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CAN WE DETECT A HEAVY MUON NEUTRINO IN $K\to\mu\nu$?*

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ABSTRACT

In left-right symmetric models with an intermediate mass scale a heavy right-handed muon neutrino is expected to exist whose mass may be as low as about 100 MeV. We present a cosmological consistent scheme in which $m_{\nu_{\mu R}} \lesssim 380$ MeV and $m_{\nu_{\mu L}} \sim$ 300-500 KeV lies very close to the present experimental limit. The signal of the heavy neutrino in $K \to \mu\nu$ decay is expected to be at least a few parts in a thousand compared to the prominent "massless" neutrino signal, which makes it feasible with the present experimental precision.

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In a recent letter by Nussinov and myself[1] we suggested that there may exist a right-handed electron neutrino ν_{eR} whose mass is as low as a few tens or a few hundred MeV. Such a mass was shown to be sufficiently large to explain the smallness of its left-handed partner $m_{\nu_{eL}}$ in left-right symmetric models,[2,3] in which parity is spontaneously broken at a scale intermediate between the grand unification scale and the electroweak unification scale. One of the cleanest and most obvious signatures of such a massive neutrino, discussed in Ref. 1, is the appearance of a new peak in the positron momentum spectrum in π^+, $K^+ \rightarrow e^+\nu$ decays.[4]

The extension of this study to the heavy partner of the light muon neutrino is straightforward. There exists, however, a minor subtlety with a crucial subsequence to which I would like to address myself in this note. It seems at first sight that due to the strong helicity enhancement of the decays π, $K \rightarrow e\nu_{eR}$ (the electron being so light), the electronic decay modes are much more sensitive to a new spectral line than the muonic modes. However, whereas the electronic signal may be rather weak (and unobservable yet) if W_R is sufficiently heavy,[1] it will be argued here that the strength of the muonic signal may essentially be independent of m_{W_R}. We will show that with the present experimental precision one may be able to observe the heavy ν_μ in a careful study of $K \rightarrow \mu\nu$ decays, if indeed its mass lies below 380 MeV.

In order to set up the stage to substantiate our assertion, we start by writing down the single generation[5] (ℓ) neutrino mass matrix in the left- and right-handed Majorana basis[3]

$$M_{\nu_\ell} = \begin{pmatrix} 0 & m_{\nu_{\ell D}} \\ m_{\nu_{\ell D}} & m_{\nu_{\ell R}} \end{pmatrix} \tag{1}$$

In the left-right symmetric models $\nu_{\ell R}$ obtains a large Majorana mass $m_{\nu_{\ell R}}$ at the scale of left-right symmetry breaking. This mass is related to m_{W_R} by the unknown ratio of Yukawa to gauge couplings $gm_{\nu_{\ell R}} = h^M_\ell\, m_{W_R}$. The Dirac term $m_{\nu_{\ell D}}$, which mixes the two chirality states, is related to the charged lepton mass m_ℓ by the ratio of the corresponding Yukawa couplings $h^D_{\nu_\ell}/h^D_\ell$ which we may rather safely assume to be between 0.1 and 10, $m_{\nu_{\ell D}} \simeq (0.1 - 10)m_\ell$.

With $m^2_{\nu_{\ell R}} >> m^2_{\nu_{\ell D}}$ the diagonalization of M_{ν_ℓ} leads to a light and to a heavy mass eigenvalue which are respectively

$$\begin{aligned} m_{\nu_{\ell \mathrm{Light}}} &\simeq (10^{-2} - 10^2)\,\frac{m^2_\ell}{m_{\nu_{\ell R}}} \\ m_{\nu_{\ell \mathrm{Heavy}}} &\simeq m_{\nu_{\ell R}} \quad . \end{aligned} \tag{2}$$

The two mass eigenstates are almost pure chirality states, each containing a tiny component of the opposite chirality. Thus the heavy mass eigenstate is given by

$$|\nu_{\ell H}\rangle \simeq |\nu_{\ell R}\rangle + \frac{m_{\nu_{\ell D}}}{m_{\nu_{\ell H}}}\,|\nu_{\ell L}\rangle \quad . \tag{3}$$

The present experimental limits on $m_{\nu_{eL}}$ (60 eV[6]) and on $m_{\nu_{\mu L}}$ (570 KeV[7]) yield via Eq. (2) the quite safe lower bound values of 40 and 190 MeV for $m_{\nu_{\ell H}}$ and $m_{\nu_{\mu H}}$, respectively.[8] Thus, in order to naturally accommodate the (essentially left-handed) light neutrino masses within their experimental limits, one may envisage a situation in which their (essentially right-handed) heavy partners are as light as the muon, the pion or so.

