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Abstract

Lepton number assignment of the charged heavy leptons (suggested by the SLAC-LBL $\mu^{\pm}e^{\mp}$ events) has definite signatures which can be tested experimentally. We study the signatures and calculate the decay rates when the neutral currents are also contributing.

+) Alexander von Humboldt Fellow

Introduction

The discovery of the "anomalous" $\mu^{\pm}e^{\mp}$ events at SLAC[1] has aroused a lot of theoretical speculation. One of the possible explanations is that such events come from the pair production of oppositely charged heavy leptons, $\ell^{\pm}$, and their subsequent decays into leptons, e.g.

$$\ell^- \rightarrow \nu_\ell + \bar{\nu}_{e(\mu)} + e^-(\mu^-)$$

If this turns out to be the case, then one immediately asks the question: What is the lepton number of the heavy leptons, $\ell^{\pm}$? - whether these heavy leptons carry the lepton numbers of $\mu^{\pm}$, $e^{\pm}$ or a new lepton number. The question is obviously of fundamental importance. The purpose of this note is to study this question.

First of all we remark that if ℓ^- (or ℓ^+) has the same lepton number as μ^- (or μ^+), it could be produced by the $\nu_\mu(\bar{\nu}_\mu)$ beams available at NAL and CERN. Albright has argued from present neutrino data that they are unlikely to be the candidate for the "anomalous" μe events in e^+e^--annihilation[2]. Moreover the mass of an negatively charged muon type heavy lepton is set experimentally above 8 GeV.[3] Since no $\nu_e(\bar{\nu}_e)$ experiment is presently available, no such experimental constraint is imposed if $\ell^{\pm}$ has the electronic lepton number.[4] We shall concentrate below on the difference between charged heavy leptons, $\ell^{\pm}$, carrying electronic lepton number and a new lepton number. (The latter case is usually referred as sequential).

If $\ell^{\pm}$ has the electronic lepton number,[5] one has two alternative assignments: ℓ^- has the lepton number as e^+ or e^- with the respective decays

$$\ell^- \rightarrow \bar{\nu}_\ell + e^- + \bar{\nu}_e$$
$$\ell^- \rightarrow \nu_\ell + e^- + \bar{\nu}_e$$

In the first case, one finds by Fermi Statistics

$$\Gamma(\ell^- \to \bar{\nu}_\ell + \bar{\nu}_e + e^-) = 2\,\Gamma(\ell^- \to \bar{\nu}_\ell + \bar{\nu}_\mu + \mu^-)$$

It follows then

$$\sigma(e^+e^-) : \sigma(\mu^+e^- + \mu^-e^+) : \sigma(\mu^+\mu^-) :: 4:4:1$$

where

$$\sigma(\ell_1\ell_2) = \sigma(e^+e^- \to \ell^+\ell^- \to \ell_1\ell_2 + \cdots)$$

The present SLAC data is consistent with the above ratios being 1:2:1.(1) It indicates that the $\ell^\pm$ do not carry the $e^\mp$ lepton numbers. Thus the possibilities left are: either $\ell^\pm$ have the same quantum number as $e^\pm$ or else they carry a new lepton number. If the latter is true, there exists then a new neutrino (massive or massless). If the former is true, one may or may not have a new neutrino. We device tests to distinguish between these two assignments. The tests essentially consist of measuring the transitions $\ell^\pm \to e^\pm + x$, where x can be either leptons or hadron (s). We shall also comment on how to distinguish such decays from the heavy hadron decays which can also simulate the heavy lepton decays.

The paper is organized as follows: In Section II we discuss the qualitative features of the two $\ell^\pm$ lepton number assignments. These properties are testable experimentally and should be looked for. In Section III, we calculate starting from a phenomenological Lagrangian all the leptonic and semileptonic decays of $\ell^\pm$, involving non-diagonal neutral current transitions $\ell^\pm \to e^\pm + x$. Section IV contains remarks.

II. Experimental Tests for the Lepton Number of Charged Heavy Lepton

If ℓ^- has the quantum number of e^-, then in addition to the charged current decay modes

$$\ell^- \to \nu_\ell + \bar{\nu}_e + e^- \, , \quad \nu_\ell + \bar{\nu}_\mu + \mu^- \tag{2.1}$$

$$\ell^- \to \nu_\ell + \text{hadrons} \tag{2.2}$$

it can also decay via neutral current modes,

$$\ell^- \to e^- + e^+e^- \, , \quad e^- + \mu^+\mu^- \, , \quad e^- + \nu_e \bar{\nu}_e$$
$$e^- + \nu_\mu \bar{\nu}_\mu \, , \quad e^- + \nu_\ell \bar{\nu}_\ell \tag{2.3}$$

$$\ell^- \to e^- + \text{hadrons} \tag{2.4}$$

where in (2.3) [see Fig.1] $\nu_\ell = \nu_e$ if $m(\nu_\ell) = 0$, otherweise it is a different particle with the same lepton number as ν_e . The decay rates and branching ratios for (2.1) and (2.2), assuming only charged currents already exist in literature [(6)], but will have to be modified if non-diagonal neutral currents are present. These modifications together with the decay rates for (2.3) and (2.4) are presented in Section III.

