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 the 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: sterile neutrinos, neutrino masses
1. Introduction

The existence of three active neutrinos and of the mass eigenstates $\nu_1, \nu_2, \nu_3$ is well established, but the existence of a forth heavy mass eigenstate, $\nu_h$, mainly in the direction of a sterile neutrino, remains an open question. Sterile neutrinos are SU(3)×SU(2)×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 $\gamma$-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 MeV < $m_h$ < 388 MeV, the decay $K^+ \rightarrow \pi^-\mu^+\mu^+$ 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 MeV $\lesssim m_h \lesssim 400$ 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, 13, 14, 15, 16, 17, 18, 19, 20].
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 \[24, 25, 26, 27\]. For masses \(8 \, \text{MeV} \lesssim m_h \lesssim 105 \, \text{MeV}\), 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 \(\nu_h\) with the active neutrinos \(\nu_a\) \((a = e, \mu, \tau)\) 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 \(V\) 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 \(V\) 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 \(\nu_h\) mixes mainly with \(\nu_{\mu}\) 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 \(\nu_h\) production

The different massive neutrinos \(\nu_i, i = 1, 2, 3, 4\), if they exist, are produced in meson decays, e.g. \(\pi^\pm \rightarrow \mu^\pm \nu_i\), 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

\[T_i = \frac{(m_{\pi}^2 + m_{\mu}^2 - 2m_{\pi}m_{\mu} - m_{\nu_i}^2)}{2m_{\pi}},\]  

(2.1)

as long as \(T_i > 0\). Here \(T_i\) is the muon kinetic energy; \(m_{\pi}, m_{\mu}\), and \(m_{\nu_i}\) are the masses of pion, muon and the \(i\)th neutrino mass eigenstate, respectively. The dominant line is obtained for nearly massless neutrinos, \(\nu_{1,2,3}\), at \(T_0 = 4.120 \, \text{MeV}\). 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 same is true for muons from \(K\) decays. Searches for peaks in pion decays \[12, 13, 14, 15\].
Figure 1: The exclusion plot for $|\langle VU \rangle_{\mu h}|^2$ 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.

[16, 17, 18, 19, 20, 21] and in kaon decays [22, 23] found no signal and set stringent bounds on $|\langle VU \rangle_{\mu h}|^2$ for masses $m_h < \sim 360$ MeV. The corresponding excluded regions from pion and kaon decays are shown in Figs. 1 and 2 as gray regions, respectively. Different lines represent limits obtained in different experiments (see captions of Figs. 1 and 2).

3. Bounds on $\nu_h$ 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 $|\langle VU \rangle_{\mu h} U_{ah}|$, as shown in Fig. 4.

A heavy neutrino mixed with active neutrinos can decay into different channels depending on its mass. If 1 MeV $\lesssim m_h \lesssim 105$ MeV, $\nu_h$ 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 $U_{ah}$,

\footnote{In the literature the mixing is often parametrized by a mixing angle $\theta$. We have that $\sin^2 \theta \equiv |U_{ah}|^2$.}
then electron mass $m_e \ll m_h < m_{\pi^0}$, and we assume that in the CC current $(VU)_{eh} \sim 0$, the decay width is given by [33]:

