MEASUREMENT OF THE PRODUCTION OF μ e EVENTS IN ANTINEUTRINO-NUCLEON INTERACTIONS

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ABSTRACT

We have measured the ratio of μ^+e^- events to all μ^+ events in an antineutrino hydrogen-neon experiment using the Fermilab 15 ft. bubble chamber. Based on 12 events with $p_\mu >$ 4.0 GeV/c and $p_e >$ 0.8 GeV/c we find this ratio to be .22±.07%. Using a model of charmed particle production to correct for the cuts on p_e and p_μ we obtain a ratio of .35±.11%. The data indicate a higher ratio for $E_{\bar{\nu}} > 60$ GeV.

I INTRODUCTION

The experiment on which I shall report was performed by a collaboration(1) of four laboratories: Fermilab, Institute of High Energy Physics at Serpukhov, Institute of Theoretical and Experimental Physics at Moscow, and The University of Michigan. In this experiment we continue(2) the search for μ e events produced in an antineutrino beam.

The production of μ e pairs in neutrino interactions at high energies is well established(3,4,5) . Their production rate is ~ .5% of the total charged current cross section, and a higher yield of strange particles is observed for these events relative to all charged current events.

Corresponding experiments in antineutrino beams(2,6) have had considerably fewer events to study and the question of μ e production could not be answered on the same level of sensitivity. Furthermore, it is important to compare the data on μ e production in neutrino and antineutrino beams with the production of dimuons observed in counter experiments,(7,8,9) where all data strongly support the quark model(10) of charmed particle production.

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II THE EXPERIMENT

The new data come from an exposure of 85,000 pictures using the Fermilab 15 ft. bubble chamber filled with a hydrogen-neon mixture containing 64 at. % of neon. The density of this mixture is 0.77g cm^{-3} and the radiation length is 39 cm.

The chamber was exposed to a broad-band double-horn-focused antineutrino beam. An absorptive plug downstream of the target was used to suppress the neutrino contamination to about 5% of the flux (that is ~ 12% of the event rate). The proton energy was 400 GeV and the average intensity was 1.0 x 10^{13} protons/pulse. The energy spectrum of antineutrino events is shown in figure 1.

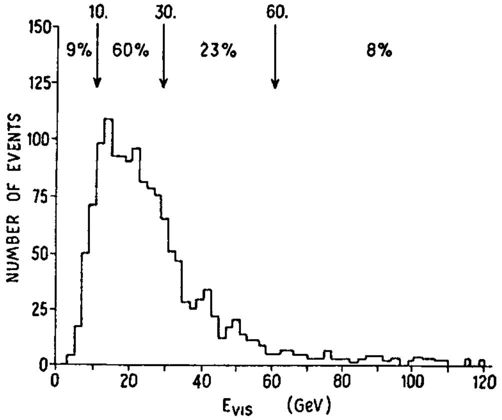

Fig. 1. Distribution of visible energy for events with a μ^+.

The film was divided equally among the four laboratories and scanned for neutral-induced events with visible momenta along the beam direction greater than about 1 GeV/c. Events consisting of only a single charged track were not included. A total of about 20,000 events were found.

Scanners examined all tracks coming from the primary interaction vertex for evidence of electrons or positrons; that is spiralization, sudden change of curvature, bremstrahlung, trident formation, annihilation (for positrons), or large δ rays. All primary vertices were examined by two scanners independently and possible electron or positron tracks were noted. Physicists studied all events with such tracks provided they passed a momentum cut of > 300 MeV/c, measured with a template. Obvious pairs were rejected. Single electron or positron tracks were retained if they exhibited at least two of the criteria mentioned above.

To detect the muons we relied mainly on the external muon identifier (EMI) which consists of approximately 600g cm^{-2} of absorber inside the vacuum vessel of the bubble chamber followed by 23 m^2 of multiwire proportional chambers.(11) The EMI detected approximately 80% of the muons with momentum (p_μ) greater than 4.0 GeV/c. About 70% of the remainder were detected by a kinematic method which selects as the muon that track with large (> 1.6 GeV/c) transverse momentum (p_T) relative to the total momentum of the other tracks. Figure 2 shows the distribution of p_T for muons and for hadrons and demonstrates that this selection does not misidentify any hadrons.

