VTL-PUB-51
(May 1978)

HADRON PRODUCTION IN νNe AND $\bar{\nu}$Ne INTERACTIONS

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ABSTRACT: The inclusive distributions of hadrons produced in $\nu_\mu(\bar{\nu}_\mu)$Ne interactions are found to be similar to inclusive distributions in $\pi^\pm$Ne interactions.

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FERMILAB-PUB-78-156-E

It has long been recognized in strong interactions that the comparison of hadron production on nuclear targets with production on free nucleons provides important information about the space-time development of the hadronic states, i.e., the nucleus serves as an analyzer for hadronic matter "in statu nascendi".[1] It is now being stressed that similar fundamental information can be obtained from lepton-nucleus interactions.[2]

We previously presented low-statistics results on this question using electron neutrinos, and found that the nucleus appears to affect the inclusive distributions in a way similar to the effects observed with hadron beams.[3] In this paper we present results for inclusive production of hadrons in ν_μNe and $\bar{\nu}_\mu$Ne interactions, with improved statistics and a more detailed analysis of the effect of the nucleus. We show that the hadrons produced in $\nu(\bar{\nu})$Ne interactions give results similar to $\pi^\pm$Ne interactions and the differences between nuclear and nucleon targets are quantitatively similar for ν- and π-beams.

The data reported here come from a study of neutrino interactions in the Fermilab 15-foot bubble chamber filled with a 64% neon-36% hydrogen (atomic) mixture. Thus $\gtrsim$ 96% of the interactions occur on Ne. We neglect the small hydrogen background. The radiation and interaction lengths are 39 cm and $\sim$ 1.4 m, respectively. For each interaction we require a non-interacting leaving track with momentum $p > 4$ GeV/c, that is identified as a muon by the EMI with likelihood[4], $\mathcal{L} > 5$, and that the total visible energy $E_{vis} > 10$ GeV. The neutrino energy is reconstructed from measurements of the charged secondaries using the method of p_T balance in the ν-μ plane to correct the total hadronic momentum.[5]

We have identified a number of protons, N_p, by ionization and range. However, this is reliable only in the momentum interval 0.2 to 1.0 GeV/c.

Thus, protons with p $\gtrsim$ 1.0 GeV will be included in the positive ("minimum-ionizing, non-muon") secondary tracks, N_+, while the negative tracks, N_-, are free of such contamination.

The $\nu_\mu(\bar{\nu}_\mu)p$ interactions[6,7] with which we compare are available only for $\geq$ 1 pion; thus, in our data we also require $\geq$ 1 pion (i.e., one or more tracks not identified as protons). Since there are few events with hadronic invariant mass W > 10 GeV, we restrict ourselves to 1.0 < W < 10.0 GeV.[8] This leaves 289 ν_μ and 263 $\bar{\nu}_\mu$ events. In comparing with $\pi^\pm$Ne interactions at 10.5 GeV/c[9] ($\sqrt{s}$ = 4.4 GeV) we make the further restriction 3 < W < 6 GeV, resulting in 138 ν_μ and 118 $\bar{\nu}_\mu$ events.

The average charged multiplicities $< N_p >$, $< N_+ >$, and $< N_- >$ given in Table I for the W ranges 1 to 10 GeV and 3 to 6 GeV, agree well with the values obtained in $\pi^\pm$Ne interactions.[9] We observe no dependence of the average multiplicity on Q^2 for fixed W intervals.[10] In Fig. 1 we give the dependence of $< N_\pm > = < N_+ > + < N_- >$ on W and show that it is compatible with the values obtained in $\pi^\pm$Ne and π^-C interactions.