Let us now consider for instance a typical $K \to \ell\nu$ experiment in which a search is made for a secondary charged lepton momentum peak.

Since in such a search one is looking for neutrinos with a definite non-zero mass the final state is given by the left-right admixture of Eq. (3). In the rate of this process, the two chirality states add up incoherently. The contributions of $\nu_{\ell R}$ and $\nu_{\ell L}$ to the rate are suppressed relative to the rate into the light neutrino mode by the factors $(m_{W_L}^2 + m_{LR}^2)^2/m_{W_R}^4$ and $(m_{\nu_{\ell D}}/m_{\nu_{\ell H}})^2$, respectively. Here we have allowed for $W_L - W_R$ mixing given by the parameter m_{LR}^2.

$$\frac{\Gamma(K \to \ell\nu_{\ell H})}{\Gamma(K \to \ell\nu_{\ell L})} = \rho \left(\frac{\left(m_{W_L}^2 + m_{LR}^2\right)^2}{m_{W_R}^4} + \left(\frac{m_{\nu_{\ell D}}}{m_{\nu_{\ell H}}}\right)^2 \right) \quad . \tag{4}$$

The additional factor ρ is a well-known function of the ratios of square masses $\ell \equiv m_\ell^2/m_K^2$ and $\nu \equiv m_{\nu_{\ell H}}^2/m_K^2$.

$$\rho = \frac{\left(\ell + \nu - (\ell - \nu)^2\right)\left(1 + \ell^2 + \nu^2 - 2(\ell + \nu + \ell\nu)\right)^{1/2}}{\ell(1 - \ell)^2} \quad . \tag{5}$$

Whereas the second term in Eq. (4) may be disregarded in the electronic decay mode (which may thus be used to set lower bounds on m_{W_R})[1] it plays a crucial role in the muonic mode. To illustrate that this is indeed the case, let us consider for instance a heavy neutrino with a mass of $m_{\nu_{\ell H}}$ = 200 MeV. In the case $\ell = e$ we obtain a very small value

$$\left(\frac{m_{\nu_{eD}}}{m_{\nu_{eH}}}\right)^2 \simeq \frac{m_{\nu_{eL}}}{m_{\nu_{eH}}} < 3 \times 10^{-7} \tag{6}$$

still below the present sensitivity of $K \to e\nu$ experiments. On the other hand, for $\ell = \mu$ we find a much larger value

$$\left(\frac{m_{\nu_{\mu D}}}{m_{\nu_{\mu H}}}\right)^2 \gtrsim \left(\frac{0.1\ m_\mu}{m_{\nu_{\mu H}}}\right)^2 \simeq 2 \times 10^{-3} \tag{7}$$

i.e., *the secondary peak in* $K \to \mu\nu$ *decays should be observed with a strength of at least a few parts in a thousand relative to the primary* $\nu_{\mu L}$ *peak.*

A recent high precision $K \to \mu\nu$ experiment at KEK,[9] particularly made to search for a secondary muon line, led to the following experimental bound on a heavy neutrino in the mass range $160 < m_{\nu_{\mu H}} < 230$ MeV:

$$\frac{1}{\rho}\,\frac{\Gamma(K \to \mu\nu_{\mu H})}{\Gamma(K \to \mu\nu_{\mu L})} < 3 \times 10^{-5} \quad . \tag{8}$$

By comparing this result with the prediction of Eqs. (4) and (7) one may definitely rule out a heavy neutrino in this mass range.

Similarly an earlier K decay experiment,[10] originally made to search for the $\mu\nu\nu\bar{\nu}$ mode, may be used to extract the limit

$$\frac{1}{\rho}\,\frac{\Gamma(K \to \mu\nu_{\mu H})}{\Gamma(K \to \mu\nu_{\mu L})} < 4 \times 10^{-6} \tag{9}$$

for massive neutrinos in the range $230 < m_{\nu_{\mu H}} < 300$ MeV. Again this bound is smaller by more than two orders of magnitude than the predicted value and rules out neutrino masses in this range.