If ℓ^- is a sequential heavy lepton, then only (2.1) and (2.2) are possible decay modes [(7)] with $\nu_\ell \neq \nu_e$, even if $m(\nu_\ell) = 0$. In principle, the mass of the neutral heavy lepton, ν_ℓ , can be measured by the cross section and momentum distributions of $e^+e^- \to \ell^+\ell^- \to \mu^\pm e^\mp$ + neutrinos.

The non-diagonal neutral current processes will have one of the following signatures:

(1) $e^+e^- \to \mu^\pm e^\mp$ + hadrons + missing momentum.[8] - Events of this kind can not come from the decays of sequential heavy leptons. They can arise either by heavy lepton decays involving (2.3) and (2.4) or by leptonic and semi-leptonic decays of heavy hadrons. These two mechanisms can be disentangled by looking at the energy momentum distribution of the final states. (For example, $\mu^\mp$ from $\ell^\mp$ decay must follow three-body decay). One should particularly look for the processes

$$e^+e^- \to \mu^\pm e^\mp \underbrace{\pi^0}_{\hookrightarrow 2\gamma}, \quad \mu^\pm e^\mp \underbrace{\rho^0}_{\hookrightarrow \pi^+\pi^-} \qquad (2.5)$$
$$\mu^\pm e^\mp \omega^0, \quad \mu^\pm e^\mp \eta, \cdots\cdots$$

In the case of a single hadron in the final states, the $e^\mp$ and the hadron must have a unique invariant mass equal to m_ℓ if due to $\ell^\mp$ decay and will not do so if due to new hadron decay - in the latter case, the hadron follows three-body decay (see Fig.2). Thus these two cases can be distinguished.

(2) If ℓ carrys electronic lepton number, then the branching ratio for $\ell^- \to \mu^- + \bar{\nu}_\mu + \nu_\ell$ and $\ell^- \to e^- + \bar{\nu}_e + \nu_\ell$ could differ due to the neutral current contribution. Thus (a small) deviation in the ratio of "anomalous" e^+e^- and $\mu^+\mu^-$ cross sections from being 1 could indicate non-zero neutral current contribution.

(3) Four charged lepton production in e^+e^- annihilation. - Observation of the following processes and narrow $e^-e^+e^-$ resonance in

$$e^+e^- \to \mu^\pm e^\mp + e^+e^-(\mu^+\mu^-) + \text{missing momentum} \qquad (2.6)$$

of order G_F^2 will prove that ℓ^- has the same lepton number as e^-. Moreover $\sigma(\mu^\pm e^\mp + e^+e^-) = 2\sigma(\mu^\pm e^\mp + \mu^+\mu^-)$. A word of caution. - The strengths of leptonic decays (2.3) and semi-leptonic decays (2.4) are a priori unrelated, thus it is necessary to check both (1) and (3) experimentally.

In conclusion, in order to establish that the charged heavy lepton is sequential, one must check that the signatures (1)–(3) are not found. On the other hand, a clean signature (even one or few events) of (1)-(3) would prove non-sequential charged heavy lepton. In the latter case, one must further check the following:

(4) If ℓ carrys electronic number, no processes of the kind $e^+e^- \to \mu^+\mu^-$ + <u>hadrons</u> + missing momentum is allowed.

III. Neutral Current Contribution to Heavy Charged Lepton Decays

We start with the following weak interaction Hamiltonian

$$H_{eff} = \frac{G_F}{\sqrt{2}} \left(J^{W,\mu}(x) \, J_\mu^{+W}(0) + J^{Z,\mu}(x) \, J_\mu^{+Z} \right)$$

where $G_F = 1.05 \times 10^{-5} \, m_p^{-2}$ is the Fermi coupling constant. J_μ^W and J_μ^Z are the charged and neutral weak currents respectively. The charged currents are defined by

$$J_\mu^{W,\,leptonic} = \bar{\nu}_e \gamma_\mu (1-\gamma_5) e + \bar{\nu}_\mu \gamma_\mu (1-\gamma_5) \mu \qquad (3.1)$$
$$+ \bar{\nu}_\ell \gamma_\mu \left(g_L \frac{1-\gamma_5}{2} + g_R \frac{1+\gamma_5}{2} \right) \ell$$

$$J_\mu^{W,\,hadronic} = \left(V_\mu^{1\pm i2} - A_\mu^{1\pm i2} \right) \cos\theta + \left(V_\mu^{4\pm i5} - A_\mu^{4\pm i5} \right) \times \sin\theta \qquad (3.2)$$

The neutral weak currents are parametrized as follows:

$$J_\mu^{Z,\,leptonic} = \alpha\, \bar{\nu}_e \gamma_\mu \left(\frac{1-\gamma_5}{2}\right) \nu_e + \beta\, \bar{\nu}_\ell \gamma_\mu \left(\frac{1-\gamma_5}{2}\right) \nu_e$$
$$+ \bar{e} \gamma_\mu \left(a_L \frac{1-\gamma_5}{2} + a_R \frac{1+\gamma_5}{2} \right) e \tag{3.3}$$
$$+ \bar{e} \gamma_\mu \left(b_L \frac{1-\gamma_5}{2} + b_R \frac{1+\gamma_5}{2} \right) \ell + \cdots$$
$$+ h.c. + \{ e \to \mu,\ \ell \to M,\ \nu_{e,\ell} \to \nu_{\mu,M} \}$$

and

$$J_\mu^{Z,\,hadronic} = h_3 V_\mu^{(3)} + h_8 V_\mu^{(8)} + h_0 V_\mu^{(0)} + k_3 A_\mu^{(3)} + k_8 A_\mu^{(8)} + \cdots$$

