]"; (iii) in ref. [16] for the solid line shown as "[3]"; (iv) in ref. [17] for the dashed line "[4]"; (v) in ref. [19] for the dashed-double dotted line labelled "[5]". The bounds are 90% C.L., except for the one marked "[5]", which is 95% C.L.

same is true for muons from K decays. Searches for peaks in pion decays [12 – 21] and in kaon decays [22, 23] found no signal and set stringent bounds on $|(VU)_{\mu h}|^2$ for masses $m_h \lesssim 360\,\mathrm{MeV}$. The corresponding excluded regions from pion and kaon decays are shown in figures 1 and 2 as gray regions, respectively. Different lines represent limits obtained in different experiments (see captions of figures 1 and 2).

3. Bounds on ν_h decays

A heavy neutrino produced in $\pi^\pm$ and $K^\pm$ decays would subsequently decay, and its decay products could be detected. The absence of such detection translates into strong bounds on the mixing angles with active neutrinos. In the mass range 10–390 MeV, we set a new bound on $|(VU)_{\mu h} U_{ah}|$, as shown in figure 4.

A heavy neutrino mixed with active neutrinos can decay into different channels depending on its mass. If $1\,\mathrm{MeV} \lesssim m_h \lesssim 105\,\mathrm{MeV}$, ν_h decays via neutral currents into (i) an active neutrino and an electron-positron pair, $\nu_h \to \nu_a + e^+ + e^-$, (visible channel) and (ii) into three neutrinos, $\nu_h \to \nu_a + \nu_j + \bar{\nu}_j$, (invisible channel).

In the simplest case, when sterile neutrinos directly couple only to one active neutrino in the neutral current with mixing U_{ah},[1] the mass of the heavy neutrino is much larger then electron mass $m_e \ll m_h < m_{\pi^0}$, and we assume that in the CC current $(VU)_{eh} \sim 0$,

[1] In the literature the mixing is often parametrized by a mixing angle θ. We have that $\sin^2\theta \equiv |U_{ah}|^2$.

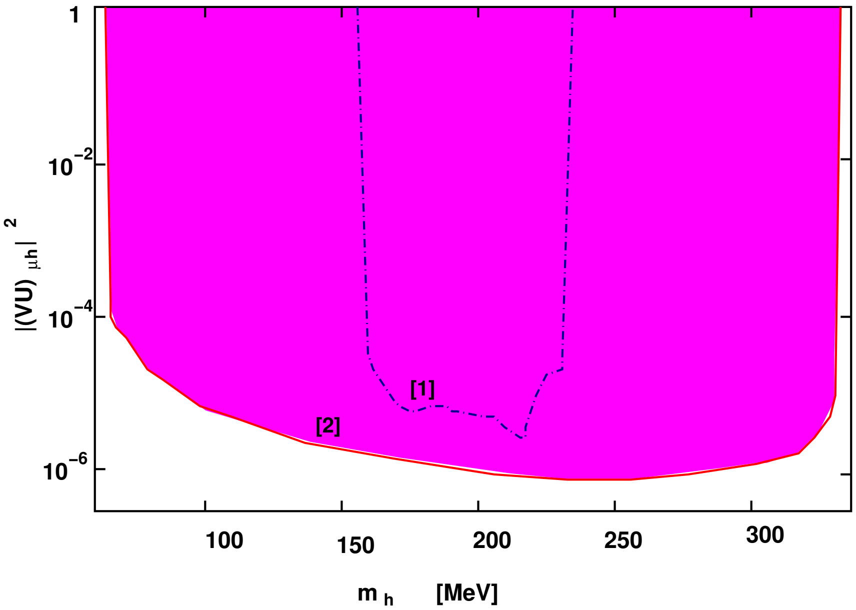

Figure 2: The same as in figure 1 but for ν_h from kaon decays. The bounds are taken from ref. [22] for the dash dotted line indicated as "[1]" at 2 σ and from the data of the experiment by R. S. Hayano et al., ref. [23], for the solid line labelled "[2]" at 90% C.L.

