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IMPROVED LOWER LIMITS ON NEUTRAL FERMION MASSES*

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ABSTRACT

Present lower limits on the mass of a neutral fermion N coupled with full strength to an electron via the right-handed weak current are set only by the absence of the decay $K^+ \rightarrow Ne^+$: $m(N) \geq 0.5 \text{ GeV}/c^2$. It is shown that searches for the decays $\tau \rightarrow \nu_\tau Ne$ or $F \rightarrow Ne$, followed by $N \rightarrow e\nu$, can raise the lower bound on $m(N)$ to well over $1 \text{ GeV}/c^2$ if no signal is seen in present or soon-to-be-acquired data. Estimates for the branching ratios for these processes are given. If N couples to $e \cos \phi + \mu \sin \phi$ with full strength, reference to ϕ may be eliminated by summing over e and μ in all final states.

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Many models of current interest of the weak interactions employ, for one reason or another, a neutral fermion N coupled right-handedly to an electron in the same manner as ν_e couples left-handedly: thus,

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad , \quad \begin{pmatrix} N \\ e^- \end{pmatrix}_R \quad (1)$$

would be a pair of weak doublets to which the electron belongs.^{F1-F3, [1], [2]}

Since $K^+ \rightarrow Ne^+$ does not occur, the mass of N must exceed $0.5 \text{ GeV}/c^2$.^{[3], F4} In this note we explore two likely sources of N if m_N lies between 0.5 and about $1.5 \text{ GeV}/c^2$: the decays

$$\tau \rightarrow \nu_\tau Ne \quad (2)$$

and

$$F \rightarrow Ne \quad (3)$$

In Eq. (2) τ denotes the charged fermion of mass $\sim 1.9 \text{ GeV}/c^2$ discovered^{[4]-[6]} and confirmed^[7] within the past two years^{F5}. We shall assume its neutrino ν_τ is massless.^{F6, [8]} F denotes the lowest-mass charmed-strange pseudoscalar meson:^[9]

$$F^+ = c\bar{s}, \quad F^0 = c\bar{c} \quad (4)$$

whose mass is probably around $2 \text{ GeV}/c^2$.^[10] The N , in turn, may be observed via the decay

$$N \rightarrow e\nu \quad (5)$$

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The lowest-mass eigenstate N coupled right-handedly to e may not appear as in Eq. (1) but instead as

$$\begin{pmatrix} N \\ e^- \cos \phi + \mu^- \sin \phi \end{pmatrix}_R \quad (6)$$

with a heavier particle N^* coupled to $\mu^+ \cos \phi - e^+ \sin \phi$.⁽¹⁾ If so, all discussions are still valid as long as e in Eqs. (2), (3), and (5) is replaced by $(e$ or $\mu)$.

By estimating branching ratios for the processes (2), (3) and (5), we shall show that present data are capable of establishing a bound $m(N) \geq 1 \text{ GeV}/c^2$ if no signal is seen for process (2). The process (3) should permit this bound to be extended to around $1.5 \text{ GeV}/c^2$ once a copious source of F 's can be found. (Cf. ref. [11] for a similar discussion of $F \rightarrow \tau \nu_\tau$.)

Estimates of the branching ratio for Eq. (5) proceed in a manner very similar to those for τ decays^{[3],[12]}. The decays $N \rightarrow e^- e^+ \nu_e$, $N \rightarrow e^- \mu^+ \nu_\mu$ have rates

$$\Gamma(N \rightarrow e^- e^+ \nu_e) = (m_N/m_\mu)^5 \Gamma_\mu \quad (7)$$

$$\Gamma(N \rightarrow e^- \mu^+ \nu_\mu) = (m_N/m_\mu)^5 \Gamma_\mu f(m_N/m_\mu) \quad (8)$$

where (see, e.g., Ref. [3])

$$f(x) = 1 - 8x^2 + 8x^6 - x^8 + 24x^4 \ln \frac{1}{x} \quad (9)$$

and

$$\Gamma_\mu = 4.55 \times 10^5 \text{ sec}^{-1}$$

The decay $N \rightarrow e^- \pi^+$ may be estimated via PCAC:

$$\Gamma(N \rightarrow e^- \pi^+) = \frac{\Gamma_\pi}{2} \frac{m_\pi^2}{m_\mu^2 m_N^2} \left(\frac{m_N^2 - m_\pi^2}{m_\pi^2 - m_\mu^2} \right)^2 \quad (10)$$