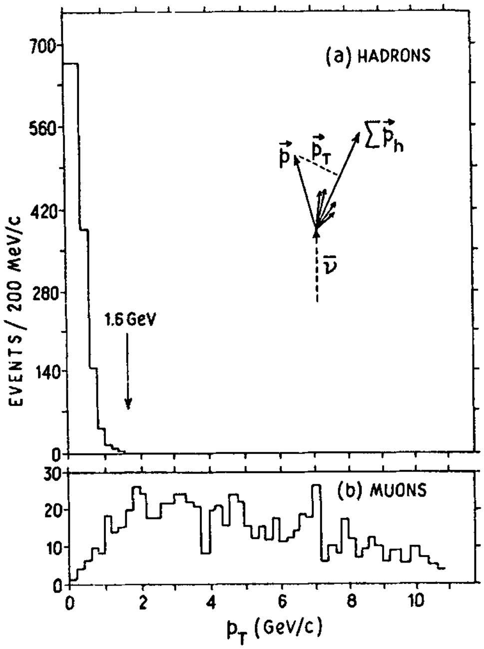

Fig. 2. Distribution of events vs. p_T which is the transverse momentum of a selected track relative to the direction defined by the sum of the momenta of the hadrons ($\Sigma\vec{p}_h$). In (a) the selected track is a hadron. In (b) it is the muon.

We estimated the number of charged current events in our fiducial volume by measuring 25% of the events found by the scanners. However, all events with single electrons or positrons were measured. The data are summarized in Table 1. The results shown are for $p_\mu > 4.0$ GeV/c. For muons below this momentum both the EMI geometric acceptance and background problems are important. The single electron events have $p_e > .8$ GeV/c. Below this momentum, background from electromagnetic processes (mainly Compton scattering) becomes relatively large. The picture quality is such that a close-in Compton electron vertex (within about 2.5 cm of the interaction vertex) may not be resolved.

The number of charged current events in Table I has been corrected for missing single-track events.(12) The estimates of antineutrino energy (E_ν) were made using an average correction for neutral energy loss characteristic of the total event sample.(13) No correction was made for random scanning losses which affect both μ e events and other charged current events equally. Also no correction was applied for EMI acceptance which is assumed to be the same for μ e events as for all other charged current events.

TABLE I. Uncorrected data for charged current and μ e events.

$E_{\bar\nu}$ (GeV)	$\bar\nu \to \mu^+ X$	$\bar\nu \to \mu^+ e^- X$	$\nu \to \mu^- X$	$\nu \to \mu^- e^+ X$
10 - 30	4243	4	276	2
30 - 60	1536	3	296	1
60 -150	540	5	196	3
All	6319	12	768	6

III CORRECTIONS TO THE DATA

In order to obtain the relative rate of μ e events to charged current events it is necessary to correct the data in Table I for electron detection efficiency; for background processes which simulate electrons from the primary vertex; and for the signal loss due to the cuts imposed on p_μ and p_e. We now discuss these corrections.

(1) Electron detection efficiency.

This is the product of two factors. The first, referred to as the pick efficiency, is the probability that the scanner detects an electron track from the primary vertex and thereby brings the event to the attention of a physicist. The second is the identification efficiency which is the probability that the track picked by the scanner passes the identification test applied by the physicist, namely, that it have at least two signatures characteristic of an electron. All primary vertices were examined by two scanners independently and approximately 2000 were flagged by scanners for examination by physicists. Most of these contained positron electron pairs, not single electrons. From an analysis of these data we estimate that the pick efficiency for single electrons is .85±.05. The electron identification efficiency was measured by examining a sample of gamma pairs close to the primary vertex. It was found to be .83±.05 for electrons with $p_e > 0.8$ GeV/c. We therefore estimate the electron detection efficiency to be .72±.07.