the decay width is given by [33]:

$$\Gamma_{\nu_h} = \frac{1 + (g_L^a)^2 + g_R^2}{768\pi^3} G_F^2 m_h^5 \, |U_{ah}|^2 \,, \tag{3.1}$$

where $g_L^e = 1/2 + \sin^2\theta_W$, $g_L^{\mu,\tau} = -1/2 + \sin^2\theta_W$, $g_R = \sin^2\theta_W$. If the heavy neutrino mixes with ν_e in the charged current, the decay $\nu_h \to \nu_e e^+ e^-$ would receive an additional contribution from CC interations. In the absence of charged currents, the corresponding branching ratios are equal to $B_e = (\tilde{g} - 1)/\tilde{g} \approx 0.11$ for the visible channel and $B_\nu = 1/\tilde{g} \approx 0.89$, for the invisible channel. Here we have defined $\tilde{g} \equiv 1 + (g_L^a)^2 + g_R^2$. For larger masses, new channels are open, namely $\nu_h \to \pi^0 \nu_\mu$ and $\nu_h \to \mu^+\mu^-\nu_a$ which are mediated by neutral currents, and $\nu_h \to \mu^- e^+ \nu_e$, $\nu_h \to \mu^+\mu^-\nu_\mu$ and $\nu_h \to \pi^+\mu^-$, due to CC interactions. For $m_h > m_\pi$, the two-body decays dominate and typically the half-life time is of order $\tau_h \sim (10^{-8} - 10^{-9})\ |U_{\mu h}|^{-2}\ (|(VU)_{\mu h}|^{-2})$s, for the NC (CC) mediated processes.

3.1 Searches for accelerator neutrino decays

The decay length of a sterile neutrino with energy $E_h \gg m_h$ is $L_\mathrm{d} = c\ \tau_h \gamma_F$, where $\gamma_F = E_h/m_h$ is the ν_h gamma factor. The fraction of heavy neutrinos that can reach the detector before decaying is $\exp(-R_\mathrm{cr}/L_\mathrm{d})$, where R_cr is the distance from the neutrino production site to the detector. Of these neutrinos, for $h/L_d \ll 1$, a fraction $B_\mathrm{vis}\, h/L_d$ decays in the detector via a visible channel. Here B_vis is the branching ratio of the given decay channel and h is the length of the detector. The number of heavy neutrino decays