Let us emphasize at this point that our statements rely heavily on the left-right symmetric models in which the heavy neutrino state is expected to be given by the left-right chirality admixture of Eq. (3). Our estimate in Eq. (7) rests on the assumption that $m_{\nu_{\mu D}}$ and m_μ do not differ by more than an order of magnitude or so. A much smaller value of $m_{\nu_{\mu D}}$ leads to a weaker signal, however it spoils the spirit of the left-right symmetric model which was proposed to explain the lightness of $\nu_{\ell L}$ in a natural manner.[3]

Our scheme assumes that $m_{\nu_{\mu H}}$ lies in the region of smallest possible values consistent with Eq. (2) and with the present bound on $m_{\nu_{\mu L}}$. This implies, of course, that *the actual value of the latter does not lie far below its experimental limit, i.e.,* $m_{\nu_{\mu L}} \sim$ *200-570 KeV.* It also led to the large left-right admixture in Eq. (2), which was the basis for our prediction of a large $K \to \mu\nu_{\mu H}$ decay rate.

There is a general difficulty with having neutrinos in this mass range of a few hundred KeV:[11] They would contribute too much energy density to the present universe, unless they decay sufficiently fast — essentially with a lifetime $\tau_{\nu_{\mu L}} < 10^{11}$ sec.

Are our neutrinos decaying with a sufficient rate?

It turns out that the answer to this question is positive in a very natural and aesthetic manner. It has been noted[12] that Majorana neutrino mass eigenstates break the GIM cancellation mechanism and thus lead to neutrino flavor changing neutral currents. The (otherwise troublesome) process $\nu_{\mu L} \to \nu_{eL}\nu_{eL}\bar{\nu}_{eL}$ will thus occur with a lifetime[12]

$$\tau_{\nu_{\mu L}} \simeq 4\left(\frac{m_{\nu_{\mu H}}}{m_{\nu_{\mu D}}}\right)^4\left(\frac{m_\mu}{m_{\nu_{\mu L}}}\right)^5 \tau_\mu \quad . \tag{10}$$

Using Eq. (7) we conclude that the cosmological limit of 10^{11} sec. is obeyed with $m_{\nu_{\mu L}} > 300$ KeV, i.e., indeed $\nu_{\mu L}$ must have its mass near the present experimental limit. Note that the relatively large value of the left-right admixture parameter of Eq. (3) allowed the neutrino to decay with sufficient rate. To us this seems the most natural way to accommodate $m_{\nu_{\mu L}}$ in the vast experimentally unexplored domain between 50 eV and 570 KeV.[13] Let us note in passing that *one may turn the argument around and use the cosmological limit to predict the values of* $m_{\nu_{\mu L}}$

and $m_{\nu_{\mu H}}$ *as suggested by us.* This is done in a separate publication and (to us at least) it demonstrates the realistic nature of our scheme.

Summing up, the main conclusions of this letter are the following: In the left-right symmetric models which have an intermediate mass scale the heavy muon neutrino may be as light as a hundred MeV and $\nu_{\mu L}$ will then have a mass of a few hundred KeV. If the former is lighter than 380 MeV it should give rise to a signal in $K \rightarrow \mu\nu$ decays with a strength of at least a few parts in a thousand relative to the prominent $\nu_{\mu L}$ signal. The precision achieved in past $K \rightarrow \mu\nu$ experiments is sufficient for detecting such neutrinos. The mass region between 160 and 300 MeV is ruled out by past experiments. Future experimental searches in the region around the pion and muon mass and above 300 MeV are awaited with great interest.

Finally if a secondary peak is indeed found, it will be crucial to measure the polarization of the muons under the peak. The polarization depends on the relative magnitude of the two terms in Eq. (4). If, e.g., W_R is sufficiently heavy and the $W_L - W_R$ mixing sufficiently weak (m_{W_R}/m_{W_L}, $m_{W_R}/m_{LR} > 10$), the measured polarization will very closely correspond to the one accompanied by a massive left-handed neutrino. However, if for instance W_R is light ($m_{W_R} \sim 2\text{-}3\ m_{W_L}$), as anticipated in Ref. 3, the polarization will evidently have a different value. This may then discriminate against the scheme of Ref. 4, in which a secondary peak is interpreted as the result of mixing between $\nu_{\mu L}$ and $\nu_{\tau L}$.

It is exciting and thrilling to realize that the good old $K \rightarrow \mu\nu$ *decay may be the first process to open a window into the yet unvisited domain of left-right symmetric physics. It is also encouraging to hope that we are so close to actually measuring* $m_{\nu_{\mu L}}$, *as the cosmological argument implies.*

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