Gauge-Theory Heavy Muons: An Experimental Search*

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We have observed 1522 neutrino events with a μ^- secondary and 8 events with a μ^+ secondary from a beam consisting mostly of neutrinos. The μ^+ events are consistent in number and kinematic properties with beam contamination by $\bar{\nu}_\mu$. This experiment sees no evidence for production of heavy positively charged leptons. Assuming a coupling constant equal to the universal Fermi constant and a branching ratio to muons $B=0.3$, our 90% confidence lower limit corresponds to $M_{Y^+} \gtrsim 8.4$ GeV/c^2.

Recently, several experiments[1] have been conducted to search for new members of the lepton families. Thus far, no evidence has been found for their existence up to masses of about 2.5 GeV/c^2. However, there are theoretical reasons to pursue the question of whether such positively charged heavy muons exist, since they may help provide[2] the mechanism for nondivergent behavior of the weak interactions at high energies. In some gauge models using heavy muons and electrons, calculations[3] indicate that the positively charged heavy muon must be less massive than about 7 GeV/c^2, in order to be consistent with present experimental measurements of the muon magnetic moment. We report here the conclusions of an experiment in the mass range up to about 8 GeV/c^2.

The experiment was performed in the narrow-band neutrino beam at the National Accelerator Laboratory. Extracted protons of energy 300 GeV bombarded the production target. The secondary hadron beam was set to transmit positive hadrons with an average energy of 165 GeV, and $\Delta p/p \approx 0.35$. The π^+ and K^+ decays in the 345-m decay pipe provide a spectrum of neutrinos with two peaks, at $E_\nu \approx 50$ and 135 GeV. We also expect, at much smaller energies ($E_\nu \lesssim 25$ GeV), a contamination of neutrinos and antineutrinos from pion and kaon decays occurring in the region immediately downstream of the production target, prior to momentum and sign selection. Because the beam is sign selected, all negative hadrons are removed before the decay-pipe region. The antineutrinos from this source form the major background in this experiment.

The neutrino detection apparatus,[4] located 500 m from the end of the hadron decay region, consists of 160 tons of iron interspersed with scintillation counters and spark chambers, followed by an iron-core toroidal magnet and additional spark chambers. The target is 576 in. long and 60×60 in.^{2} in cross section. Both final-state energies from the reaction

$$\nu_\mu + N \to \mu^- + \text{hadrons} \tag{1}$$

are determined with this apparatus: The muon energy is measured by observation of the bend angle in the iron-core magnet, and the hadron energy is measured by calorimetry using the scintillation counters located inside the steel target. The apparatus was triggered whenever a particle traversed trigger counters located on both sides of the spectrometer magnet, or when more than 10 GeV in hadron energy was dissipated in the calorimeter.

Positively charged heavy muons (Y^+) would be produced[5] by a reaction analogous to Reaction (1):

$$\nu_\mu + N \to Y^+ + \text{hadrons}. \tag{2}$$

The heavy lepton would subsequently decay in the mode

$$Y^+ \to \mu^+ + \nu_\mu + \nu_\mu, \tag{3}$$

with a calculable rate $\Gamma(\mu^+) \gtrsim 10^{13}$ sec^{-1}, and a branching ratio $B = \Gamma(\mu^+)/\Gamma(\text{all})$. This ratio will lie within the limits $0 < B < 0.67$, depending on the other possible modes of decay. The decay mode most likely to compete with Reaction (3) would be $Y^+ \to \nu_\mu + \text{hadrons}$. Current algebra relates[5] B to the asymptotic ratio $\kappa = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. For $\kappa = 2$, as in the "colored-quark model," the result is that $B \approx 0.3$ for $M_Y \gtrsim 2$ GeV/c^2.

For this heavy-muon search, the spectrometer polarity was set to focus positives, and hence maximize the acceptance. Events with a single final-state muon traversing the spectrometer magnet were selected from the triggered sample. In order to guarantee neutrino production, it was further required that the production vertex was located well inside the target: at least 3 in. from the transverse edges of the steel, 40 in. from the upstream end, and 126 in. from the downstream end. There were 1530 events satisfying these conditions. Eight of these events had a positive muon in the final state; the rest were negatively charged. Figure 1 shows the distribution in the total observed energy for the latter 1522 events. This shows the characteristic two-peak spectrum expected from the pion and kaon neutrinos. The widths of these peaks result partly from the beam resolution during the run (~ 18%), and the apparatus resolution (~ 25%).

The primary signature of heavy-muon production is the observation of positively charged muons created from a beam consisting of neutrinos with little contamination from antineutrinos. Such "wrong-sign muons" can arise from the following sources: (a) production by background antineutrinos ($\bar{\nu}_\mu + N \to \mu^+ +$hadrons); (b) incorrect determination of the muon charge with the spectrometer magnet; (c) production and decay of heavy muons by Reactions (2) and (3); (d) production and decay of charged intermediate vector bosons; (e) some other "exotic" mechanism, such as violation of the conservation of muon number. The production and decay of charged bosons (d) would provide additional signatures, and a report on the search for such anomalous effects will be the subject of a future paper.