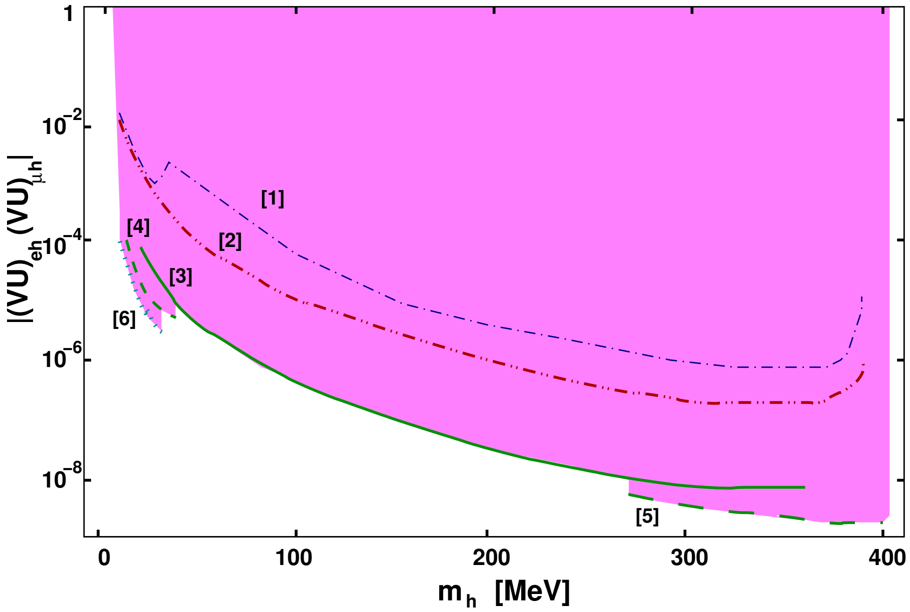

Figure 3: The bounds on $|(VU)_{\mu h}(VU)_{eh}|$ versus m_h obtained from searches of ν_h decays. The excluded region is indicated in gray color (magenta color online). The limits are taken for the lines labelled as (i) "[1]" (dashed-dotted line) from the data in ref. [24] ; (ii) "[2]" (dashed-double dotted line) from the experiment in ref. [27]; (iii) "[3]" (solid line) from refs. [25, 26]; (iv) "[4]" and "[5]" (dashed lines) from the analysis in ref. [26]; (v) "[6]" (dotted line) from the experiment reported in ref. [25]. The limits are at 90% C.L..

in the detector is then given by (see, e.g., ref. [27])

$$\mathsf{N} = N_{\pi,K} B(M \to \mu\nu_h) B_{\rm vis} \frac{h}{L_d} \Omega\epsilon\,, \tag{3.2}$$

where $N_{\pi,K}$ is the number of pions and kaons, $B(M \to \mu\nu_h)$ is the branching ratio of the meson decays into a muon and a heavy neutrino, Ω and ϵ are the detector acceptance and efficiency, respectively. In a similar way one can consider heavy neutrinos produced in muon decays.

Limits on the mixing of the heavy neutrino with ν_e and ν_μ were set by different experiments [24–27]. We review them in figure 3. In the mass range $1\,\mathrm{MeV} \leq m_h \leq 33.9\,\mathrm{MeV}$ the excluded region comes from heavy neutrino production in pion decays. For higher masses, $40\,\mathrm{MeV} \lesssim m_h \lesssim 360\,\mathrm{MeV}$, kaon decays were taken into account. Different visible decay channels have been studied. The channel $K^+ \to \mu^+\nu_h \to \mu^+(\mu^- e^+ \nu_e) + \mathrm{c.c.}$ was used to constrain the elements of the mixing matrix VU, for masses up to $\sim 260\,\mathrm{MeV}$ (see figure 3). For heavier masses a new decay channel is open, $K^+ \to \mu^+\nu_h \to \mu^+(\pi^+\mu^-)+$ c.c., and dominates.

We note that in refs. [24–27] the NC contribution to the decay of ν_h has not been taken into account. They mediate the principal decay modes both for neutrinos with $m_h < m_{\pi^0}$: ($\nu_h \to \nu\nu\bar{\nu}$) and with $m_h > m_{\pi^0}$: ($\nu_h \to \pi^0\nu$.) However this omission does not affect the bounds obtained in refs. [24–27] because their visible decay channel is always dominated

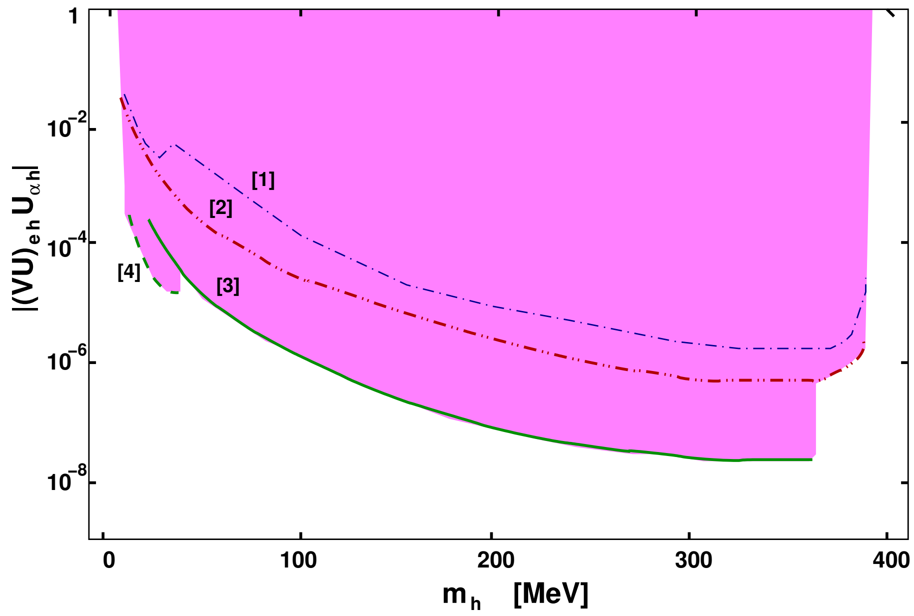

Figure 4: The same as in figure 3 but for the bounds on $|(VU)_{\mu h}U_{ah}|$. For the lines labelled as "[1]"–"[4]", the limits are obtained from a reanalysis of the data reported in the references as indicated for figure 3.

