Heavy Leptons and Trimuons in an SU(3) ⊗ U(1) Model

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We consider models in which heavy leptons are produced in neutrino reactions and then decay sequentially into trimuons. In all these models leptons and quarks are in the $\underline{3}$ or $\underline{3}^*$ representation of the gauge group SU(3) ⊗ U(1).

The recent report[1,2] of trimuon events in ν_μ-induced reactions with a rate of $\sim 5\times 10^{-4}$ relative to muon production has created a great deal of interest because of the possibility that these events are caused by the production and subsequent decay of a heavy charged lepton, M.[1,3-5] A relative rate of 5×10^{-4} appears unobtainable, however, in conventional [SU(2)× U(1)] schemes as the authors of Refs. 3–5 argue. The problem is twofold in that the M^- production cross section is kinematically suppressed,[3,4,6] and that one needs to consider the relative branching ratios of the two-stage sequential decay of M^- into three μ's plus neutrinos. One is led to consider extensions of the gauge group $SU(2)_L \otimes U(1)$ to groups in which ν_μ and M^- can be in the same multiplet. Alternatively one could attempt to extend present hadronic mechanisms, but it is difficult to obtain the desired trimuon rate by these means.[1]

If larger groups are considered,

$$R_\nu(\mu\mu\mu) = \frac{\sigma(\nu_\mu N \to \mu^-\mu^-\mu^+ X)}{\sigma(\nu_\mu N \to \mu^- X)}$$

can be increased because of a new charged intermediate vector boson, $W'^{\pm}$, which couples with full strength to the $\nu_\mu M^-$ current. This larger gauge group accommodates both W and W': Since we want ν_μ to couple to μ^- via the W, and M^- via the W', the natural minimal gauge group is SU(3) × U(1) with quarks and leptons in triplets. [SU(3) is too small if we want integrally charged leptons in triplets.] The decay scheme of M^- into a heavy neutral lepton requires that there be a right-handed triplet $(N_\mu, M^-, \mu^-)_R$ as well, where N_μ is a neutral lepton; $N_{\mu L}$ is a singlet and ν_μ is only left-handed so that the neutrino remains massless.

In the ν_μ-nucleus collision, the following leptonic sequence occurs:

$$\begin{array}{l} \nu_\mu \to M_L^- \to M_R^- \to N_{\mu R} + \mu_L^- + \bar{\nu}_\mu \\ \qquad\qquad\qquad\qquad\quad \llcorner\!\!\rightarrow \mu_R^- + \mu_L^+ + \nu_\mu . \end{array} \tag{1}$$

This seems to be in reasonable agreement[3,4] with the trimuon data for masses $m_M \sim 7$ GeV and $m_N \sim 3.5$ GeV.

The problem with this decay scheme is that if W' couples to ordinary quarks, the branching ratio of $M_R \to N_R \mu^- \nu_\mu$ relative to $M_L^- \to \nu_\mu +$hadrons is very small. We find

$$R_\nu(\mu^-\mu^-\mu^+) \approx K \frac{G_F'^2}{G_F^2} \frac{\Gamma(M\to N\mu\nu)}{\Gamma(M)} \frac{\Gamma(N\to\mu\mu\nu)}{\Gamma(N)}, \tag{2a}$$

$$R_\nu(\mu^-\mu^-\mu^+) < K \frac{G_F'^2}{G_F^2} \frac{\Delta G_F^2}{5G_F'^2 + 5G_F^2\Delta} \frac{1}{5}, \tag{2b}$$

where G_F' is the equivalent Fermi coupling for W'. K is a kinematic suppression factor[3,4,6] for M production $\sim 5\times 10^{-2}$ (it includes an extra $\frac{1}{3}$ factor because $\bar{u}_L d_L$ couples to W, so that the hadron current coupling to W' must be $\bar{u}_R d_R$); Δ is a three-body phase-space factor; and $\Gamma_{N\to\mu^-\mu^+\nu}/\Gamma_N \lesssim \frac{1}{5}$. For $m_M = 7$, and $m_N = 3.5$, one finds $\Delta = 0.16$, and $R_\nu(\mu\mu\mu)$ appears to be too small to fit experiment.[7] Before turning to modifications of this more conventional type of model, we would like to consider a variation which we regard as an extremely promising candidate for a model of weak and electromagnetic interactions.

