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# MIXING OF A HEAVY NEUTRINO WITH THE ELECTRON NEUTRINO*

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## ABSTRACT

We show that recent monojet searches in electron-positron annihilation experiments can be used to extend significantly the limits on the mixing of a massive fourth generation neutrino with the electron neutrino. When combined with other limits from hadron decays and secondary vertex searches in hadron and electron-positron annihilation experiments, bounds of $|U_{14}|^2 \lesssim 10^{-6}$ for neutrino masses of 10 $MeV/c^2$ to over 10 $GeV/c^2$ are obtainable by analysis of existing data.

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It continues to be of importance to know how many fundamental fermions there are, and in particular if there is a fourth generation of quarks and leptons. The lightest member of such a new generation is very likely the neutrino, in principle making it most accessible to discovery in present experiments.

If such a neutrino were massless, we will have to wait for "neutrino counting" from decays of the $Z^0$ for its discovery. But if it has a mass, then the weak and mass eigenstates generally will not coincide. For example, the neutrino associated by the weak interactions with the electron,

$$\nu_e = \sum_{i=1}^{4} U_{1i}\nu_i, \tag{1}$$

will be a superposition of the mass eigenstates $\nu_i$. The unitary matrix $U$ is the analogue of the Kobayashi-Maskawa matrix[1] for three generations of quarks. In a specific theory its elements may be predicted, or at least related to the lepton masses. Such is the case, for example, in the O(18) grand unified model[2,3] recently proposed, which predicts a fourth left-handed generation as well as four right-handed mirror generations of quarks and leptons. Since some versions[3] of this model would have mixing in the left-handed neutrino sector between the fourth (heavy, but with a mass below 40 GeV/$c^2$) neutrino and the electron neutrino at the level of $|U_{14}| = \mathcal{O}(10^{-1})$, there is particular interest in analyzing what are the experimental limits on such a possibility in the domain of mixing angle versus neutrino mass. In this paper we show that present $e^+e^-$ data already allow the limits on $|U_{14}|^2 \lesssim \mathcal{O}(10^{-6})$ to be extended into the 10 to 20 Gev/$c^2$ range of masses for a fourth generation heavy neutrino which mixes with the electron neutrino.

Most previous limits[4] on mixing of a heavy neutrino with the electron neutrino come from hadron leptonic or semileptonic decays. A powerful technique[5] is to study $\pi \to e\nu$ or $K \to e\nu$ decays at rest, searching for additional monochromatic peaks in the electron energy spectrum, from $\pi \to eN$ or $K \to eN$, where we have used $N$ to represent a fourth generation neutrino. Upper limits on such peaks, whose intensity would be proportional to $|U_{14}|^2$, are shown in Fig. 1 as obtained in recent experiments.[6–8] A different, but related technique in that it relies on hadronic decays, is to allow hadrons to decay in flight and then to look for the potential subsequent decay of the heavy neutrino downstream. If we restrict ourselves to mixing only with the electron neutrino, then both the production and the decay rate of the heavy neutrino will involve a factor of $|U_{14}|^2$. Such a method is limited in neutrino mass range by the mass of the decaying hadron, so that in addition to using $\pi$ and $K$ decays in flight as in Ref. 9, one also looks at charmed meson decays from a beam dump as in Ref. 10. The combined result of the techniques discussed to this point is to limit $|U_{14}|^2$ to be less than $\mathcal{O}(10^{-6})$ for neutrino masses of $\approx$ 10 MeV to $\approx$ 1.7 GeV.

To reach higher neutrino masses we turn to $e^+e^-$ colliders where we are only limited by the total center of mass energy for $e^+e^- \to N\overline{\nu}_e$ (and half of it for $e^+e^- \to N\overline{N}$). If the heavy neutrino is in a weak doublet, as we are assuming by taking it to be part of a fourth generation, then its production in $e^+e^- \to N\overline{\nu}_e$ proceeds entirely through $W$ exchange with a cross section[11]

$$\sigma(e^+e^- \to N\overline{\nu}_e) = |U_{14}|^2 \frac{G_F^2 s}{6\pi} \left(1 - \frac{M_N^2}{s}\right)^2 \left(1 + \frac{M_N^2}{2s}\right) \qquad (2)$$

where $M_N$ is the neutrino mass and s the square of the center of mass energy.

