Fermi National Accelerator Laboratory

FERMILAB-Pub-78/69-EXP
7420.180

(Submitted to Phys. Rev. Lett.)

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September 1978

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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*Work supported in part by the U. S. Department of Energy and National Science Foundation.

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ABSTRACT

A clear observation of μ^+e^- events produced in an antineutrino heavy neon-hydrogen experiment using the Fermilab 15-Ft. bubble chamber is reported. The relative production rate, Vee yield, and scaling variable distributions are presented, and the events are interpreted as charmed particle production from ocean quarks.

The production of μe pairs in neutrino interactions[1-4] and dimuon pairs in neutrino and antineutrino interactions[5-7] has been well established. In this letter, which reports our further study of μe production by antineutrinos,[8] we study the production rate and general properties of a sample of 12 μ^+e^- events.[9]

These data come from a new exposure of 85,000 pictures in the Fermilab 15-Ft. bubble chamber to the broad band antineutrino beam. The primary proton beam had an energy of 400 GeV. The bubble chamber was filled with a mixture of 64% neon and 36% hydrogen by atoms resulting in a radiation length of 39 cm and an interaction length of 125 cm.

The film was scanned for neutral induced events. Electrons and positrons produced at the primary vertex were recognized using as track signatures spiralization to a point, a sudden change in curvature, bremsstrahlung, trident formation, annihilation (for positrons), or large delta rays. A partial rescan showed the efficiency for so recognizing electrons to be 85 ± 5%. Obvious e^+e^- pairs were discarded. The sample of single electron events was purified by requiring the electron to exhibit two signatures, at least one of which was a bremsstrahlung conversion. Application of this selection rule to known electrons from γ conversion pairs showed its efficiency to be 83 ± 5% for electrons with momenta P_e greater than 0.8 GeV/c.

To identify muons we relied primarily on the external muon identifier (EMI).[10] To detect muons which the EMI failed to identify because of instrumental inefficiency or geometric acceptance we also used a kinematical method (BIGPT).[11] We required that the muon momentum P_μ and the visible energy E_{vis} satisfy $P_\mu > 4$ GeV and $E_{vis} > 10$ GeV.[12]

The most serious background is Compton electrons spatially unresolved from the primary vertex, which decreases as the electron momentum increases. Examination of events on the scan table indicates that, on the average, Compton electrons within 2.5 cm would not be recognized as such. In order to retain adequate signal above the Compton background we required that the electron momentum satisfy $P_e > 0.8$ GeV/c,[13] resulting in an estimated background of 1.5 events from this source. Other sources of background considered were electron neutrino events in which a hadron is misidentified as a muon, δ-rays close to the primary vertex, very asymmetric Dalitz pairs or close-in gamma conversions, and small angle K_{e3} decays in flight; these contribute 0.5 background events to the μ^+e^- sample and 0.3 background events to the μ^-e^+ sample produced by the neutrino contamination in the beam.

Using the above selection criteria we obtained a sample of 12 μ^+e^- events and 6 μ^-e^+ events with estimated backgrounds of 2 events and 0.3 events, respectively, in a sample of 6320 antineutrino and 770 neutrino charged current events.[14] One μ^+e^+ and no μ^-e^- events were found. In Table I we give the distribution of the μ^+e^- events in different energy intervals.[15] Correction for the efficiency of finding a primary electron and identifying it by two signatures gives the relative μ^+e^- cross sections presented in column 4 of Table I for $P_\mu > 4$ GeV/c and $P_e > 0.8$ GeV/c.

In Table II we list the properties of the 12 μ^+e^- events.[16] The mean value of E_{vis} for these events is 62 GeV whereas for all other charged current events it is 28 GeV.