where the superscripts refer to the SU(3) transformation property of the hadronic currents. The leptonic widths are (neglecting $O(\frac{m_e}{m_\ell})$ terms) as follows

$$\frac{\Gamma(\ell^- \to e^- + \bar{\nu}_e + \nu_\ell)}{\Gamma(\mu^- \to \nu_\mu + e^- + \bar{\nu}_e)} = \left(\frac{m_\ell}{m_\mu}\right)^5 \left[\left\{ \left(\frac{|g_L|^2 + |g_R|^2}{4}\right) + |\beta|^2 \left(\frac{|b_L|^2 + |b_R|^2}{4}\right) \right\} f_1(z) + 2\, \mathrm{Re}\left(\frac{g_R^* g_L}{4}\right) f_2(z) \right] \tag{3.5}$$

$$\frac{\Gamma(\ell^- \to e^- + e^+ e^-)}{\Gamma(\mu^- \to \nu_\mu + e^- + \bar{\nu}_e)} = \frac{1}{4} \left(\frac{m_\ell}{m_\mu}\right)^5 \left(|a_L|^2 + |a_R|^2\right)\left(|b_L|^2 + |b_R|^2\right) \tag{3.6}$$

The expressions for $\ell^- \to e^- \mu^+ \mu^-$ and $\ell^- \to \mu^- \bar{\nu}_\mu \nu_\ell$ can be immediately written from the above two equations, neglecting $O(\frac{m_\mu}{m_\ell})$ terms. Fermi statistics then gives:

$$2\Gamma(\ell^- \to e^- + \mu^+ \mu^-) = \Gamma(\ell^- \to e^- + e^+ e^-) \tag{3.7}$$

and the absence of neutral current contribution leads to:

$$\frac{\Gamma(\ell^- \to \mu^- \bar{\nu}_\mu \nu_\ell)}{\Gamma(\mu^- \to \nu_\mu e^- \bar{\nu}_e)} = \left(\frac{m_\ell}{m_\mu}\right)^5 \left[\left(\frac{|g_L|^2 + |g_R|^2}{4}\right) f_1(z) + 2 \operatorname{Re}\left(\frac{g_R^* g_L}{4}\right) f_2(z)\right] \tag{3.8}$$

where $Z = m(\nu_\ell)/m(\ell)$

and

$$f_1(z) = (1 - z^4)(z^4 - 8z^2 + 1) + 24 z^4 \ln(1/z)$$

$$f_2(z) = 4z(1 - z^2)^3 - 6z(1+z^2)(1 - z - 4z^2 \ln(1/z)) \tag{3.9}$$

The neglect of $O(\frac{m_\mu}{m_\ell})$ terms does not introduce any appreciable effect if $m_\ell > 1.5$ GeV.

Hadronic Decay Modes

Defining the spectral functions ρ_1^W and ρ_2^W for the charged weak currents and ρ_1^Z, ρ_2^Z for the neutral weak currents by:

$$\sum_F \langle 0| J_\mu^{W(Z)}(0) |F\rangle\langle F| J_\nu^{\dagger W(Z)}(0) |0\rangle\, \delta^4(q - p_F)(2\pi)^3$$
$$\equiv \rho_1^{W(Z)}(q^2)(q_\mu q_\nu - q^2 g_{\mu\nu}) + \rho_2^{W(Z)}(q^2)\, q_\mu q_\nu \tag{3.10}$$

then, if the hadrons have invariant mass $\sqrt{t}$, we obtain

$$\frac{d\Gamma}{dt}\left(\ell^{\pm} \to e^{\pm} + \text{hadrons}\right) = \frac{G_F^2 m_\ell^3}{16\pi}\left(1 - \frac{t}{m_\ell^2}\right)\left(\frac{|b_L|^2 + |b_R|^2}{4}\right) \times g_1^Z(t) \tag{3.11}$$

where

$$g_1^Z(t) = \rho_1^Z(t)\left(1 + \frac{t}{m_\ell^2} - \frac{2t^2}{m_\ell^4}\right) + \rho_2^Z(t)\left(1 - \frac{t}{m_\ell^2}\right) \tag{3.12}$$

The semi-leptonic decays of $\ell^{\pm}$, involving charged weak currents, have been studied in detail in the literature(6) and we shall not discuss them here. The hadronic continuum as well as the single particle contribution involving the neutral current can be calculated in an analogous way and are given below.

Hadronic Continuum Contribution

To estimate the hadronic continuum contribution, we shall invoke the notion of asymptotic chiral symmetry(9) and asymptotic SU(3) symmetry(10) which is probably a reasonable assumption when t is large (t > 1 GeV^2). Expressing $\rho^Z_{1,2}(t)$ in terms of the parameters introduced through Eq.(3.4)

$$\rho_1^Z(t) = |h_3|^2 \rho_{1V}^{33}(t) + |h_8|^2 \rho_{1V}^{88}(t) + |h_0|^2 \rho_{1V}^{00}(t) + |k_3|^2 \rho_{1A}^{33}(t) + |k_8|^2 \rho_{1A}^{88}(t) \tag{3.13}$$

$$\rho_2^Z(t) = |k_3|^2 \rho_{2A}^{33}(t) + |k_8|^2 \rho_{2A}^{88}(t) \tag{3.14}$$

the asymptotic chiral SU(3) x SU(3) symmetry can now be formulated as follows:

$$\lim_{t\to\infty} \rho_{2A}^{ij}(t) = 0 \qquad i, j = 3, 8 \tag{3.15}$$

$$\lim_{t\to\infty} \rho_{1A}^{ii}(t) = \lim_{t\to\infty} \rho_{1V}^{ii}(t) \qquad i, j = 3, 8 \tag{3.16}$$