Because of the nuclear target we might expect protons in the final state as observed in hadron-nucleus collisions. The invariant inclusive cross section of identified protons, Fig. 2, agrees well with that obtained in $\pi^\pm$Ne and π^-C interactions. Furthermore, it was noted in Ref. 9 that $< N_+ >_{\pi^\pm Ne}$ is greater than $< N_- >_{\pi^\mp Ne}$ (see Table I); whereas, by charge symmetry these quantities should be equal if only pions are included in the data sample. Thus the difference, $< N_+ >_{\pi^\pm Ne} - < N_- >_{\pi^\mp Ne} \equiv < N_p^f >$, is a measure of the number of fast, unidentified protons.[11] A similar result (Table I) is obtained for $< N_+ >_{\nu_\mu(\bar{\nu}_\mu)Ne} - < N_- >_{\bar{\nu}_\mu(\nu_\mu)Ne}$ for 3 < W < 6 GeV. This suggests an excess of fast protons in $\nu(\bar{\nu})$Ne interactions which is quantitatively similar to the excess observed in πNe interactions.

In the case of hadron beams the nucleus (A) to nucleon (η) ratio of charged multiplicities at the same incident energy, $R_A \equiv < N >_A / < N >_\eta$, has been a useful parameter for comparison with theory. In order to account for the differences between interactions on neutrons and protons we define $< N_\pm >_\eta = (\sigma_p < N_\pm >_p + \sigma_n < N_\pm >_n)/(\sigma_p + \sigma_n)$ where σ_p and σ_n are the inelastic cross sections for the projectile (pion or neutrino) on a "free" proton or neutron, respectively.[12] We summarize R_A in Table I for all charged particles excluding identified protons.[8]

We also have studied the dispersion of the charged multiplicity distribution and the transverse momentum distributions of the produced hadrons and found them to be in accord with those observed in pion-nucleus interactions.[13]

The laboratory rapidity distribution, $F(\xi) \equiv (1/\sigma_{inel})d\sigma/d\xi$, which is the average number of charged harons per unit rapidity interval, is useful in studying target fragmentation, where most of the effects of the nucleus have been observed in hadron-nucleus interactions.[1,14] In calculating the hadronic rapidity, $\xi \equiv \frac{1}{2}\ln\frac{E + p_L}{E - p_L}$, the longitudinal direction for neutrino interactions is defined to be along the direction of the total visible hadronic momentum while for hadronic interactions the direction is that of the incident beam particle.

In order to compare rapidities of secondaries from the hadronic systems produced by incident pions and neutrinos, the "mass" of the virtual W, which is not negligible compared with the center-of-mass energy, must be taken into account. Neglecting the pion mass, the laboratory rapidity of the hadronic center-of-mass will be greater for neutrinos by an amount

$\Delta\xi = \ell n(1 + Q^2/(W^2 - m_p^2)) = -\ell n\ (1-x)$. Figure 3a shows this effect when laboratory rapidities of the νNe secondaries are compared with πNe secondaries. In Fig. 3b we have subtracted $\Delta\xi$ from the laboratory rapidity of each νNe secondary and the essentially kinematic difference disappears. The differences which persist at large ξ are consistent with the ΔW interval and the fast proton contribution for which corrections have been made in the πNe data but not in the $\nu(\bar{\nu})$ data. Thus we conclude that no dynamic mechanism appears to distinguish the two systems at this statistical level.

The effect of the nucleus can be seen in Fig. 3c,d where we compare the rapidity distributions of $\nu(\bar{\nu})$ interactions on neon ($F_{Ne}(\xi)$) and nucleons ($F_{\eta}(\xi)$) for favored and unfavored charges.[15] We have averaged νNe and $\bar{\nu}$Ne interactions and used charge symmetry to obtain the nucleon target data.[12] As with $\pi^{\pm}$Ne interactions[14] we observe an excess of charged particles in the target fragmentation region for $\nu(\bar{\nu})$Ne interactions. The ratio $F_{Ne}(\xi)/F_{\eta}(\xi)$ given in Fig. 4 over the rapidity region $-1 < \xi < 2$ shows that indeed the effect is quantitatively similar for neutrino and pion interactions and concentrated in the target fragmentation region.

