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CHARACTERISTICS OF HADRONS PRODUCED IN ν_μNe AND $\bar{\nu}_\mu$Ne INTERACTIONS *

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ABSTRACT

The inclusive distributions of hadrons produced in ν_μ $(\bar{\nu}_\mu)$Ne interactions are similar to the distributions of hadrons in $\pi^\pm$Ne interactions. The experimental z distributions of the ratios $(\pi^+/\pi^-)_\nu$ and $(\pi^-/\pi^+)_{\bar{\nu}}$ are found to be in good agreement; however, a systematic deviation from the existing quark model parametrizations is observed.

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In this paper we present a study of the inclusive production of hadrons in ν_μNe and $\bar{\nu}_\mu$Ne interactions. We show that the distributions of hadrons produced in $\nu(\bar{\nu})$Ne interactions are similar to those in $\pi^{\pm}$Ne interactions and the differences between nuclear and nucleon targets are quantitatively similar for ν- and π-beams. Preliminary results on the study of nuclear effects in $\nu(\bar{\nu})$Ne interactions were presented previously but with lower statistics.[1) In this paper, we also present results on the structure of the quark fragmentation functions from $\nu(\bar{\nu})$Ne interactions and compare the results with the quark model predictions.

The data come from a study of neutrino interactions in the 15-foot Fermilab bubble chamber filled with a heavy NeH_2 mixture (64% atomic Ne). A wide-band beam with one horn focusing (but without a plug) was used in this exposure which resulted in comparable numbers of neutrino and antineutrino charged-current interactions.

For each event, the momentum of the track identified by the EMI as a muon was required to be greater than 4 GeV/c, and the total visible energy $E_{vis} > 10$ GeV. The neutrino energy was reconstructed from the measured momenta of charged secondaries by using the method of P_T balance in the ν-μ plane to correct for neutral energy losses.[2)] All charged hadrons were assumed to be pions unless identified as protons by ionization and range. The operating conditions of the chamber allowed for a determination of the number of proton tracks, N_p, within the momentum range $0.2 < P_p < 1.0$ GeV/c. Thus, assuming that $K^{\pm}$ contamination is negligible,[3)] the number of positive (minimum-ionizing, non-muon) secondaries, N_+, contains π^+'s and protons with $P_p > 1.0$ GeV/c, while the negative tracks, N_-, consist of π^-'s only. We require that each event has at least one fast hadron produced ($N_\pm = N_+ + N_- \geq 1$). The πNe[4)] data with which we compare are available only for $\sqrt{s} = 4.4$ GeV. We therefore restrict the neutrino data to a region of comparable hadronic energy, imposing a cut $3 \leq W < 6$ GeV. This leaves 138 νNe and 118 $\bar{\nu}$Ne events. For the study of quark fragmentation functions, we use the region $1 \leq W < 10$ GeV, which contains 289 νNe and 263 $\bar{\nu}$Ne events.

In Fig. 1 we show that the average multiplicities of fast particles produced in $\nu(\bar{\nu})$Ne interactions, $\langle N_\pm \rangle$, follow the same energy (W) dependence as observed for πNe interactions. We have previously shown that within the statistical significance of the data there is no Q^2 dependence of $\langle N_\pm \rangle$ for fixed W intervals.[1)]