by the charged current (CC) interactions. Since the flavor of the final neutrino is not detected in these experiments, the channels $K^+ \to \mu^+\nu_h \to \mu^+(e^-e^+\nu_e)$, mediated by CC, and $K^+ \to \mu^+\nu_h \to \mu^+(e^-e^+\nu_{e,\mu,\tau})$, mediated by NC, are effectively indistinguishable. The former channel was used to constrain the $|(VU)_{eh}(VU)_{\mu h}|$ mixing. However, the same data can be used for setting a bound on $|(VU)_{\mu h}U_{ah}|$, with $a = e, \mu, \tau$, if one includes the contribution due to the latter channels.

We used the limit on $|(VU)_{eh}(VU)_{\mu h}|$ from refs. [24–27], corrected it by including the contribution from the NC to the total decay width, with $(VU)_{eh}$ negligible, and the branching ratio of $K^+ \to \mu^+\nu_h \to \mu^+(e^-e^+\nu_a)$ channel, and translated it into the new bound on $|(VU)_{\mu h}U_{ah}|$. These bounds have not been previously discussed in the literature and are reported in figure 4. The new limits are given at the same confidence level as the ones on $|(VU)_{eh}(VU)_{\mu h}|$.

If $V = 1$, our limit on $|U_{\mu h}|^2$ turns out to be the strongest limit in the mass range $34\,\text{MeV} \lesssim m_h \lesssim 200\,\text{MeV}$ (see figure 5).

Analogously, the bounds on $|U_{eh}|^2$ [25, 26] from $\pi^+, K^+ \to e^+\nu_h \to e^+(e^+e^-\nu_e)$ + c.c., mediated by CC interactions, can be used to constrain $|(VU)_{eh}U_{ah}|$ from the decays $\pi^+, K^+ \to e^+\nu_h \to e^+(e^+e^-\nu_a)$ + c.c., which are induced by neutral currents. Also these bounds are new but a detailed analysis is beyond the scope of the present article.

3.2 Decays of atmospheric heavy neutrinos

We point out that one can also set an independent limit based on non-observation of atmospheric sterile neutrino decays by Super-Kamiokande. In the following we provide a

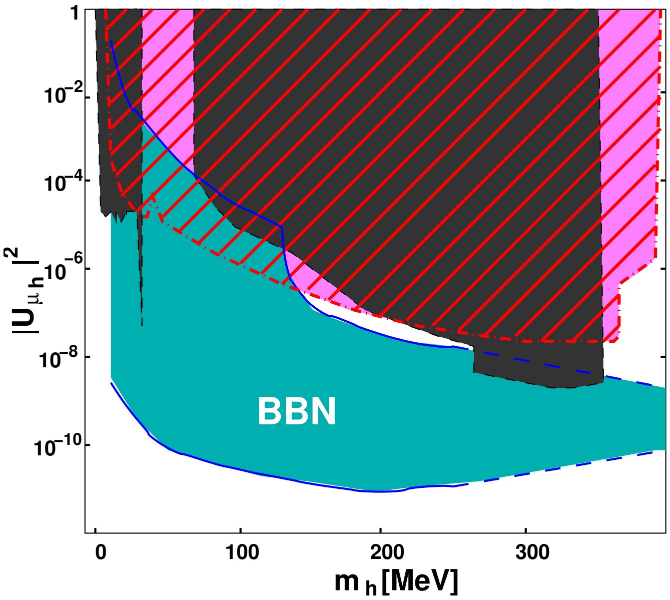

Figure 5: The strongest bound (indicated as line "[3]" in figure 4 from the reanalysis of data from ref. [25, 26] (diagonally hatched region with dashed-dotted contours). The limits from big bang nucleosynthesis are indicated with the light blue-light gray region with continuous contours, and the previous bounds from experimental searches are shown as dark gray regions with dashed contours. For simplicity, here we take $VU = U$.