where

$$\Gamma_\pi = 3.84 \times 10^7 \text{ sec}^{-1}$$

Vector dominance yields the result

$$\begin{aligned} \Gamma(N \rightarrow e^- \rho^+) &= \frac{G_F^2}{12\pi^2} \left(\frac{4s}{g_\rho^2} \right) (m_N^2 - m_\rho^2)^2 \\ &\times (m_\rho^2/m_N^2) (1 + 2m_\rho^2/m_N^2) \end{aligned} \quad (11)$$

where

$$g_\rho^2/4\pi \approx 2.5$$

Eqs. (10) and (11) provide an estimate for $N \rightarrow e + (\text{all hadrons})$ for m_N sufficiently small. A complementary estimate, valid for all m_N , is obtained by neglecting the final-state interactions and masses in $N \rightarrow e^- + (3 \text{ colors of } u\bar{d})$. This gives

$$\Gamma(N \rightarrow e^- u\bar{d}) = 3(m_N/m_\mu)^5 \Gamma_\mu \quad (12)$$

For $0.5 \text{ GeV}/c^2 \leq m_N < 1.3 \text{ GeV}/c^2$, Eq. (12) falls just below the sum of (10) and (11). It begins to exceed this sum at $m_N = 1.3 \text{ GeV}/c^2$, which may be taken as the onset of hadron final states besides π and ρ . Thus, for $0.5 \text{ GeV}/c^2 \leq m_N < 1.3 \text{ GeV}/c^2$, we shall take

$$\begin{aligned} \Gamma_N = & \Gamma(N+e^-e^+v_e) + \Gamma(N+e^-u^+v_u) \\ & + \Gamma(N+e^-u^+\pi^+) + \Gamma(N+e^-p^+) \end{aligned} \quad (13)$$

while for $m_N \geq 1.3 \text{ GeV}/c^2$ we take

$$\begin{aligned} \Gamma_N = & \Gamma(N+e^-e^+v_e) + \Gamma(N+e^-u^+v_u) \\ & + \Gamma(K+e^-u\bar{d}) \end{aligned} \quad (14)$$

The predicted values of Γ_N and branching ratios to $e^- \pi^+$ and $e^- p^+$ are shown in Table I. Note the importance of $e^- p^+$ for $m_N \geq 1 \text{ GeV}/c^2$. For present purposes we concentrate on the more easily detected $e^- \pi^+$ channel.

For $\tau \rightarrow \nu_\tau Ne$ one finds simply

$$B_\tau \equiv \Gamma(\tau \rightarrow \nu_\tau Ne) / \Gamma_\tau = \frac{f(m_N/m_\tau)}{5 + f(m_N/m_\tau)} \quad (15)$$

with $f(x)$ given by Eq. (9). In the denominator of (15), the number 5 denotes the pairs of "massless" fermions to which the weak current in $\tau^+ + \bar{\nu}_\tau$ can couple: e^+v_e , μ^+v_μ , and three colors of $u\bar{d}$.

An estimate of $\Gamma(F \rightarrow Ne)$ must rely on SU(4) or on an explicit quark model to determine the F -weak current coupling f_F .

Writing

$$\langle 0 | A_\mu(0) | F^+(q) \rangle = q_\mu f_F \quad (16)$$

for the matrix element of the axial-vector charm and strangeness-changing current $A_\mu(0)$, we have

$$\begin{aligned} \Gamma(F \rightarrow Ne) = & \Gamma(K \rightarrow \nu\bar{\nu}) \cot^2 \theta_c \left(\frac{f_F}{f_K} \right)^2 \\ & \times \frac{m_N^2/m_F^2}{m_\mu^2/m_K^2} \left[\frac{1 - m_N^2/m_F^2}{1 - m_\mu^2/m_K^2} \right]^2 \end{aligned} \quad (17)$$

We shall take $f_F = f_K$ (the SU(4) value) for purposes of illustration, and $\cot^2 \theta_c = 18$.

The total decay rate of F has been estimated in Ref. [13]:

$$\Gamma_F = \Gamma_\mu (m_c/m_\mu)^5 (2 + [3.7 \text{ to } 4.8]) \quad (18)$$

In Eq. (18), m_c is the charmed quark mass, the 2 refers to semileptonic decays to $e\nu$ and $\mu\nu$, and the term in [] is the (modestly enhanced) contribution of the nonleptonic decays. This term would be 3 (for the number of colors of $u\bar{d}$) in the absence of enhancement.

Taking $m_c = 1.9 \text{ GeV}/c^2$ and 4 in [] in Eq. (18), we find

$$\Gamma_F = 5 \times 10^{12} \text{ sec}^{-1} \quad (19)$$

which will be used in quoting branching ratios.