(2) Background processes

The most important of these are close-in Compton electrons. If the Compton electron vertex should occur within ~ 2.5 cm of the interaction vertex it probably would not be resolved. A less important source of electromagnetic background are asymmetric gamma conversions within 2.5 cm of the primary vertex or assymetric Dalitz pairs having an undetected electron or positron. To estimate the size of these backgrounds we computed the energy spectrum of gammas under the assumption that the gammas all came from neutral pion decay. Other sources of background considered were: electron neutrino events in which a hadron is misidentified as a muon by the EMI; δ-rays close to the primary vertex; and small angle K_{e3} decays in flight. After correction for electron detection efficiency, the background from all sources mentioned above was estimated to be 2.0 events for electrons and less than 0.3 events for positrons with $p_e > 0.8$ GeV/c.

(3) Signal loss due to momentum cuts

This correction depends on the model assumed to produce the μ e events. We believe that the kinematic properties of these events are consistent with a model in which the muon is the leading lepton and the electron comes from the decay of a charmed particle produced at the hadron vertex. Hence we have used such a model to correct for our momentum cuts. Specifically, we used a variation of the standard quark model suggested by Barnett.(14) The electrons were assumed to come entirely from the decays of $\bar{D}$ mesons and we chose the momentum spectrum expected for a four body decay of the $\bar{D}$. Figure 3 shows the spectrum of p_e estimated from the model along with the experimental distribution for the 12 μ^+e^- events. Figure 4(a) shows the effect of the momentum cuts, estimated from the model, as a function of antineutrino energy. The effect of the cut on muon momentum is quite severe in the lowest energy

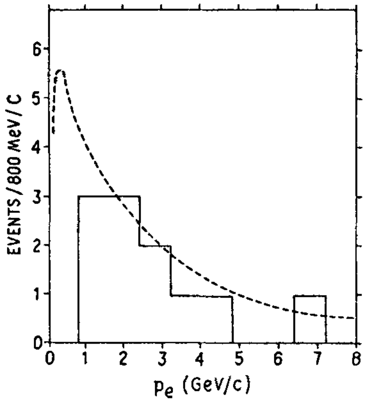

Fig. 3 Distribution of electron momentum for the 12 μ^+e^- events. The broken curve is calculated assuming the electrons come from D decay.

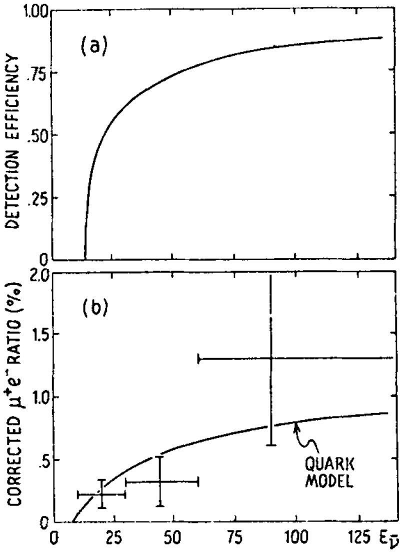

Fig. 4 (a) Estimated effect of momentum cuts on detection efficiency for μ^+e^- events. (b) Corrected μ^+e^- ratio.

interval ($10 < E_{\nu} < 30$ GeV) because near threshold the production of charmed particles is excluded, for kinematic reasons, from the region of low y. The effect of the cut on p_{μ}, however, is to exclude events with high y, thereby restricting charmed particle production to the central region of the y distribution. The effect of both momentum cuts, averaged over the entire range of our antineutrino energy spectrum, was to eliminate approximately 40% of the μ e events.

IV RESULTS AND CONCLUSIONS

The corrected results are shown in Table II. Other features of the μ^+e^- events are shown in Table III.

TABLE II. Corrected values for the rate of μ^+e^- events as a percentage of all antineutrino induced charged current events.

$E_{\bar{\nu}}$ (GeV)	$\sigma(\mu^+e^-)/\sigma(\mu^+)$ with cuts on p_e, p_μ	$\sigma(\mu^+e^-)/\sigma(\mu^+)$ with model dependent corrections
10-30	0.11±.06%	0.22±.15%
30-60	0.23±.14%	0.32±.19%
60-150	1.1 ±.6%	1.3 ±.7%
All	0.22±.07%	0.35±.11%

TABLE III. Some features of the 12 μ^+e^- events. x and y are the scaling variables. W is the invariant mass of the hadrons. These quantities have not been corrected for missing neutral energy.