qualitative analysis of Super-Kamiokande data in order to put a bound on the decays of heavy neutrinos, if produced in the atmosphere. We also give an estimate for the limit on $|U_{ah}|^2$, which we expect to be correct within a factor of 2–3. We assume for simplicity that $(VU)_{\mu h}$ dominates in the charged current while $(VU)_{eh} \sim 0$.

Heavy neutrinos can be copiously produced in the atmosphere and can decay inside the Super-K detector generating such a high event rate. The differential flux dF_h/dE of heavy sterile neutrinos produced in the atmosphere in pion, kaon and muon decays is related to the active neutrino flux F_a $(a = e, \mu, \tau)$:

$$\frac{dF_h(E)}{dE} = |(VU)_{\mu h}|^2 \frac{dF_\mu(E)}{dE}\,, \tag{3.3}$$

where $dF_a(E)/dE$ is the differential flux of (active) atmospheric neutrinos.

The expected rate of decays, R, detected in a given energy bin is

$$\mathsf{R}(E_1) = B_e \epsilon(E_1) \left\{ \int_{E_1}^{E_1+\Delta E} dE \frac{dF_h}{dE} A \frac{h}{L_\mathrm{d}} e^{-R_\mathrm{cr}/L_\mathrm{d}} \right\}, \tag{3.4}$$

where B_e is the branching ratio of the $\nu_h \to e^+e^-\nu_a$ channel, due to NC, and $\epsilon(E_1)$ is the efficiency to detect the decay products visible in the detector, E_1 is their average energy, A is the detector area. This rate should not exceed the rate of events observed by the Super-K experiment per energy bin, $\mathsf{R}(E_1) < R_\mathrm{event}(E_1)$.

It is clear that the highest number of events should come from neutrinos with the smaller gamma-factor γ_F, $\gamma_F \sim 2-3$ (we conservatively take $\gamma_F \gtrsim 2$ to ensure that the production of ν_h is not suppressed by threshold effects). If the gamma factor of ν_h is small,

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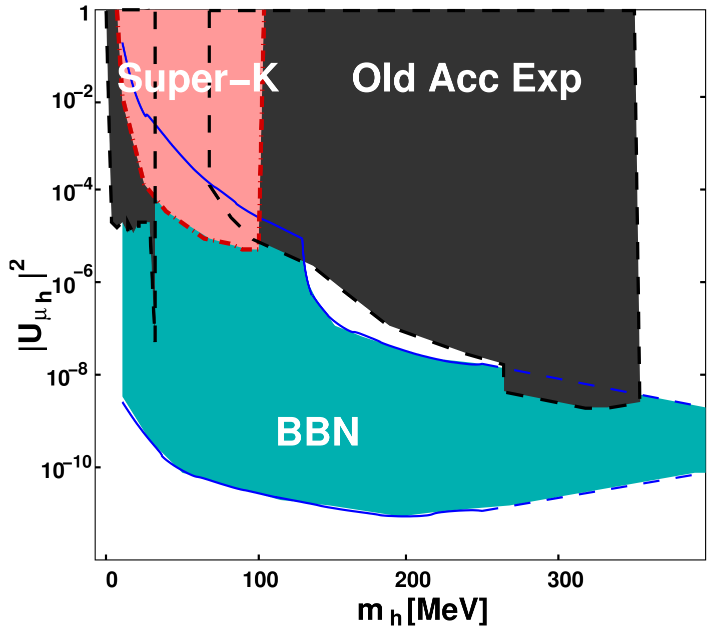

Figure 6: The exclusion plot based on the non-observation of e-like events from the heavy Dirac neutrino decays in Super-Kamiokande detector at a rate higher than the observed π^0-like event rate [28] (region with red dash-dotted contour). Also shown are the bounds from big bang nucleosynthesis (light blue-light gray region with continuous contours), and from experimental searches (regions with dashed contours). We assume $VU = U$.