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

where $g_L^e = 1/2 + \sin^2 \theta_W$, $g_L^\mu = -1/2 + \sin^2 \theta_W$, $g_R = \sin^2 \theta_W$. If the heavy neutrino mixes with $\nu_e$ in the charged current, the decay $\nu_h \rightarrow \nu_e e^+ e^-$ would receive an additional contribution from CC interactions. In the absence of charged currents, the corresponding branching ratios are equal to $B_e = (\bar{g} - 1)/\bar{g} \approx 0.11$ for the visible channel and $B_\nu = 1/\bar{g} \approx 0.89$, for the invisible channel. Here we have defined $\bar{g} = 1 + (g_L^2) + g_R^2$. For larger masses, new channels are open, namely $\nu_h \rightarrow \pi^0 \nu_\mu$ and $\nu_h \rightarrow \mu^+ \mu^- \nu_\alpha$ which are mediated by neutral currents, and $\nu_h \rightarrow \mu^- e^+ \nu_\mu$, $\nu_h \rightarrow \mu^+ \mu^- \nu_\mu$ and $\nu_h \rightarrow \pi^+ \mu^-$, due to CC interactions. For $m_h > m_\pi$, the two-body decays dominate and typically the half-life time is of order $\tau_h \sim (10^{-9} - 10^{-10}) |U_{\mu h}|^{-2} (|(VU)_{\mu h}|^{-2})s$, 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 $L_d = c \tau_h \gamma_F$, where $\gamma_F = E_h/m_h$ is the $\nu_\mu$ gamma factor. The fraction of heavy neutrinos that can reach the detector before decaying is $\exp(-R_{ct}/L_d)$, where $R_{ct}$ is the distance from the neutrino production site to the detector. Of these neutrinos, for $h/L_d \ll 1$, a fraction $B_{vis} h/L_d$ 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 $|\langle V U \rangle_{\mu h} (V U)_{eh}|$ versus $m_h$ obtained from searches of $\nu_h$ 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])

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

(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, $\Omega$ and $\epsilon$ 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 $\nu_e$ and $\nu_\mu$ were set by different experiments [24, 25, 26, 27]. We review them in Fig. 3. In the mass range 1 MeV $\leq m_h \leq$ 33.9 MeV the excluded region comes from heavy neutrino production in pion decays. For higher masses, 40 MeV $\lesssim m_h \lesssim$ 360 MeV, kaon decays were taken into account. Different visible decay channels have been studied. The channel $K^+ \to \mu^+ \nu_h \to \mu^+ (\mu^- e^+ \nu_e) + \text{c.c.}$ was used to constrain the elements of the mixing matrix $V U$, for masses up to $\sim$260 MeV (see Fig. 3). For heavier masses a new decay channel is open, $K^+ \to \mu^+ \nu_h \to \mu^+ (\pi^+ \mu^-) + \text{c.c.}$, and dominates.

We note that in Refs. [24, 25, 26, 27] the NC contribution to the decay of $\nu_h$ 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, 25, 26, 27] because their visible decay channel is always dominated 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 $|(VU)_{e h}(VU)_{\mu h}|$ mixing. However, the same data can be used for setting a bound on $|(VU)_{\mu h}U_{a h}|$, with $a = e, \mu, \tau$, if one includes the contribution due to the latter channels.

We used the limit on $|(VU)_{e h}(VU)_{\mu h}|$ from Refs. [24, 25, 26, 27], corrected it by including the contribution from the NC to the total decay width, with $(VU)_{e h}$ 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 $|(VU)_{\mu h}U_{a h}|$. These bounds have not been previously discussed in the literature and are reported in Fig. 4. The new limits are given at the same confidence level as the ones on $|(VU)_{e h}(VU)_{\mu h}|$.

If $V = 1$, our limit on $|U_{\mu h}|^2$ turns out to be the strongest limit in the mass range $34$ MeV $\lesssim m_h \lesssim 200$ MeV (see Fig. 3).

Analogously, the bounds on $|U_{e h}|^2$ [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 $|(VU)_{e h}U_{a h}|$ 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 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
Figure 5: The strongest bound (indicated as line “[3]” in Fig. 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 $V_U = U$.

$|U_{ah}|^2$, 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 $F_a$ ($a = e, \mu, \tau$):

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

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

$$
R(E_1) = B_\epsilon \epsilon(E_1) \left\{ \int_{E_1}^{E_1 + \Delta E} \frac{dF_h}{dE} A \frac{h}{L_d} e^{-R_{cr}/L_d} \right\},
$$

where $B_\epsilon$ is the branching ratio of the $\nu_h \rightarrow e^+ e^- e^- \nu_a$ 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, $R(E_1) < R_{\text{event}}(E_1)$.

It is clear that the highest number of events should come from neutrinos with the smaller gamma-factor $\gamma_F$, $\gamma_F \sim 2 - 3$ (we conservatively take $\gamma_F \gtrsim 2$ to ensure that the production of $\nu_h$ is not suppressed by threshold effects). If the gamma factor of $\nu_h$ is small,
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 $\pi^0$-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 $V U = U$.

