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SEARCHING FOR HEAVY UNSTABLE NEUTRINOS*

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(1) The number in the last line of page 3 should be 0.4×10^{-14} instead of 2×10^{-14}.

(2) The numerical coefficient in Eq. (5) should be 10^9 instead of 2×10^8.

(3) The numerical coefficient in Eq. (6) should be 3×10^{12} instead of 4×10^{11}.

(4) The number of expected events with final state pairs of e^-e^+, $e\mu$, π^+e^-, $\mu^-\mu^+$ and $\pi^+\mu^-$ (page 5 second line) should be about 270, 70, 4000, 3 and 530 respectively instead of 18, 5, 270, 0.2 and 7.

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ABSTRACT

If a heavy (τ) neutrino exists with a mass between a few MeV and a few hundred MeV, neutrino beams will exhibit the phenomena of decay into well defined final states such as $e^-e^+\nu_e$, $e\mu\nu$, πe. We demonstrate the feasibility of the decay signals and their high sensitivity to neutrino mixing parameters as small as 10^{-3} in low energy neutrino experiments. We suggest a new type of neutrino decay experiments to search for these decays.

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Whereas the electron and muon neutrinos are known to be light, the present upper limit on the τ-neutrino mass is the quite large value of 250 MeV.[1] If neutrinos are massive their mass eigenstates mix in the weak eigenstates. A neutrino beam originating from $K \to \mu\nu$ decay, 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 a hundred eV or so) neutrino beams may exhibit the phenomenon of neutrino oscillations.[2] If the τ-neutrino is however heavier than one MeV the neutrino beam will for all practical purposes contain a fraction of nonoscillating heavy neutrinos which, while traveling in the beam, may decay.

The purpose of this letter is to study the effects of heavy unstable neutrino species in neutrino beams. The characteristic signatures of this phenomenon will be discussed, the high sensitivity of the signal to very small neutrino mixing parameters will be demonstrated and, finally, suggestions for future experiments will be made.

The neutrino mass and weak eigenstates are related by the mixing matrix U:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ \vdots & & & \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{bmatrix} \tag{1}$$

In order to study the entire mass domain $1 < m_3 < 250$ MeV, let us consider for instance a neutrino beam initiated from $K^+ \to \mu^+\nu$ decays. In addition to the light neutrino species ν_μ and ν_e (which may oscillate between themselves) the beam will contain a small fraction R_3 of heavy neutrinos ν_3 given by

$$R_3 = \frac{\Gamma(K \to \mu\nu_3)}{\Gamma(K \to \mu\nu_\mu)} = |U_{\mu 3}|^2 \rho \quad . \tag{2}$$

The value of the kinematic factor ρ lies between 1 and 4 for the above values of m_3. While traveling in the beam the heavy neutrinos ν_3 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_3 are assumed. Note that neutrinos with a mass of merely a couple of MeV have a phase space enhanced lifetime which is much longer than

$$\tau_3 = |U_{e3}|^{-2} \left(\frac{m_\mu}{m_3}\right)^5 \tau_\mu \quad , \tag{3}$$

which violates the cosmological limit of 10^3 sec.[3] The upper bound $m_3 < 250$ MeV may be lifted for the possibly existing higher generation neutrinos.

Consider for instance the case $m_3 = m_\mu$ in which the neutrino lifetime into the dominant decay mode $e^-e^+\mu_e$ is simply $|U_{e3}|^{-2}\tau_\mu$. In order to discuss the feasibility of detecting the ν_3 decay products let us compare the decay probability of ν_3 to the interaction probability of the ν_μ beam with an hadronic target. The decay probability of ν_3 along 1 cm in a detector is given by

$$\frac{m_3}{E\ \tau_3\ c} \simeq 1.5 \times 10^{-6}\ |U_{e3}|^2\ E^{-1}\ [\mathrm{cm}^{-1}] \tag{4}$$

where the neutrino energy E is given in units of GeV. The interaction probability of ν_μ at this energy E with an hadronic target of unit density is 0.4×10^{-14} E[cm^{-1}]. Including the branching ratio factor of

Eq. (2),($\rho \sim 2$) we find the ratio of the number of ν_3-decay events to the number of ordinary charged-current interaction events:

$$\frac{\text{Number of } \nu_3 \to e^- e^+ \nu_e}{\text{Number of } \nu_\mu N \to \mu + X} \simeq 10^9 \, |U_{\mu 3} U_{e3}|^2 \, E^{-2} \quad . \qquad (5)$$

Comparison with $\nu_\mu e$ interaction leads to a three order of magnitude larger ratio:

$$\frac{\text{Number of } \nu_3 \to e^- e^+ \nu_e}{\text{Number of } \nu_\mu e \to \nu_\mu e} \simeq 3 \times 10^{12} \, |U_{\mu 3} U_{e3}|^2 \, E^{-2} \quad . \qquad (6)$$

Equation (6) illustrates the high sensitivity of the decay signal down to very small mixing parameters of the order of 10^{-3} for low energy neutrino beams ($E \sim 1$-3 GeV). Low energy neutrino experiments, in which a few tens of $\nu_\mu e$ scattering events are measured, are expected to provide a couple of events with e^+e^- pairs if the mixing is as small as 10^{-3}. The number of neutrino decay events grows with the fourth power of the mixing parameters. Note that the strength of the decay signal is proportional to m_3^6 (Eqs. (3)(4)), hence for $m_3 = 10$ MeV, for instance, we expect six orders of magnitude fewer decay events than given by Eq. (6). This would make the signal detectable for mixing parameters of the order 10^{-1} and unobservable for much smaller mixing.

