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Limits on the mixing of heavy decaying neutrinos

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If a heavy neutrino ν_h exists with a mass between 1 MeV and 1 GeV or so, then neutrino beams, from conventional sources or from beam-dump setups, will decay into final states such as $e^-e^+\nu$ and $e\mu\nu$. We examine previous measurements of the $\nu_\mu e \rightarrow \nu_\mu e$ cross section, limits on anomalous μe events in low-energy neutrino experiments, and the measured rates of electrons and muons produced by prompt neutrinos in beam-dump experiments. New upper limits, of order 10^{-6} to 10^{-5}, are set on the mixing $|U_{eh}|^2$ for 160 MeV $< m(\nu_h) \lesssim 1$ GeV and on $|U_{\mu h}|^2$ for 310 MeV $< m(\nu_h) \lesssim 1$ GeV. These are complementary to bounds derived from recent experimental searches for secondary peaks in leptonic decays of pions and kaons.

Whereas the electron and muon neutrinos are known to be light, the present upper limit on the τ-neutrino mass has the quite large value of 250 MeV.[1] From a theoretical point of view massive neutrinos are quite natural consequences of gauge theories. If neutrinos are massive their mass eigenstates mix in the weak eigenstates. A neutrino beam originating from $K \rightarrow \mu\nu$, for instance, may contain in addition to its major part of light neutrinos a minor component of heavy ones. If the mass difference between the various neutrino species is small (i.e., smaller than 100 eV or so), neutrino beams may exhibit the phenomenon of neutrino oscillations.[2] However, if the τ neutrino (or some other neutrino) is heavier than 1 MeV the neutrino beam will for all practical purposes contain a fraction of nonoscillating heavy neutrinos which may decay while traveling in the beam. The idea that neutrino beams may contain heavy species which may decay in flight has occurred to others.[3,4] In this paper we wish to illustrate the high sensitivity of the heavy-neutrino-decay signal to very small mixing parameters. While examining past neutrino experiments we use this sensitivity to place new bounds on the mixing of heavy neutrinos to the electron and the muon families. Experiments specially designed to look for neutrino decay in flight may considerably improve these bounds.

For most of the discussion we will consider any kind of heavy neutrino, hereafter denoted by ν_h, assumed to mix into the electron and muon families with parameters U_{eh} and $U_{\mu h}$, respectively. Only the last part of our study will be limited to the most obvious possibility $\nu_h = \nu_3$, i.e., the supposed heavy neutrino will be taken to couple mainly to the τ lepton. For the rest of the discussion ν_h could be, e.g., a higher-generation neutrino, associated with a yet unobserved heavy charged lepton, a right-handed neutrino, etc. To simplify the analysis ν_h will be assumed to couple to the electron and the muon with either $(V-A)$ or $(V+A)$ currents. Our approach will be purely phenomenological and will be limited to the mass range

$$10 \text{ MeV} \lesssim m_h \equiv m(\nu_h) \lesssim 1 \text{ GeV} . \tag{1}$$

At present there exist upper bounds on U_{eh} and $U_{\mu h}$ only for heavy masses up to 310 MeV. The best limits were obtained from recent dedicated searches for secondary momentum peaks in the two-body leptonic decays of the pion and the kaon.[5] An upper bound on $|U_{lh}|^2$ $(l=e,\mu)$ of the order 10^{-6} to 10^{-4} was derived, from these experiments and from $e\nu/\mu\nu$ branching-ratio measurements in π and K decays,[6] for the following mass regions:

$$5 \leq m_h \leq 160 \text{ MeV (Ref. 7)}: \quad |U_{eh}|^2 < 10^{-6} - 10^{-4} ; \tag{2}$$

$$5 \leq m_h \leq 30 \text{ MeV (Ref. 8)}, \quad 70 \leq m_h < 310 \text{ MeV (Ref. 9)}:$$