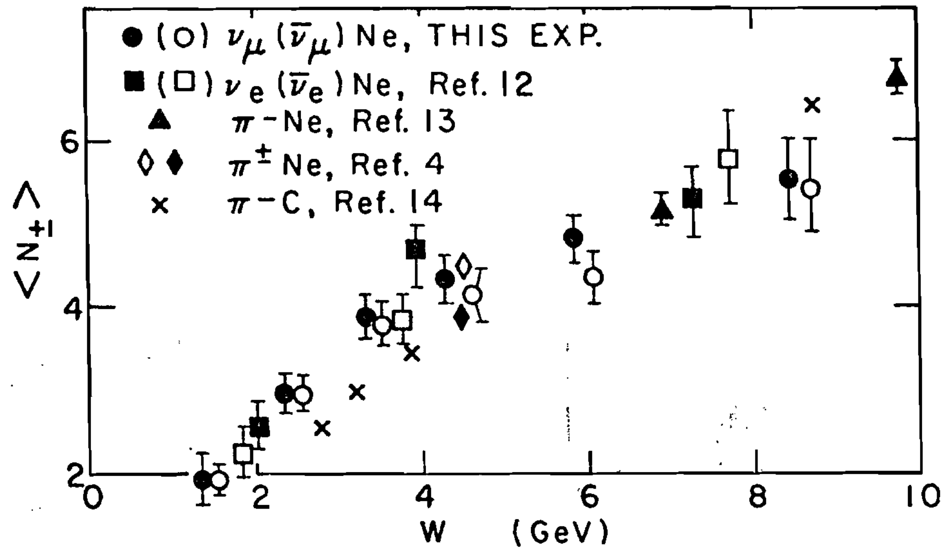

Fig. 1. Average multiplicities of charged secondaries as a function of W (or $\sqrt{s}$).

TABLE I

Average multiplicities of charged secondaries and values of $R_A = \langle N_\pm \rangle_A / \langle N_\pm \rangle_\eta$ for $\nu(\bar{\nu}_\mu)$Ne ($3 \leq W < 6$) and $\pi^\pm$Ne ($\sqrt{s} = 4.4$) interactions

INTER-ACTION	$\langle N_+ \rangle$	$\langle N_- \rangle$	$\langle N_p \rangle$	$\langle N_p^f \rangle$	R_A
ν_μNe	2.64 ± .09	1.55 ± .08	0.71 ± .12[a)]	0.52 ± 1.2	1.22 ± .05
π^+Ne	2.86 ± .04	1.37 ± .02	0.76 ± .04[a)]	0.78 ± 0.4	1.20 ± .05
$\bar{\nu}_\mu$Ne	1.75 ± .10	2.12 ± .08		0.20 ± .13	1.13 ± .05
π^-Ne	1.83 ± .02	2.08 ± .02		0.46 ± .03	1.11 ± .04

a) Combined for $\pi^\pm$Ne or $\nu(\bar{\nu})$Ne

The average multiplicities $\langle N_+ \rangle$, $\langle N_- \rangle$, and $\langle N_p \rangle$ for $\nu(\bar{\nu})$Ne and $\pi^{\pm}$Ne interactions are given in Table I. We observe very good agreement between the interactions with the same charge transferred to the target, i.e., $\nu(\bar{\nu})$Ne ($W^{\pm}$Ne) and $\pi^{\pm}$Ne interactions give similar results.

Because of the nuclear target we might expect nucleons in the final state as observed in hadron-nucleus interactions. In Ref. 4, the inclusive spectra of charged secondaries produced in π^+Ne were compared with the secondaries of the opposite charge produced in π^-Ne. These spectra should be the same, by charge symmetry, if only pions are included in the data sample. The excess of positive particles, observed in π^+Ne and π^-Ne interactions, was interpreted as resulting from the fast, unidentified protons, whose average multiplicity is, by charge symmetry

$$\langle N_p^f \rangle_{\pi^{\pm}Ne} = \langle N_+ \rangle_{\pi^{\pm}Ne} - \langle N_- \rangle_{\pi^{+}Ne} .$$

As shown in Table I, a similar result is obtained for $\nu(\bar{\nu})$Ne interactions by using $\langle N_p^f \rangle_{\nu(\bar{\nu})Ne} = \langle N_+ \rangle_{\nu(\bar{\nu})Ne} - \langle N_- \rangle_{\bar{\nu}(\nu)Ne}$. This suggests an excess of fast protons in $\nu(\bar{\nu})$Ne interactions, which is quantitatively similar to the excess observed in πNe. We have also verified that the characteristics of slow protons produced in $\nu(\bar{\nu})$Ne agree well with those obtained in πNe interactions.[1)] Hence the mechanism for knocking out nucleons from the nuclear target may be the same for π- and ν-induced interactions.

In the case of hadron beams, the ratio of charged multiplicities $R_A = \langle N \rangle_A / \langle N \rangle_{\mathfrak{N}}$ for nuclear (A) and nucleon ($\mathfrak{N}$) targets has been a useful parameter for comparison with different models. In order to account for the differences between interactions on neutrons and protons, we define

$\langle N_{\pm} \rangle_{\mathfrak{N}} = (\sigma_p \langle N_{\pm} \rangle_p + \sigma_n \langle N_{\pm} \rangle_n)/(\sigma_p + \sigma_n)$, where $\sigma_p (\sigma_n)$ are the inelastic cross sections for the projectile (pion or neutrino) on a "free" proton (neutron) and $\langle N_{\pm} \rangle_p$, ($\langle N_{\pm} \rangle_n$) are the corresponding average multiplicities. We use charge symmetry, i.e.,