We conclude that the hadrons produced in νNe and $\bar{\nu}$Ne interactions have quantitatively similar inclusive distributions to hadrons produced in $\pi^{\pm}$Ne interactions. In particular, most of the nuclear effects occur in the target fragmentation region. We note that our study covers only "low-energies" $< W > \simeq 5$ GeV. It will be important to continue these comparisons at higher energies to see if there are any differences between neutrino-nucleus and hadron-nucleus interactions in the central region of rapidity.

We gratefully acknowledge the assistance of the 15-foot bubble chamber crew and the staffs of the neutrino laboratory and accelerator divisions

of Fermilab. We wish to thank B. Anderson, J.D. Bjorken, S. Brodsky, W. Czyz, S.D. Ellis, and J. Weis for helpful discussions and the DOE and NSF for partial support. One of us (THB) acknowledges an A.P. Sloan Fellowship.

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9. W.M. Yeager et al., Phys. Rev. D16, 1294 (1977). νNe($\bar{\nu}$Ne) interactions are compared to π^+Ne (π^-Ne) interactions since the $\nu(\bar{\nu})$ transfers one unit of positive (negative) charge to the hadronic system.
10. Most of the data are for $Q^2 < 10$ GeV^2.

11. Here we assume $< N_- > \equiv < N_{\pi^-} >$ and $< N_+ > = < N_{\pi^+} > + < N_p^f >$. The presence of $K^\pm$ is a negligible contribution (see Refs. 7 and 9).
12. We use charge symmetry to obtain the cross section on neutrons, i.e. $< N_+ >_{\pi^\pm p} = < N_- >_{\pi^\mp n}$ or $< N_+ >_{\nu(\bar{\nu})p} = < N_- >_{\bar{\nu}(\nu)n}$ etc. and assume for $\nu(\bar{\nu})$ interactions the naive quark model for which $\sigma_n/\sigma_p = 2$ (1/2).
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14. See, e.g., W. Busza, Proc. of the XIIIth Int. Colloquium on Multiparticle Reactions, Tutzing, 545 (1976). E.L. Feinberg, Physics Reports 56 (1972).
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TABLE CAPTIONS:

TABLE I : Average multiplicities of charged secondaries and values of $R_A = \langle N_\pm \rangle_A / \langle N_\pm \rangle_{\eta}$.

FIGURE CAPTIONS:

FIG. 1 : Comparison of average multiplicities of charged secondaries vs. W (or $\sqrt{s}$).

FIG. 2 : Inclusive cross section of identified protons.

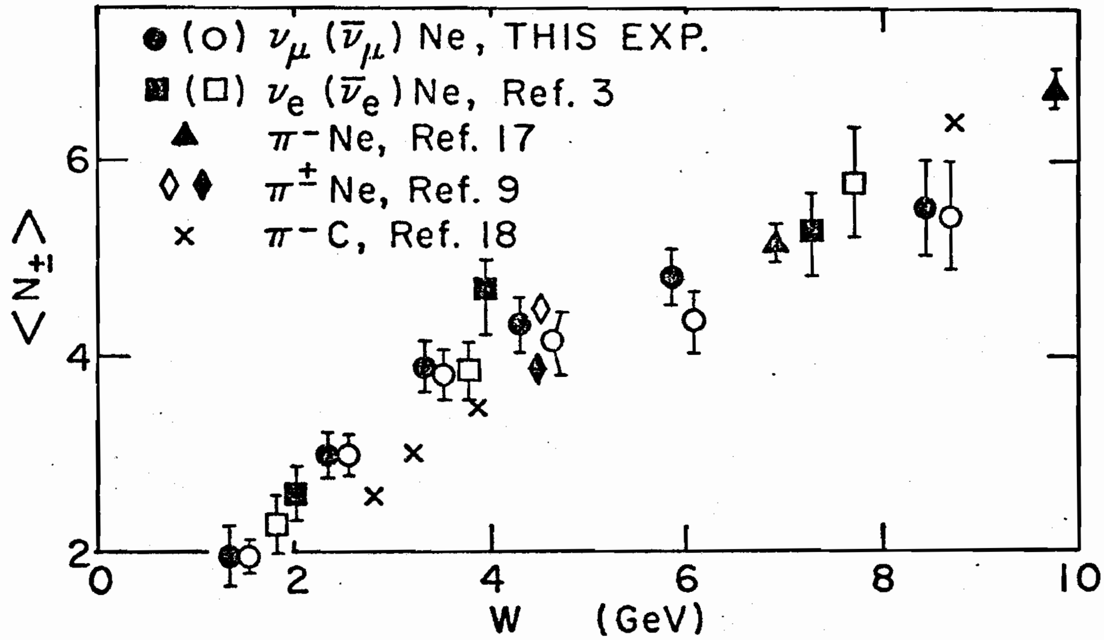
FIG. 3 : Rapidity distributions for $\nu(\bar{\nu})$ interactions ($3 < W < 6$ GeV) and $\pi^\pm$ interactions ($\sqrt{s} = 4.4$ GeV): a,b) Comparison of $\pi^\pm Ne \rightarrow \pi^\pm X$ (solid line) with $\nu Ne \rightarrow \pi^\pm X$ (●) and $\bar{\nu} Ne \rightarrow \pi^\pm X$ (Δ) with and without corrections for virtual W mass (see text); c,d) Comparison of $\nu(\bar{\nu})$-Nucleon (solid line) with $\nu(\bar{\nu})$Ne (□) for favored and unfavored particles, respectively.

