VTL-PUB-44
(SEPT. 1977)

STUDY OF HADRONIC SYSTEMS PRODUCED IN $\nu_e(\bar{\nu}_e)$Ne INTERACTIONS*

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ABSTRACT: The hadronic system produced in $\nu_e(\bar{\nu}_e)$Ne interactions in the Fermilab 15-foot bubble chamber is studied and compared with hadrons produced in $\nu_\mu(\bar{\nu}_\mu)$p and $\pi^\pm$Ne interactions. The differences between νNe and νp interactions are found to be similar to the differences between πNe and πp observed in other experiments.

* Paper presented by H.J. Lubatti at the ν77 Conference, Elbrus, USSR, June 1977.

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FERMILAB-CONF-77-153-E

I. INTRODUCTION: The study of hadron-nucleus interactions and their comparison with hadron-nucleon interactions has received much theoretical[1] and experimental[2] attention in the past few years. Such comparisons give information about the reinteraction (rescattering) of the produced hadronic system within the nucleus and allow one to study the time development of the hadronic system produced in the interaction. For example, in strong interactions it has been determined that the notion that each hadron is produced instantaneously and then can interact in the nucleus with a probability similar to that of a free hadron (the simple cascade picture) is wrong. This was determined by comparing the multiplicity of charged hadrons produced in hadron-nucleon and hadron-nucleus interactions.[2] It is then argued that hadrons produced in strong interactions, in fact, require a certain time before they become the observable particles.[3]

For the production of hadrons by weak interactions, there is no experimental information on the behavior of the hadronic system at short times after production. Such information may give additional insight into the nature of hadronic production in weak interactions. Thus, a study of the production of hadrons by neutrinos on nuclear targets when compared to reactions on nucleon targets at similar energies can give information on whether or not the hadrons are produced in a point interaction in neutrino collisions.

In this paper, we present preliminary results from a comparison of our data for $\nu_e(\bar{\nu}_e)$Ne interactions with data from $\nu_\mu(\bar{\nu}_\mu)$p interactions. We also compare with πNe interactions. This study is confined to our $\nu_e(\bar{\nu}_e)$ events since these events have been studied in detail for μe final states[4]; in particular, all neutral particles have been measured and a good measurement of the effective mass of the observed hadrons (W_{vis}) is available. We will show that the hadrons produced in neutrino-nucleus interactions when compared to those produced in neutrino-nucleon interactions exhibit the same characteristics (to within 20-30%) as π^--nucleus interactions relative to π-nucleon interactions.

II. DATA SELECTION: The data reported here come from a study of neutrino interactions in the FNAL 15-foot bubble chamber filled with an (atomic) 64% neon-36% hydrogen mixture. Thus, approximately 95% of the interactions occur on Ne. The radiation and interaction lengths are 39 cm and 1.4 m, respectively. The short radiation length (compared with the chamber size) provides good detection efficiency for γ's which results in a good measurement of the total hadronic energy.

The electron neutrino events for this analysis were selected and processed according to the following criteria:†

(i) All events were double-scanned and checked by a physicist who decided if there were an electron or positron candidate emanating from the vertex.

(ii) Only events in which the $e^-(e^+)$ had two signatures were kept in the final sample.

(iii) The $e^-(e^+)$ are required to have momentum $P_e > 800$ MeV/c, $M_{e^\pm x^\mp} > M_{\pi^o}$ (where $x^\mp$ is any non-interacting track which could be the companion in a Dalitz pair), and for the e^- to be inconsistent ($\gtrsim 2\sigma$) with being a δ-ray.

(iv) All charged tracks, γ's, V^o's, and neutral stars were measured, and the neutral energy, where appropriate, added to obtain W_{vis}.

(v) All events with a leaving track identified as a muon by the external-muon-identifier (EMI)[4] are excluded from this sample.

(vi) The total visible energy $E_{vis} \equiv \Sigma p_x \gtrsim 10$ GeV, where the sum is over all measured particles (including γ-rays, V^o's, and neutral stars) and x is the beam direction.