Associated with the 12 μ^+e^- events are 10 neutral strange particle decays (Vees). Table II gives our identification, using kinematic fitting, of these Vees as $K_S^o \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, or $\bar{\Lambda} \to \bar{p}\pi^-$. For ambiguous Vees the identification with the lower probability is given in parentheses. The K_S^o in event 11 and $\Lambda(K_S^o)$ in event 12 appear to have undergone small angle scatters before decay. The Vee in event 3 consists of a positron and a negative hadron; it is likely to be either a K_{e3} decay or $\bar{\Lambda}$ beta decay. The yield of ten Vees in these μ^+e^- events differs markedly from the 0.8 Vees expected in 12 ordinary charged current events.[17]

Opposite sign dilepton events are presently interpreted as resulting from the decay of charmed hadrons. In antineutrino interactions charmed hadron production is expected to proceed predominantly by the transition of an antistrange quark ($\bar{s}$) in the ocean to an anticharm quark ($\bar{c}$): $\bar{\nu} + \bar{s} \to \mu^+ + \bar{c}$. If the $\bar{c}$ is dressed as a charmed meson, e.g. $\bar{D}^o$ or D^-, the subsequent decay will produce a K^+ or K^o. If the $\bar{c}$ is dressed as a charmed baryon, e.g. $\bar{\Lambda}_c$, its decay will produce a $\bar{\Lambda}$ or $\bar{\Sigma}$. Charmed baryon production involves creating a baryon-antibaryon pair and is likely to be suppressed. However this is the probable interpretation of event 12. The observed number of Vees implies a total of 21 ± 8 neutral strange particles in our 12 μ^+e^- events.[18] The orphan strange quark (s) from the $s\bar{s}$ ocean pair is likely to produce a $\bar{K}N$ or Λ/Σ final state.

Therefore there is no clear procedure to correctly estimate the number of undetected charged strange particles. The data, however, are not inconsistent with the above picture of charmed hadron production which predicts a total of two strange particles per event.

Making plausible assumptions about charmed hadron production within the context of the quark-parton model and allowing for experimental acceptance and neutrino beam energy spectrum, Lai[19] has obtained reasonable agreement with the opposite sign dimuon data from the CDHS collaboration.[7] We use Lai's model, computed by him for our experimental conditions and with quark fragmentation functions that fit the CDHS data, to assess our data.[20] This model indicates that the average acceptance for the μ^+e^- events is 62%. Corrected relative production rates R_{corr} are shown in Table I; for μ^+e^- production we find a corrected rate of (0.36 ± 0.11)% of antineutrino charged current events, and for μ^-e^+ a rate of (1.9 ± 1.0)% of neutrino-charged current events. Our μ^-e^+ rate is not inconsistent with the (0.5 ± 0.15)% reported in Ref. 3 for the same process.[21] Distributions of X_{vis} and Y_{vis} for μ^-e^+ events are shown in Fig. 1 together with the model predictions which are characteristic of production from anti-quarks. Also shown for comparison are x and y distribution functions for ordinary charged current events.[22] The model is consistent with the concentration of events at low X_{vis} (ten of the 12 events have $X_{vis} < 0.3$) and with the existence of events at higher values of Y_{vis}. We conclude that our μ^+e^- events are examples of production and subsequent semileptonic decay of charmed hadrons.

We thank C. Lai and C. Quigg for helpful discussions and we acknowledge the contributions made to this experiment by the Bubble Chamber, Neutrino Laboratory and Accelerator Operations staffs at Fermilab and by the scanning, measuring, and secretarial staffs at our respective institutions.

REFERENCES

[1]J. Blietschau et al., Phys. Lett. 58B, 361 (1975) and 60B, 207 (1976).

[2]J. von Krogh et al., Phys. Rev. Lett. 36, 710 (1976); P. Bosetti et al., Phys. Rev. Lett. 38, 1248 (1977).

[3]C. Baltay et al., Phys. Rev. Lett. 39, 62 (1977).

[4]P. C. Bosetti et al., Phys. Lett. 73B, 380 (19[illegible]).

[5]A. Benvenuti et al., Phys. Rev. Lett. 34, 419 (1975) and 35, 1199, 1203 (1975).

[6]B. C. Barish et al., Phys. Rev. Lett. 36, 939 (1976) and 38, 577 (1977).

[7]M. Holder et al., Phys. Rev. Lett. 69B, 377 (1977) and 70B, 396 (1977).

[8]J. P. Berge et al., Phys. Rev. Lett. 38, 266 (1977).

[9]Four μ^+e^- events have been reported in H. C. Ballagh et al., Phys. Rev. Lett. 39, 1650 (1977) and one μ^+e^- event in Ref. 4.

[10]R. J. Cence et al., Nucl. Instr. Methods, 138 2, 245 (1976).