The ratios B_T [Eq. (15)], $B_F \equiv \Gamma(F+Ne)/\Gamma_F$, B_TB_N , and B_FB_N [$B_N \equiv B(N+e^+e^-)$; see Table 1] are displayed in Figure 1.

The kinematics of 3-body weak decays leads to a rapid suppression of B_T as m_N grows. By contrast, B_F reaches its maximum value at $m_N = m_F/\sqrt{2} = 1.16 \text{ GeV}$. The product B_TB_N is largest for lower m_N , since the opening of the $e\bar{e}$ channel leads to a rapid decrease in B_N . However, B_FB_N does not drop nearly as rapidly with increasing m_N as does B_TB_N .

At energies such that $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = \sigma(e^+e^- \rightarrow \mu^+\mu^-)$ and $\sigma(e^+e^- \rightarrow \text{"hadrons"}) = 5\sigma(e^+e^- \rightarrow \mu^+\mu^-)$,^{F7} roughly one observed "hadron" event in $5/(2 B_TB_N)$ should have a final state consisting of

$$\left\{ \begin{array}{l} e^+e^-\tau^+ + \dots \\ m(e^+e^-\tau^+) = m_N \end{array} \right\} \quad (20)$$

The major background to Eq. (21) will arise from charged hadron tracks which simulate electrons.^[4] However, $m(e^+h^+)$ in such events will be spread over a wide range of mass. Even in a "worst case" we estimate that in a sample of 50,000 "hadron"^{F7} events one should be able to detect a signal (20) if it corresponds to at least a hundred events in one mass bin,^{F8} corresponding to $B_TB_N \geq 1/2\%$ or $m_N \leq 1.1 \text{ GeV}/c^2$.

The events in $\tau^+\tau^-$ production richest in the signal (20) are those of the form $+-\pm$ or $++--$, where the signs denote charges of visible tracks. The branching ratio $\tau \rightarrow (1 \text{ charged particle})$ should be large ($\sim 87\%$ ^[12] if any $\tau \rightarrow \nu_\tau Ne$ contribution is neglected). Thus $e^+e^- \rightarrow \tau^+\tau^-$ is unlikely to lead to more than 4 charged tracks, while true hadronic events with at least 5 visible charged tracks should be quite common.

The signal for $F+Ne \rightarrow e^+e^-\pi^+$ is much cleaner^{F8} than that for $\tau^+ \rightarrow \nu_\tau Ne^+ \rightarrow \nu_\tau e^+\pi^+$, as both $e^+\pi^+$ and $e^+e^-\pi^+$ must have definite mass. The major obstacle will be statistics: at present, F has not yet been detected.^{F9} A statistical model^[14] implies

$$\begin{aligned} B(F^+ \rightarrow K^+ \bar{K}^0 \xrightarrow{L \rightarrow \pi^+ \pi^-}) &= 2-3\% \quad \text{F10} \\ B(F^+ \rightarrow \eta \pi^+ \xrightarrow{L \rightarrow \gamma \gamma}) &= 2\% \\ B(F^+ \rightarrow K^+ K^- \pi^+) &= 4-5\% \end{aligned} \quad (21)$$

with no other more copious easily-detected decay modes. Thus, once F is seen, Figure 1 shows that for $m_N \leq 1.5 \text{ GeV}/c^2$, the $e^+e^-\pi^+$ mode should be at least 10% of any single detectable mode of F^+ .^{F11} The prediction of $B(F+Ne)$ is, of course, subject to the uncertainties mentioned earlier in Γ_F and Γ_F .

The kinematic factors involving the replacement of e by μ in Eqs. (2), (3) and (5) turn out to be negligible throughout the "interesting" mass range $0.5 \text{ GeV}/c^2 \leq m_N \leq 1.5 \text{ GeV}/c^2$. Thus, for example, if the charged leptons couple right-handedly to N

as in Eq. (6) rather than Eq. (1), we may write

$$\Gamma(F+Ne) = \Gamma(F+Ne) \Big|_{\phi=0} \cos^2 \phi \quad , \quad (22)$$

$$\Gamma(F+N\mu) = \Gamma(F+Ne) \Big|_{\phi=0} \sin^2 \phi \quad , \quad (23)$$

so

$$\Gamma(F+Ne) + \Gamma(F+N\mu) = \Gamma(F+Ne) \Big|_{\phi=0} \quad . \quad (24)$$