$\langle N_+ \rangle_{\pi^{\pm}p} = \langle N_- \rangle_{\pi^{+}n}$, $\langle N_+ \rangle_{\nu(\bar{\nu})p} = \langle N_- \rangle_{\bar{\nu}(\nu)n}$, etc. to obtain the cross sections on neutrons, and assume the naive quark model in which σ_n/σ_p equals 2 for neutrino and 1/2 for antineutrino interactions. We summarize R_A for fast secondaries in Table I and find very good agreement between the values of R_A for $\nu(\bar{\nu})$Ne and $\pi^{\pm}$Ne interactions.

In hadron-nucleus reactions most of the effects of the nucleus have been observed in the target fragmentation region.[5] To study this region, the laboratory rapidity distribution, $F(\xi) = (1/\sigma_{inel})d\sigma/d\xi$, which is the average number of charged hadrons per unit rapidity interval, has been very useful. In calculating the rapidity, $\xi = \frac{1}{2} \ell n \frac{E + P_L}{E - P_L}$, the direction of the hadronic system in neutrino interactions is defined to be along the direction of the total visible hadronic momentum. In Fig. 2a,b we compare the rapidity distributions of $\nu(\bar{\nu})$ interactions on neon $[F_{Ne}(\xi)]$ and on nucleons $[F_{\eta}(\xi)]$[6,7] for favored or unfavored particles, i.e., for particles of the same or of opposite charge as the charge transferred to the target. We have averaged the νNe and $\bar{\nu}$Ne data and used charge symmetry, as described above, to obtain elementary target data. An excess, more pronounced for unfavored particles, is observed for $\nu(\bar{\nu})$Ne interactions in the target fragmentation region. Since this region is free from fast proton contamination, the excess is interpreted as resulting from the more copious production of pions on the nuclear target. In Fig. 3a,b we give the ratio $F_{Ne}(\xi)/F_{\eta}(\xi)$ for neutrino and pion interactions, to show that the nuclear effect is quantitatively similar and concentrated

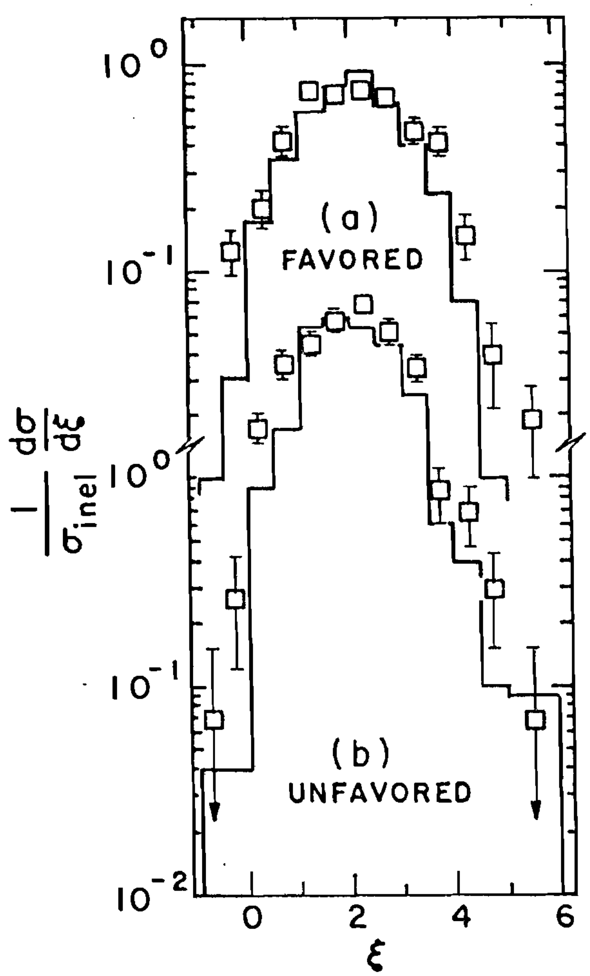

Fig. 2. Laboratory rapidity distributions of $\nu(\bar{\nu})$-nucleon (solid line) and $\nu(\bar{\nu})$Ne (□) interactions ($3 \leq W < 6$) for a) favored, b) unfavored particles.