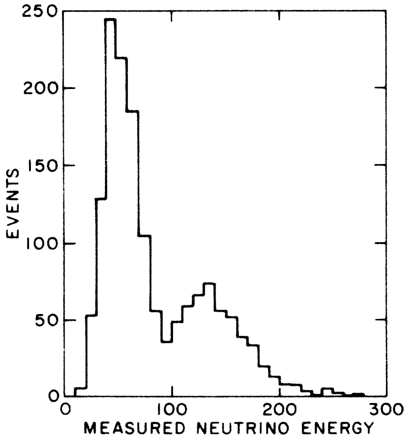

FIG. 1. Distribution in total measured energy (GeV) for 1522 observed neutrino events with negative muon secondary.

Processes (a) and (b) form the sole backgrounds for this experiment. We estimate that we expect to misidentify less than 0.9 events out of 1522 right-sign events as a result of resolution and large-angle scattering in the magnet (b). In order to calculate the number of wrong-sign events from antineutrinos (a), we have determined our energy-dependent acceptance in a Monte Carlo calculation, which assumed the usual quark-model structure functions.[1,5] This calculation reproduced the general features of the observed distributions in neutrino interaction vertex, in muon position at several counters and the magnet, and in the scaling variables (x, y) shown by the 1522 accepted μ^- events.

The relative number of background $\bar{\nu}$ was calculated, with the normalization constrained by preliminary analysis of hadron fluxes in this beam. We calculate an expected level of 10.2 ± 5.1 observed μ^+ events from this source. As a check, we ran for some period with a primarily antineutrino beam. Under those circumstances the wrong-sign muons are μ^- from ν interactions, and they form a relatively larger fraction of the total observed events. We estimate 6.1 ± 3.0 ν background events for this case, relative to 60 observed $\bar{\nu}$ events with a μ^+ in the final state. There were six wrong-sign events observed, in good agreement. We conclude that 11.1 ± 5.1 wrong-sign events with a final-state μ^+ are to be expected from background sources (a) and (b) in the ν sample. The observed eight events are consistent with this estimate.

We have also attempted to exploit the kinematic differences between heavy-muon production (c) and background, primarily process (a). There are two major differences to be expected.

(1) Production and acceptance of heavy muons, especially at large mass, are dominated by the highest-energy kaon neutrinos, typically $\langle E_\nu \rangle \simeq 150$ GeV, with the average observed energy $\langle E_{\text{meas}} \rangle \simeq 80$ GeV. Production of μ^+ by $\bar{\nu}$, on the other hand, should reflect a steeply falling flux curve characteristic of background $\bar{\nu}$, and would peak considerably lower. Figure 2(a) shows the expected distributions in $E_{\text{meas}} = E_\mu + E_{\text{had}}$ for events observed under these two assumptions, with the data histogram superimposed. The data are consistent with the expected background, and much less consistent with production and decay of high-mass leptons.

(2) The distribution in the observed inelasticity $y_{\text{meas}} = E_{\text{had}}/E_{\text{meas}}$ is expected to be substantially

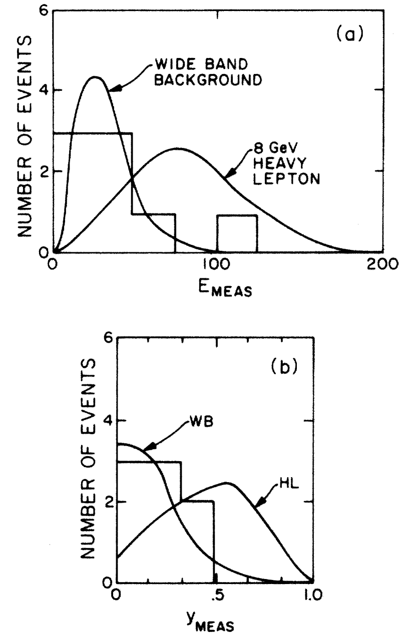

FIG. 2. (a) Distribution in total observed energy E_{meas}, in GeV, for eight μ^+ events, and (b) distribution in observed inelasticity y_{meas}. The data are shown as histograms. Expected distributions for wide-band background ("WB") from $\bar{\nu}$ interactions and 8-GeV/c^2 heavy-lepton production ("HL") are shown as solid curves. These calculated curves include the apparatus acceptance.

different for Y^+ decay and $\bar{\nu}$ production.[1] Figure 2(b) shows the y_{meas} distributions to be expected for wide-band antineutrino interactions and for heavy-lepton decay, with the histogram of the data superimposed. The data lie at small values, more consistent with background than with production of heavy leptons.

We conclude that the observed wrong-sign events are consistent with expected backgrounds, both in absolute numbers and in internal distributions. To determine the sensitivity of the search for heavy leptons as a function of mass, we used the same Monte Carlo calculation discussed previously. In this calculation the differential and total cross sections for process (2) were determined by quark-model predictions.[5] This is expected to be a lower limit on the production of such particles. The polarization of the Y^+ was calculated for each event,[6] and the subsequent decay distribution in accordance with usual $V-A$ assumptions.[7] This Monte Carlo program was also used to obtain the theoretical curves for y_{meas} and E_{meas} already discussed.