A similar argument applies to $\tau \rightarrow \nu_\tau N$ (e or μ) and $N \rightarrow (e \text{ or } \mu) +$ (anything).^{F12} Consequently, the final state of interest in Eq. (20) is replaced by

$$e^+ e^- \pi^+ + \dots \quad , \quad (25)$$

where $e^+ e^- \pi^+ = e^+ e^- , \mu^+ \mu^- , e^+ \mu^- , \text{ or } \mu^- e^+ ,$ ^{F13}

Given the coupling (6), an interesting lower bound, independent of ϕ , can be placed on those events of the form $e^+ e^- \rightarrow e^+ \mu^- +$ (more charged tracks) due to τ decays. To idealize, let B_τ be very small. Imagine one τ to decay to $\nu_\tau e \nu_e$ and $\nu_\tau \mu \nu_\mu$ each with $B = 1/5$ and to $\nu_\tau +$ hadrons with $B = 3/5$. Let the other decay to Ne with $B = B_\tau \cos^2 \phi$ and to N_μ with $B = B_\tau \sin^2 \phi$, where B_τ is given by Eq. (15). Let N decay to $e \nu_e$ with $B = (1/5) \cos^2 \phi$, to $\mu \nu_\mu$ with $B = (1/5) \sin^2 \phi$, and so on, and estimate its semihadronic decays in terms of three colors of free massless $u\bar{d}$ quarks. Then we find that

$$\begin{aligned} & \sigma(e^+ e^- \rightarrow \nu^+ e^- + \text{[additional tracks]}) \\ &= \left[\frac{18}{25} + \frac{64}{25} \sin^2 \phi \cos^2 \phi \right] B_\tau \sigma(e^+ e^- \rightarrow \tau^+ \tau^-) \\ &\geq \frac{18}{25} B_\tau \sigma(e^+ e^- \rightarrow \tau^+ \tau^-) \end{aligned} \quad (26)$$

The left-hand side of Eq. (26) refers to events in which all charged particles are identified and at least one $e^+ \mu^-$ pair is present. This is somewhat of an idealization. Nonetheless, it should be possible to obtain some useful upper bound on B_τ (and hence to raise the lower bound on m_N above $0.5 \text{ GeV}/c^2$) from the following piece of data. In a sample which yielded 23 events of the form

$$e^+ e^- \rightarrow e^+ \mu^- + \text{[no other detected charged or neutral particles]} \quad , \quad (27)$$

only 7 events of the form (26) were seen, with an expected background of 8.5. [7], [17] The process (27) should account for roughly $2 \times (1/5)^2 = 8\%$ of $\tau^+ \tau^-$ production. A signal of four events in process (26) would then correspond to $B_\tau \leq 2\%$, or $m_N \geq 1.0 \text{ GeV}/c^2$, if efficiencies for detecting (26) and (27) were comparable. As they are not, we must leave the precise estimate to the experimenters themselves.

A major reason^[1] for having N belong to a right-handed doublet as in Eq. (1) or (6) is to suppress parity violation in atomic physics experiments.^[18] However, if N belonged to a

triplet, the quantities B_T , B_F , and Γ_N would be doubled, while B_N would remain the same. Hence even more stringent lower bounds could be placed on m_N . Our predictions may be similarly scaled to account for any arbitrary coupling strength associated with the right-handed transitions in Eq. (1) or (6). (Assignments of e_R^- to a multiplet with $|I_{WZ}| > 1/2$ can be excluded on the basis of neutrino experiments: see Ref. [19].)

The decays

$$F^+ \rightarrow N\mu^+, N \rightarrow \mu^- + (\text{anything})^+ \quad (28)$$

could be responsible for some of the observed neutrino interactions that give rise to three moons. [15], [16] In

$$\nu X \rightarrow \mu^- F^+ Y \quad (29)$$

the F^+ will carry most of the hadronic energy if the process is diffractive. If (28) and (29) each occur with a $\sim 1\%$ branching ratio, one or two of the observed events could be accounted for. ^{F14}

To conclude: present lower limits on the masses of certain neutral fermions can be raised appreciably by examining the products of $\tau^+(1.9)$ and $F^+(\sim 2.0)$ decays. The τ serves mainly below $1 \text{ GeV}/c^2$, while F (if its production is not abnormally suppressed) should be useful up to about $1.5 \text{ GeV}/c^2$. In the past two years two weak transitions have been seen between light fermions and ones between 1 and $2 \text{ GeV}/c^2$ in mass:

$$s \leftrightarrow c \quad (30)$$

and

$$\nu_\tau \leftrightarrow \tau \quad (31)$$

These transitions could play a crucial role in determining whether more (such as Eq. (1) or Eq. (6)) exist.

