a second particle peak, consistent with the onset of the dominance of central-region π^- production.

To conclude, it has been shown that a semiempirical model incorporating a large contribution of resonance production consistently describes double-charge-exchange inclusive π^- production at high values of x. From this model, we estimate that the production of meson resonances could constitute as much as 40% of both leading-particle reactions $\pi^\pm p \to \pi^\pm X$ and $K^\pm p \to K^\pm X$ at $x \approx 0.85$. Furthermore, in these reactions both neutral and charged resonance production will contribute. Therefore, any triple-Regge analysis should correct for meson resonances produced by exchange processes.

We would like to express our thanks to the many people at the Fermi National Accelerator Laboratory who have contributed to the successful operation of the single-arm spectrometer and of the accelerator. Particular thanks are due to Travis Minto and Roger Strong for their technical assistance and also to Dr. Joel Butler, Dr. Charles Young, and Dr. Michael Marx for their efforts during the early stages of the experiment. This work was supported in part by the U. S. Department of Energy under Contracts No. E(11-1)-3130B, No. EY 76-C-02-3000, and No. E(11-1)-3069 and the Istituto Nazionale di Fisica Nucleare, Italy.

[a]Present address: DESY, Hamburg, West Germany.

[b]Visitor from Centre d'Etudes Nucléaires, Saclay, Gif-Sur-Yvette, France.

[1]Fermilab Single Arm Spectrometer Group, Phys. Rev. Lett. 35, 1195 (1975), and Phys. Rev. D 15, 3105 (1977).

[2]J. Brodsky and J. Gunion, in *Proceedings of the Seventh International Colloquium on Multiparticle Reactions, Tutzing,* edited by J. Benecke *et al.*, (Max-Planck-Institut für Physik und Astrophysik, Garching, West Germany, 1976); W. Ochs, Nucl. Phys. B118, 397 (1977).

[3]B. Hyams *et al.*, Nucl. Phys. B64, 134 (1973); G. Grayer *et al.*, Nucl. Phys. B75, 189 (1974).

[4]N. Biswas *et al.*, Phys. Rev. D 2, 2529 (1970); G. Grayer *et al.*, Nucl. Phys. B50, 29 (1972); Y. Eisenberg *et al.*, Phys. Lett. 48B, 354 (1974).

[5]D. Fong *et al.*, Phys. Lett. 60B, 124 (1975).

[6]D. Linglin, Nucl. Phys. B55, 408 (1973); P. Estabrooks *et al.*, SLAC Report No. SLAC-PUB-2004 (to be published).

Experimental Limits on Heavy Lepton Production by Neutrinos

A. M. Cnops, P. L. Connolly, S. A. Kahn, H. G. Kirk, M. J. Murtagh, R. B. Palmer, N. P. Samios, M. Tanaka, and T. T. Tso
Brookhaven National Laboratory, Upton, New York 11973

and

C. Baltay, D. Caroumbalis, H. French, M. Hibbs, R. Hylton, M. Kalelkar, W. Orance, and E. Schmidt[a]
Columbia University, New York, New York 10027
(Received 7 November 1977)

We present upper limits on the production of heavy leptons ($L^\pm$) by neutrinos via the process $\nu_\mu + \mathrm{Ne} \to L^\pm + \cdots$, $L^\pm \to e^\pm + \nu + \bar{\nu}$. These limits imply that the L^- and L^+, if they couple in full strength to ν_μ, are heavier than 7.5 and 9 GeV, respectively. They also imply that the coupling strength ν_μ to the recently discovered 1.9-GeV heavy lepton τ is less than 0.025 of the normal ν_μ-μ coupling.

The possible existence of charged leptons heavier than the electron and the muon has been often discussed in the past. Recently, experimental evidence has been found for the existence of such a particle, called the τ, near 1.9 GeV in mass,[1] and possibly for even more massive ones.[2] The question then naturally arises whether such a lepton has the quantum number of the electron, or the muon, or does it have a new unique lepton number. If its lepton number is the same as that of the muon, then it should be produced in ν_μ interactions, and decay, among other things, into $e^\pm \nu\bar{\nu}$ as shown in the diagram of Fig. 1. For any given mass of the heavy lepton $L^\pm$, both the production cross section and the decay branching ratio into $e^\pm \nu\bar{\nu}$ are calculable. The experimental signal for this process is e^+ or e^- without any other charged leptons in the final state produced in a ν_μ beam.