In order to eliminate the need for reliance on normalized background calculations, we have chosen to apply a cut to both the data and the Monte Carlo calculation. For the requirement $y_{\text{meas}} > 0.5$, all μ^+ events are removed from the data sample [see Fig. 2(b)], while the expected background μ^+ is reduced to <0.6 events. The number of events expected from heavy-lepton decay is reduced by roughly a factor of 2, independent of Y^+ mass, with this cut.

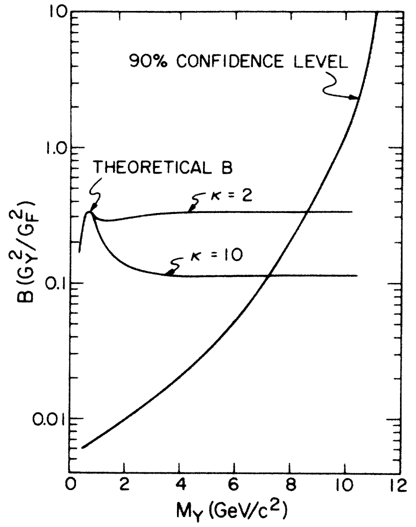

FIG. 3. 90% confidence limit on heavy-lepton mass versus $B(G_Y/G_F)^2$. The theoretical branching ratio B is also shown for two assumptions for the asymptotic value of ratio $\kappa = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$.

Figure 3 shows the resulting 90% confidence limit as a function of heavy-lepton mass and the product BG_Y^2/G_F^2. If we assume, for example,[5] $B = 0.3$ and $G_Y = G_F$, we find $M_Y > 8.4$ GeV/c^2. The theoretical estimate of the branching ratio B depends on usual current-algebra assumptions and the asymptotic ratio κ. The colored-quark assumption, $\kappa = 2$, gives $M_Y > 8.4$ GeV/c^2 with $G_Y = G_F$. Experimentally, values as high as $\kappa = 6$ have been measured.[8] Our limit on the heavy-muon mass is somewhat insensitive to the actual asymptotic limit. Even for $\kappa = 10$, $B = 0.12$ is expected, and the limit is $M_Y > 7.2$ GeV/c^2. We conclude that unless some pathological anomaly provides enormous coupling to hadrons for 7-GeV/c^2 heavy muons, their existence with equal coupling $(G_Y = G_F)$ is unlikely.

For lower masses, the hadronic-decay-rate calculations are less dependent on extrapolation. In this case, the limit of Fig. 3 represents a limit on the relative couplings of a heavy lepton. For example, at $M_Y = 1$ GeV/c^2, we expect $B = 0.3$ and find $|G_Y|^2<0.02|G_F|^2$.

In conclusion, we see no evidence for a charged positive heavy muon (lepton number = +1) coupled to muon neutrinos. It now appears, in contrast to very simple gauge models, that if such a heavy lepton exists it either is very massive or has a small effective coupling constant.

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[7] Heavy leptons produced by neutrinos would have predominantly negative helicity. The μ^+ from a $V-A$ decay interaction have smaller laboratory acceptance than from $V+A$ decay. For example, if $M_Y = 8$ GeV/c^2, the $V+A$ decay assumption would produce a factor of 1.25 increase in the expected number of detected μ^+.

[8] Preliminary result reported by B. Richter at the Conference on Lepton Induced Reactions, Irvine, California, 7–8 December 1973 (unpublished).

Approximate Scaling of Multiplicity Distributions as a Function of Missing Mass

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Data from $p+p\to p+X$ at 102, 205, and 405 GeV and from $\pi^-+p\to p+X$ at 205 GeV exhibit an approximate scaling property in the charged-prong multiplicity distributions as a function of the missing mass for the range $5\leq M_X\leq 13$ GeV.

A well-known empirical fact[1] is the approximate scaling of the charged-particle multiplicity cross sections $\sigma_N(s)$ in the reaction $p+p\to X$:

$$P_N(s)=\frac{\sigma_N(s)}{\sigma(s)}\cong\frac{1}{\langle N(s)\rangle}\psi\left(\frac{N}{\langle N(s)\rangle}\right), \qquad (1)$$

where $\sigma(s)$ is the inelastic cross section and $\langle N(s)\rangle$ the average charged multiplicity. Although the variation of the scaling function ψ with the center-of-mass energy $\sqrt{s}$ is definite,[2-4] it is small, hence the usefulness of Eq. (1). Based upon a geometrical picture,[5] Barshay and Yamaguchi[6] suggested looking for a more difficult scaling behavior in the reaction $p+p\to p+X$. In particular they suggested looking for scaling of multiplicity distributions as a function of the missing mass of X, hereafter denoted by M:

$$P_n(M^2,s)=\frac{\sigma_n(M^2,s)}{\sigma(M^2,s)}\cong\frac{1}{\langle n(M^2,s)\rangle}\tilde{\Psi}\left(\frac{n}{\langle n(M^2,s)\rangle},s\right). \qquad (2)$$

Here n is the associated multiplicity, $n=N-1$.