TEST OF VECTORLIKE WEAK LEPTON CURRENTS IN e^+e^- ANNIHILATION

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For some of the vectorlike weak currents such as the one suggested by Fritzsch et al., the radiative decay of heavy leptons allows us to test it for arbitrary values of parameters in e^+e^- annihilation at presently available energies, provided that the charged heavy lepton is identified with the U-particle. Existing data already constrain the mass of the neutral lepton N_M to be $\lesssim 8$ GeV.

There exist a class of interesting models of elementary fermions based on the idea of vectorlike weak currents [1,2]. In this scheme one generally seeks the dynamical origin of parity violation at the mass scale of new particles we are just witnessing. This way of understanding parity violation makes such a scheme very attractive. This naive left-right symmetry is particularly transparent in the "minimal" vectorlike model recently discussed by Fritzsch, Gell-Mann and Minkowski [2]. The lepton sector of their model looks like

$$\begin{pmatrix} \nu_e & N_M & \vdots & \nu_\mu \\ e^- & M^- & \vdots & \mu^- \end{pmatrix}_L , \quad \begin{pmatrix} N_M & \nu_e & \vdots & N_\mu \\ e^- & M^- & \vdots & \mu^- \end{pmatrix}_R , \tag{1}$$

Here M^- and N_M are massive Dirac spinors, and N_μ a massive Majonara spinor. The ordinary weak and electromagnetic vector fields $W_\mu^\pm$, Z_μ and A_μ interact with those leptons via $SU(2) \times U(1)$ gauge coupling; all the Fermion pairs in (1) transform as a doublet under SU(2). There are, of course, several other models of vectorlike weak currents based on the SU(2) $\times$ U(1), which include SU(2) singlets as well as doublets [3,4], e.g.,

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \quad e_R^- ; \quad \begin{pmatrix} \nu_e \\ E^- \end{pmatrix}_R , \quad E_L^- , \tag{2}$$

and similarly for the muon sector, When the mass of, e.g., N_M in (1) becomes large compared with the intermediate boson mass M_W, $m_N^2 \gg M_W^2$, the multiplet (1) resembles the sequential heavy lepton [e.g. 5] with a right-handed current or the multiplet (2), which can in principle be tested based on the $e\mu$ distributions in $e\bar{e}$ annihilation [6,7].

For $m_N^2 < M_W^2$, which is the base of actual interest [2], we can test the multiplet structure (1) in more detail because the radiative decay

$$M^- \to e^- + \gamma , \tag{3}$$

is enhanced when the neutral heavy lepton N_M becomes heavier than the charged lepton M^-. This enhanced radiative decay is due to the interference between the left- and right-handed currents, and it is essentially the same as the enhanced magnetic moment [8] in the original vectorlike model [1]. Similar enhancement mechanism has been recently utilized by De Rujula et al. to explain the enhanced $\Delta I = 1/2$ component in the non-leptonic weak decay [9].

We find the radiative decay rate of M^- in the multiplet (1)

$$\frac{\Gamma(M^- \to e^- \gamma)}{\Gamma(M^- \to e^- \nu_e \bar{\nu}_e)} = \frac{6\alpha}{\pi} \left(\frac{m_N}{m_M}\right)^2 \eta^2 , \tag{4}$$

where, unlike the case of the muon magnetic moment [8], the parameter η in (4) (see eq. (13) below) is bounded from below

$$\eta \geqslant 1 , \qquad \text{for } m_N \geqslant m_M , \tag{5}$$

provided that the characteristic Fermion mass scale is smaller than the W-boson mass [2]. The $\mu e \gamma$ cross section in units of the ordinary radiationless $e\mu$ events [10] in $e\bar{e}$ annihilation is given by

$$\frac{\sigma(\mu e \gamma)}{\sigma(e\mu)} \approx 1.5 \times \left(\frac{m_N}{m_M}\right)^2 \eta^2 \ \% , \tag{6}$$

and a signal of the radiative decay (3) at the center of

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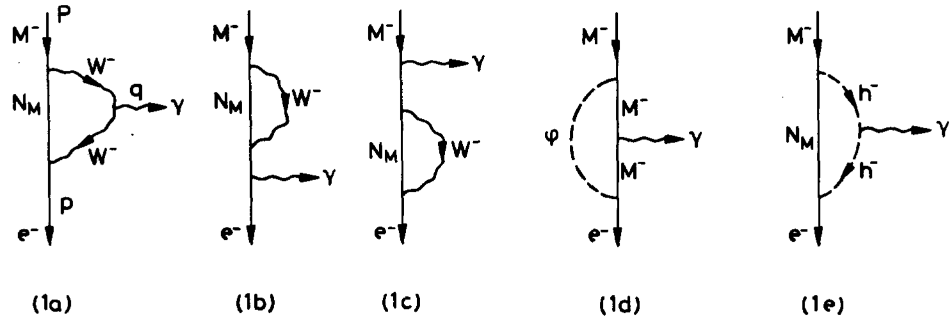

Fig. 1. Some of the relevant diagrams for the radiative decay of M^-. φ and h^- stand for neutral and charged Higgs scalars, respectively.

mass energy s is

$$E_e + E_\gamma = \sqrt{s}/2, \quad \text{and } (p_e + p_\gamma)^2 = m_M^2 . \tag{7}$$

It is attractive to identify M^- with the U-particle found by Perl et al. [10].