$\gamma_F \sim 2 - 4$, 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 $\pi^0 \rightarrow \gamma \gamma$ ($\pi^0$-like events). We use the data reported in Ref. \(^{28}\) where the invariant mass distribution for $\pi^0$-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

$$m^2_{12} = (p_1 + p_2)^2 = m_h^2 + m^2_\nu - 2m_h E_\nu$$ (3.5)

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

We compute the number of $2e$-like events in each bin of $m^2_{12}$ expected from $\nu_h$ 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 $\nu_h$ decays with the $\pi^0$-like events, $N_{\text{exp}}$, in each invariant mass $m^2_{12}$ bin, we obtain an upper bound on $|\langle (V U)_{\mu h} U_{ah} \rangle|$. We show this bound in Fig. \(^{6}\) (vertically hatched region), if $V = 1$, for Dirac sterile neutrinos which mix mainly with $\nu_\mu$. 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 $\nu_h$ with $\gamma_F < 2$, threshold effects in the production of $\nu_h$ in pion and muon decays, the zenith angle dependence and $\gamma_F$-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 $\gamma_F$ 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 $\nu_h$.

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 $|\langle VU \rangle_{\mu h}U_{\mu h}|$ based on these events are typically of the same order of magnitude but are somewhat weaker than those shown in Fig. 3.

For masses $m_h \lesssim 7 - 8$ 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 $e^\pm$, $\mu^\pm$, $\pi^0$ and $\pi^\pm$ generated in their decays would be detected. In MiniBooNE [29], the detector is of length $\sim 10$ 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 $\mu$s. The data read-out of the signal in the detector is done in a time-window around the beam spill of 1.5 and 10-20 $\mu$s 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_χ 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 ν_χ → 3ν_α, ν_χ → e^+e^-ν_α, ν_χ → μ^±e^±ν_α, and for m_χ > m_π in π^0ν_α, π^±e^±, π^±μ^±. The CC induced decays would allow to constrain the product |⟨(VU)_{eh}(VU)_{μh}⟩|, while the NC processes |⟨(VU)_{μh}⟩|U_{ah}|. The flux contains ν_χ 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×10^{-7} for m_χ ∼ 100 MeV. The sensitivity would be of the order of a few×10^{-9} and a few×10^{-10} for heavy neutrino masses m_χ ∼ 200 MeV and 300 MeV, respectively.

In contrast with the other experiments, MINOS has a very good discrimination of μ^+ and μ^−. Neutrinos with m_χ ≥ 210 MeV would decay in this channel with a branching ratio which is typically ∼ 10^{-3}. The decay ν_χ → μ^+μ^-ν_μ receives a contribution from CC interactions and therefore allow to constrain not only |⟨(VU)_{μh}⟩|U_{ah}| but also |⟨(VU)_{μh}⟩|^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_χ.

We note that a possible future detection of the peak in the invariant mass distribution for 2 e-like events from ν_χ → e^+e^-ν_α, after the contribution due to π^0-decays is subtracted, for 2 μ-like events due to ν_χ → μ^+μ^-ν_α and for π^± and e^± (μ^±) produced in the decays ν_χ → π^±e^±(μ^±) 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 independent measurements we have that |⟨(VU)_{μh}⟩|U_{μh}| ≠ |⟨(VU)_{μh}⟩|^2, it would be possible to establish that V ≠ 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)_{μh}⟩|, |⟨(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.

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 $^4\text{He}$ (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 an earlier freeze out of the $n/p$-ratio. In addition, the decay of $\nu_h$ into light neutrinos, in particular, $\nu_e$, would modify their spectrum and the equilibrium of the $n - p$ reactions. We report in Figs. 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 $m_h = 200 \text{ MeV}$. It was shown that in the region 140–200 MeV the dominant decay channel 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 $m_h > 200 \text{ MeV}$ a detailed analysis similar to the one in Ref. [32] should be performed but is beyond the scope of the present study. In Figs. 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 $m_s \lesssim T_{\text{core}}$, where $T_{\text{core}} = 30 – 80 \text{ MeV}$ 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 $T_{\text{core}}$, 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 [33]. 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 Fig. 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 $\nu_\mu$. 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 set 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 $10 \text{ MeV} \lesssim m_h \lesssim 390 \text{ MeV}$. 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.