With asymptotic U(3) symmetry, spectral function of different SU(3) components are related (to the spectral function of electromagnetic currents) one has

$$\lim_{t\to\infty} \rho_{1V}^{00}(t) = \lim_{t\to\infty} \rho_{1V}^{88}(t) = \lim_{t\to\infty} \rho_{1V}^{33}(t) = \frac{1}{8\pi^2} \lim_{s\to\infty} \frac{\sigma'_{e^+e^-\to \text{hadron}}}{\sigma_{e^+e^-\to\mu^+\mu^-}} \tag{3.17}$$

where $\sigma'_{e^+e^-\to \text{hadrons}}$ denotes hadronic total cross section excluding heavy lepton contribution. We get (using 3.10-3.17)

$$\frac{\Gamma(\ell^- \to e^- + \text{hadron Continuum})}{\Gamma(\ell^- \to \mu^- + \bar\nu_\mu + \nu_\ell)} = \frac{3}{4}\, h\, C\, R(\Lambda^2/m_\ell^2) \tag{3.18}$$

$$\times \left[\frac{|b_L|^2 + |b_R|^2}{\left(|g_L|^2 + |g_R|^2\right) f_1(z) + 2\,\mathrm{Re}\left(g_R^* g_L\right) f_2(z)} \right]$$

Where

$$C = \lim_{s\to\infty} \frac{\sigma'_{e^+e^-\to \text{hadrons}}}{\sigma_{e^+e^-\to\mu^+\mu^-}} = \text{Constant} \tag{3.19}$$

$$h = |h_0|^2 + |h_3|^2 + |h_8|^2 + |k_3|^2 + |k_8|^2 \tag{3.20}$$

and

$$R(\Lambda^2/m_\ell^2) = \left(1 - \frac{\Lambda^2}{2m_\ell^2} + \frac{\Lambda^6}{2m_\ell^6} - \frac{\Lambda^8}{m_\ell^8}\right) \tag{3.21}$$

where Λ is the threshold for estimating the hadron continuum (usually taken to be ~ 1 GeV). For comparison, the charged current contribution to the hadron continuum is given by

$$\frac{\Gamma(\ell^- \to \nu_\ell + \text{hadronic Continuum})}{\Gamma(\ell^- \to \nu_\ell + \mu^- + \bar{\nu}_\mu)} = \frac{3}{2} C R(\Lambda^2/m_\ell^2) \tag{3.22}$$

Single-Particle Contributions

The various single particle contribution can be obtained from (3.11) by using the following pole dominated forms of the various spectral functions. (The superscript refer to the intermediate state saturating the spectral function). The $\rho^{\alpha\beta}$ $(\alpha,\beta = 0,8)$ are evaluated by assuming the usual SU(3) breaking.

$$\rho_1^{\pi} = \rho_1^{\eta} = \rho_1^{\eta'} = 0$$

$$\rho_2^{\pi} = \frac{1}{2} F_\pi^2\, \delta(t - m_\pi^2)$$

The formula for ρ_2^{η}, $\rho_2^{\eta'}$ is similar with $F_\pi \to F_\eta$, $m_\pi \to m_\eta$ etc.

$$\begin{aligned}
\rho_{1V}^{\rho} &= \frac{m_\rho^2}{f_\rho}\, \delta(t - m_\rho^2) \\
\rho_{1V}^{88,\omega} &= \frac{3}{4}\left(m_\omega^2 f_Y^{-1} \sin\theta_Y\right)^2 \delta(t - m_\omega^2) \\
\rho_{1V}^{00,\omega} &= \frac{3}{2}\left(m_\omega^2 f_B^{-1} \cos\theta_B\right)^2 \delta(t - m_\omega^2) \\
\rho_{1V}^{08,\omega} &= \frac{3}{2\sqrt{2}}\left(m_\omega^2 f_B^{-1} \cos\theta_B\right)\left(m_\omega^2 f_Y^{-1} \sin\theta_Y\right) \\
&\quad \times \delta(t - m_\omega^2)
\end{aligned} \tag{3.23}$$

cont.

$$\rho_{IV}^{88,\phi} = \frac{3}{4}\left(m_\varphi^2 f_Y^{-1}\cos\theta_Y\right)^2 \delta\left(t-m_\varphi^2\right)$$

$$\rho_{IV}^{00,\phi} = \frac{3}{2}\left(m_\varphi^2 f_B^{-1}\sin\theta_B\right)^2 \delta\left(t-m_\varphi^2\right) \qquad (3.23)$$

$$\rho_{IV}^{08,\phi} = \frac{3}{2\sqrt{2}}\left(m_\varphi^2 f_Y^{-1}\cos\theta_Y\right)\left(m_\varphi^2 f_B^{-1}\sin\theta_B\right) \times \delta\left(t-m_\varphi^2\right)$$

We refer to Ref.(11) for the definition of various coupling constants and mixing parameters used in Eq.(3.23). The decay rates using (3.23) are listed in Table 1, where we have normalized with respect to the charged weak current process $\ell^\pm \to \pi^\pm + \bar{\nu}_\ell(\nu_\ell)$.