[11]BIGPT selects as the muon the charged particle with the highest transverse momentum P_t relative to the other visible particles provided it does not interact, $P_t > 1.6$ GeV/c, its angle with $\bar{\nu}$ beam < 0.2 rad, and the angle with the $\bar{\nu}$ beam of the total visible momentum of event < 0.1 rad. For discussion see P. A. Gorichev, Proceedings of the International Conference on Neutrino Physics and Neutrino Astrophysics, Elbrus, USSR 1977, Vol. II. p. 180.

[12]E_{vis} for a given event is computed as the sum over all observed

particles of their momenta in the beam direction and would be equal to the antineutrino energy $E_{\bar{\nu}}$ if there were no unobserved particles.

[13]Our previous μe study, in a light neon-hydrogen mixture, Ref. 8, employed as a cutoff $P_e < 0.3$ GeV/c. If we used this P_e cutoff in the current heavy neon experiment, we would expect 7.7 background events due to unresolved Compton electrons.

[14]The number of charged current events was obtained from a general measurement of 25% of the total data. The method discussed in Ref. 8 was used to correct for 1-prong events. No correction for muon recognition efficiency is necessary, because it effects both the μe sample and ordinary events in the same way.

[15]For ordinary charged current events we estimate in an average way $E_{\bar{\nu}}$ using the procedure described in Fermilab-IHEP-ITEP-Michigan Neutrino Group, Phys. Rev. Lett. 39, 382 (1977). This correction procedure is not appropriate for the individual μe events described here.

[16]The usual scaling variables are defined as follows: $y = (E_{\bar{\nu}} - E_\mu)/E_{\bar{\nu}}$, where E_μ is the muon energy; $x = Q^2/2M_p(E_{\bar{\nu}}-E_\mu) = (4E_{\bar{\nu}} E_\mu \sin^2\theta/2)/2M_p(E_{\bar{\nu}}-E_\mu)$, where $-Q^2$ and θ are the four-momentum transfer and the angle respectively between the incident antineutrino and the muon, and M_p is the proton mass. Because $E_{\bar{\nu}}$ is difficult to determine precisely, we employ Y_{vis} and X_{vis} which are y or x evaluated at $E_{\bar{\nu}} = E_{vis}$.

[17] Y. G. Rjabov, Proceedings of the XVII International Conference on High Energy Physics, Tbilisi, USSR, 1976 Vol. 2, p. B120.

[18] We ignore the Vee in event 3. Since K_S^O decay space overlaps much of Λ decay space, but not vice versa, we assign the $\Lambda(K_S^O)$ in both event 4 and event 12 as Λ's. A correction factor of 3/2 is applied to the number of visible Λ, $\overline{\Lambda}$, and K_S^O to account for invisible decay modes; in the case of K^O there is an additional factor of 2 to correct for K_L^O. We also correct for the ~10% of neutral strange particles that are lost either because they interact before decay or the decay is too close to the $\bar{\nu}$ interaction point.

[19] C. Lai, Fermilab-PUB-78/18-THY (1978) (to be published in Physical Review).

[20] Reference 19 studies various quark fragmentation functions D(z) and concludes that although none fits all aspects of the CDHS data, D(z) ~ constant and $D(z) \sim e^{-3z}$ are preferred forms.

[21] The $\mu^- e^+$ relative rate reported in Ref. 3 is not corrected for acceptance; however, since in that experiment there was no explicit P_μ cut and $P_e > 0.3$ GeV/c, the equivalent acceptance corrections would be small.

[22] Fermilab-IHEP-ITEP-Michigan Neutrino Group, Phys. Rev. Lett. <u>39</u>, 382 (1977).

Table I: Relative rates of μ^+e^- production for selected antineutrino energy intervals. The rates R are corrected for background and scan efficiency but are restricted to $P_e > 0.8$ GeV/c and $P_\mu > 4$ GeV/c. The rates R_{corr} are corrected for acceptance losses using the model of Ref. 19.

$E_{\bar{\nu}}$ (GeV)	μ^+X (Events)	μ^+e^-X (Events)	$R=\frac{\sigma(\mu^+e^-X)}{\sigma(\mu^+X)}$ (%)	R_{corr} (%)
10- 30	4240	3	0.08±0.05	0.12±0.08
30- 60	1540	4	0.31±0.17	0.51±0.27
60-150	540	5	1.1 ±0.6	1.4 ±0.8
All	6320	12	0.22±0.07	0.36±0.11

Table II: Properties of μ^+e^- events.