Such a process will be observed as an $e^+e^-$ collision which results in missing energy and momentum (due to the $\overline{\nu}_e$) on one side and, if $M_N$ is not too large, a jet of decay products of $N$ on the other; i.e., a monojet event. In another context, such events have recently been searched for at PEP[12–14] and at PETRA.[15] At $\sqrt{s} = 29\text{GeV}$, the cross section from Eq. (2) for $e^+e^- \to N\overline{\nu}_e$ or $\overline{N}\nu_e$ is (4.7 pb)$|U_{14}|^2$, up to corrections of order $M_N^2/s$. After allowance for the experimental acceptance for the process under consideration here, we have combined the PEP data, with the resulting upper limit on $|U_{14}|^2$ shown in Fig. 1, which extends out to $M_N \approx 12$ GeV/$c^2$. This new limit is already a considerable improvement over that following from universality[16] and, as we shall discuss below, can be extended by further analysis of existing data.

In contrast to Eq. (2), the cross section[11] for $e^+e^- \to Z_V \to N\overline{N}$ at energies below the $Z$ mass,

$$\sigma(e^+e^- \to N\overline{N}) = \frac{G_F^2 s}{24\pi} \frac{(1 - \frac{4M_N^2}{s})^{\frac{1}{2}}(1 - \frac{M_N^2}{s})}{1 - \frac{s}{M_Z^2}} (1 - 4\sin^2\theta_W + 8\sin^4\theta_W), \quad (3)$$

does not contain a factor of $|U_{14}|^2$ if $N$ is in a weak doublet. At PEP with $\sqrt{s}$=29 GeV and with $\sin^2\theta_W = 0.22$, Eq. (3) predicts a cross section of 0.3 pb if we neglect terms in $M_N^2/s$.

A very powerful technique is to use this as the production mechanism for a heavy neutrino and to note that its decay width is proportional to $|U|^2$, so that a search for secondary vertices sweeps out a region[17] in $|U|^2$ versus $M_N$ space. The results of such a search[18] between 0.2 mm and 10 cm from the interaction point are shown as excluding the diagonal region in Fig.1, running up to masses of almost 14 GeV.

The excluded region can be considerably enlarged by further analysis of the existing data.The dashed line in Fig.1 represents $\gamma c\tau$ of 1 meter for the $N$ produced in the process $e^+e^- \to N\overline{N}$ at $\sqrt{s} = 29$GeV. It should be possible to push the lower boundary of the region excluded by the secondary vertex search close to this line.[19] At the other extreme, the upper boundary is determined by how close to the collision point one can find vertices, as well as by backgrounds from $D$ and$B$ meson decays. If the requirement of observation of a secondary vertex is dropped, then a search may be conducted[20,21] directly for $e^+e^- \to N\overline{N}$, followed by subsequent decay of the $N$ and $\overline{N}$ (close to the collision point). Since we are interested in a heavy neutrino mixing with the electron neutrino, the decay of the $N(\overline{N})$ via a charged current will result in an $e^-(e^+)$ plus a virtual $W^+(W^-)$, manifesting itself as $e^+\nu_e, u\bar{d}, \ldots$ $(e^-\overline{\nu}_e, d\overline{u}, \ldots)$. Thus one looks for two "low" mass jets each containing an $e^{\pm}$. There is sufficient data available now to conduct such a search and exclude a further region lying above that covered by the present vertex search, out to masses $M_N$ of 5 to 7 GeV/$c^2$ before backgrounds (e.g., from $b\bar{b}$ production) overtake the potential signal .[22] The limits coming from $e^+e^- \to N\overline{\nu}_e$ may be extended as well: First, by the straightforward increase of integrated luminosity and/or detector acceptance, which will lower the upper limit on $|U_{14}|^2$ in the mass range already covered, and second, by changing experimental cuts to maximize acceptance for larger values of $M_N$. In this way it should be possible to push the region where there are useful bounds on $|U_{14}|^2$ out toward $M_N \approx 20$ GeV from PEP data[23] and higher yet from PETRA.[24]

