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Evidence against 1.8-GeV/c^2 heavy charged muons*

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Arguments are presented which tend to rule out the existence of 1.8-GeV/c^2 heavy charged muons coupled to the ordinary left-handed neutrino ν_μ with full strength G_F. With better statistics, a stronger conclusion can be drawn.

Recently evidence for anomalous $\mu^{\pm}$-$e^{\mp}$ events in e^+-e^- collisions has been reported[1] at SPEAR. While such events could arise from associated charmed-particle production or heavy-lepton pair production, analysis indicates the latter is favored[2] with a heavy-lepton mass near 1.8 GeV/c^2.

If this interpretation of the μ-e events is correct, one naturally wishes to ascertain the quantum numbers of the heavy leptons produced. Leptons of a new variety are quite likely, but heavy electrons or heavy muons are also a possibility. In this note we show that 1.8-GeV/c^2 heavy charged muons coupled with full strength G_F to the ordinary left-handed neutrino are on the verge of being ruled out.

The Caltech-Fermilab collaboration has placed a lower limit of 8.4 GeV/c^2 on the mass of a heavy M^+ muon[3] by their failure to see a significant μ^+ signal from the possible chain reaction $\nu_\mu+N\to M^+ +X$, $M^+\to\mu^+\nu_\mu\nu_\mu$. Hence we concern ourselves here only with neutrino production of negative heavy muons in the inclusive reaction

$$\nu_\mu+N\to M^-+X \tag{1}$$

and antineutrino production of M^+ antimuons in the corresponding reaction.

If one considers only charged-current couplings, the pertinent decay modes are

$$M^-\to\nu_\mu+\text{hadrons}, \tag{2a}$$

$$M^-\to\mu^-+\bar{\nu}_\mu+\nu_\mu, \tag{2b}$$

and

$$M^-\to e^-+\bar{\nu}_e+\nu_\mu. \tag{2c}$$

Neutral-current couplings would contribute to the decay mode (2b) as well as

$$M^-\to\mu^-+\text{hadrons} \tag{2d}$$

and

$$M^-\to\mu^-+\bar{\nu}_e+\nu_e. \tag{2e}$$

Since the structure of the neutral-current couplings is rather uncertain in contrast to the $V-A$ structure favored for the charged currents, we shall restrict our attention primarily to charged-current couplings.[4]

A number of previous studies of heavy leptons exist in the literature,[5] and we shall make use of some of the results. Relying on the e^+-e^- annihilation data, one expects[6] for a mass of 1.8 GeV/c^2 a branching ratio of approximately 60% for the hadronic mode (2a) and 20% for each of the two leptonic modes (2b) and (2c). On the other hand, the production cross section for (1) is expected to rise from zero at threshold to become asymptotically equal to the cross section for the direct inclusive process

$$\nu_\mu+N\to\mu^-+X. \tag{3}$$

At 30 GeV, the heavy-muon production cross section should reach half the direct $\nu\to\mu^-$ cross section.[7]

Production of M^- and subsequent decay through the hadronic mode (2a) fakes the neutral-current inclusive process

$$\nu_\mu+N\to\nu_\mu+X, \tag{4}$$

while decay through the muonic mode (2b) imitates (3). Decay through the electronic mode (2c) should give rise to an excess of electron events. Both the excess-electron and the enhanced neutral-to-charged-current ratio tests have been applied by Asratyan *et al.*[8] to place a lower limit of 1.8 GeV/c^2 (90% c.l.) on the mass of the M^- with information obtained from the CERN Gargamelle (GGM) neutrino experiments,[9] where the beam energy is generally less than 10 GeV.

Since their analysis was made, new information has been obtained from the higher-energy neutrino beams at Fermilab. Data taken in counter experiments by the Harvard-Penn-Wisconsin-Fermilab (HPWF) and Caltech-Fermilab (CITF) collaborations[10,11] reveal no new information regarding excess electron signals; however, the neutral- to charged-current ratios (R) determined in ν and $\bar{\nu}$ production are not noticeably larger than those measured at the lower CERN energies:

$$R_\nu = \begin{cases} 0.22 \pm 0.03 & \text{(GGM)} \\ 0.11 \pm 0.05 & \text{(HPWF)}, \\ 0.21^{+0.21}_{-0.10} & \text{(CITF)} \end{cases} \quad (5a)$$

$$R_{\bar{\nu}} = \begin{cases} 0.43 \pm 0.12 & \text{(GGM)} \\ 0.32 \pm 0.09 & \text{(HPWF)}. \\ 0.43^{+0.43}_{-0.21} & \text{(CITF)} \end{cases} \quad (5b)$$

On the basis of a ~50% cross section ratio for (1) compared to (3) and an 80% branching ratio for "apparent" neutral-current events and 20% for charged-current events, we would expect ratios R which are

$$\frac{R_{\text{HPWF,CITF}}}{R_{\text{GGM}}} \simeq \frac{1+0.5(0.8)}{1+0.5(0.2)} = 1.3 \quad (6)$$

times higher at Fermilab than at CERN. This is not borne out by the new data.