After making these cuts, a total of 74 e^- events and 47 e^+ events are obtained.††

III. RESULTS: The energy spectra of the ν_e and $\bar{\nu}_e$ events are shown in Fig. 1. In Fig. 2 the $y = E_h/E_\nu$ distributions obtained for ν_e and $\bar{\nu}_e$ interactions are shown. The electron momentum measurements, which are difficult in such a dense liquid, are still being studied. Nevertheless, within our statistics and expected backgrounds, the y distributions are consistent with that which is expected - uniform for ν_e interactions and peaked at low values for $\bar{\nu}_e$ interactions. In any case, in this paper we study only hadronic quantities (and use W_{vis}) which are less sensitive to the electron energies.

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† A more detailed description of some of these criteria is given in the paper by C. Ballagh et al. in these proceedings (Ref. 4).

†† No fiducial volume cuts are included. Making such cuts does not alter any of our conclusions.

In the following we will compare our results with those obtained in $\nu_\mu(\bar{\nu}_\mu)p$ interactions.[5,6] These data are available only for $\gtrsim 3$ charged prongs. Thus, we will require $\gtrsim 1$ pion; i.e., one or more tracks which cannot be identified as protons. This leaves 68 ν_e and 44 $\bar{\nu}_e$ events.

The invariant mass distribution (W) of the hadronic system produced in our electron neutrino sample is compared with the W distribution observed in $\nu_\mu p$[5] and $\bar{\nu}_\mu p$[6] interactions in Fig. 3. The distributions are sufficiently similar that we believe we can compare laboratory rapidity distributions, charge multiplicities, and transverse momentum distributions of hadrons produced in $\nu_e(\bar{\nu}_e)$Ne interactions with similar quantities for hadrons produced in $\nu_\mu(\bar{\nu}_\mu)p$ interactions.

We first compare the laboratory rapidity distributions , $F(\xi) \equiv (1/\sigma)\, d\sigma/d\xi$, which measure the average number of charged hadrons per $\Delta\xi$ interval. 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 along the direction of the incident beam particle (see Fig. 4). In Fig. 5 we compare the $F(\xi)$ distribution of all charged hadron tracks (excluding identified protons) in $\nu_e(\bar{\nu}_e)$Ne interactions with $\nu_\mu(\bar{\nu}_\mu)p$ interactions and observe that there is an excess at small values of laboratory rapidity for the neutrino nucleus interactions. An excess at small ξ_{LAB} also has been observed when comparing hadron nucleus interactions to hadron nucleon interactions.[2] A quantitative measurement of the excess at small ξ_{LAB} is given by integrating $F(\xi)$ over the interval $-1 < \xi_{LAB} < 1$ and taking the ratio F_{Ne}/F_p. We obtain for this ratio 2.2 ± 0.3 and 2.2 ± 0.4 for ν_eNe and $\bar{\nu}_e$Ne, respectively, which is to be compared with the ratio 2.1 ± 0.1 obtained for $\pi^\pm$Ne interactions in the same rapidity interval at $P_{LAB} = 10.5$ GeV/c.[7]

In order to see if the rapidity spectrum obtained for neutrino nucleus interactions is significantly different from that obtained in π nucleus interactions, we compare, in Fig. 6, $(1/\sigma)d\sigma/d\xi$ for $\pi^\pm$Ne at $\sqrt{s}_{\pi Ne} = 4.43$ GeV ($P_{LAB} = 10.5$ GeV/c)[7] with $\nu_e(\bar{\nu}_e)$Ne interactions in the interval $3 < W < 6$ GeV. We note that within the statistical significance of the data the rapidity distributions agree well at small values of ξ_{LAB}. Hence, the differences between hadrons produced in $\nu_e(\bar{\nu}_e)$Ne collisions and those produced in πNe collisions when comparing at $\langle W \rangle_{\nu Ne} \approx \sqrt{(s)}_{\pi^- Ne}$ are less than 20%.