The model that we wish to consider is one in which the hadrons are in triplets and singlets,

$$\begin{pmatrix} u \\ d \\ b \end{pmatrix}_L, \begin{pmatrix} u \\ b \\ d \end{pmatrix}_R, \begin{pmatrix} c \\ s \\ h \end{pmatrix}_L, \begin{pmatrix} g \\ h \\ s \end{pmatrix}_R, \quad c_R, \; g_L, \tag{3}$$

with a discrete symmetry[8,9] imposed so that at stage one only b and h acquire masses via octet Higgs-meson couplings. We also impose discrete symmetries on the octet couplings to forbid any general mixing between d, b, s, and h (small mixings between d and b only, and between s and h only, may be introduced at a second stage in which the light quarks are given mass). Triplet

Higgs multiplets then couple c_R to u_L and c_L, and g_L to u_R and g_R, generating Cabibbo angles and masses for the c and g (no charm-changing neutral currents are introduced by this procedure). The nine gauge bosons ($W^{\pm}$, $W'^{\pm}$, W^0, $\overline{W}^0$, Z, Z', and γ) transform like ($\rho^{\pm}$, $K^{*\pm}$, K^{*0}, and $\overline{K}^{*0}$, combinations of ω, ρ, and φ). Instead of putting the leptons in the $\underline{3}$ representation, we put them in the $\underline{3}^*$:

$$\begin{pmatrix} \mu^- \\ \nu_\mu \\ M_1{}^0 \end{pmatrix}_L, \begin{pmatrix} \mu^- \\ M_1{}^0 \\ M_2{}^0 \end{pmatrix}_R, \begin{pmatrix} e^- \\ \nu_e \\ E_1{}^0 \end{pmatrix}_L, \begin{pmatrix} e^- \\ E_1{}^0 \\ E_2{}^0 \end{pmatrix}_R, \qquad (4)$$

$$E_{2L}{}^0, \quad M_{2L}{}^0.$$

The initial motivation is that this ensures that, no matter what Higgs couplings we use, the neutral-current coupling to the electron is pure vector ($e_L{}^-\gamma_\mu e_L{}^- + e_R{}^-\gamma_\mu e_R{}^-$) and hence we have an essentially null result for parity nonconservation in the atomic physics experiment on Bi.[10] The fact that there is no E^- or M^- also lessens the danger of overly large contributions to the muon $g-2$ or to the rate of $\mu \rightarrow e\gamma$. We believe these reasons are important in the absence of sure knowledge of the symmetry-breaking mechanisms.

Conventional charged-current weak interactions occur via $W^{\pm}$ exchange including the high-y anomaly due in this case[11] to the $\bar{b}_R\mu_R$ current. $\Delta S = 2$ transitions are of normal magnitude.

In addition to the Higgs triplets necessary to couple c_R and g_L, we need another set with shifted charges to couple $E_{2L}{}^0$ and $M_{2L}{}^0$ to the lepton triplets (and induce potential mixing). For reasonable values of the vacuum expectation values of the Higgs fields, we have calculated the Z and Z' masses and mixings and get excellent agreement with experiment for neutrino inclusive and elastic scattering off protons and for ν_μ- ($\bar{\nu}_\mu$-) e^- scattering. The detailed fits, to be presented elsewhere, are less sensitive to mixings than one might expect.

Note that in our model $M_1{}^0$, $M_2{}^0$, $E_1{}^0$, and $E_2{}^0$ are all unstable if their masses are sufficiently large. We will focus on the situation in which $M_1{}^0$ has a mass of $\gtrsim 4$ GeV and $M_2{}^0$ a mass $\gtrsim 1.5$ GeV. Labeling by $G_F{}'$ and $G_F{}^0$ the effective Fermi-coupling constants of W' and W^0, we have, with appropriate[12] approximate weights given parenthetically (X means hadronic states),

$$\begin{aligned} M_{1L}{}^0 &\rightarrow \begin{cases} \mu_L{}^- X_R & (5G_F{}'^2); \\ \mu_L{}^- \mu_R{}^+ M_{2R}{}^0 & (G_F{}'^2\Delta); \end{cases} \\ M_{1R}{}^0 &\rightarrow \begin{cases} \mu_R{}^- X_R & (5G_F{}^2); \\ \mu_R{}^- \mu_L{}^+ \nu_\mu & (G_F{}^2); \end{cases} \end{aligned} \qquad (5)$$

while $M_2{}^0$ has only the decay mode $M_2{}^0 \rightarrow \mu_R{}^- X_R$ (neglecting $M_2{}^0 \rightarrow \mu_R{}^- E_2{}^0 e^+$). $M_1{}^0$ is similar to the lepton introduced as a potential explanation[13] for dimuon events except, of course, for the presence of the decay $M_1{}^0 \rightarrow M_2{}^0\mu^+\mu^- \rightarrow \mu^-\mu^+\mu^- X_R$.