$$\Gamma\left(\ell^\pm \to \pi^\pm + \bar{\nu}_\ell(\nu_\ell)\right) = \frac{G_F^2 m_\ell^3 F_\pi^2}{16\pi}\left[\left(\frac{|g_L|^2+|g_R|^2}{4}\right) f_1(z) + 2\,\mathrm{Re}\left(\frac{g_g^* g_L}{4}\right) f_2(z)\right] \qquad (3.24)$$

$$\simeq 3\times 10^{11}\ \mathrm{sec}^{-1} \quad \text{for } g_L = 1,\ g_R = 0,\ m_\ell = 1.8\ \mathrm{GeV},\ m_{\nu_\ell} = 0$$

Terms of order $\left(\frac{m_\pi^2}{m_\ell^2}\right)$ and $\left(\frac{m_e^2}{m_\ell^2}\right)$ are neglected in all the equations. Z and $f_{1,2}(Z)$ are defined previously.

Leptonic Branching Ratios

For practical purposes we have calculated the leptonic branching ratios as follows [setting $m_{\nu_\ell}=0$]

$$\frac{\Gamma\left(\ell^- \to \mu^- \bar{\nu}_\mu \nu_e\right)}{\Gamma_{total}} = \left[\frac{1}{2+\delta|\beta|^2+\frac{3}{2}\delta\gamma+X+\delta Y}\right] \qquad (3.25)$$

$$\frac{\Gamma(\ell^- \to e^- \bar{\nu}_e \nu_\ell)}{\Gamma_{total}} = \left[\frac{1 + \delta|\beta|^2}{2 + \delta|\beta|^2 + \frac{3}{2}\delta\gamma + X + \delta Y}\right] \tag{3.26}$$

$$\frac{\Gamma(\ell^- \to e^- e^+ e^-)}{\Gamma_{total}} = \left[\frac{\delta\gamma}{2 + \delta|\beta|^2 + \frac{3}{2}\delta\gamma + X + \delta Y}\right] \tag{3.27}$$

$$\Gamma(\ell^- \to e^- \mu^+ \mu^-) = \frac{1}{2}\Gamma(\ell^- \to e^- e^+ e^-) \tag{3.28}$$

where

$$\delta = \left(\frac{|b_L|^2 + |b_R|^2}{|g_L|^2 + |g_R|^2}\right)$$

$$\gamma = \left(|a_L|^2 + |a_R|^2\right)$$

$$X = \frac{12\pi^2}{m_\ell^2} \int_0^{m_\ell^2} \left(1 - t/m_\ell^2\right) g_1^W(t) \tag{3.29}$$

$$Y = \frac{12\pi^2}{m_\ell^2} \int_0^{m_\ell^2} \left(1 - t/m_\ell^2\right) g_1^Z(t)$$

and

$$g_1^W(t) = \rho_1^W(t)\left(1 + \frac{t}{m_\ell^2} - \frac{2t^2}{m_\ell^4}\right) \tag{3.30}$$

$\rho_{1,2}^{W,Z}(t)$ are the spectral functions defined through (3.10). We emphasize that the parameter γ which enters in the weak contribution to the process $e^+e^- \to e^+e^-$, can be, in principle, very different due to the different masses of the heavy bosons mediating $e^+e^- \to e^+e^-$ and $\ell^\pm \to e^\pm e^+e^-$.

IV. Remarks

After discussing methods to test the quantum numbers of the new charged heavy lepton and calculating the decay rates in previous sections, we list here some possible lepton schemes (in Table 2). Definite features can be used to rule out or distinguish different models.[12] Future experiments may soon narrow down the alternative possibilities. In the framework of gauge theories, it has been speculated the "quark-lepton symmetry"—if leptons and quarks can be embedded in a unified framework. If this conjecture makes sense, the lepton spectrum may shed light on the quark spectrum. Another interesting and yet unsolved problem is the m_e/m_μ mass ratio. Attempts in the past to calculate the m_e/m_μ mass ratio have failed in simple renormalizable models. It gives us hope if the actual lepton spectrum becomes known. It may be meaningful to talk about this "symmetry of the leptons" if their spectrum can be experimentally established.

Finally, we like to comment on the magnitudes of neutral currents. At present, no data on the various processes (in Section II) which can test the lepton number of the heavy lepton is available. No events of the kind (1-3) of Section II are reported[1] which are inconsistent with being background. But, one notes that the SLAC-LBL data has uncertainty in hadron-lepton identification and (thus) in the estimate of the background. The fact that no large cross sections of neutral current induced processes have been seen can be interpreted to say that the neutral current contribution is small. Even if small, it is important to look for the signals we have suggested. A few clean events of processes (1)—(3) in Section II would establish the non-sequential nature of the heavy lepton and the existence of neutral currents coupling to ℓ^- and e^-.