We have searched for heavy-lepton production

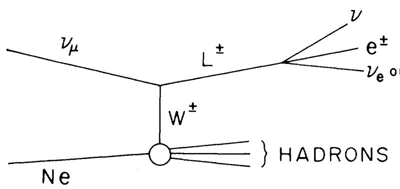

FIG. 1. Diagram describing the process $\nu_\mu + \text{Ne} \to L^\pm + \cdots$, $L^\pm \to e^\pm \nu\bar{\nu}$.

and decay via the process of Fig. 1 in an experiment using the Fermilab 15-ft. bubble chamber filled with a heavy neon-hydrogen mix (64 at.% neon) exposed to the two-horn focused wideband ν beam with an average of 10^{13} 400-GeV protons per pulse hitting the neutrino target. The neutrino spectrum extends from a few GeV up to ~200 GeV, peaking near 25 GeV. The chamber magnetic field was 30 kG. The heavy neon fill used has a radiation length of 40 cm and an interaction length of 125 cm, so that electrons are likely to radiate with high efficiency (the chamber is ~10 radiation lengths), hadrons are likely to interact (the chamber is ~3 interaction lengths), but muons will leave the chamber without interacting.

We present here results based on the first 46 000-picture run of the experiment, which corresponds to a total of 27 600 charged-current ν_μ interactions.

The film was double scanned for events with an e^+ or an e^- in the final state. Events in which the e^+ or e^- were part of a Dalitz pair were discarded. The $e^\pm$ were identified on the scan table by the following signatures: (a) a charged track that curls up with minimum ionization, (b) a charged track that radiates, followed by conversion into a visible e^+e^- pair.

All events found were examined by physicists, measured and geometrically reconstructed in TVGP. For the present search, events in which the e^+ or e^- was identified by at least two signatures and had a momentum greater than 1 GeV/c were selected.[3] We obtain a sample of 187 events with an e^- and 80 events with an e^+. Only those events without a muon can be heavy-lepton candidates.

In the e^- sample the number of leaving negative tracks is consistent with the number of noninteracting hadrons we expect, as estimated from the number of interacting negative tracks and the measured relative probability of a hadron to interact or leave the chamber without interaction. We thus take the 187 events to be e^- events without muons.

In the e^+ sample 58 of the 80 events have a leaving negative track. We believe that the bulk of these are μ^-e^+ events from charm production.[4] We estimate the true number of e^+ events with hadrons and no μ^- by taking the 22 events without a leaving negative track and correcting for those events where a negative hadron leaves without interacting. These 22 events have 27 interacting negative tracks, from which we estimate that 6 events had an e^+ with a leaving negative hadron. Thus, the number of e^+ events with hadrons and no μ^- is 28.

The most likely interpretation for these events is that they are ν_e and $\bar{\nu}_e$ interactions:

$$\nu_e + \text{Ne} \to e^- + \cdots, \quad 187 \pm 14 \text{ events};$$

$$\bar{\nu}_e + \text{Ne} \to e^+ + \cdots, \quad 28 \pm 6 \text{ events}.$$

From the calculated ν_e/ν_μ and $\bar{\nu}_e/\nu_\mu$ event ratios of (1.3 ± 0.4) and $(0.14 \pm 0.04)\%$, respectively, we expect 215 ± 60 ν_e and 23 ± 8 $\bar{\nu}_e$ interactions[5] in this sample. Therefore, there is no significant excess to be interpreted as a signal for heavy-lepton production. Subtracting the calculated number of events from the observed number, we obtain the 90% confidence level upper limits of 52 e^- and 18 e^+ events that could be ascribed to heavy-lepton production. We apply some small corrections (90% scan efficiency, 95% $e^\pm$ identification efficiency, and 3% and 4% backgrounds in e^- and e^+ events, respectively, due to Compton and other sources, and 14% miscellaneous losses) and compare with 27 600 charged-current ν_μ interactions, 79% of which are in the reduced fiducial volume of the $e^\pm$ events, to obtain the 90% confidence level upper limits:

$$\frac{\nu_\mu + \text{Ne} \to L^- + \cdots, L^- \to e^- + \cdots}{\nu_\mu + \text{Ne} \to \mu^- + \cdots} \leq 3 \times 10^{-3},$$

$$\frac{\nu_\mu + \text{Ne} \to L^+ + \cdots, L^+ \to e^+ + \cdots}{\nu_\mu + \text{Ne} \to \mu^- + \cdots} \leq 1 \times 10^{-3}.$$

The number of heavy leptons expected, relative to the total number of charged-current interactions, has been calculated by Albright, Smith, and Vermaseren[6] as a function of the mass $m(L^\pm)$, averaging over the incident ν spectrum used in this experiment, as shown in Fig. 2. Also shown in Fig. 2 is this production ratio multiplied by the calculated[7] branching ratio of the heavy lepton into $e\nu\bar{\nu}$. From a comparison of our limits with these calculations, we conclude the following:

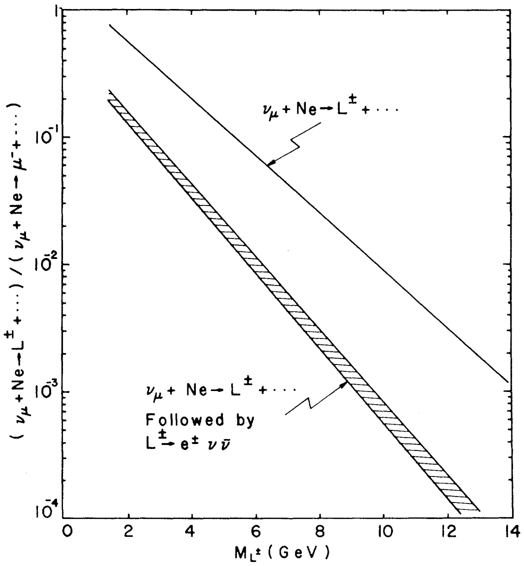

FIG. 2. Production rate of heavy leptons relative to the total charged-current cross section, and the production rate multiplied by the calculated branching ratio of the heavy lepton into $e^\pm \nu\bar{\nu}$. The width of the lower curve represents the uncertainty in the branching ratio calculation.

(a) Muon-type heavy leptons that couple with the usual $V-A$ interaction to the standard quarks must be heavier than[8]

$$m(L^-) \geqslant 7.5 \text{ GeV}, \quad m(L^+) \geqslant 9 \text{ GeV}.$$

(b) If the τ[1] with a mass 1.9 GeV has the same lepton number as the μ and is coupled with full strength to ν_μ, its production is 60% of the charged-current events. Using the measured ~20% branching ratio of τ^- into e^-,[1] we would expect ~12% e^- events whereas our limit is 3×10^{-3}. Thus, the coupling strength of ν_μ to τ must be less than 0.025 of the coupling strength of the ν_μ to μ. Alternatively, if the τ meson is not a member of the same multiplet as the μ but there is mixing between the μ and the τ, then our results imply a limit[9] on the mixing angle of $\tan^2\theta \leqslant 0.025$.

We are grateful to all the people at Fermilab, as well as the scanning and measuring personnel at Columbia University and Brookhaven National Laboratory, whose hard work made this experiment possible. We thank Carl Albright for making the results of his calculations available to us, as well as for many interesting discussions. We also thank Byron Roe for helpful discussions on the neutrino flux calculations. This work is supported by the U.S. Department of Energy under Contract No. EY76-C-02-0016 and by the National Science Foundation.

---

[a]Present address: Fermilab, P. O. Box 500, Batavia, Ill. 60510.

[1]M. L. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975), and in Proceedings of the 1977 Symposium on Lepton and Photon Interactions, Hamburg, Germany (unpublished); H. Meyer, in Proceedings of the Orbis Scientiae 1977, Coral Gables (unpublished).

[2]A. Benvenuti *et al.*, Phys. Rev. Lett. 38, 1110 (1977).

[3]In the analysis for $\mu^- e^+$ events [C. Baltay *et al.*, Phys. Rev. Lett. 39, 62 (1977)], we used a 300-MeV/c cut on the e^+ momentum. We use the higher 1-GeV/c cut here since for e^- there are backgrounds due to Compton electrons that do not exist for e^+.

[4]See Baltay, Ref. 3.

[5]The main uncertainty in the ν_e/ν_μ and $\bar{\nu}_e/\nu_\mu$ flux-ratio calculations comes from the uncertainties on the K/π ratios, since absolute normalizations, etc., cancel out in the flux ratios. We used the K/π ratios from the measurements of W. F. Baker *et al.*, Phys. Lett. 51B, 303 (1974); B. Aubert *et al.*, Colloq. Int. CNRS 245, 385 (1975), and the Caltech-Fermilab experiment (O. Fackler, private communication).

[6]C. H. Albright, J. Smith, and J. A. M. Vermaseren, State University of New York at Stony Brook Report No. ITP-SB-77-43 (to be published). For this calculation, $V-A$ coupling to the standard quarks was assumed. The effect of the experimental 1-GeV/c cut on the electron momenta is negligible on the production rates. The results of these calculations are in good agreement with those of J. D. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D 7, 887 (1973); and A. Soni, Phys. Rev. D 9, 2092 (1974).

[7]C. H. Albright and C. Jarlskog, Nucl. Phys. B84, 467 (1975).

[8]This limit on the L^+ mass is similar to the one obtained by B. C. Barish *et al.*, in *Proceedings of the Sixth Hawaii Topical Conference on Particle Physics, Honolulu, Hawaii, 1975*, edited by P. N. Dobson *et al.* (Univ. of Hawaii Press, Honolulu, Hawaii, 1976). We are not aware of any previous limit on the production rate or the mass of an L^- with the quantum numbers of the muon.

[9]The limits on this mixing that can be obtained from the experimental upper limits on the decay $\tau \to \mu + \gamma$ (Ref. 1) are not as restrictive as the limits obtained in this experiment, since the only first-order electromagnetic coupling describing this process is nonrenormalizable [F. E. Low, Phys. Rev. Lett. 14, 238 (1965)]. Higher-order couplings are allowed but only of the order of weak times electromagnetic [F. Wilczek and A. Zee, Nucl. Phys. B106, 461 (1976)] and thus result in a small branching ratio for the radiative decays of heavy leptons.