$$|U_{\mu h}|^2 < 10^{-6} - 10^{-4} .$$

Recently it was also suggested that much less stringent bounds on $U_{\mu h}$ for the yet unsearched domain $30 < m_h < 70$ MeV may be obtained from a careful analysis of μ capture in ^{3}He (Ref. 10) and from precision measurements of the Michel spectrum in muon decay.[11] *No bounds exist, however, on U_{eh} for $m_h > 160$ MeV and on $U_{\mu h}$ for $m_h > 310$ MeV. In this paper we will derive such limits of the order of the ones in Eq. (2) for masses up to ~ 1 GeV.* These limits will be obtained while studying previous measurements of the $\nu_\mu e \rightarrow \nu_\mu e$ cross section, limits on anomalous μe events in neutrino experiments, and the measured rates of electrons and muons produced by prompt neutrinos in beam-dump experiments.

Consider for instance a neutrino beam initiated from K decays. The relative abundance of heavy neutrinos in the beam is given by the parameter

$$R_h = \frac{\Gamma(K \rightarrow \mu\nu_h) + \Gamma(K \rightarrow e\nu_h)}{\Gamma(K \rightarrow \mu\nu_\mu)}$$

$$= |U_{\mu h}|^2 \rho_\mu + |U_{eh}|^2 \rho_e . \tag{3}$$

The two-body kinematic factor ρ_l $(l=e,\mu)$ is given in terms of the ratios of masses squared $\delta_l = m_l^{\,2}/m_K^{\,2}$ and $\delta_h = m_h^{\,2}/m_K^{\,2}$:

$$\rho_l=\frac{[\delta_l+\delta_h-(\delta_l-\delta_h)^2][1+\delta_l{}^2+\delta_h{}^2-2(\delta_l+\delta_K+\delta_l\delta_h)]^{1/2}}{\delta_\mu(1-\delta_\mu)^2}\,, \tag{4}$$

and vanishes for $m_h \geq m_K - m_l$. While traveling in the beam, the heavy neutrinos may decay into the following dominant modes: $e^-e^+\nu_e$, $e^-\mu^+\nu_\mu$, $\mu^-e^+\nu_e$, π^+e^-, $\mu^-\mu^+\nu_\mu$, $\pi^+\mu^-$. The higher-mass decay modes open up when increasing values of m_h are assumed. In order to estimate the magnitude of the decay signal into, e.g., the $e^-e^+\nu_e$ mode let us compare the decay probability of ν_h to the interaction probability of the ν_μ beam with a hadronic target. The decay probability of ν_h with energy E_h (in GeV) along 1 cm in the detector is given by (we assume $m_h > 10$ MeV)

$$\frac{m_h}{E_h\tau_h c}\simeq 1.6\times10^{-6}\left[\frac{m_h}{m_\mu}\right]^6 |U_{eh}|^2 E_h{}^{-1}\,. \tag{5}$$

The charged-current interaction probability of ν_μ at an energy E (in GeV) with a hadronic target of density ρ is $\approx 0.4\times10^{-14}\rho E$ cm^{-1}. Including the factor R_h of Eq. (3) we find the ratio of the number of ν_h decay events to the number of ordinary charged-current-interaction events, along equally long decay and interaction regions:

$$\frac{\Gamma(\nu_h\to e^-e^+\nu_e)}{\Gamma(\nu_\mu N\to\mu X)}\simeq 4\times10^8\left[\frac{m_h}{m_\mu}\right]^6\frac{|U_{eh}|^2(|U_{eh}|^2\rho_e+|U_{\mu h}|^2\rho_\mu)}{\rho E E_h}\,. \tag{6}$$

When normalizing the decay rate by the much smaller cross section for $\nu_\mu e\to\nu_\mu e$ we find, assuming a target with $n_e\approx\frac{1}{2}n_N$,

$$\frac{\Gamma(\nu_h\to e^-e^+\nu_e)}{\Gamma(\nu_\mu e\to\nu_\mu e)}\simeq 3\times10^{12}\left[\frac{m_h}{m_\mu}\right]^6\frac{|U_{eh}|^2(|U_{eh}|^2\rho_e+|U_{\mu h}|^2\rho_\mu)}{\rho E E_h}\,. \tag{7}$$