From Fig. 5 we see that the $(1/\sigma)d\sigma/d\xi$ distributions differ only at small ξ_{LAB} and that if we integrate over all ξ the average multiplicity of charged particles will not be very different for $\nu_e(\bar{\nu}_e)$Ne and $\nu_\mu(\bar{\nu}_\mu)$p interactions. In Table I we give the numerical values of the average multiplicities for negative and all charged hadrons,[†] and observe that this is the case. We also show the ratios $\langle N \rangle_{\nu(\bar{\nu})Ne} / \langle N \rangle_{\nu(\bar{\nu})p}$. Within errors these quantities agree with values observed in hadron nucleus interactions.[7,9] The multiplicities for $\nu_e(\bar{\nu}_e)$Ne interactions are compared in Fig. 7 with those obtained in $\pi^\pm$ nucleus interactions. As expected from the ξ distributions, Fig. 6, $\nu(\bar{\nu})$Ne has the same average multiplicity as $\pi^\pm$Ne and follows the general trend observed for low A nuclei.[2]

Thus, νNe interactions show the same small increase in average charge multiplicity over νp interactions that is observed in the comparison of πNe to πp interactions. Moreover, as with hadron nucleus interactions, the increase occurs at small values of laboratory rapidity. These two observations have resulted in the rejection of the simple cascade model and lead to various space-time pictures for describing hadron-nucleus interactions.[2]

We next look at the momentum of individual hadrons transverse to the direction of the total hadronic momentum and note in Fig. 8 that $\nu_e(\bar{\nu}_e)$Ne can be fit well by $dN/dp_T \sim p_T \exp(-\beta p_T)$. We obtain $\beta = 5.6 \pm 0.1\ (\text{GeV/c})^{-1}$ which agrees very well with $\beta = 5.6 \pm 0.1\ (\text{GeV/c})^{-1}$ and $\beta = 6.0 \pm 0.1\ (\text{GeV/c})^{-1}$ obtained for π^+ and π^- mesons, respectively, in π^-C interactions.[8] The average transverse momentum of the negative hadrons in $\nu_e(\bar{\nu}_e)$Ne combined is compared in Table II with that obtained in πN and πNe at 10.5 GeV[7] and π^-C at 40 GeV.[8]

Figure 9 gives the dependence of the invariant inclusive cross sections on the momentum of identified protons for reactions $\nu_e(\bar{\nu}_e)\text{Ne} \to p + X$ and $\pi^\pm\text{Ne} \to p + X$ at 10.5 GeV/c[7] and π^-C at 40 GeV/c.[10] As one can see within errors, data for $\nu_e(\bar{\nu}_e)$Ne and $\pi^\pm$Ne agree well. Since most of the protons are "knock-on" protons this suggests that the deposition of energy is similar in ν-nucleus and hadron-nucleus interactions.[††]

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† All identified protons are excluded.

†† The observation that hadron-nucleus interactions have the same invariant inclusive cross section for "slow" protons has been called "nuclear scaling".[11]

IV. CONCLUSION: We thus conclude that the differences between νNe and νp interactions are similar to the differences observed in the comparison of πNe and πp interactions. These are preliminary results. A more complete analysis which includes our $\nu_\mu(\bar{\nu}_\mu)$Ne data will be published elsewhere.

ACKNOWLEDGMENTS:

We are deeply grateful to the Fermilab personnel: the neutrino lab team for improvising an operable one-horn system; to the accelerator staff for good extracted beam; to the 15-foot bubble chamber team who achieved remarkably good chamber conditions permitting use of ionization information. We especially acknowledge the efforts of our scanning, measuring, and computing staffs. This research was supported in part by ERDA and NSF.

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TABLE I

The Average Multiplicity of Negative and Charged Hadrons (Identified Protons Removed) and the Ratio $\langle N \rangle_{\nu Ne} / \langle N \rangle_{\nu p}$ in $\nu_e(\bar\nu_e)$Ne and $\nu_\mu(\bar\nu_\mu)$p Interactions

	NEGATIVE PARTICLES	ALL PARTICLES
$\langle N \rangle_{\nu_e Ne}$, this experiment	1.19 ± 0.13	4.12 ± 0.39
$\langle N \rangle_{\nu_\mu p}$, Ref. 5	1.02 ± 0.04	3.72 ± 0.13
$\frac{\langle N \rangle_{\nu_e Ne}}{\langle N \rangle_{\nu_\mu p}}$	1.17 ± 0.13	1.11 ± 0.10
$\langle N \rangle_{\bar\nu_e Ne}$, this experiment	1.89 ± 0.16	3.70 ± 0.32
$\langle N \rangle_{\bar\nu_\mu p}$, Ref. 6	1.64 ± 0.03	3.14 ± 0.07
$\frac{\langle N \rangle_{\bar\nu_e Ne}}{\langle N \rangle_{\bar\nu_\mu p}}$	1.15 ± 0.10	1.18 ± 0.11