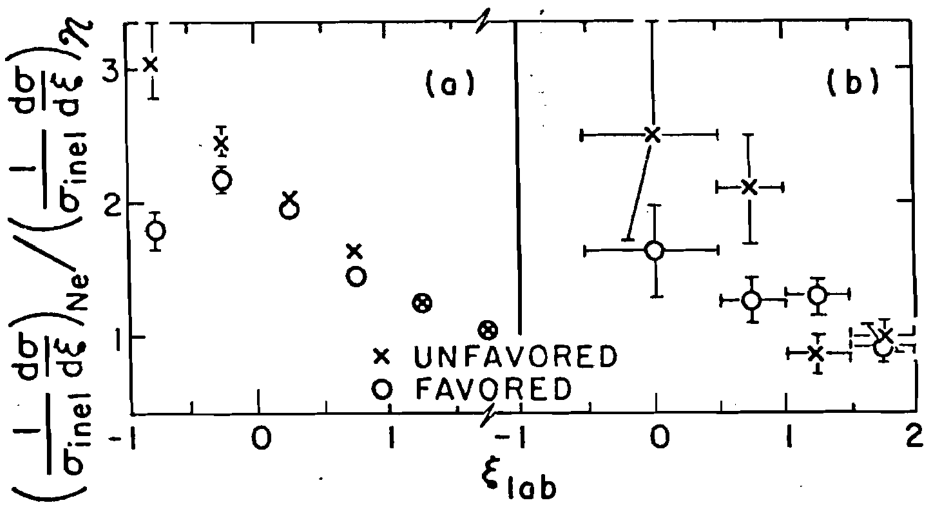

Fig. 3. Ratios of the laboratory rapidity distributions $F_{Ne}(\xi)/F_{\eta}(\xi)$ for: a) $\pi^{\pm}Ne$ ($\sqrt{s}$ = 4.4 GeV) where data of Ref. 8 are used to obtain $F_{\eta}(\xi)$; b) $\nu(\bar{\nu})Ne$ ($3 \leq W < 6$) interactions, for favored and unfavored particles.

in the target fragmentation region. The observation that the nuclear effect is more pronounced for unfavored particles has not been reported before.

The direct comparison of the rapidity distribution for $\nu(\bar{\nu})Ne$ and $\pi^{\pm}Ne$ interactions is shown in Fig. 4. In order to compare rapidities of secondaries produced in ν- and π-induced interactions, one must take into account that the velocities, or laboratory rapidities of the center-of-mass systems, are different, even at the same center-of-mass energy. This is because the "mass" of the virtual W is not negligible compared with the center-of-mass energy, as is usually the case for hadronic beams. Neglecting the pion mass, the laboratory rapidity of the hadronic center-of-mass will be greater for neutrinos by an amount $\Delta\xi = \ell n(1 + Q^2/(W^2 - m_p^2))$. If this effect is not taken into account, the distributions do not agree well for any values of ξ; however, the comparison of the corrected laboratory rapidities of $\nu(\bar{\nu})Ne$ secondaries to $\pi^{\pm}Ne$ secondaries shows very good agreement in the target fragmentation region. The slight differences at large ξ are consistent with the effects due to the size of the W interval when compared to the fixed $\sqrt{s}$ and the contribution from fast protons which have been removed from πNe but not from $\nu(\bar{\nu})Ne$ data.