$\gamma_F \sim 2-4$, most of the emitted e^- and e^+ produce in the Super-K detector 2 separate Cerenkov-light cones, which would be interpreted as 2 e-like events coming from the decay of $\pi^0 \to \gamma\gamma$ (π^0-like events). We use the data reported in ref. [28] where the invariant mass distribution for π^0-like events is shown per energy bin of 10 MeV, for 1489.2 days and 22.5 kton of fiducial volume, $V \sim Ah$. In the case of a three-body decay, the invariant mass reconstructed from the energy and momentum of e^+ and e^- is

$$m_{12}^2 = (p_1 + p_2)^2 = m_h^2 + m_\nu^2 - 2m_h E_\nu \,, \tag{3.5}$$

where $p_{1,2}$ are the four-momenta of e^+ and e^-, and $m_\nu \ll m_h$ and E_ν are the mass and the energy carried away by the undetected ν_μ, in the reference frame of ν_h. We assume, for simplicity, that the heavy neutrino decays in 3 relativistic particles, ν_a, e^+ and e^-, each having, on average, 1/3 of the total energy. The reconstructed invariant mass can be related to the heavy neutrino mass $m_{12}^2 \simeq 1/3\ m_h^2$.

We compute the number of 2e-like events in each bin of m_{12}^2 expected from ν_h decays, with $\gamma_F \sim 2-4$. We take into account the energy dependence of dF_h/dE: the differential flux is with good approximation constant for $E \lesssim 100$ MeV, and then it decreases (see, e.g., ref. [34]). Comparing the number of expected events from the ν_h decays with the π^0-like events, N_{exp}, in each invariant mass m_{12}^2 bin, we obtain an upper bound on $|(VU)_{\mu h} U_{ah}|$. We show this bound in figure 6 (vertically hatched region), if $V = 1$, for Dirac sterile neutrinos which mix mainly with ν_μ. For Majorana neutrinos the bound is somewhat stronger because the decay rate is larger, as they could decay both in one channel and in its CP-conjugate. A more detailed analysis which includes the contribution of decays of ν_h with $\gamma_F < 2$, threshold effects in the production of ν_h in pion and muon decays, the zenith angle dependence and γ_F-dependence of the suppression factor $\exp(-R_{cr}/L_d)$, should be performed but it is not the main focus of our paper. However we expect our conservative bound to remain valid within a factor of a few, as it would be strengthened by the inclusion of events with $\gamma_F < 2$, the suppression $\exp(-R_{cr}/L_d)$ is not very important for the masses and mixing parameters considered, the number of decays with large γ_F which could be misinterpreted as single e-like events is suppressed by a larger L_d and, for large masses, by a smaller flux of ν_h.

Most of the decay products e^+e^- from heavy neutrinos with larger gamma factors, $\gamma_F \gg 3$, would produce 2 nearly overlapping Cerenkov rings, which would be recorded as a single e-like event with twice the energy. Limits on the allowed range of m_h and $|(VU)_{\mu h}U_{ah}|$ based on these events are typically of the same order of magnitude but are somewhat weaker than those shown in figure 6.

For masses $m_h \lesssim 7-8\,\mathrm{MeV}$, the Super-K threshold limits one's ability to set a bound because only neutrinos with $E_h \gg m_h$ would be above the threshold.

In principle one could use the same technique to constrain the mixing angle for heavy sterile neutrino with masses up to $m_h < m_K - m_\mu$, produced in K decays. However, this bound would be very weak because too few neutrinos come from K decays. Our bound based on the Super-K data is a factor of few weaker than the bound that we obtained by re-analyzing the accelerator data, as discussed above. A much tighter bound, possibly stronger than the present limit for masses in the 8–105 MeV range, could probably be obtained if one included the directional and other information from the Super-K data not available to us. The bound can be further improved in the future, after more data is collected by Super-K or by a bigger detector, e.g., Hyper-K.