TABLE II

The Mean Values of Transverse Momentum for Negative Particles

TYPE OF INTERACTION	$\langle p_T \rangle$ (MeV/c)
ν_eNe, this experiment	362 ± 29
$\bar\nu_e$Ne, this experiment	373 ± 34
π^-Ne, 10 GeV/c, Ref. 7	348 ± 4
π^+Ne, 10 GeV/c, Ref. 7	368 ± 6
π^-p, 10 GeV/c, Ref. 7	309 ± 4
π^+p, 10 GeV/c, Ref. 7	306 ± 6
π^-C, 40 GeV/c, Ref. 8	354 ± 1

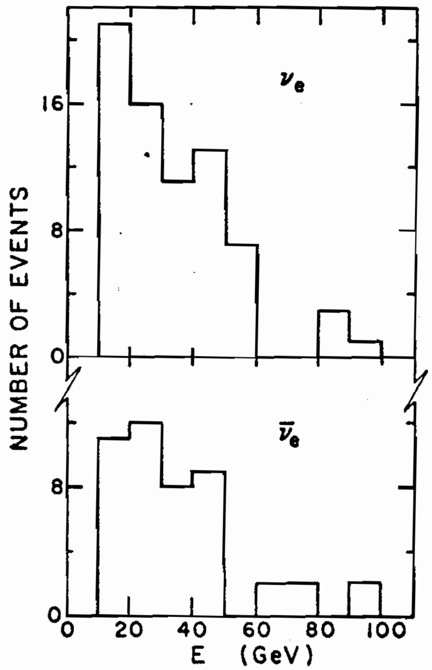

Fig. 1. Visible energy spectrum of events with identified e^+ or e^-.

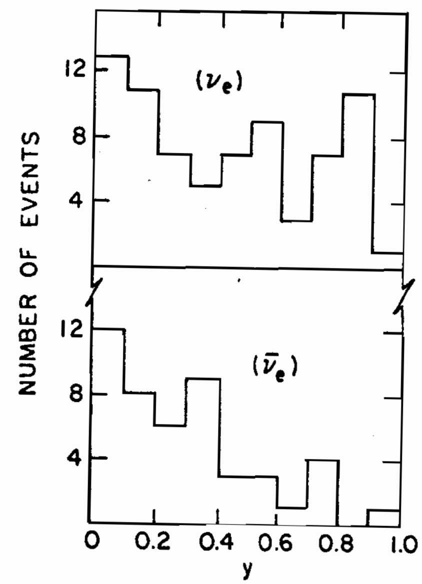

Fig. 2. $y = E_h/E_\nu$ distributions for ν_e and $\bar{\nu}_e$ events.