Similarly, if $m_h > m_\mu + m_e$ then the rate of $\nu_h\to\mu^-e^+\nu_e$ is given by

$$\frac{\Gamma(\nu_h\to\mu^-e^+\nu_e)}{\Gamma(\nu_\mu N\to\mu X)}\simeq 4\times10^8\left[\frac{m_h}{m_\mu}\right]^6 f\left[\frac{m_\mu}{m_h}\right]\frac{|U_{\mu h}|^2(|U_{eh}|^2\rho_e+|U_{\mu h}|^2\rho_\mu)}{\rho E E_h}\,, \tag{8}$$

$$f(x)=1-8x^2+8x^6-x^8-12x^4\ln x^2\,.$$

Equations (6) to (8) illustrate the high sensitivity of the decay signal to very small mixing parameters for $m_h \gtrsim m_\mu$, in particular for low neutrino energies. When reanalyzing neutrino experiments this sensitivity may be used to place new bounds on U_{eh} for $m_h > 160$ MeV and on $U_{\mu h}$ for $m_h > 310$ MeV. We first study the latter case.

In order to obtain new bounds on $U_{\mu h}$ for the yet unsearched domain $310 < m_h < 370$ MeV, we investigate the present limit on the sequence $K\to\mu\nu_h$, $\nu_h\to\mu^-e^+\nu_e$ the rate of which is controlled by $|U_{\mu h}|^4$. This would lead in neutrino experiments to events with μe pairs with no accompanying hadron. In a CERN neutrino experiment[12] a dozen (12.3±4.5) unaccounted μe events were observed after a careful subtraction of the various conventional sources of background. Most of these events had no accompanying particle. We realize that not all of these events had the characteristic signatures of a possible heavy neutrino ($m_h \lesssim 370$ MeV) decaying within the beam, such as, e.g., a sufficiently small μe opening angle. We therefore do not attempt to interpret them as such. We will rather use the rate of the anomalous μe events (deduced in Ref. 12 after an exhaustive investigation) to represent an upper limit on $\nu_h\to\mu e\nu$. The reported rate corresponds to a ratio of μe to all charged-current events of $(6.9\pm2.5)\times10^{-5}$. A heavy neutrino with $m_h \geq 310$ MeV may originate only from K decay. The K-to-π ratio of the neutrino beam introduces a factor of 0.1 in the theoretical estimate of the magnitude of the decay signal. We estimate that another order-of-magnitude suppression is introduced by the experimental cut requiring $E_\mu > 0.65$ GeV, $E_e > 2$ GeV. Hence we obtain from Eq. (8)

$$4\times10^6\left[\frac{m_h}{m_\mu}\right]^6 f\left[\frac{m_\mu}{m_h}\right]\frac{|U_{\mu h}|^4\rho_\mu}{\rho\langle E\rangle\langle E_h\rangle} \lesssim \frac{\Gamma(\nu_h\to\mu^-e^+\nu_e)}{\Gamma(\nu_\mu N\to\mu X)} < 10^{-4}\,. \tag{9}$$

With $\rho=2.7$, $\langle E\rangle=2.2$ GeV, and $\langle E_h\rangle=3$–4 GeV deduced from the K neutrino spectrum we find the new upper limit:

$$310 \leq m_h \leq 370\ \text{MeV},\quad |U_{\mu h}|^2 \lesssim 10^{-6}\,. \tag{10}$$

This is comparable in magnitude to the limit obtained recently for $200 \lesssim m_h \lesssim 300$ MeV in a dedicated experimental search for secondary peaks in $K\to\mu\nu$ decays.[9] When our arguments are used in this mass region the bound one obtains is somewhat weaker than Eq. (10). This method may be applied to $U_{\mu h}$ only for $m_h > m_\mu + m_e$.