Acknowledgments

The authors thank B. C. Choudhary, R. Saakyan and R. Shrock for very fruitful discussions. We also thank G. Fuller, S. Nussinov, S. Palomares-Ruiz, and G. Raffelt for helpful comments. This work was supported in part by the DOE Grant DE-FG03-91ER40662 and the NASA ATP grant NAG5-13399.
References

[1] A. D. Dolgov, “Neutrinos in cosmology”, Phys. Rept. 370 (2002) 333 [arXiv:hep-ph/0202122].

[2] S. Dodelson and L. M. Widrow, “Sterile-neutrinos as dark matter”, Phys. Rev. Lett. 72 (1994) 17 [arXiv:hep-ph/9303287]; X. d. Shi and G. M. Fuller, “A new dark matter candidate: Non-thermal sterile neutrinos”, Phys. Rev. Lett. 82 (1999) 2832 [arXiv:astro-ph/9810076]; A. D. Dolgov and S. H. Hansen, “Massive sterile neutrinos as warm dark matter”, Astropart. Phys. 16 (2002) 339 [arXiv:hep-ph/0009083].

[3] G. Gelmini, S. Palomares-Ruiz and S. Pascoli, “Low reheating temperature and the visible sterile neutrino”, Phys. Rev. Lett. 93 (2004) 081302 [arXiv:astro-ph/0403323].

[4] A. Kusenko and G. Segrè, “Neutral current induced neutrino oscillations in a supernova”, Phys. Lett. B 396 (1997) 197 [arXiv:hep-ph/9701311]; G. M. Fuller, A. Kusenko, I. Mocioiu and S. Pascoli, “Pulsar kicks from a dark-matter sterile neutrino”, Phys. Rev. D 68 (2003) 103002 [arXiv:astro-ph/0307267]; for review, see A. Kusenko, “Pulsar kicks from neutrino oscillations”, Int. J. Mod. Phys. D 13 (2004) 2065 [arXiv:astro-ph/0409521].

[5] E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, “Baryogenesis via neutrino oscillations”, Phys. Rev. Lett. 81 (1998) 1359 [arXiv:hep-ph/9803255].

[6] T. Asaka and M. Shaposhnikov, “The nuMSM, dark matter and baryon asymmetry of the universe”, Phys. Lett. B 620 (2005) 17 [arXiv:hep-ph/0505013].

[7] C. Picciotto and M. Pospelov, “Unstable relics as a source of galactic positrons”, Phys. Lett. B 605 (2005) 15 [arXiv:hep-ph/0412178].

[8] S. H. Hansen and Z. Haiman, “Do we need stars to reionize the universe at high redshifts? Early reionization by decaying heavy sterile neutrinos”, Astrophys. J. 600 (2004) 26 [arXiv:astro-ph/0305126].

[9] L. S. Littenberg and R. Shrock, “Implications of improved upper bounds on |\Delta(L)| = 2 processes”, Phys. Lett. B 491 (2000) 285 [arXiv:hep-ph/0005285].

[10] C. Dib, V. Gribanov, S. Kovalenko and I. Schmidt, “Lepton number violating processes and Majorana neutrinos”, Part. Nucl. Lett. 106 (2001) 42 [arXiv:hep-ph/0011213].

[11] T. Appelquist, M. Piai and R. Shrock, “Fermion masses and mixing in extended technicolor models”, Phys. Rev. D 69 (2004) 015002 [arXiv:hep-ph/0308061].

[12] R. E. Shrock, “General Theory Of Weak Leptonic And Semileptonic Decays. 1. Leptonic Pseudoscalar Meson Decays, With Associated Tests For, And Bounds On, Neutrino Masses And Lepton Mixing”, Phys. Rev. D 24 (1981) 1232.

[13] R. Abela et al., “Search For An Admixture Of Heavy Neutrino In Pion Decay”, Phys. Lett. B 105 (1981) 263 [Erratum-ibid. B 106 (1981) 513].

[14] F. P. Calaprice et al., “Search For Finite Mass Neutrinos In The Decay Pi+ → Mu+ Muon-Neutrino”, Phys. Lett. B 106 (1981) 175.