The one remaining place in Fig. 1 with a potential "window" for $|U_{14}|^2 \gtrsim 10^{-6}$ lies between the regions excluded by the CHARM beam dump experiment[10] and the Mark II vertex search.[18] The upper part of this "window" is covered by recent results from a Fermilab beam dump experiment.[25] The lower part could be largely filled in, as was recently emphasized,[26] by beam dump experiments utilizing $B$ decays. Thus for a fourth generation neutrino mixing with the electron neutrino we may relatively soon be able to exclude most of the territory in Fig. 1.

Finally, what if instead we consider a heavy neutrino which is a left-handed singlet instead of a member of a weak doublet ? We still can define the unitary matrix in Eq. (1) and the previous limits on $|U_{14}|^2$ from hadron decays all still hold. If $N$ is in a right-handed doublet, Eq. (3) still holds; but if in a right-handed singlet, the cross section for $e^+e^- \to N\overline{N}$ picks up a factor of $|U|^4$, making it negligibly small for interesting values of $|U|^2$, and we lose the restrictions obtained from the search for secondary vertices in the process $e^+e^- \to N\overline{N}$. In either case we now have both a $W$ exchange and direct channel $Z$ contribution to the amplitude for $e^+e^- \to N\overline{\nu}_e$. Instead of Eq. (2), we find:

$$\sigma(e^+e^- \to N\overline{\nu}_e) = \frac{|U_{14}|^2 G_F^2 s}{24\pi}\left(1-\frac{M_N^2}{s}\right)^2\left(1+\frac{M_N^2}{s}\right)\left(1+4\sin^2\theta_W+8\sin^4\theta_W\right) \tag{4}$$

If $\sin^2\theta_W$=0.22, then the cross section in Eq. (4) is 0.57 times that in Eq. (3) and the monojet searches have a correspondingly lower sensitivity in setting an upper limit on $|U|^2$. However, the limits they set are still better in the high mass region than any other constraint, e.g., universality.

In summary we have shown that presently available data from $e^+e^-$ experiments allows us to considerably extend the mass range in which we have fairly stringent limits on the mixing of a heavy neutrino with the electron neutrino. In particular, if we are considering a fourth generation left-handed neutrino, upper bounds of $\mathcal{O}(10^{-6})$ on $|U_{14}|^2$ up to $M_N \approx 14$ GeV/$c^2$ and of $10^{-3}$ to $10^{-2}$ for $M_N$ up to about 30 GeV/$c^2$ should be obtainable by analysis of existing data and combining the data from different experiments.

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## FIGURE CAPTIONS

1. Limits on $|U_{14}|^2$ as a function of neutrino mass, $M_N$, as obtained from (1) TRIUMPH $\pi \rightarrow e\nu$, Ref. 6; (2) SIN $\pi \rightarrow e\nu$, Ref. 7; (3) KEK $K \rightarrow e\nu$, Ref. 8; (4) CHARM experiment at CERN with a wide band beam, Ref. 9; (5) CHARM experiment at CERN searching for $D \rightarrow eN$ in a beam dump, Ref. 10; (6) universality, Ref. 16; (7) combined monojet searches at PEP, Refs. 12, 13, and 14; (8) secondary vertex search in $e^+e^- \rightarrow N\overline{N}$ at PEP, Ref. 18. The dashed line corresponds to $\gamma c\tau$ of one meter for a fourth generation neutrino produced in $e^+e^- \rightarrow N\overline{N}$ at $\sqrt{s} = 29$ GeV.

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17. What is obtained is actually a sum over partial widths each proportional to a $|U_{i4}|^2$, but we are assuming here that the mixing is primarily with the electron neutrino.