It seems somewhat more difficult to use previous neutrino experiments to set bounds on U_{eh}. This parameter determines the rate of the sequence $K\to e\nu_h$, $\nu_h\to e^-e^+\nu_e$ which gives rise to e^+e^- pairs in the final state with no accompanying hadron. Detection of such events is difficult due to the large background from muonless π^0 production by coherent neutrino scattering off nuclei followed by the Dalitz decay of π^0 where one photon is lost. Here one may take advantage of the fact that at high energies the e^+e^- pairs from $\nu_h \rightarrow e^+e^-\nu_e$ would emerge very narrowly collimated in the nearly forward direction. The electron and positron angles with respect to the beam are limited by the very small value of m_h/E_h. This is to be compared to the much larger scattering angle of the e^+e^- pairs in the case of π^0 production, typically of magnitude $\sim (m_N/E)^{1/2}$. This background may therefore be reduced by selecting events with a very small scattering angle. At this point we recall that such a selection (with a further subtraction of the background extrapolated from the large-angle region) is in fact being made in high-energy neutrino experiments which measure the cross section of $\nu_\mu e \rightarrow \nu_\mu e$.[13,14] Here again the outgoing electrons are characterized by their small scattering angle, $\theta_e < (2m_e/E_e)^{1/2}$. Moreover, due to the finite angular resolution of the electron shower in the counter experiments[14] [$\Delta\theta$(resolution) $\sim$ 10 mrad] an e^+e^- pair from $\nu_h \rightarrow e^+e^-\nu_e$ would simulate a single electron if $\theta(e^+e^-) < \Delta\theta$(resolution). Indeed this is the case for the neutrino masses to be considered ($m_h < 0.5$ GeV) and for the high neutrino energies at the CERN SPS and at Fermilab. We therefore conclude that the decays $\nu_h \rightarrow e^+e^-\nu_e$ would be entirely hidden as background in the neutral-current $\nu_\mu e \rightarrow \nu_\mu e$ events observed in the very forward direction in high-energy counter experiments.

Note that these arguments and conclusion do not apply to the low-energy measurements of $\nu_\mu e \rightarrow \nu_\mu e$ at the CERN PS.[15] Here $\theta(e^+e^-)$ in $\nu_h \rightarrow e^+e^-\nu_e$ is not restricted to very small values (unless m_h is assumed to be sufficiently small, e.g., $m_h < 20$ MeV), i.e., smaller than the angular resolution and as small as the electron scattering angle in $\nu_\mu e \rightarrow \nu_\mu e$. Hence many of the $\nu_h \rightarrow e^+e^-\nu_e$ events would be rejected. A search for isolated forward e^+e^- pairs in low-energy neutrino experiments may be used, however, to set limits on the lifetime of light neutrinos [$m(\nu_\mu) < 500$ keV] which may have radiative decays ($\nu_\mu \rightarrow \nu_e \gamma$).[16]

Since the rate of $\nu_\mu e \rightarrow \nu_\mu e$ measured at high energies in the counter experiments agrees with the standard-model prediction, we may safely assume that the rate of $\nu_h \rightarrow e^+e^-\nu_e$ must be smaller. We apply this conservative limit to the two experiments of Ref. 14, which used the wide-band neutrino beams at Fermilab and at the CERN SPS with $\langle E \rangle \approx 20$, 31 GeV and detectors with $\rho = 2.7$, 1.3, respectively. A heavy neutrino with $m_h > 160$ MeV, to which we wish to apply the above constraint, may originate only from K decay and its average energy is estimated from the K neutrino energies $\langle E_h \rangle \sim 50$ GeV. The K-to-π beam ratio introduces a factor of 0.1 (Ref. 17) into Eq. (7). No further substantial suppression is expected to be caused by the experimental cuts on the shower energies in the above two experiments, $E_{\text{sh}} \geq 4$ GeV and $7.5 \leq E_{\text{sh}} \leq 30$ GeV, respectively. Finally, we obtain

$$10^8 \left[\frac{m_h}{m_\mu} \right]^6 |U_{eh}|^4 \rho_e < 1 \; . \tag{11}$$

This with Eq. (4) yields a new upper bound on U_{e3}:

$$160 \leq m_h \leq 480 \text{ MeV}, \quad |U_{eh}|^2 \lesssim 10^{-6}\text{--}10^{-5} \; . \tag{12}$$

