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ON NEUTRINO PRODUCTION OF HEAVY NEUTRAL LEPTONS*

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ABSTRACT

Production of heavy neutral leptons by μ-type neutrinos is investigated in the framework of a strangeness-conserving neutral current model, and the analysis is applied to the Ramm effect. The failure to observe such heavy leptons in the K-meson decay spectrum is easily understood, but the large charged current coupling strength required in the heavy lepton decay (well above the universal value) casts considerable doubt on the validity of the effect. Confirmation of the effect would suggest the existence of a new direct pion-muon interaction.

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The possible production of heavy leptons in high energy interactions has stimulated both theoretical and experimental interest.[1,2] Heavy charged leptons could be produced in pairs in high energy $e^+ - e^-$ colliding beams or in association with their characteristic neutrinos in high energy γ- nucleus or e^- - nucleus interactions. On the other hand, both charged and neutral heavy leptons could be copiously produced in high energy neutrino interactions if they carry the same muon quantum number as the conventional neutrino probe ν_μ.

The purpose of this note is to present some theoretical speculations on neutral heavy lepton production by μ-type neutrinos. This study is prompted in part by the observations due to Ramm[3] of an apparent peak in the $\pi^+ - \mu^-$ $(\pi^- - \mu^+)$ invariant mass spectrum produced in the 1967 CERN $\nu_\mu(\bar{\nu}_\mu)$ experiments. The peaks at 425 MeV suggest the production and subsequent decay of a heavy neutral lepton. This so called Ramm effect has not been highly regarded, for overwhelming evidence demonstrates that no such peaks appear in the π-μ mass distributions from $K_L^o \rightarrow \pi\mu\nu$ decays.[4] We can resolve this apparent contradiction, however, by employing a simple model. Although our analysis tends to emphasize the Ramm effect at 425 MeV, the study applies just as well to some other hypothetical heavy lepton; we select a mass of 1.2 GeV by way of example.

The apparent processes in question are

$$\nu_\mu + p \rightarrow p + h_\mu^o \tag{1}$$

and

$$h_\mu^o \rightarrow \pi^+ + \mu^- . \tag{2}$$

The theoretical model we propose for the production process (1) couples the neutral leptons to the nucleon vertex through a weak neutral current interaction. To be sure, the existence of weakly coupled neutral currents has not been demonstrated to date; however, we consider the simplest model consistent with the present data as discussed previously by Albright and Oakes:[5] the neutral hadron current is taken to be strangeness-conserving and simply the 3rd component of an isospin triplet.

In detail, we write down the weak semileptonic Hamiltonian coupling the μ -type heavy lepton according to

$$H_{SL} = \frac{G}{\sqrt{2}} \left[g_{\pm} \left(J_{\lambda}^{(+)} j_{\lambda}^{(-)} + J_{\lambda}^{(-)} j_{\lambda}^{(+)} \right) + 2 g_0 J_{\lambda}^{(3)} j_{\lambda}^{(o)} \right], \qquad (3)$$

where $J_{\lambda}^{(\pm)}$ represents the Cabibbo current, $J_{\lambda}^{(3)}$ is the 3rd component of the V - A octet current, and the lepton currents coupling the heavy lepton to the ordinary leptons are given by

$$j_{\lambda}^{(-)} = \bar{\mu} \gamma_{\lambda} (1 + \gamma_5) h_{\mu} , \quad j_{\lambda}^{(+)} = j_{\lambda}^{(-)\bigstar} , \qquad (4)$$

$$j_{\lambda}^{(o)} = \bar{h}_{\mu} \gamma_{\lambda} (1 + \gamma_5) \nu_{\mu} + \bar{\nu}_{\mu} \gamma_{\lambda} (1 + \gamma_5) h_{\mu} .$$

By charged current universality of the weak interaction, we anticipate $g_{\pm} = 1$; the neutral current, on the other hand, is very model-dependent and g_0 is unknown.[6] Strangeness conservation of the neutral hadron current forbids the direct decay $K_L^o \to h_{\mu}^o + \bar{\nu}_{\mu} \to \pi^+ + \mu^- + \bar{\nu}_{\mu}$, so the absence of h_{μ}^o in the $K_{\mu 3}^o$ decay spectrum is easily understood.