One could argue that the branching ratio for the muon mode (2b) is much larger than expected. But in this case we can demonstrate that one will then encounter difficulty with the y distributions for reaction (3). For this purpose, we rely on a Monte Carlo calculation of the type presented elsewhere[7] to study the x and y distributions for the chain reaction of M^- production followed by the muon decay mode (2b).

The results are presented in Fig. 1 for the x_{obs} and y_{obs} distributions of the chain process (1) + (2b), where

$$x_{\text{obs}} = q^2/(2ME_{\text{had}}), \quad (7)$$

$$y_{\text{obs}} = E_{\text{had}}/(E_\mu + E_{\text{had}}). \quad (8)$$

The x_{obs} distributions exhibit a sharp peaking at small x ($\lesssim 0.2$) for all energies considered. The y_{obs} distribution for neutrinos peaks at larger and larger y as E is increased, while that for antineutrinos becomes flatter.

To compare the results with the experimental data, we weight the above distributions with the

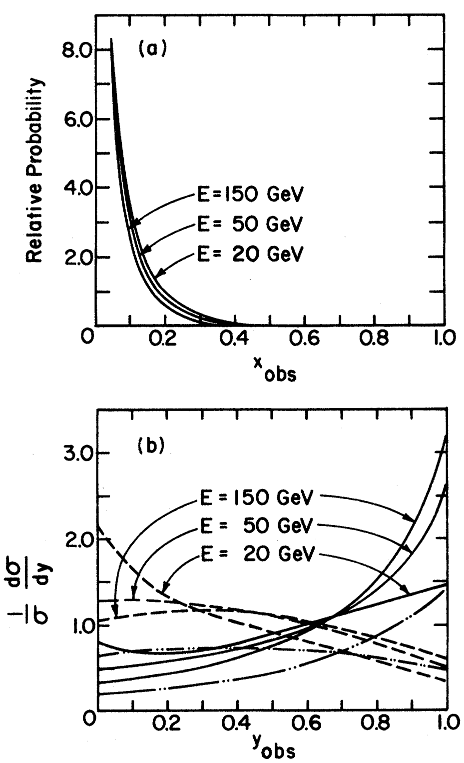

FIG. 1. (a) x_{obs} distributions for the chain reaction $\bar{\nu}_\mu + N \to (M^+ \to \mu^+\nu_\mu\bar{\nu}_\mu) + X$. The corresponding distributions for neutrino production are very similar. (b) y_{obs} distributions for the neutrino (solid curves) and antineutrino (dashed curves) chain reactions. The double-dotted curves reflect the effects of the $x \le 0.1$ cut at 50 GeV.

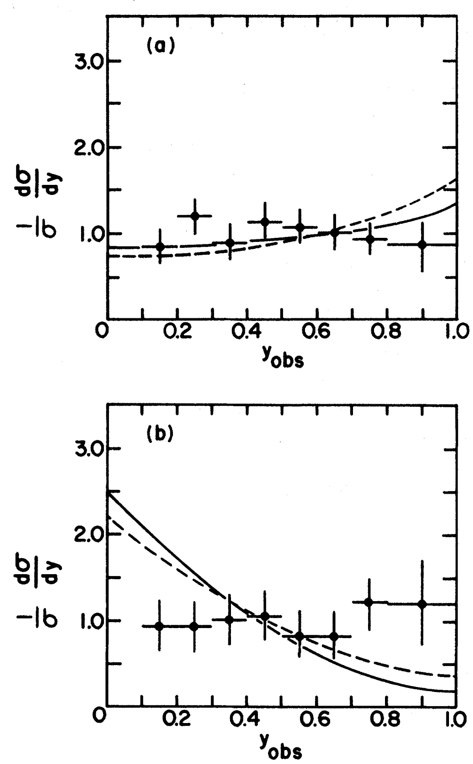

FIG. 2. y_{obs} distributions for (a) $\nu_\mu + N \to \mu^- + X$ and (b) $\bar{\nu}_\mu + N \to \mu^+ + X$ through both the direct and chain reactions at $E = 50$ GeV with the cut $x \le 0.1$. The solid curves refer to a 20% branching ratio and the dashed curves to a 50% branching ratio for the muonic mode (2b). The HPWF points are plotted for $E > 30$ GeV, $x \le 0.1$.