The present data taken at the face value gives the following limit on neutral current contribution:

(1) The "anomalous" cross section for $\mu^+\mu^-$, $\mu^+e^- + e^+\mu^-$, e^+e^- being consistent with the ratio 1:2:1 would suggest that the branching ratio for $B(\ell^- \to \mu^- + \bar{\nu}_\mu + \nu_\ell)$ and $B(\ell^- \to e^- + \bar{\nu}_e + \nu_\ell)$ are approximately equal. From (3.25) and (3.26), one would conclude

$$\delta \beta^2 < 1 \tag{4.1}$$

(2) Four charged lepton production with all lepton momentum ≥ 0.65 GeV is not seen at a comparable rate as the $\mu^{\mp}e^{\pm}$ cross section. But one notes that most of the leptons are restricted by phase space and will not satisfy the above momentum criteria. A careful search for the four charged lepton events is needed. Lack of such events would suggest from (3.27) and (3.28) that

$$\delta \gamma < 1 \tag{4.2}$$

(3) The cross section of $\mu^{\pm}e^{\mp}$ events assuming one-photon cross section for charged heavy lepton pair production gives the following branching ratio[16]

$$\left[\frac{\Gamma(\ell^- \to e^-(\mu^-) + \nu_\ell + \bar{\nu}_{e(\mu)})}{\Gamma_{total}}\right]_{Exp.} \simeq 0.17 \tag{4.3}$$

If only charged currents contribute, as in the case of the sequential heavy leptons, one finds by theoretically estimating the semi-leptonic decay rates that[17]

$$\frac{\Gamma\left(\ell^- \to e^-(\mu^-) + \nu_\ell + \bar{\nu}_e(\mu)\right)}{\Gamma_{total}} \sim 0.18 \tag{4.4}$$

For non-sequential charged heavy lepton decay one concludes form (3.25) and (3.26) with the aid of (4.1) (4.3) that $\delta Y/x$ can not be large. Because of the uncertainties in the present data as well as theoretical estimates definite conclusion can not at present be drawn.

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References and Footnotes

(1) M. L. Perl et al., Phys. Rev. Lett. 35, 1489 (1975)

(2) C. H. Albright, Fermilab preprint -75/91-THY

(3) B. Barish et al., Phys. Rev. Lett. 32, 1387 (1974)

(4) Charged heavy leptons carrying electronic lepton number could be produced in deep inelastic scattering, but being suppressed by G_F^2, they are very difficult to be produced.

(5) We assume two-component neutrinos for our discussion. If neutrinos are four-component objects and the right-handed components couple to charged heavy leptons; they can effectively be treated as the sequential case. (For massless four-component neutrinos, one can as well call the right-handed component a new kind of neutrino).

(6) Y. S. Tsai, Phys. Rev. D4, 2821 (1971); J. D. Bjorken and C.H. Lewellyn Smith, Phys. Rev. D7, 887 (1973). See M. L. Perl and P. Rapidis, SLAC-PUB-1496 (1974) for more references.

(7) We assume that neutral currents do not couple to leptons of different lepton numbers as in most gauge theory models.

(8) This mechanism to distinguish sequential charged heavy lepton from the non-sequential and new hadron decays has been pointed out by T.C. Yang, Univ. of Maryland, Tech. Report 76-025.

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(17) The number quoted here is taken from Tsai's paper after correcting the hadronic continuum contribution. However, these numbers are only a rough estimate because of the various approximations used to evaluate the decays.

Figure Caption

Fig.1 (a) Charged current contribution to ℓ^- decays

(b) Neutral current contribution to ℓ^- decays.

Fig.2 Schematic diagrams for $e^+e^- \to e^\pm\mu^\mp$ + missing momentum + $\pi^0,\rho^0,\omega,\ldots$ due to (a) charged heavy lepton pair decays and (b) charged hadron pair decays

Table Caption

Table 1 Two-body decay rates of charged heavy leptons by neutral weak currents

Table 2 Classifications of lepton models.

Table 1: θ_B, θ_y and f_B, f_y are respectively the ω-ϕ mixing angles and coupling constants introduced in Ref.11.

$$\frac{\Gamma(\ell^\pm \to e^\pm + \pi^0)}{\Gamma(\ell^- \to \nu + \pi^-)} = \frac{1}{2}\,\delta\,|k_3|^2$$

$$\frac{\Gamma(\ell^\pm \to e^\pm + \eta)}{\Gamma(\ell^- \to \nu + \pi^-)} = \frac{1}{2}\,\delta\,|k_8|^2\,\frac{F_\eta^2}{F_\pi^2}\left(1-\frac{m_\eta^2}{m_\ell^2}\right)^2$$

$$\frac{\Gamma(\ell^\pm \to e^\pm + \eta')}{\Gamma(\ell^- \to \nu + \pi^-)} = \frac{1}{2}\,\delta\,|k_8|^2\,\frac{F_{\eta'}^2}{F_\pi^2}\left(1-\frac{m_{\eta'}^2}{m_\ell^2}\right)^2$$

$$\frac{\Gamma(\ell^\pm \to e^\pm + \rho^0)}{\Gamma(\ell^- \to \nu + \pi^-)} = \delta\,|h_3|^2\left(\frac{m_\rho^2}{F_\pi F_\rho}\right)^2\left(1-\frac{m_\rho^2}{m_\ell^2}\right)^2\left(1+\frac{2m_\rho^2}{m_\ell^2}\right)$$

$$\frac{\Gamma(\ell^\pm \to e^\pm + \omega)}{\Gamma(\ell^- \to \nu + \pi^-)} = \delta\left(\frac{m_\omega^2}{F_\pi}\right)^2\left(1-\frac{m_\omega^2}{m_\ell^2}\right)^2\left(1+\frac{2m_\omega^2}{m_\ell^2}\right)$$
$$\times\left[|h_8|^2\,\frac{\sin^2\theta_Y}{f_Y^2}+|h_0|^2\,\frac{\cos^2\theta_B}{f_B^2}+2\,\mathrm{Re}\,(h_8^* h_0)\times\frac{\sin\theta_Y\cos\theta_B}{f_Y f_B}\right]$$