The production matrix element corresponding to (1) becomes

$$M \left(\nu_{\mu} + p \to p + h_{\mu}^o \right) = \frac{G}{\sqrt{2}} \, 2 g_0 \langle p' \,|\, J_{\lambda}^{(o)} \,|\, p \rangle \bar{h}_{\mu} \gamma_{\lambda} (1 + \gamma_5) \nu_{\mu} \qquad (5)$$

$$= \frac{G}{\sqrt{2}} \, g_0 \, \bar{u}_{p'} \left[F_1^V \gamma_{\lambda} - \frac{\Delta\mu}{2m} F_2^V \sigma_{\lambda\rho} (p' - p)_{\rho} + g_A F_1^A \gamma_{\lambda} \gamma_5 \right] u_p$$

$$\times \; \bar{h}_{\mu} \gamma_{\lambda} (1 + \gamma_5) \nu_{\mu}$$

by virtue of an isospin rotation of the hadron part of the matrix element in $\nu_\mu + n \rightarrow p + \mu^-$. The form factors F_1^V and F_2^V are just the isovector electromagnetic form factors while F_1^A is the direct axial vector form factor. The cross section for (1) calculated from Eq. (5) is very similar in shape to that for $\nu_\mu + n \rightarrow p + \mu^-$, with threshold at E_ν(lab) = 0.5 GeV for $m_h = 425$ MeV and at 2.0 GeV for $m_h = 1.2$ GeV. The asymptotic ratio for the two cross sections is just

$$\lim_{E_\nu \to \infty} \sigma \left(\nu_\mu + p \rightarrow p + h_\mu^0\right) / \sigma\, (\nu_\mu + n \rightarrow p + \mu^-) = g_0^2 \cos^{-2} \theta \qquad (6)$$

in terms of g_0 and the Cabibbo angle.

Turning to the decay process (2), we can understand this transition to occur via the charged current part of Eq. (3) which couples the leptons to the pion as in π^+ decay. The decay matrix element becomes

$$\begin{aligned} M\left(h_\mu^o \rightarrow \pi^+ \mu^-\right) &= \frac{G}{\sqrt{2}}\, g_\pm \cos\theta < \pi^+ \,|\, J_\lambda^{(1+i2)} \,|\, 0 > \bar{\mu}\, \gamma_\lambda (1 + \gamma_5)\, h_\mu \\ &= -i \frac{G}{\sqrt{2}}\, g_\pm\, f_\pi^{(+)} \cos\theta \;\; \bar{\mu}\, (\gamma \cdot q')(1+\gamma_5)\, h_\mu\,, \end{aligned} \qquad (7)$$

where the (charged) pion decay constant is $f_\pi^{(+)}/\sqrt{2} = 94$ MeV and q' is the pion 4-momentum. A mass of $m_h = 425$ MeV corresponding to the Ramm effect yields

$$w\left(h_\mu^o \rightarrow \pi^+ \mu^-\right) = (3.3 \times 10^9) g_\pm^2 \;\; \sec^{-1} \qquad (8a)$$

for the partial rate, while a mass of 1.2 GeV in turn implies

$$w\left(h_\mu^o \rightarrow \pi^+ \mu^-\right) = (1.2 \times 10^{11})\, g_\pm^2 \;\; \sec^{-1}. \qquad (8b)$$

Other possible decay modes are

$$h_\mu^o \rightarrow \pi^o \nu_\mu , \tag{9a}$$

$$h_\mu^o \rightarrow \pi^+\pi^o\mu^- , \pi^+\pi^-\nu_\mu , \tag{9b}$$

$$h_\mu^o \rightarrow \nu_\mu \nu_\ell \bar{\nu}_\ell , \nu_\mu \ell^- \ell^+ , \tag{9c}$$

where the leptons indicated by the script ℓ can be either of the muon or electron variety.[7] The partial rates are tabulated[8] in Table I for both heavy lepton masses of 425 MeV and 1.2 GeV. It is clear that for values of $g_\pm$ and g_0 of order unity, the dominant modes are expected to be (2), (10a), and (10c) for the Ramm effect.

If g_0 and $g_\pm$ are of order unity, however, the partial rate for $h_\mu^o \rightarrow \pi^o \nu_\mu$ is embarrassingly large, for the rapid decay $\pi^o \rightarrow 2\gamma$ should have produced many pairs of electron showers and no visible μ^-. Such events have not been copiously produced in either the 1967 CERN-neutrino experiment in propane or in the early Brookhaven neutrino experiment.[9] We shall proceed by imposing the constraint

$$| g_0 | << | g_\pm | \tag{10}$$

below.