3.3 Future accelerator experiments

Present and future accelerator neutrino experiments KEK to Kamioka (K2K) [30], MiniBooNE [29] and MINOS [31], have the possibility of setting new, possibly stronger, bounds on the mixing parameters. Neutrinos are produced in the decay of pions, muons and kaons. The number of proton on target is very high: 10^{20} for K2K and 10^{21} for MiniBooNE and MINOS. The average neutrino energies are around 1 GeV for K2K and MiniBooNE and 2.5-3 GeV for MINOS. If heavy neutrinos are produced, they would travel toward the detectors where the $e^\pm$, $\mu^\pm$, π^0 and $\pi^\pm$ generated in their decays would be detected. In MiniBooNE [29], the detector is of length ~ 10 m, and collects the Cerenkov and scintillation lights. Both K2K and MINOS have a near and a far detector which can both be used to search for heavy neutrino decays. The K2K long-baseline experiment [30] uses a near 1 Kton water Cherenkov detector and as a far detector Super-K. The MINOS [31] experiment has a near and a far iron-scintillator detectors of length $h \sim 20 - 30$ m, respectively. For the far detector timing can be used to reduce the backgrounds. The neutrino beam is pulsed with a typical duration of the spill of few μs. The data read-out of the signal in the detector is done in a time-window around the

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beam spill of 1.5 and 10-20 μs for K2K and MINOS, respectively. The heavy neutrinos will take longer to reach the detector, typically few to tens of μs after the light neutrinos. Therefore a sizable fraction, if not most, of the heavy neutrino decay signal could be time-separated from the background given by the accelerator ν_e and ν_μ interactions. Directionality can be used to disentangle a ν_h signature from active atmospheric neutrinos.

As discussed previously, depending on their masses and on the mixing with the active neutrinos, the heavy neutrinos decay mainly in $\nu_h \to 3\nu_a$, $\nu_h \to e^+e^-\nu_a$, $\nu_h \to \mu^\pm e^\mp \nu_\mu$, and for $m_h > m_\pi$ in $\pi^0\nu_a$, $\pi^\pm e^\mp$, $\pi^\pm\mu^\mp$. The CC induced decays would allow to constrain the product $|(VU)_{eh}(VU)_{\mu h}|$, while the NC processes $|(VU)_{\mu h}U_{ah}|$. The flux contains ν_h with different γ_F, which would give different signatures in the detector. A detailed analysis which takes into account the heavy neutrino spectrum, the different decay channels and their signals in the detector, the relative backgrounds needs to be performed in order to achieve a good evaluation of the sensitivities for these experiments. Nevertheless we can provide an order of magnitude estimate for the limits which can be reached on the mixing parameters. Searching for 2 e-like, single e-like, μ-like and pion events, K2K, MiniBooNE and MINOS should be able to reach sensitivities as good as a few$\times 10^{-7}$ for $m_h \sim 100\,\mathrm{MeV}$. The sensitivity would be of the order of a few$\times 10^{-9}$ and a few$\times 10^{-10}$ for heavy neutrino masses $m_h \sim 200\,\mathrm{MeV}$ and $300\,\mathrm{MeV}$, respectively.

In contrast with the other experiments, MINOS has a very good discrimination of μ^+ and μ^-. Neutrinos with $m_h \gtrsim 210\,\mathrm{MeV}$ would decay in this channel with a branching ratio which is typically $\sim 10^{-3}$. The decay $\nu_h \to \mu^+\mu^-\nu_\mu$ receives a contribution from CC interactions and therefore allow to constrain not only $|(VU)_{\mu h}U_{ah}|$ but also $|(VU)_{\mu h}|^2$. As no significant background is expected for this decay mode, this would be a clear signature of the existence of heavy neutrinos. The number of events would allow to establish the value of the relevant mixing angle and the reconstructed invariant mass the value of m_h.