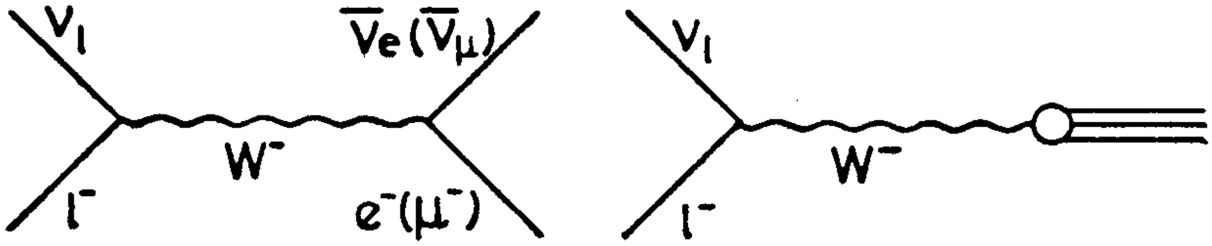
$$\frac{\Gamma(\ell^\pm \to e^\pm + \omega)}{\Gamma(\ell^- \to \nu + \pi^-)} = \delta\left(\frac{m_\varphi^2}{F_\pi}\right)^2\left(1-\frac{m_\varphi^2}{m_\ell^2}\right)^2\left(1+\frac{2m_\varphi^2}{m_\ell^2}\right)$$
$$\times\left[|h_8|^2\,\frac{\cos^2\theta_Y}{f_Y}+|h_0|^2\,\frac{\sin^2\theta_B}{f_B^2}+2\,\mathrm{Re}\,(h_8^* h_0)\,\frac{\cos\theta_Y\sin\theta_B}{f_B f_Y}\right]$$

$$\frac{\Gamma(\ell^\pm \to e^\pm + A_1)}{\Gamma(\ell^- \to \nu + \pi^-)} = \delta\,|k_3|^2\left(\frac{m_{A_1}^2}{f_{A_1} F_\pi}\right)^2\left(1-\frac{m_{A_1}^2}{m_\ell^2}\right)\times\left(1+\frac{2m_{A_1}^2}{m_\ell^2}\right)$$

where
$$\delta = \left(\frac{|b_L|^2+|b_R|^2}{|g_L|^2+|g_R|^2}\right)$$

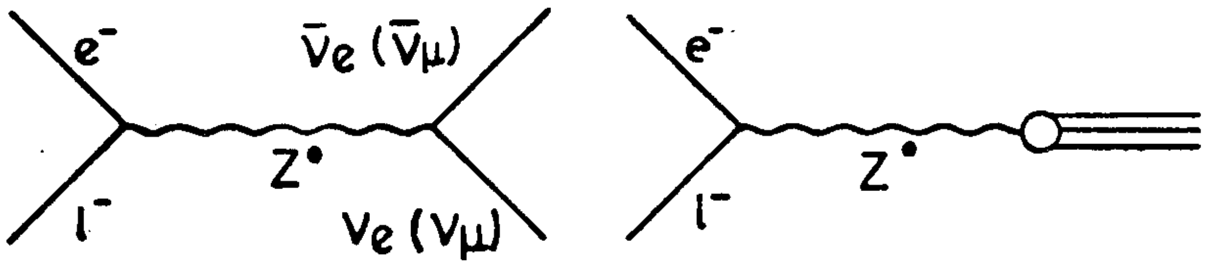
Lepton representations \ Heavy leptons	Charged	Neutral
Doublets = SU(2) x U(1) models[13]	Most models have only one sequential charged heavy leptons, produced only in e^+e^- annihilation.	One or more, but not produced by ordinary neutrino scattering in most models.
Triplets: a) 3 triplets with Han-Nambu charge structure[14]	Two sequential charged heavy leptons produced in e^+e^- annihilation	One produced by ν_μ scattering and one produced by ν_e scattering
Triplets: b) arbitrary charge structure[15]	Flexible	Flexible
Quadruplets with electron and muon lepton number (or more)	Two (or more) non-sequential, produced in e^+e^- annihilation and neutrino scattering	Two (or more), produced by ordinary neutrino scattering.