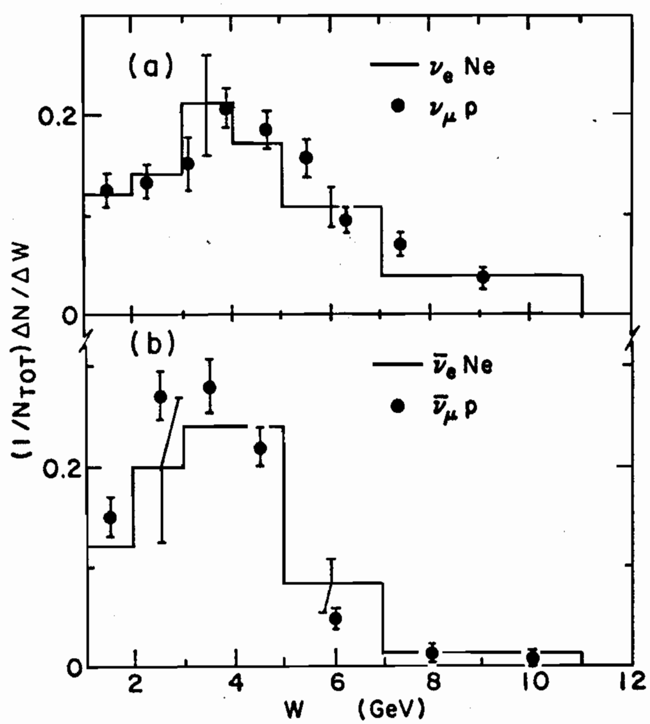

Fig. 3. Invariant mass distribution (W) of hadronic system for: (a) ν_e Ne and ν_μ p (Ref. 5) interactions (b) $\bar{\nu}_e$ Ne and $\bar{\nu}_\mu$p (Ref. 6) interactions.

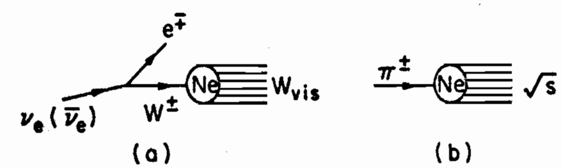

Fig. 4. Hadronic production in the laboratory system for: (a) ν_e ($\bar{\nu}_e$)Ne interactions & (b) $\pi^{\pm}$Ne interactions.

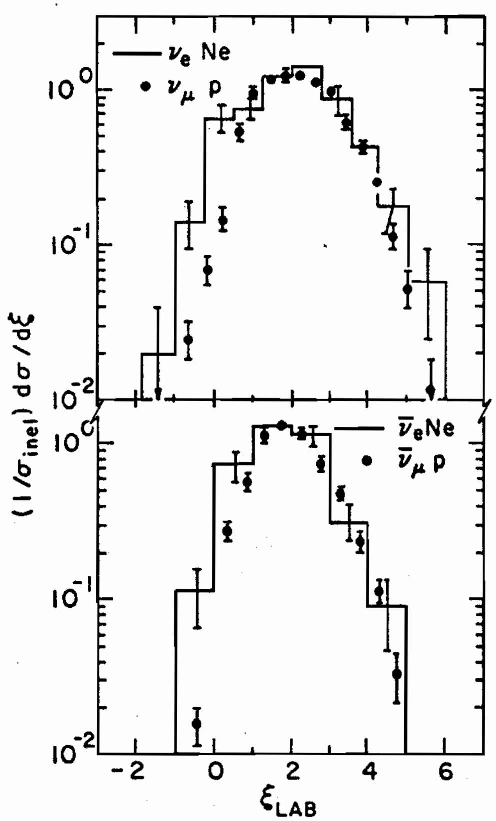

Fig. 5. Comparison of laboratory rapidity for $\nu_e(\bar{\nu}_e)$Ne and $\nu_\mu(\bar{\nu}_\mu)$p interactions.

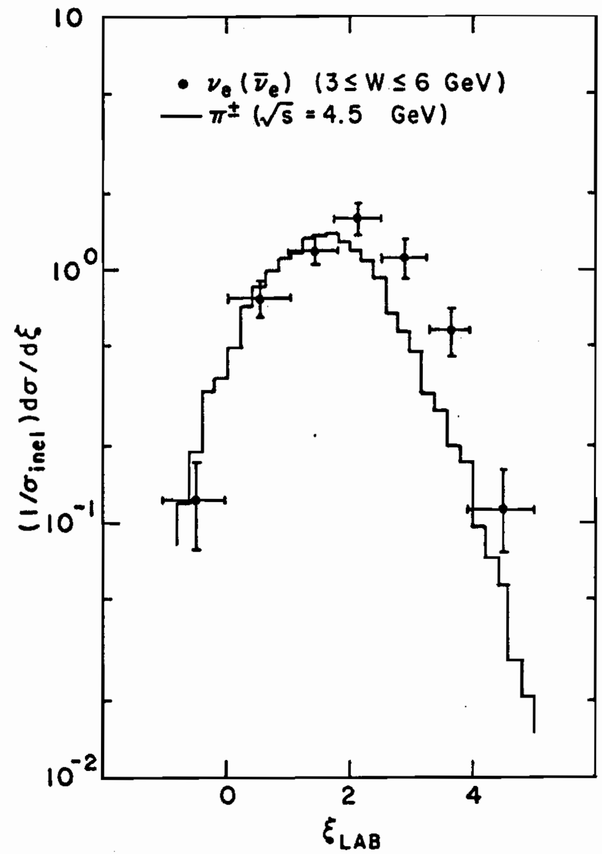

Fig. 6. Comparison of laboratory rapidity $\xi_{LAB} = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$ for $\nu_e(\bar{\nu}_e)$Ne (combined) and $\pi^{\pm}$Ne (Ref. 7)