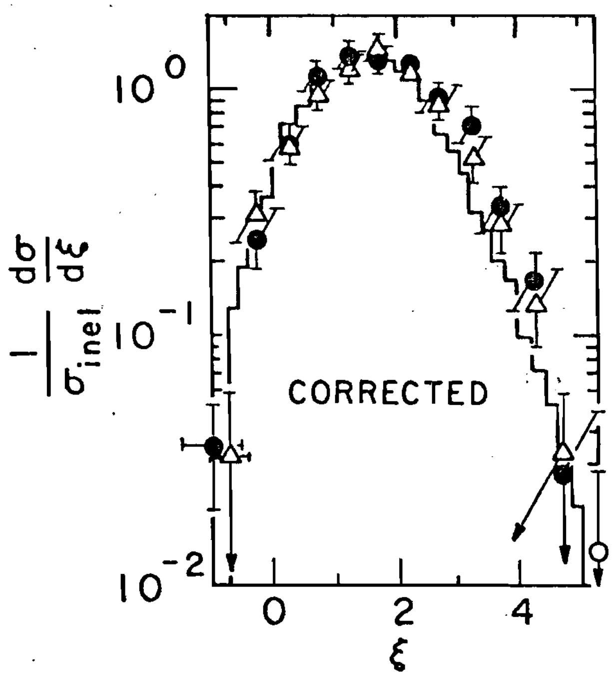

Fig. 4. Comparison of the laboratory rapidity distributions for $\pi^{\pm}Ne \rightarrow \pi^{\pm}X$ at $\sqrt{s}$ = 4.4 GeV (solid line) with $\nu Ne \rightarrow \pi^{\pm}X$ (●) and $\bar{\nu}Ne \rightarrow \pi^{\pm}X$ (Δ) for (3 < W < 6). $\nu(\bar{\nu})Ne$ data were corrected for virtual W mass (see text).

In neutrino interactions the distribution of the average charged multiplicity per unit interval of the fractional momentum, $D(z) \equiv (1/\sigma_{inel})\, d\sigma/dz$, where $z \equiv P_h/P_q$, has been found very useful for studying the fragmentation of the scattered quark q into observed hadrons h.[9] In this study, we define z using the "light-cone" variable, i.e., $z \equiv \frac{E + P_L}{E_W + P_W}$ which for $z \gtrsim 0.2$ is approximately the same as the variable $x_F^{lab} \equiv p_{\parallel}^{lab}/p_{max}^{lab}$ used extensively in hadronic interactions.

In Fig. 5a,b we compare the z distributions of favored and unfavored $\nu(\bar{\nu})Ne$ secondaries to the x_F distributions of $\pi^{\pm}Ne$ secondaries and note very good agreement between the ν- and π-induced interactions. Since no correction for fast protons has been made in either the $\pi^{\pm}Ne$ or $\nu(\bar{\nu})$ data, we can conclude that fast protons, whose x_F distribution in $\pi^{\pm}Ne$ is approximately the