	E_{vis} (GeV)	μ^+ ID	p_μ (GeV/c)	p_e (GeV/c)	Y_{vis}	X_{vis}	Vee Observed
1)	23.1	EMI	7.7	3.8	0.67	0.07	Λ
2)	25.1	EMI	8.5	1.2	0.66	0.02	
3)	25.8	EMI	6.2	3.4	0.76	0.21	"K_L^o"
4)	30.4	BOTH	10.7	1.9	0.65	0.08	$\Lambda(K_s^o)$
5)	31.7	EMI	6.2	1.7	0.81	0.26	
6)	42.6	BOTH	36.3	1.2	0.15	0.69	
7)	46.9	EMI	5.1	1.0	0.89	0.14	
8)	68.4	BOTH	54.2	2.3	0.21	0.01	K_s^o
9)	86.5	BIGPT	64.0	3.2	0.26	0.45	K_s^o
10)	102.4	BIGPT	86.9	4.6	0.15	0.21	Λ; K_s^o
11)	115.1	BIGPT	103.9	2.7	0.10	0.09	K_s^o (a)
12)	141.9	BOTH	87.9	6.6	0.38	0.12	$\Lambda(K_s^o)$ (a); $\bar{\Lambda}$

(a) Likely to have undergone small angle nuclear scatter before decay.

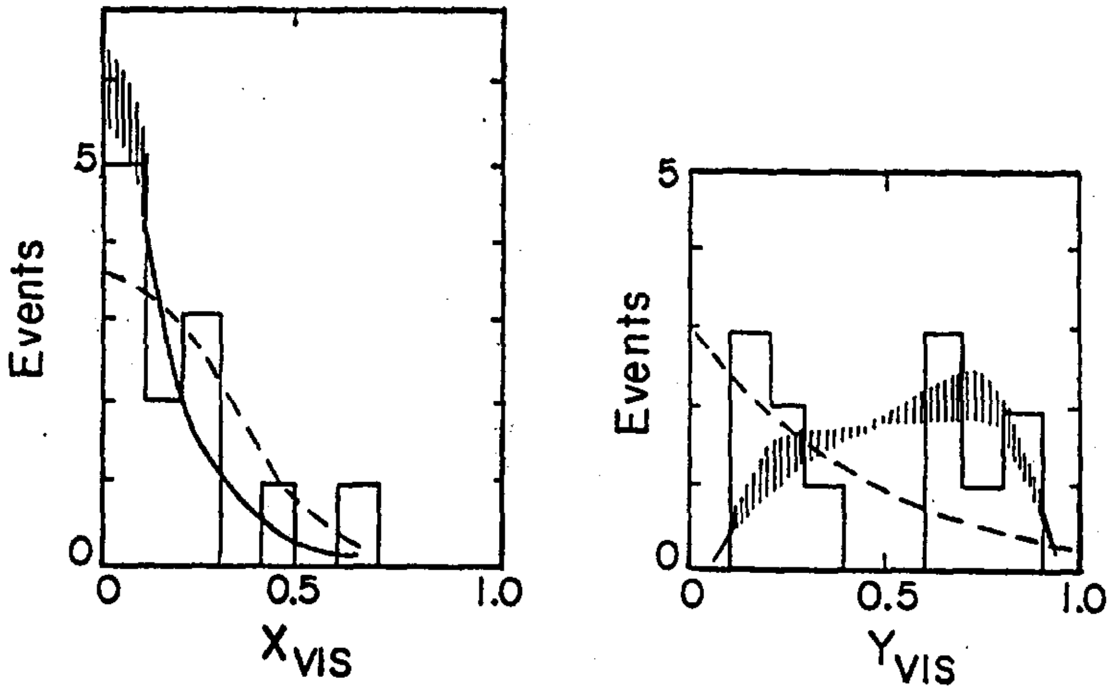

Fig. 1: Distributions of X_{vis} and Y_{vis} for $\mu^- e^+$ events. The solid lines and shading indicate the range of predictions of the charm hadron production model of Lai, Ref. 19 for the two preferred D(z) functions. The dashed lines show distribution functions obtained from ordinary charged current events, Ref. 22.