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FOOTNOTES

- F1. We shall be concerned only with essentially "full-strength" transitions. We assume that N has a left-handed component as well, whose (generally small) coupling to e^- is specified by the mechanism that generates masses. (See [1]).
- F2. Our interest in this model was engendered by the works of Ref. [1], of which the last contains a large list of further references and motivations for the couplings of Eq. (1).
- F3. For an example of a way in which such a structure might arise, see Ref. [2].
- F4. Strictly speaking, $m_N > m_K - m_\pi - \epsilon$, where ϵ is a small quantity that need not concern us here.
- F5. In common parlance, this is a "heavy lepton". Thus, "lepton" has come to mean any fermion not "dressed" by the strong interactions. To avoid this etymological irony, we suggest the term "ork", reserving "lepton" to mean a "light ork". For a picture of a (nearly bare) Ork, see L. Frank Baum, "The Scarecrow of Oz", Rand McNally, New York, 1915, p. 32.
- F6. The question of whether we take $V-A$ or $V+A$ couplings in $\tau \leftrightarrow \nu_\tau$ need not concern us. However, we must assume there is no neutral fermion distinct from ν_τ to which τ can decay. The need for $\nu_\tau \neq \nu_e, \nu_\mu$ has been stressed in Ref. [8].
- F7. The "high-energy" ($\langle E_{cm} \rangle = 6.9$ GeV) data of Ref. [6] would satisfy this condition.

- F8. I thank Don Meyer for discussions related to this point.
- F9. We anticipate that this situation should change presently; see Ref. [14].
- F10. Destructive interference between two terms in $H_W^{n,1}$ may suppress $\Gamma(F^+ \rightarrow K^+ \bar{K}^0)$ below this value; see Ref. [13].
- F11. The absence of a $\cot^2 \theta_c$ factor in the prediction for $D^+ \rightarrow \pi^+ e^+$ corresponding to Eq. (17) makes the detection of this mode unlikely, though the D^+ has been seen. (See Ref. [14] for a discussion of its decays.)
- F12. The higher threshold in N -up will shift the peak of the $B_F B_N$ curve in Figure 1 toward $0.9 \text{ GeV}/c^2$ as ϕ increases toward $\pi/2$.
- F13. Charm production, followed by the semileptonic decays of both charmed particles, is expected to provide a small background to the final states (20) and (25), with $m(\ell^+ \bar{\nu})$ spread over an appreciable range. The charmed-pair background can be reduced when one is considering $e^+ e^- \rightarrow \tau^+ \tau^-$ by selecting events with low multiplicity as discussed above; for $F \rightarrow \pi$ background problems will not be nearly as severe.
- F14. One event in Ref. [16] has $m_{\mu^+ \mu^-} > m_F$ for the second fastest and third-fastest muon. It could involve the diffractive production of a heavier meson like ω , followed by its subsequent two-body leptonic decay in the manner noted here.

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TABLE I

Total decay rates and some branching ratios for decays of neutral fermion N coupled to e via $V + A$ current

m_N GeV/c ²	$\Gamma(N)$ sec ⁻¹	$B(N \rightarrow e^- \pi^+)$ %	$B(N \rightarrow e^- \rho^+)$ %
0.5	9.0×10^9 (a)	79 (b)	-
0.6	1.8×10^{10}	73	-
0.7	3.2×10^{10}	67	-
0.8	5.5×10^{10}	59	2 (c)
0.9	1.1×10^{11}	44	19
1.0	1.9×10^{11}	35	30
1.1	3.0×10^{11}	29	16
1.2	4.5×10^{11}	25	38
1.3	6.3×10^{11}	23	39
1.4	9.2×10^{11}	20	36
1.5	1.3×10^{12}	17	34
1.6	1.8×10^{12}	15	31
1.7	2.4×10^{12}	13	28
1.8	3.2×10^{12}	12	26

(a) 7.4×10^8 sec⁻¹ if N coupled to μ .

(b) $B(N \rightarrow \mu^- \pi^+) = 82\%$ if N coupled to μ .

(c) Higher threshold if N coupled to μ .

FIGURE CAPTION

Figure 1. Branching ratios $B_\tau \equiv \Gamma(\tau \rightarrow \nu_\tau Ne)/\Gamma_\tau$ and $B_\rho \equiv \Gamma(\rho \rightarrow Ne)/\Gamma_\rho$ (dashed lines), and $B_\tau B_N$, $B_\rho B_N$ (solid lines), $B_N \equiv \Gamma(N \rightarrow e \pi)/\Gamma_N$. See text for assumptions.

Figure 1

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