The same considerations, when applied to $m_h < m_\pi - m_e$, will not include the K-to-π ratio of 0.1 and will use $\langle E_h \rangle \sim \langle E \rangle \approx 20$ or 30 GeV. The bound of order 10^{-5} may be extended down to $m_h \approx m_\mu$. It is amusing to note that a similar limit was recently obtained for this mass region in an experiment specially designed to search for subsidiary peaks in $\pi \rightarrow e\nu$ decay.[7] For lower values of m_h the bound we derive on the mixing $|U_{eh}|^2$ becomes weaker and grows with $(m_\mu/m_h)^4$. For instance, for $m_h = 50$ MeV we find the bound to be of the order of 10^{-4}–10^{-3} whereas a limit of 10^{-6} was obtained in Ref. 7.

We now wish to study the present limits on the mixing of neutrinos supposed to be heavier than the kaon, i.e., $m_K < m_h \lesssim 1$ GeV. Such neutrinos are absent in neutrino beams from conventional sources (π and K decays), however, would be present among the neutrinos emerging from the decays of heavy flavor hadrons[5] (or in τ decays). The latter decays are supposed to be the source of the flux of prompt electron and muon neutrinos observed in a series of beam-dump expriments[18] in excess over the flux expected from conventional sources. In the subsequent discussion it will be assumed that these neutrinos are indeed the decay products of charmed hadrons produced in hadronic collisions. We then face the possibility that also heavy neutrinos emerge from these decays, such as $D \rightarrow e\nu_h X$ and $D \rightarrow \mu\nu_h X$, through their mixing with the electron and the muon families. Subsequently ν_h may decay into the various modes ($e^-e^+\nu_e$, $\mu e\nu$, etc.) again via the corresponding mixing parameters. The decay rate normalized by, e.g., the charged-current interaction rate of the prompt ν_e's (along equally long decay and interaction regions) is given by

$$\frac{\Gamma(\text{prompt } \nu_h \rightarrow e^-e^+\nu_e)}{\Gamma(\text{prompt } \nu_e N \rightarrow eX)} \simeq 4 \times 10^8 \left[\frac{m_h}{m_\mu} \right]^6 \frac{|U_{eh}|^2(|U_{eh}|^2 + |U_{\mu h}|^2)}{\rho E E_h} \; . \tag{13}$$

The phase-space difference between $D \rightarrow l\nu_h X$ and $D \rightarrow l\nu_l X$ ($l = e,\mu$) is ignored when assuming that the relative branching ratio of these two processes is given by $|U_{lh}|^2$.

The measured rate of electrons and the energy and transverse-momentum spectra of the observed prompt neutrinos agree with the hypothesis of charm production followed by the sequence $D \rightarrow e\nu_e X$, $\nu_e N \rightarrow eX$.[18] The sequence $D \rightarrow e\nu_h X$, $\nu_h \rightarrow e^-e^+\nu_e$ would obviously give rise to a different characteristic behavior. In particular note the different energy behavior in Eq. (13). A very conservative hypothesis on the ν_h decay rate within the detector would be to only assume that, when averaged over the neutrino energies, it is smaller than the corresponding prompt ν_e charged-current interaction rate:

$$4 \times 10^8 \left[\frac{m_h}{m_\mu} \right]^6 \frac{|U_{eh}|^4}{\rho \langle E \rangle \langle E_h \rangle} < 1 \; . \tag{14}$$

A value of order one on the left-hand side refers to the (unlikely) possibility that a large fraction of the prompt electron events are actually events with small-angle separated e^+e^- pairs misidentified as single-electron events. Using as typical values[18] $\langle E \rangle \sim \langle E_h \rangle \sim 50$ GeV, $\rho \sim 1$ we find the upper bound

$$0.5 \le m_h \le 1 \text{ GeV}, \quad |U_{eh}|^2 \lesssim 10^{-6}\text{--}10^{-5} . \tag{15}$$

We estimate that this bound may be improved by an order of magnitude through a careful examination of low-E_{vis} events. Similar bounds may be derived for $U_{\mu h}$ when one considers the sequence $D \to \mu \nu_h X$, $\nu_h \to \mu^- e^+ \nu_e$. This may also close the gap $370 \le m_h \le 500$ MeV for which one finds $|U_{\mu h}|^2 \lesssim 10^{-4}$.