We note that a possible future detection of the peak in the invariant mass distribution for 2 e-like events from $\nu_h \to e^+e^-\nu_a$, after the contribution due to π^0-decays is subtracted, for 2 μ-like events due to $\nu_h \to \mu^+\mu^-\nu_a$ and for $\pi^\pm$ and $e^\mp$ $(\mu^\mp)$ produced in the decays $\nu_h \to \pi^\pm e^\mp(\mu^\mp)$ decays, would signal the existence of a sterile neutrino and would allow a measurement of its mass and mixing. If the different decay channels can be well distinguished, a comparison of the observed branching ratios with the theoretically predicted ones would allow to confirm the hypothesis of heavy neutrino decays as the origin of the observed signal. Furthermore, if from indipendent measurements we have that $|(VU)_{\mu h}U_{\mu h}| \neq |(VU)_{\mu h}|^2$, it would be possible to establish that $V \neq 1$ and test the existence of mixing in the charged lepton sector.

As already noticed in the previous discussion, the data from the MiniBooNE and MINOS experiments can be used to constrain also the combinations $|(VU)_{eh}|^2$, $|(VU)_{eh}$ $(VU)_{\mu h}|$, $|(VU)_{eh}U_{ah}|$, once the proper decay channels and branching ratios are taken into account. Also for these mixing terms, we expect a strengthening of the present bounds.

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4. Bounds from cosmology and astrophysics

Heavy sterile neutrinos in the MeV mass range would be produced in the Early Universe and subsequently decay affecting the predictions of Big-Bang Nucleosynthesis (BBN) for the abundance of light elements and in particular of ^{4}He (see, e.g., ref. [32]). The main effect would be to increase the energy density, leading to a faster expansion of the Universe and to a ealier freeze out of the n/p-ratio. In addition, the decay of ν_h into light neutrinos, in particular, ν_e, would modify their spectrum and the equilibrium of the $n-p$ reactions. We report in figures 5 and 6, the bounds on the masses and mixing angle of the heavy sterile neutrino, which can be obtained from big bang nucleosynthesis. Note that in ref. [32] the BBN bounds were derived up to m_h 200 MeV. It was shown that in the region 140–200 MeV the dominant decay chanel is into pions. We extrapolate those bounds above the QCD phase transition up to 400 MeV (dashed border of the BBN excluded region) taking into account the change in relativistic degrees of freedom, which softens the BBN bounds. In order to produce a more careful BBN bound for $m_h > 200\,\mathrm{MeV}$ a detailed analysis similar to the one in ref. [32] should be performed but is beyond the scope of the present study. In figures 5 and 6 we indicate our estimated BBN bound above 200 MeV with dashed lines to underline that these limits should be considered valid within factors of a few.

In principle, SN1987A could be used to exclude sterile neutrinos with mixing angles $10^{-7} \lesssim |U_{\mu h}|^2 \lesssim 10^{-2}$ and masses $m_s \lesssim T_{\rm core}$, where $T_{\rm core} = 30 - 80\,\mathrm{MeV}$ is the core temperature of the neutron star at about 0.1 second after the onset of the supernova explosion [32]. For masses in excess of $T_{\rm core}$, the production of sterile neutrinos is suppressed by the Boltzmann factor. The emission of sterile neutrinos from the core depends on the pattern of their mixing with active neutrinos, and in some cases the emission history can be very complicated [35]. Given the uncertainty in the SN models, one cannot set a reliable bound outside the range already excluded by the combined BBN and new accelerator neutrino bounds shown in figure 5.

5. Conclusions

We have considered heavy sterile neutrinos mixed mainly with muon neutrinos in the charged current. These neutrinos would be produced in pion and kaon decays due to their mixing with ν_μ. They would subsequently decay into standard model particles, e.g. neutrinos, electrons and positrons. The non-observation of the decay products in past dedicated experiments has sets some stringent bounds on the mixing angle between heavy and active neutrinos. We have reanalyzed the existing accelerator data and set new bounds on heavy neutrinos with masses in the range $10\,\mathrm{MeV} \lesssim m_h \lesssim 390\,\mathrm{MeV}$. In addition, we have used the Super-Kamiokande data to set a new independent bound on the mixing of a sterile neutrino with mass in the 8-105 MeV range. We have also discussed the potential of future experiments, as K2K, MiniBooNE and MINOS, in improving the present limits.

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