relative cross section for M^- production and the branching ratio for the muon decay mode. The HPWF group has conveniently presented their data[12] with cuts for $E>30$ GeV and $x<0.1$. Above 30 GeV we take the relative cross section for (1) compared to the direct reaction (3) to be 0.5 and at first assume the branching ratio for the muon mode to be 20% as before. We estimate that 60% of the M^- events would occur for $x_{obs}\leq 0.1$ while only 20% of the direct $\nu\to\mu$ events would be observed in this region.[13] Hence the chain reaction (1) followed by (2b) should be weighted by a factor of $0.5\times 0.2\times 0.6/0.2=0.3$ relative to the direct process.

The calculated y distributions for the 20% branching ratio are shown as solid curves in Fig. 2 along with the HPWF data points[13] for $E>30$ GeV, $x\leq 0.1$. The predictions do not agree well with the present data. The surprisingly flat antineutrino y distribution is not well understood but presumably reflects charmed particle production.[14] The neutrino y distribution does not show a rise at high y_{obs} although the disagreement is only a 1.5 standard deviation effect.

Let us now consider an extreme 50% branching ratio for the muonic mode (2b) and 50% for the electronic mode (2c) so as to reduce the apparent ratio in (6) to 1.0 and thereby remove the R discrepancy. The y_{obs} distributions are then altered as shown by the dashed curves in Fig. 2, and the high y discrepancy in neutrino production becomes more pronounced. Hence by changing the muonic decay branching ratio, we have eliminated one discrepancy but enhanced another.

In conclusion, we have shown that the ratios R and the y_{obs} distributions for small x taken together tend to rule out a heavy M^- muon of mass 1.8 GeV/c^2 coupled with strength G_F to the ordinary left-handed neutrino. One would obviously like to have better statistics to strengthen the argument. However, we note that this conclusion will not be weakened if neutral-current couplings for the M^- are taken into account, for the decay modes (2d) and (2e) will enhance the rise at high y even more.[15]

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

[2]This preferred interpretation results from a study of the charged lepton momentum distributions expected in the decays of heavy particles into two or three particles. Cf. G. Feldman, in Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, 1975 (unpublished).

[3]B. C. Barish *et al.*, Phys. Rev. Lett. 32, 1387 (1974).

[4]We comment on the effect of neutral-current couplings at the end of our discussion.

[5]See, for example, J. D. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D 7, 887 (1973); A. Soni, *ibid.* 9, 2092 (1974); C. H. Albright and C. Jarlskog, Nucl. Phys. B84, 467 (1975); C. H. Albright, C. Jarlskog, and M. O. Tjia, *ibid.* B86, 535 (1975).

[6]See Ref. 5. The branching ratios quoted are also consistent with the heavy-lepton interpretation cited in Ref. 2.

[7]See C. H. Albright and C. Jarlskog in Ref. 5 and C. H. Albright, Phys. Rev. D 12, 1319 (1975).

[8]A. E. Asratyan *et al.*, Phys. Lett. 49B, 488 (1974).

[9]F. J. Hasert *et al.*, Nucl. Phys. B73, 1 (1974); A. Pullia, in *Proceedings of the XVII International Conference on High Energy Physics, London, 1974,* edited by J. R. Smith (Rutherford Laboratory, Chilton, Didcot, Berkshire, England, 1974), p. IV-114.

[10]B. Aubert *et al.*, Phys. Rev. Lett. 32, 1457 (1974).

[11]B. C. Barish *et al.*, in proceedings of the High Energy Neutrino Conference, Paris, 1975 (unpublished).

[12]B. Aubert *et al.*, Phys. Rev. Lett. 33, 984 (1974).

[13]The actual y_{obs} distributions predicted with this cut on x_{obs} at $E=50$ GeV are shown as double-dotted curves in Fig. 1(b).

[14]The possibility that the major part of the y anomaly arises from heavy-M^0 production and decay is not consistent with the data. See Ref. 7; L. N. Chang, E. Derman, and J. N. Ng, Phys. Rev. Lett. 35, 6 (1975); A. Pais and S. B. Treiman, *ibid.* 35, 1206 (1975); A. Benvenuti *et al.*, *ibid.* 35, 1203 (1975).

[15]This is especially true for the decay mode (2d), where the hadrons from the decay contribute significantly to the numerator in y_{obs}.