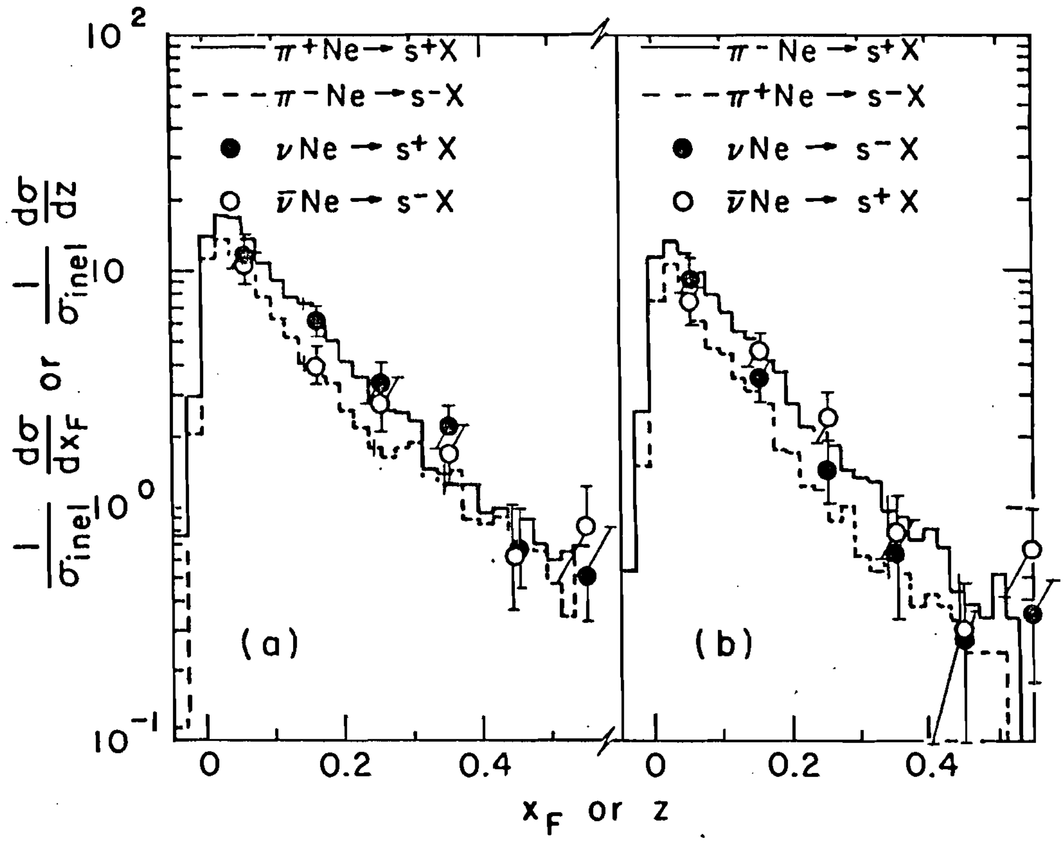

Fig. 5. Comparison of the x_F^{lab} distributions of $\pi^\pm Ne \rightarrow s^\pm X$ ($\sqrt{s}$ = 4.4 GeV) with z distributions of $\nu(\bar{\nu})Ne \rightarrow s^\pm X$ ($3 \leq W < 6$), where s^+ (s^-) is the positive (negative) fast particle, for a) favored, b) unfavored particles.

same as that of pions,[4] have the same z distribution in $\nu(\bar{\nu})$Ne interactions.

Having had both ν- and $\bar{\nu}$-interactions in our data sample, we can compare them with one of the basic predictions of the quark-parton model; namely, that in the quark fragmentation region ($z \gtrsim 0.2$), the ratio $(\pi^+/\pi^-)_\nu$ should be the same as the ratio $(\pi^-/\pi^+)_{\bar{\nu}}$, as both of them are described by the function $1/\omega(z) \equiv D_u^{\pi^+}(z)/D_u^{\pi^-}(z) = D_d^{\pi^-}(z)/D_d^{\pi^+}(z)$.[9] In Fig. 6a we compare the ratios $(N_+/N_-)_\nu$ and $(N_-/N_+)_{\bar{\nu}}$ and note that the values of the ratios for neutrino interactions are systematically larger than