[15] R. C. Minehart et al., “A Search For Admixture Of Massive Neutrinos In The Decay Pi → Muon-Neutrino”, Phys. Rev. Lett. 52 (1984) 804.

[16] M. Daum et al., “Search For Admixtures Of Massive Neutrinos In The Decay Pi+ → Mu+ Neutrino”, Phys. Rev. D 36 (1987) 2624.
[17] D. A. Bryman and T. Numao, “Search For Massive Neutrinos In The \( \pi^+ \rightarrow E^+ \nu \) Decay”, Phys. Rev. D 53 (1996) 558.
[18] M. Daum et al., “Search for a neutral particle of mass 33.9-MeV in pion decay”, Phys. Lett. B 361 (1995) 179.
[19] M. Daum et al., “The KARMEN time anomaly: Search for a neutral particle of mass 33.9-MeV in pion decay”, Phys. Rev. Lett. 85 (2000) 1815 [arXiv:hep-ex/0008014].
[20] R. Bilger et al. [Karmen Collaboration], “Search for the hypothetical pi \( \rightarrow \mu x \) decay”, Phys. Lett. B 363 (1995) 41 [arXiv:nucl-ex/9508001].
[21] P. Astier et al. [NOMAD Collaboration], “New Results On A Search For A 33.9-Mev/C**2 Neutral Particle From Pi+ Decay In The Nomad Experiment”, Phys. Lett. B 527 (2002) 23.
[22] Y. Asano et al., “Search For A Heavy Neutrino Emitted In K+ \( \rightarrow \mu + \) Neutrino Decay”, Phys. Lett. B 104 (1981) 84.
[23] R. S. Hayano et al., “Heavy Neutrino Search Using K(Mu2) Decay”, Phys. Rev. Lett. 49 (1982) 1305.
[24] F. Bergsma et al. [CHARM Collaboration], “A Search For Decays Of Heavy Neutrinos”, Phys. Lett. B 128 (1983) 361.
[25] G. Bernardi et al., “Search For Neutrino Decay”, Phys. Lett. B 166 (1986) 479.
[26] G. Bernardi et al., “Further Limits On Heavy Neutrino Couplings”, Phys. Lett. B 203 (1988) 332.
[27] S. A. Baranov et al., “Search for heavy neutrinos at the IHEP-JINR neutrino detector”, Phys. Lett. B 302 (1993) 336.
[28] S. Nakayama, PhD Thesis, University of Tokyo, Mar. 2003 http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/pub/shoei-d.ps.gz
[29] E. Church et al. [BooNe Collaboration], “A proposal for an experiment to measure muon-neutrino \( \rightarrow \) electron-neutrino oscillations and muon-neutrino disappearance at the Fermilab Booster: BooNE”, FERMILAB-PROPOSAL-0898.
[30] See, e.g., T. Maruyama, “Status Of K2k Experiment”, Nucl. Instrum. Meth. A 503 (2003) 118.
[31] MINOS Technical Design Report, NuMI note 337, http://www-numi.fnal.gov/minwork/info/minos_ddr.html; D. Michael, “The MINOS Experiment”, Nucl. Phys. Proc. Suppl. 118 (2003) 189.
[32] A. D. Dolgov, S. H. Hansen, G. Raffelt and D. V. Semikoz, “Heavy sterile neutrinos: Bounds from big-bang nucleosynthesis and SN 1987A”, Nucl. Phys. B 590 (2000) 562 [arXiv:hep-ph/0008138].
[33] A. D. Dolgov, S. H. Hansen, G. Raffelt and D. V. Semikoz, “Cosmological and astrophysical bounds on a heavy sterile neutrino and the KARMEN anomaly”, Nucl. Phys. B 580 (2000) 331 [arXiv:hep-ph/0002223].
[34] G. Battistoni et al., “A 3-dimensional calculation of atmospheric neutrino flux”, Astropart. Phys. 12 (2000) 315 [arXiv:hep-ph/9907408].
[35] K. Abazajian, G. M. Fuller and M. Patel, “Sterile neutrino hot, warm, and cold dark matter”, Phys. Rev. D 64 (2001) 023501 [arXiv:astro-ph/0101524].