Table 2



ν_l
l^-
W^-
$\bar{\nu}_e(\bar{\nu}_\mu)$
$e^-(\mu^-)$
ν_l
l^-
W^-

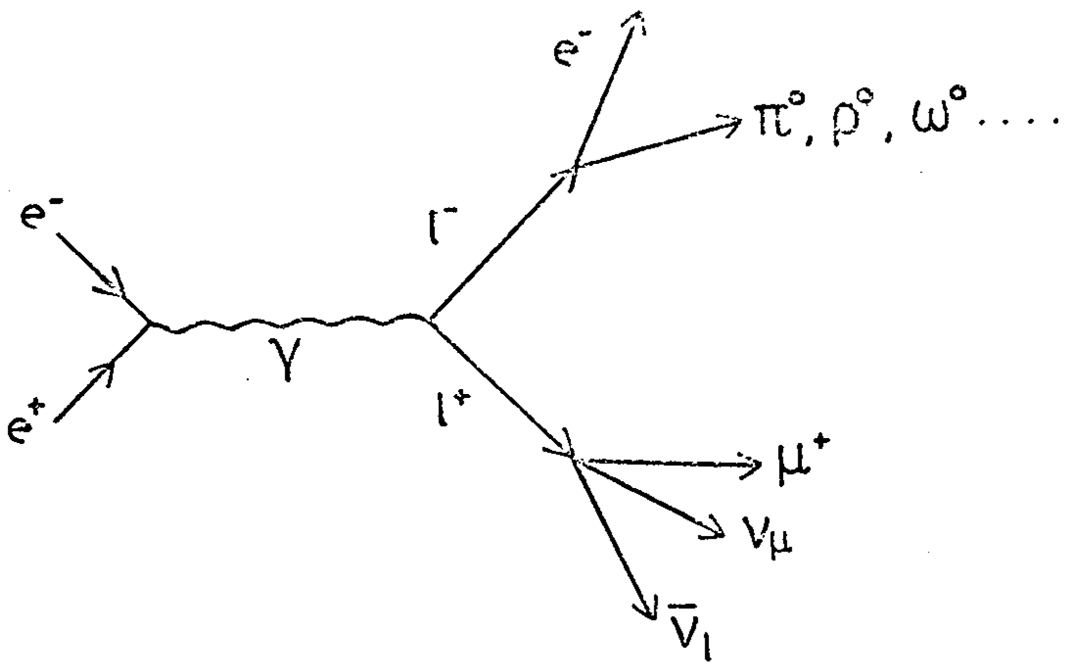
(1a)



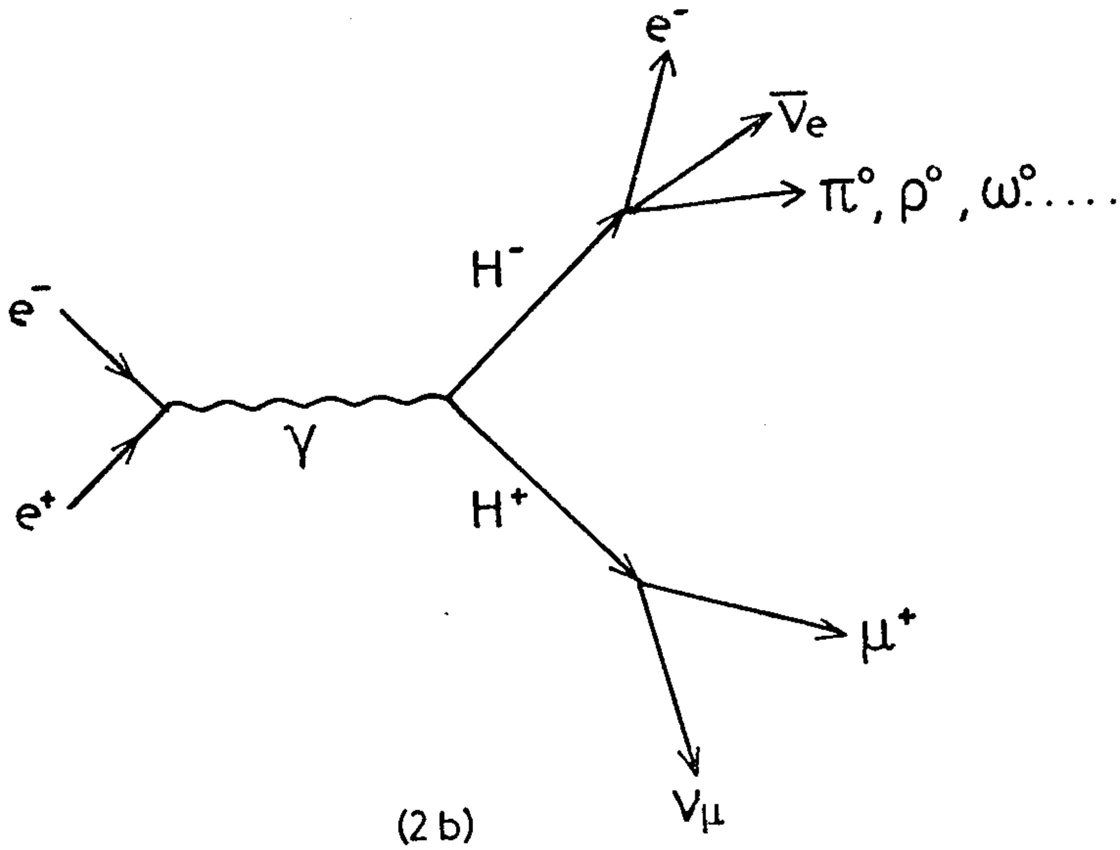
e^-
l^-
Z^*
$\bar{\nu}_e\ (\bar{\nu}_\mu)$
$\nu_e\ (\nu_\mu)$
e^-
l^-
Z^*

(1b)

Fig.1


e⁻
$\pi^\circ, \rho^\circ, \omega^\circ \ldots$
l^-
e⁻
γ
e⁺
l^+
μ^+
ν_μ
$\bar{\nu}_l$

(2a)


e⁻
$\bar{\nu}_e$
$\pi^\circ, \rho^\circ, \omega^\circ \ldots$
H^-
e⁻
γ
e⁺
H^+
μ^+
ν_μ

(2 b)

Fig.2