If $m_\mu + m_e < m_3 < m_\pi + m_e$ the heavy neutrino may also decay into $e^- \mu^+ \nu_\mu$ with a decay rate which is phase space suppressed by at least two orders of magnitude relative to the rate into $e^- e^+ \nu_e$. The strength of the decay signal into $\mu^- e^+ \nu_e$ is similar however proportional to $|U_{\mu 3}|^4$. Finally, for illustration purpose, we consider the case $m_3 = 250$ MeV and calculate the number of the various decay events for a $K^+ \to \mu^+ \nu$ initiated neutrino beam with energy $E = 2$ GeV. We assume the mixing parameters to be 10^{-3}

and normalize the number of events to a single $\nu_\mu e$ scattering event on a unit density target. The number of expected events with final state pairs of e^-e^+, $e\mu$, π^+e^-, $\mu^-\mu^+$ and $\pi^+\mu^-$ should be about 270, 70, 4000, 3 and 530 respectively.

We have considered for simplicity a pure $K \to \mu\nu$ initiated beam. It is straightforward to generalize this discussion to the realistic circumstances of π - K admixtured neutrino beams and to include their very small ν_e component. Here one must note that π decay initiated beams impose stronger limits on the mass m_3. Again we wish to stress that since the decay signal falls with E and in order to avoid background from heavy flavor leptonic decays, low energy neutrino beams are preferable over high energy beams for the purpose of carrying out this search.

Let us emphasize at this point that the heavy neutrino decay signals are unique with the small angle that the e^-e^+, $e\mu$ etc., pairs are expected to form with the beam direction. (They definitely do not look like neutrino oscillation events.) Electron and muon detectors with good angular separation are ideal for these searches. *In order to minimize background from neutrino interactions, a neutrino decay experiment should have a long vacuum decay pipe in front of the detector. The momenta of the pairs of e^+e^-, $e\mu$ etc., may then be reconstructed backwards into the decay pipe to identify the neutrino decay events.*

It seems to us practically impossible to use previous neutrino experiments to set reliable bounds on the mixing parameters since, for instance, our most obvious signal of e^-e^+ pairs was most probably disregarded when considered as background from π^0 Dalitz decays. Let us only mention in passing a CERN PS neutrino experiment by Faissner et al.,[4] in which a dozen unaccounted μe events were observed.

We realize that not all of these events had the characteristic signatures of a possibly decaying neutrino, i.e., no accompanying particle and a small electron transverse momentum out of the $\nu\mu$ plane. Still we may perhaps obtain a rough limit on the mixing parameters by taking a handful of events as an upper limit on the possibly neutrino decay events (*assuming* that all such events were detected). The average neutrino energy of these events was 3-4 GeV and their rate corresponds to the ratio of Eq. (5) being 10^{-4}. Since most of the neutrinos are from π-decay we may assume $m_\mu < m_3 < m_\pi$. Assuming further a phase space suppression factor of 10^{-3} for $\nu_3 \to e\mu\nu$ we finally end up with a very rough estimate $|U_{e3}| < 10^{-2}$.

It was suggested by Shrock[5] to search for heavy neutrinos by looking for secondary peaks in the lepton spectrum of stopped π and K decays into $e\nu$ and $\mu\nu$. High precision measurements of this kind were recently carried out[6] and set limits on the neutrino mixing parameters. The upper bounds on $|U_{e3}|$ and $|U_{\mu 3}|$ are both of the order of $10^{-3} - 10^{-2}$ for the two mass regions $10 < m_3 < 160$ MeV and $160 < m_3 < 300$ MeV, respectively. No bounds on U_{e3} and on $U_{\mu 3}$ exist for $m_3 > 160$ MeV and for $30 < m_3 < 160$, respectively. A dedicated $K \to \mu\nu$ experiment at KEK proposed to look for heavy neutrino peaks over the entire momentum spectrum is currently under progress,[7] however it suffers from strong background at $m_3 < 100$ MeV. The search proposed by us for heavy unstable neutrinos is complementary to these experiments. It is interesting to note that heavy neutrinos with lifetimes of, e.g., Eq. (3), escape the detector before decaying in the stopped π or K decay experiments. As demonstrated here these decays may actually be observed in neutrino beam decay experiments.

For the sake of simplicity we have used throughout our entire discussion the "standard" scheme in which only left-handed neutrinos exist and our heavy neutrino was thus assumed to be the τ-neutrino or a higher generation neutrino. In a recent letter with Nussinov[8] we have suggested that in left-right symmetric models the right-handed neutrinos may have masses in the above discussed mass range. The phenomena of unstable heavy neutrinos in neutrino beams, with signatures as studied here, applies to this case as well. In particular for a heavy $\nu_{\mu R}$ the signals are expected to be quite enhanced (i.e., correspond to mixing parameters of the order $10^{-2} - 10^{-1}$ in our above analysis) due to the rather larger branching ratio of $K \to \mu\nu_{\mu R}$.[9]

In conclusion, *the searches proposed here to look for heavy unstable neutrinos in neutrino beams may add a new dimension to the quite a few neutrino oscillation experiments currently under progress and planned for the future. It turns out that these experiments, which are sensitive to neutrino mass differences in the domain of order 1 – 10 eV, may be quite simply turned into neutrino decay experiments which are highly sensitive to masses in the far away lying region of order 10 – 100 MeV. When considering neutrino oscillation experiments*[2] *it is conventional to use the square of the mixing parameter as a measure of the sensitivity of an experiment. In these terms the suggested neutrino decay experiments have a potential sensitivity of* 10^{-6} *which is far from being reached by any neutrino oscillation experiment.*

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