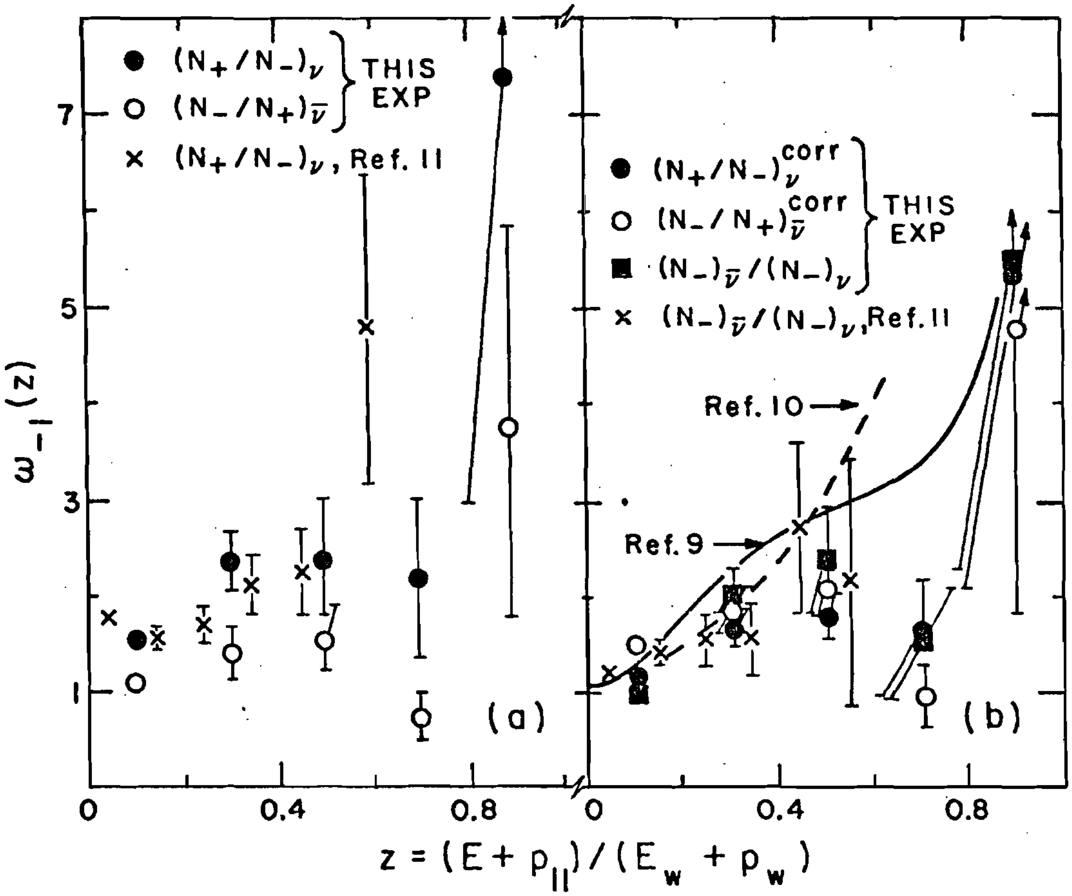

Fig. 6. The ratios $(N_+/N_-)_\nu$ and $(N_-/N_+)_{\bar{\nu}}$ as a function of z, for $1 \leq W < 10$ GeV a) uncorrected, b) corrected for proton contamination. The corrected ratios are also compared with the ratio $(N_-)_{\bar{\nu}}/(N_-)_\nu$ and with the parametrizations of Field and Feynman, and Sehgal.

those for the antineutrino. This is to be expected if fast protons are included in the positive secondaries. Using the previously obtained average multiplicities of fast protons, $< N_p^f >_{\nu(\bar{\nu})}$, and assuming that their distribution is the same as the z distribution of positive pions, we calculated corrected values $(N_+/N_-)_\nu^{corr}$, $(N_-/N_+)_{\bar{\nu}}^{corr}$, which are presented in Fig. 6b. In the same figure we show the ratio $N_-(\bar{\nu})/N_-(\nu)$, which is free from proton contamination, and by isospin symmetry can be described by $1/\omega(z)$. As expected from the quark-parton model, all three ratios are in good agreement which indicates that the fast proton contamination has been properly taken into account.

Comparison with the parametrizations of $1/\omega(z)$ by Feynman and Field (solid curve)[9] and by Sehgal (dashed curve)[10] shows that our data lie systematically below both curves (Fig. 6b). This discrepancy is most significant in the region $0.6 < z < 0.8$. A similar tendency is observed for the BEBC results [11] which are also plotted in this figure; however, because of the different methods of the energy estimation, these data are not available for $z > 0.6$.

We conclude that the hadrons produced in $\nu(\bar{\nu})$Ne interactions have quantitatively similar characteristics to hadrons produced in $\pi^{\pm}$Ne. In particular, the effect of the nuclear target is the same for $\nu(\bar{\nu})$ and $\pi^{\pm}$ beams; most of the nuclear effect is concentrated in the target fragmentation region, where a slightly higher effect is observed for the unfavored particles.

The experimental z distributions of the ratios $(N_+/N_-)_\nu^{corr}$ and $(N_-/N_+)_{\bar{\nu}}^{corr}$ are in a good agreement; however, a systematic deviation from the quark model parametrizations is observed throughout the whole z range.

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REFERENCES

1. T.H. Burnett et al., VTL-PUB-50 (1978). To be published in the proceedings of the Vanderbilt Conference (1978).

2. The total visible hadronic momentum is increased in magnitude to balance the momentum transverse to the ν direction in the νμ plane. We have verified that no distortion which could affect any of our conclusions results from this procedure. See. H. Rudnicka, University of Washington Internal Report VTL-HEP-58 (1977).

3. As was reported in Refs. 4 and 7.

4. W.M. Yeager et al., Phys. Rev. D16, 1294 (1977).

5. See, e.g., W. Busza, Proc. of the XIIIth Int. Colloquium on Multiparticle Reactions, Tutziug, 545 (1976). E. L. Feinberg, Physics Reports 56 (1972).

6. J.W. Chapman et al., Phys. Rev. Lett. 36, 124 (1976) and J. Vander Velde private communication.

7. M. Derrick et al., Phys. Rev. D17, 1 (1978) and P. Schreiner private communication.

8. P. Bosetti et al., Nucl. Phys. B54, 141 (1973).

9. R.D. Field and R.P. Feynman, Phys. Rev. D15, 2590 (1977).

10. L.M. Sehgal, Proc. of the 1977 International Symposium on Lepton and Photon Interactions, Hamburg (1977), 837.

11. Aachen-Bonn-CERN-Imperial College-Oxford-Saclay Collaboration, presented by R. Hartmann at Washington APS meeting, April 1978.

12. T.H. Burnett et al., "Neutrino-77", ed. M. A. Markov et al. (Nauka-Moscow), Vol. II, 132 (1978).

13. B.S. Yuldashev et al. - to be published in Acta Phys. Pol. B9 (1978).

14. S. A. Azimov et al., Nucl. Phys. B107, 45 (1976).