Turning now to the production mechanism for $M_1{}^0$, it is $\nu + d_L \rightarrow M_1{}^0 + b_L$ via W^0 exchange. The b quark,[11] with an estimated mass of ~5 GeV, has a semileptonic decay mode $b_R \rightarrow u_R \mu^- \nu_\mu$, so we have the following new multimuon sources: (a) $\mu^+\mu^-$ from $M_1{}^0 \rightarrow \mu^+\mu^-\nu_\mu$ and $b \rightarrow X$; (b) $\mu^-\mu^-$ from $M_1{}^0 \rightarrow \mu^- X$ and $b_R \rightarrow u_R\mu^-\bar{\nu}_\mu$; (c) $\mu^-\mu^-\mu^+$ from $M_1{}^0 \rightarrow \mu^+\mu^- M_2{}^0$, and $b \rightarrow X$, and from $M_1{}^0 \rightarrow \mu^+\mu^-\nu_\mu$ and $b_R \rightarrow u_R\mu^-\nu_\mu$ so that

$$R_\nu(\mu\mu\mu) = K\left(\frac{G_F{}^0}{G_F}\right)^2 \left\{\frac{\Gamma(M_1{}^0 \rightarrow \mu^+\mu^- M_2{}^0)}{\Gamma(M_1{}^0)} + \frac{\Gamma(M_1{}^0 \rightarrow \mu^+\mu^-\nu_\mu)\Gamma(b_R \rightarrow u_R\mu^-\bar{\nu}_\mu)}{\Gamma(M_1{}^0)\Gamma(b)}\right\}; \qquad (6)$$

and finally (d) $\mu^-\mu^-\mu^-\mu^+$ from $M_1{}^0 \rightarrow \mu^+\mu^- M_2{}^0$ and $b_R \rightarrow u_R\mu^-\nu_\mu$. We expect the rates for (a) and (b) to be of order 2×10^{-3}, $R_\nu(\mu\mu\mu) \sim 5\times10^{-4}$ for $G_F{}^0/G_F \sim 0.5$ and $R_\nu(\mu\mu\mu\mu) \sim 5\times10^{-5}$. Momentum distributions also seem to be compatible with experiment,[14] though one would probably want a mass somewhat larger than 4 GeV (e.g., ~6 GeV) for $M_1{}^0$ if $M_1{}^0 \rightarrow \mu^+\mu^- M_2{}^0$ is to provide a large fraction of the trimuon events with the appropriate kinematics.

Turning back, for comparison to models with M^- and E^- and leptons in the $\underline{3}$ rather than the $\underline{3}^*$ representation,

$$\begin{pmatrix} \nu_\mu \\ \mu^- \\ M^- \end{pmatrix}_L, \begin{pmatrix} N_\mu \\ M^- \\ \mu^- \end{pmatrix}_R, \begin{pmatrix} \nu_e \\ e^- \\ E^- \end{pmatrix}_L, \begin{pmatrix} N_e \\ E^- \\ e^- \end{pmatrix}_R, \quad N_{\mu L}, \quad N_{eL}, \qquad (7)$$

we see that the hadronic sector probably needs to be modified by replacing u_R with t_R (where t is a quark with mass $\gtrsim 4$ GeV) in order to close off the mode $M^- \rightarrow \nu_\mu d_R \bar{u}_R$, the problem we alluded to earlier. One the M^- is produced by W' exchange

$\nu_\mu + d_R \to M^- + t_R$, the decays leading possibly to multimuon events are $M^- \to \mu^- N_\mu \bar{\nu}_\mu$ and $M^- \to \nu_\mu \times \bar{N}_\mu \mu^-$. By introducing some small mixing angle β between M_R^- and μ_R^-, the N_μ can decay into two muons $N_{\mu R} \to \mu^- \mu^+ \nu_\mu$ with an amplitude proportional to $\sin\beta\cos\beta$ so that trimuons are produced. The angle β must be kept small for a variety of reasons: (a) The muon $g-2$ would receive an intolerably large contribution[15] from the W^0 one-loop diagram; (b) the neutral current in general now has a $\bar{\mu}M$ term proportional to $\cos\beta\sin\beta$ so that $M^- \to \mu^- X$ becomes an important M^- decay mode, and $M^- \to \mu^- \mu^+ \mu^-$ a trimuon source (it is interesting to keep in mind the possibility that we may have neutrinoless M^- decay).

For a variety of reasons (e.g., to insure that the u quark stays naturally light and to provide an explanation for the high-y anomaly) one might want to consider the case in which u_R is not replaced by t_R. M^- is then produced via $\nu_\mu + d_R \to M^- + u_R$ and N_μ can decay by $N_\mu \to \mu^- u_R \bar{d}_R$. To reach a value of 2×10^{-4} for $R_\nu(\mu\mu\mu)$ one needs M_1^0 massive (~8 GeV) and N_μ relatively light (~2 GeV). It is questionable, however, whether such a light N is satisfactory.

In all these models one is essentially forced to introduce a third triplet to accommodate the heavy lepton τ^- observed[16] at Stanford Linear Accelerator Center (and additional singlets, T_{2L}^0 and possibly T_L^- with T_R^- replacing τ_R^-).