We then find the upper bound to the mass of N_M at $\approx$ 8 GeV based on 24 $e\mu$ events versus 8 $\mu e\gamma$ events [10]. This bound could be substantially lowered if one imposes the constraint (7). The neutral lepton N_M with $m_N \lesssim 8$ GeV can also be directly produced in high energy $e\bar{e}$ annihilation. The production cross section $e\bar{e} \to N_M \bar{\nu}_e$ (or $\bar{N}_M \nu_e$) via t-channel W exchange is given by [11]

$$\sigma(N_M \bar{\nu}_e) = \frac{G^2 s}{2\pi} \frac{(1 - m_N^2/s)^2}{1 + (s - m_N^2)/M_W^2} . \tag{8}$$

The ratio of the $e\mu$ signals arising from N_M and the ordinary M^+M^- at the maximum energy of the next generation of colliding machines, $s \sim 10^3$ GeV^2, is estimated at

$$\frac{\sigma(N_M \to e\mu) + \sigma(\bar{N}_M \to e\mu)}{\sigma(M\bar{M} \to e\mu)} \approx 1/2 \sim 1/3 , \tag{9}$$

based on $\Gamma(N_M \to e\mu\bar{\nu}_\mu)/\Gamma(N_M \to \text{all}) \approx 10 \sim 15\%$. We therefore expect a comparable number of $e\mu$ events at *large* collinearity angles from N_M-decay and at small collinearity angles from M^+M^--decay [6,7]. Eqs. (8) and (9) could also be used to fix the W-boson mass in $e\bar{e}$ annihilation.

If the mass of N_M is smaller than m_{M^-}, it can be observed in M-decay. A good signal of N_M may be an $e^-\pi^+$ resonance. The ratio of the $e\mu$ signal accompanied by the $e\pi$ resonance to the ordinary $e\mu$ signal [10] is estimated at

$$\frac{\sigma(\mu^+ e^-(e^+\pi^-)) + \sigma(\mu^- e^+(e^-\pi^+))}{\sigma(e\mu)} \approx 5\% , \tag{10}$$

for $m_N \approx 1$ GeV, based on $\Gamma(N_M \to e\pi)/\Gamma(N_M \to \text{all}) \approx 30\%$.

In the following we briefly sketch the derivation of (4) and (5). Some of the relevant diagrams contributing to the radiative decay (3) are shown in fig. 1.

The contributions from those diagrams have a general structure (neglecting the electron mass)

$$\mathcal{M} = \frac{-ieGm_N}{4\pi^2\sqrt{2}} \bar{u}_e(p)(1 - \gamma_5) \times [F_1(q^2)\gamma_\mu + i\sigma_{\mu\nu} q^\nu F_2(q^2)] u_M(p) \epsilon^\mu(q) . \tag{11}$$

One technical point to be noted is that figs. 1a, 1d and 1e, for example, all give rise to logarithmically divergent contributions to F_1. Moreover, these divergences do *not* cancel among themselves. These divergences together with non-diagonal wave function renormalization are absorbed by the counter term in dimensional regularization [e.g. 12]

$$\mathcal{L}_c = \frac{1}{2 - \omega} \frac{3Gm_N}{(4\pi)^2\sqrt{2}\cos^2\alpha} \times [m_e \bar{\psi}_{1L} i\not{D} \psi_{2L} + m_M \bar{\psi}_{1R} i\not{D} \psi_{2R}] , \tag{12}$$

where D_μ is the SU(2)$\times$U(1) covariant derivative, and ψ_{1L} and ψ_{2L}, for example, stand for the first and the second columns of the left-handed multiplet in (1), respectively. After the removal of divergences, the finite contributions to F_1 in the on-shell amplitude vanish. The actual evaluation of F_2 proceeds just as that of the muon anomalous magnetic moment [8]. One finally obtains $\eta \equiv F_2(0)$ for $m_N^2 < M_W^2$

$$\eta = 1 + \frac{1}{4\cos^2\alpha}\int_0^1 dx \int_0^1 dy \times \frac{x^2[1+y(1-x)]}{x^2y + x(1-y) + (1-x)(m_\varphi/m_M)^2} + \tfrac{1}{2}\tan^2\alpha \int dx \int dy \times \frac{x(1-x)\,[(m_N/m_M)^2 - xy]}{(m_h/m_M)^2 x + (1-x)[(m_N/m_M)^2 - xy]} . \tag{13}$$

The first term in η arises from the W-boson in fig. 1a, the second from the neutral Higgs scalar in fig. 1d, and the third from the charged Higgs scalar in fig. 1e, respectively. Here we assumed that the theory contains only two Higgs scalar systems, a real SU(2) triplet and a complex SU(2) triplet, which are sufficient to generate all the masses in the model [2]. If one adds extra fields such as an SU(2) doublet scalar field, the last term in η becomes a sum of charged scalar contributions. As these contributions all have the same sign as the last term in (13), our discussions are not modified even if one adds these extra fields. The angle $\cos\alpha$ in (12) and (13) is defined as a fraction of the W-boson mass arising from the real scalar triplet, which gives rise to the masses for Dirac spinors; $\cos\alpha \equiv (gv)/M_W$ with g and v the gauge coupling constants and the vacuum value of the real scalar triplet, respectively. Unlike the case of the muon magnetic moment [8], all the terms in (13) are *positive definite* for $m_N \geqslant m_M$ (in fact, the condition $m_N \geqslant \frac{1}{2} m_M$ is sufficient). This together with (11) lead to (4) and (5).

Although our discussion in this note is based on the very specific model (1), it can be applied to other models if they contain neutral heavy leptons which bridge between light and heavy charged leptons with opposite helicities.

Note added: After submitting our letter a related work by Fritzsch and Minkowski (CALT-68-538 (1976)) came to our attention, and we found a mistaken extra factor of 2 in eq. (4) in our original manuscript. They discuss only the W-boson contributions.

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