FIG. 4 : Comparison of the ratios of the laboratory rapidity distributions $F_{Ne}(\xi)/F_{\eta}(\xi)$ for: a) $\pi^\pm Ne$ ($\sqrt{s} = 4.4$ GeV) where data of Ref. 16 are used to obtain $F_{\eta}(\xi)$. b) $\nu_\mu(\bar{\nu}_\mu)$Ne interactions ($3 < W < 6$ GeV) for favored and unfavored particles.

TABLE I.

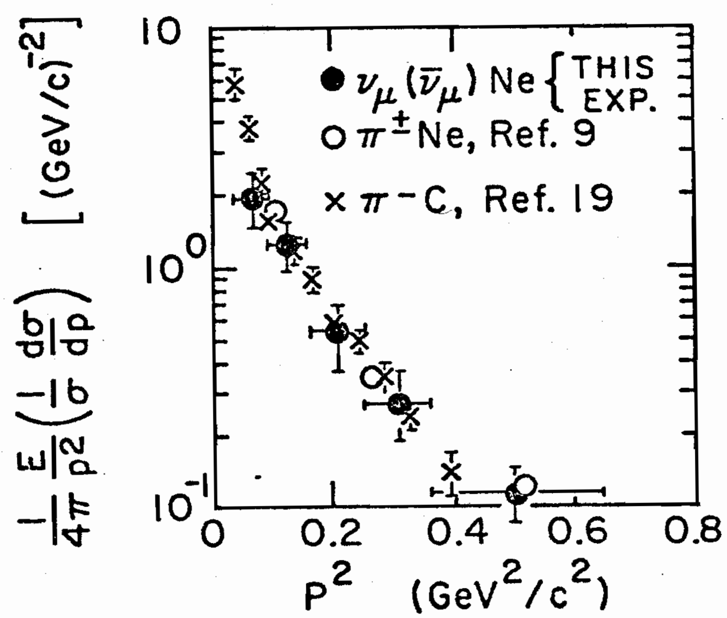
REACTION	ENERGY (GeV)	$\langle N_+ \rangle$	$\langle N_- \rangle$	$\langle N_p \rangle$ [a]	$\langle N_p^f \rangle$	R_A
ν_μNe	$3 \leq W < 6$	2.64 ± 0.09	1.55 ± 0.08	0.71 ± 0.12 [b]	0.52 ± 0.12	1.22 ± 0.05
π^+Ne	$\sqrt{s} = 4.4$	2.86 ± 0.04	1.37 ± 0.02	0.76 ± 0.04 [c]	0.78 ± 0.04	1.20 ± 0.05
$\bar{\nu}_\mu$Ne	$3 \leq W < 6$	1.75 ± 0.10	2.12 ± 0.08	--	0.20 ± 0.13	1.13 ± 0.05
π^-Ne	$\sqrt{s} = 4.4$	1.83 ± 0.02	2.08 ± 0.02	--	0.46 ± 0.03	1.11 ± 0.04
ν_μNe	$1 \leq W < 10$	2.70 ± 0.08	1.54 ± 0.07	0.68 ± 0.08 [b]	--	1.27 ± 0.04
$\bar{\nu}_\mu$Ne	$1 \leq W < 10$	1.58 ± 0.07	1.90 ± 0.06	--	--	1.04 ± 0.03