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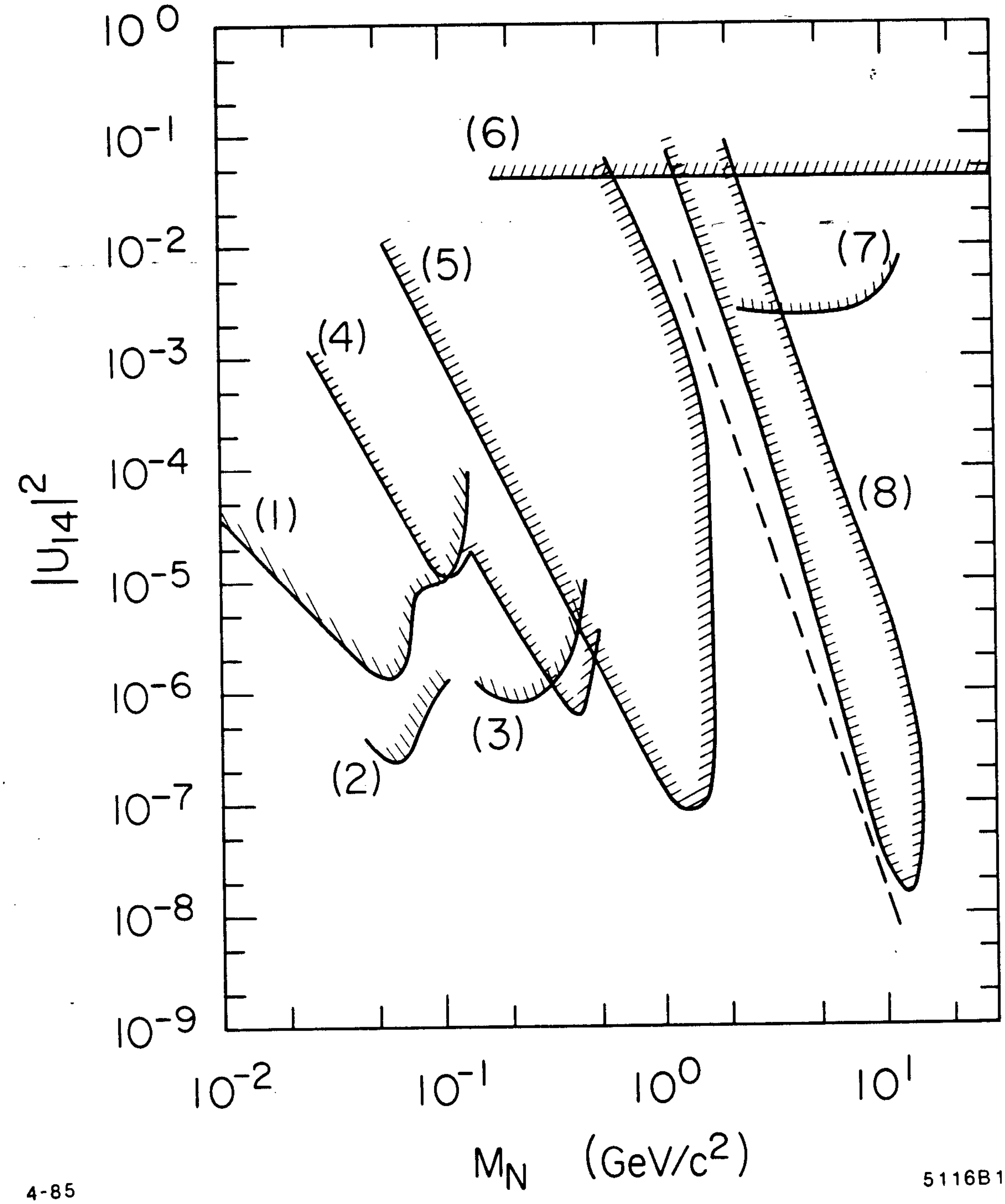

10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
|U14|^2
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
10^-2
10^-1
10^0
10^1
M_N (GeV/c^2)
4-85
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Fig. 1