To conclude, we have discussed two types of $SU(3)\times U(1)$ gauge models differing by having leptons in the $\underline{3}^*$ or $\underline{3}$ representation. For a variety of reasons, which we have outlined, we tend to prefer the former, but it is clearly too early to tell.[17] $\bar{\nu}_\mu$ scattering experiments would be of great help in distinquishing the $\underline{3}^*$ model from the $\underline{3}$ model (with u_R replaced by t_R) since in the latter there is no $\bar{b}_R u_R$ current. It will be of great interest to have good statistics for, e.g., $\mu^+\mu^-$ production in $\bar{\nu}_\mu$ experiments. Another significant difference is that tetramuons appear in both models, but for the $\underline{3}^*$ model they are $\mu^-\mu^-\mu^-\mu^+$ while for the $\underline{3}$ model they are $\mu^-\mu^-\mu^+\mu^+$ (since the t quark will decay into a μ^+; this model also has the possibility of a $\mu^-\mu^+\mu^+$ mode with a relatively low-energy μ^+). Finally one will clearly distinguish the two models by whether or not M^- and E^- are seen at PEP and PETRA.

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Spin Analysis of Charmed Mesons Produced in e^+e^- Annihilation

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We have studied the threshold production and decay angular distribution of neutral charmed mesons produced in e^+e^- annihilation. We find consistency with the expected spin values of 0 and 1 for the ground and excited states D and D^*, respectively. We rule out the alternative spin assignment of 1 for the D and 0 for the D^*.

We report on a study of the production and decay angular distributions of neutral charmed mesons[1] produced in e^+e^- annihilation at center-of-mass energies near 4.03 GeV. Throughout this Letter, we identify the neutral state decaying into $K\pi$ and $K3\pi$ at 1865 MeV/c^2 with the D^0 and the charged state decaying into $K\pi\pi$ at 1875 MeV/c^2 with the D^+.[2] A study[3] of the threshold recoil spectrum against the D^0 and D^+ has provided strong evidence for the existence of excited charmed states: the $D^{*0}(2005)$ and the $D^{*+}(2010)$. Furthermore, this study shows that D^0 production near threshold is dominated by two-body reactions such as

$$e^+e^- \to D^0\bar{D}^{*0} \text{ or } \bar{D}^0D^{*0}, \tag{1}$$

$$e^+e^- \to D^{*0}\bar{D}^{*0}, \tag{2}$$

$$e^+e^- \to D^{*+}D^- \text{ or } D^{*-}D^+, \tag{3}$$

where the D^{*0} and D^{*+} decay into D^0's via pion emission[4] and, in the case of the D^{*0}, by γ emission. In this Letter we examine angular distributions in Reactions (1) and (2) in order to test the three possible D, D^* spin assignments if one assumes that the sum of the spins for the D and the D^* is less than 2. We show that under this assumption the D is spinless, the D^* has spin 1, and their relative parity is even.[5]

Considerable information on the spin and parity of the D and D^* comes from a study of the D^* production and decay modes. Our observation of either $D^{*0}\to D^0\gamma$ or $D^{*0}\to\pi^0D^0$ produced in $e^+e^-\to D^0\bar{D}^{*0}$ or $\bar{D}^0D^{*0}$ implies that the D and D^* cannot both be spinless.[6] Observation of $D^*\to D\pi$ implies that D and D^* must have even relative parity if one meson has spin 0 and the other has spin 1. This last observation is quite helpful for it allows unique predictions for the production and decay angular distributions of $D\to K\pi$ in Reaction (1) under the two spin assignments which we will further consider: $J_D=0$ and $J_{D^*}=1$, or $J_D=1$ and $J_{D^*}=0$.

We express the expected joint D^0 production and decay distributions in terms of the three angles Θ, θ, and φ, where Θ is the polar production angle of the D^0 with respect to the annihilation axis, and θ and φ are the spherical angles of the decay kaon in the D^0 helicity frame.[7] In the limit of nonrelativistic D^{*0}'s, one computes from symmetry considerations the distributions below[8]:

$$\frac{d^3\sigma}{d\cos\Theta\, d\cos\theta\, d\varphi} \propto 1+\cos^2\Theta, \tag{4}$$

$$\frac{d^3\sigma}{d\cos\Theta\, d\cos\theta\, d\varphi} \propto \sin^2\theta(\cos^2\varphi+\cos^2\Theta\sin^2\varphi), \tag{5}$$

where Eq. (4) is for ${J_D}^P=0^\mp$, ${J_{D^*}}^P=1^\mp$, and Eq. (5) is for ${J_D}^P=1^\mp$, ${J_{D^*}}^P=0^\mp$. We shall compare these distributions to the data.

The present analysis is based on about 35 000 hadron events produced in e^+e^- annihilation at