a) For $0.2 < p_p < 0.8$ GeV/c; b) $\nu(\bar{\nu})$Ne combined; c) $\pi^\pm$Ne combined.



● (○) ν_μ ($\bar{\nu}_\mu$) Ne, THIS EXP.
■ (□) ν_e ($\bar{\nu}_e$) Ne, Ref. 3
▲ π^-Ne, Ref. 17
◊ ♦ $\pi^\pm$Ne, Ref. 9
× π^-C, Ref. 18
$\langle N_\pm \rangle$
W (GeV)

FIG. 1



● ν_μ ($\bar{\nu}_\mu$) Ne {THIS EXP.
○ $\pi^\pm$Ne, Ref. 9
× π^-C, Ref. 19
$\frac{1}{4\pi}\frac{E}{p^2}\left(\frac{1}{\sigma}\frac{d\sigma}{dp}\right)$ [(GeV/c)$^{-2}$]
P^2 (GeV^2/c^2)

FIG. 2

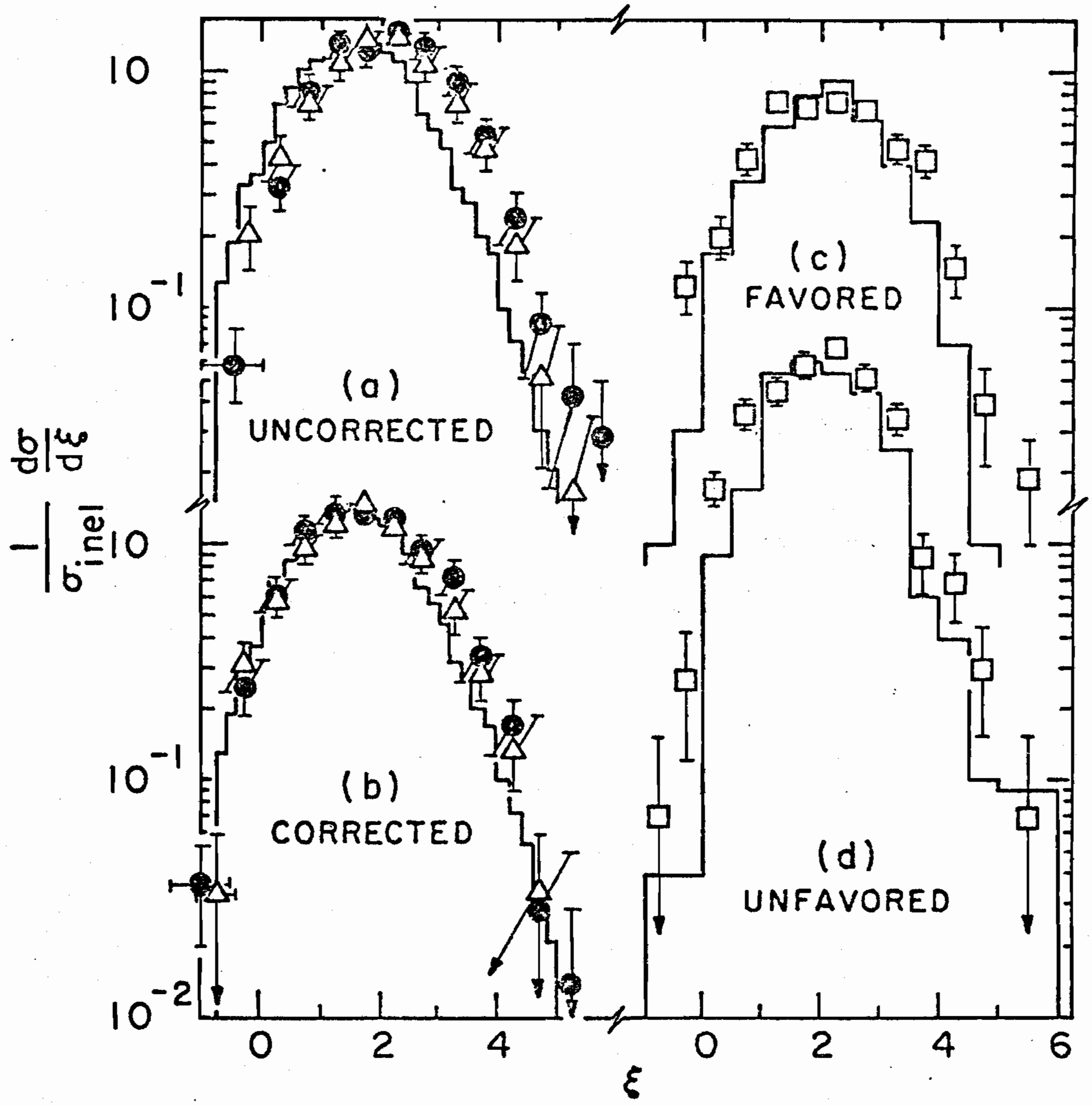

(a)
UNCORRECTED
(b)
CORRECTED
(c)
FAVORED
(d)
UNFAVORED
ξ

FIG. 3

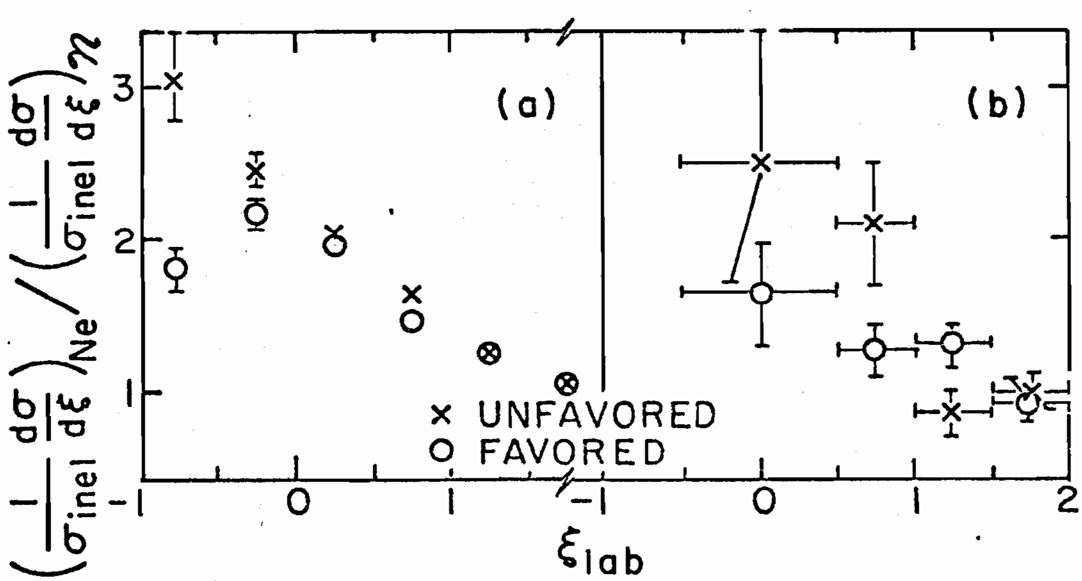

(a)
(b)
× UNFAVORED
○ FAVORED
ξ_{lab}

FIG. 4