We now try to piece together the production cross section and partial decay rates so as to achieve a consistent picture. The observed cross section for (1) is just the theoretical cross section times the branching ratio into the decay mode (2). A crude estimate from Ramm's data indicates that $\sigma_{obs} \simeq 0.1 \times 10^{-38} cm^2$ for $m_h = 425$ MeV. On the other hand, since no gaps are visible in the HLBC photographs between the apparent production and decay vertices, a lifetime bounded above by $\tau \lesssim 10^{-12}$ sec. is suggested.[3]

For the Ramm effect, the total decay rate as calculated from Table I implies

$$g_\pm^2 + 3g_0^2 \gtrsim 300 \tag{11a}$$

while the observed cross section yields

$$g_0^2\, g_\pm^2 \left(g_\pm^2 + 3\, g_0^2\right)^{-1} \simeq \frac{1}{8} \quad . \tag{11b}$$

From conditions (11a), (11b), and (10) we deduce

$$|g_\pm| \gtrsim 17 \quad , \quad |g_0| \simeq \frac{1}{2\sqrt{2}} \quad . \tag{12}$$

Condition (10) is easily satisfied, so that the branching ratio for $h_\mu^o \rightarrow \pi^o \nu_\mu$ is $\lesssim$ 0.1%. Note that $g_\pm$ is determined solely by the lifetime, while g_0 is fixed by the observed cross section.[10]

According to the above analysis, the charged current coupling is greatly enhanced relative to the neutral current coupling of heavy leptons. In particular, the universal charged current coupling strength $g_\pm = 1$ is ruled out in our model. This casts considerable doubt on the validity of the observed effect. The conditions for the production of heavier mass leptons would not be so extreme.

Obviously additional neutrino and antineutrino experiments are needed to confirm or invalidate the Ramm effect. If the existence and production of heavy neutral leptons of mass 425 MeV by μ -type neutrinos are confirmed, a new direct pion-muon interaction appears to be a likely explanation.

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FOOTNOTES AND REFERENCES

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2. V. Alles-Borelli, M. Bernardini, D. Bollini, P. L. Brunini, T. Massan, L. Monari, F. Palmonari, and A. Zichichi, Lett. Nuovo Cimento 4, 1156 (1970); A. K. Mann, Lett. Nuovo Cimento 1, 486.(1971) and J. J. Sakurai, Lett. Nuovo Cimento 1, 624 (1971).
3. C. A. Ramm, Nature 227, 1323 (1970). Ramm has more recently suggested the existence of charged heavy leptons with nearly the same mass, 425 MeV, which were also produced in the same CERN neutrino experiments and decayed electromagnetically; cf. C. A. Ramm, Nature 230, 145 (1971).
4. In Ramm's original work cited in ref. 3, he claims that some evidence exists which suggests the production of the heavy lepton in $K^{o}_{\mu 3}$ decay. This evidence is not well founded, however, and has since been refuted by higher statistics experiments (D. Dorfan, private communication).
5. C. H. Albright and R. J. Oakes, Phys. Rev. D2, 1883 (1970).
6. The factor 2 is introduced so that Eq. (3) would be isospin invariant in the symmetry limit with $g_{\pm} = g_{0}$.
7. In addition one would expect decays into heavy vector and axial vector mesons if kinematically allowed. In fact, the decay modes (9b) are greatly enhanced by the ρ meson contribution for $m_h = 1.2$ GeV.
8. We assume the neutral current couples equally to the neutrinos and to the charged leptons.

9. M. Schwartz (private communication).

10. The lower limit for $g_{\pm}$ depends critically on the lower limit placed on the lifetime for h_{μ}^{o}. If in place of $\tau \lesssim 10^{-12}$ sec. we use $\tau \lesssim 10^{-11}$ sec., the lower limit is replaced by $|g_{\pm}| \gtrsim 6$. If the charged current coupling is much larger than the lower bound quoted in (12), the correction to the anomalous muon magnetic moment will be too large and will destroy the good agreement that now exists between experiment and quantum electrodynamics. See S. C. Chhajlany and S. Pakvasa to be published.

Table I. Partial Decay Rates for a Heavy Neutral Lepton Expressed in Sec^{-1}

Decay Mode	$m_h = 425$ MeV	$m_h = 1.2$ GeV
$h_\mu^o \rightarrow \pi^+\mu^-$	$(3.3 \times 10^9)\, g_\pm^2$	$(1.2 \times 10^{11}) g_\pm^2$
$h_\mu^o \rightarrow \pi^o \nu_\mu$	$(8.5 \times 10^9) g_0^2$	$(2.3 \times 10^{11}) g_0^2$
$h_\mu^o \rightarrow \pi^+\pi^o\mu^-$	$(2.5 \times 10^7) g_\pm^2$	$(1.7 \times 10^{11}) g_\pm^2$
$h_\mu^o \rightarrow \pi^+\pi^-\nu_\mu$	$(5.0 \times 10^7) g_0^2$	$(3.4 \times 10^{11}) g_0^2$
$h_\mu^o \rightarrow \nu_\mu \nu_\ell \bar{\nu}_\ell$	$(1.1 \times 10^9)\, g_0^2$	$(2.1 \times 10^{11}) g_0^2$
$h_\mu^o \rightarrow \nu_\mu \ell^- \ell^+$	$(0.5 \times 10^9) g_0^2$	$(1.4 \times 10^{11}) g_0^2$