As the last point to be studied we wish to emphasize that beam-dump experiments may have an advantage over neutrino experiments from conventional sources in setting bounds on the mixing parameters U_{eh}, $U_{\mu h}$ if the heavy neutrino is assumed to couple mainly to the τ lepton. Whereas in the general case heavy neutrinos are taken to originate mainly from semileptonic decays of charmed hadrons into electrons and muons $[D \to e(\mu)\nu_h X]$ and their rate is suppressed by $|U_{e(\mu)h}|^2$, ν_τ's may be copiously produced in $F \to \tau \nu_\tau$ decays which involve no suppression due to mixing. The branching ratio of the latter process is experimentally unknown. Depending on one's theoretical value of f_F, the F-meson decay coupling constant, and on the F lifetime[19] various estimates indicate that this branching ratio must be somewhere between 1 and 10%.[20] We choose the lower value for safety and restrict our considerations to $m(\nu_3) < 200$ MeV so that phase-space suppression of $F \to \tau \nu_3$ due to the neutrino mass is unimportant. To obtain a conservative lower limit on the relative abundance of ν_τ's in beam-dump experiments we choose as a typical semileptonic charm-decay branching ratio the value of 10% (Ref. 21) and rather conservatively assume that associated F production comes with at least 10% of the total charm-production cross section.[22] We end up concluding that the flux of ν_τ's from F decays is at least 1% of the flux of prompt ν_e's.[23] Instead of Eq. (13) we therefore find

$$\frac{\Gamma(\text{prompt } \nu_3 \to e^- e^+ \nu_e)}{\Gamma(\text{prompt } \nu_e N \to eX)} \gtrsim 4\times 10^6 \left[\frac{m_3}{m_\mu}\right]^6 \frac{|U_{e3}|^2}{\rho E E_3} , \tag{16}$$

where m_3 and E_3 are the mass and energy of ν_3. Comparison of Eq. (16) with the more general Eq. (13), at given neutrino mass and energy, demonstrates the specially high sensitivity of the neutrino-decay signal to small mixing in the particular case $\nu_h = \nu_3$. With $\langle E \rangle \sim \langle E_h \rangle \sim 50$ GeV, $\rho \sim 1$ and again taking the value of 1 as a conservative upper limit on the left-hand side of Eq. (16) we obtain

$$|U_{eh}|^2 < 5\times 10^{-4} \left[\frac{m_\mu}{m_3}\right]^6 \quad (m_3 < 200 \text{ MeV}) . \tag{17}$$

This does not improve the limits derived previously from $\pi, K \to e\nu$ and the limt obtained in Eq. (12).

We have not considered the attenuation of the ν_h beam by its decay along the path from the beam dump to the detector. The attenuation factor along a distance d is $\exp(-dm_h/E_h\tau_h c)$ [see Eq. (5)], and becomes significant for large values of m_h ($m_h \approx 1$ GeV) and for sufficiently large values of d and $|U_{lh}|^2$. Experiments with large d are insensitive to large mixing parameters for high mass values. When introducing the attenuation factor into Eq. (14) it is straightforward to find out that with a path length of order 100—1000 m, beam-dump experiments[18] cannot exclude large mass values $m_h \approx 1$ GeV with large mixing parameters $|U_{lh}|^2 \gtrsim 0.1$.

Finally, let us stress that the various limits derived in this paper were obtained merely as by-products from experiments which were designed for a different purpose. Considerable improvement of the above limits may be achieved through a direct search for neutrino decay in flight. Such an experiment would have a long empty decay region in front of the detector in which the origin of decay events would be looked for. This idea may be applied to either conventional low-energy neutrino beams, preferably separated kaon beams, or to beam-dump setups.[24] It would enhance the possible neutrino decay rate by the great length of the decay region and reduce the background from neutrino interaction to a minimum. We expect this type of experiment to improve the present bounds on the neutrino-mixing parameters by a couple of orders of magnitude.

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