E_{VIS} (GeV)	p_μ (GeV/c)	p_e (GeV/c)	x_{VIS}	y_{VIS}	V's	W_{VIS}
69.	54.	2.3	~.01	.22	K°	5.3
20.	8.6	1.2	~.03	.57		4.5
103.	81.	3.2	.79	.21	K°	2.9
143.	87.	6.6	.11	.39	$\Lambda/K^\circ, \bar{\Lambda}/K^\circ$	9.6
29.	10.	1.8	.08	.64	Λ	5.6
24.	7.6	3.8	.08	.67	Λ	5.3
16.	6.2	3.4	.31	.61	K°_{e3}	3.5
44.	36.	1.2	.64	.17		2.2
22.	5.1	1.0	.17	.77		5.1
93.	77.	4.6	.14	.17	Λ,K°	5.0
116.	104.	2.7	.08	.11	K°†	4.8
26.	5.9	1.7	.28	.76		5.2

† 1 C fit. located ~ 3 mean lives from $\bar{\nu}$ interaction, hence could be a regenerated K°_s .

The visible energy (E_{VIS}) of these events is significantly greater than that of typical μ^+ events.

$$\langle E_{VIS} \rangle = 60 \text{ GeV for } \mu^+e^- \text{ events.}$$

$$\langle E_{VIS} \rangle = 28 \text{ GeV for all } \mu^+ \text{ events.}$$

The features of the events in Table III strongly support the interpretation that the electrons come from the semi-leptonic decays of charmed particles. According to the model of Glashow, Iliopoulos and Maiani,(10) production of charmed particles by $\bar{\nu}$ is mainly off the strange sea.

$$\begin{array}{l} \bar{\nu} + \begin{pmatrix} \bar{s} \\ s \end{pmatrix} \rightarrow \bar{c} + \mu^+ + s \\ \qquad\qquad\quad \hookrightarrow e^- + \bar{\nu} + \bar{s} \end{array}$$

Hence each μ^+e^- event should be accompanied by two strange particles, at least. In addition, since the process involves the interaction of anti fermions, the y distribution should be flat, except for threshold effects.

After correction for neutral decays, the data show 1.5±.5 neutral strange particles per μ^+e^- event. This is quite consistent with 2 strange particles (charged as well as neutral) per event, and is significantly higher than the average strange particle content of ordinary charged current events. The distribution of y_{VIS} for the μ^+e^- events is shown in figure 5, where it is contrasted with the corresponding distribution for ordinary charged current events of comparable energy.

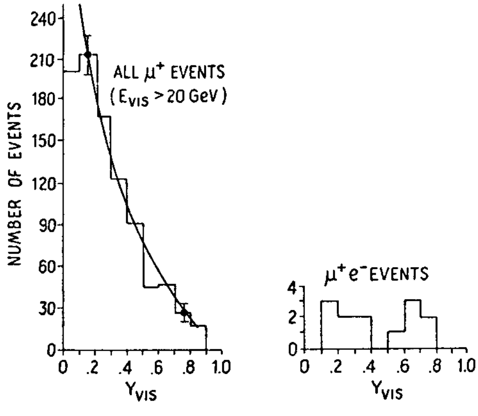

Fig. 5. Comparison of y-distributions between μ^+e^- events and all μ^+ events of comparable energy.

The conclusions we draw from this experiment are the following:

1. There is definite evidence for direct production of electrons by antineutrinos at a rate of ~ .4% of normal charged current events. However, the rate may be limited by threshold effects.
2. The features of direct electroproduction by antineutrinos strongly support the GIM(10) model.

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12. The missing single track events are expected to be confined largely to the region of small y. The number of missing events is estimated assuming a y distribution of the form $dN/dy = (1-y+1/2\, y^2) - yB(1-1/2\, y)$ with $B = 0.8$. The correction is 19% for the lowest energy interval (10 GeV $< E_{\bar{\nu}} < 30$ GeV) and negligible for $E_{\bar{\nu}} > 30$ GeV.
13. The energy of the incident antineutrino is estimated by summing the momentum of the muon and the momentum of the hadrons along the beam direction. The momentum of the hadrons is increased by 25% to account for neutrals which leave the chamber undetected.
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