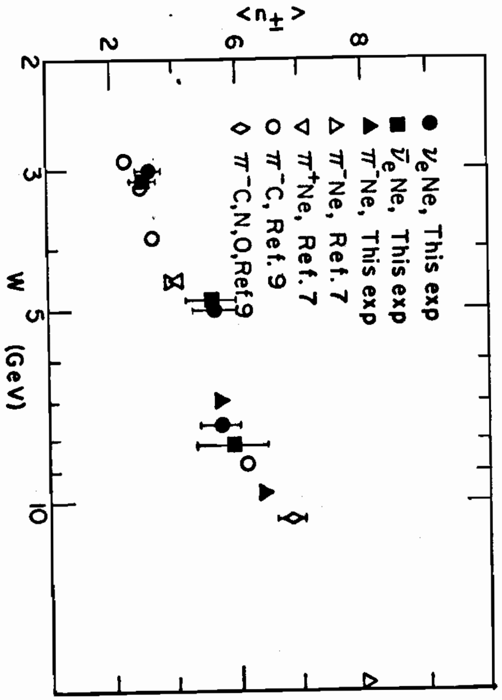

Fig. 7. Comparison of average multiplicities of charged hadrons as a function of W_{VIS} (or $\sqrt{s}$) for $\nu_e(\bar{\nu}_e)$ Ne and $\pi^\pm$ Ne interactions.

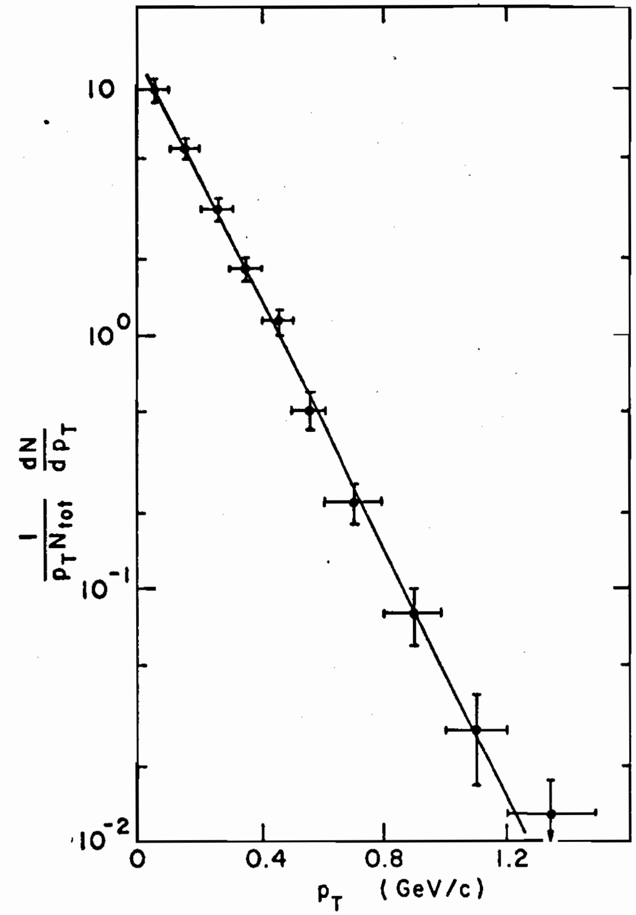

Fig. 8. Distribution of p_T for all fast hadrons when the longitudinal direction is defined by the total hadronic momentum. Curve is fit to $e^{-\beta p_T}$, with $\beta = 5.6 \pm 0.1$ (GeV/c)$^{-1}$.

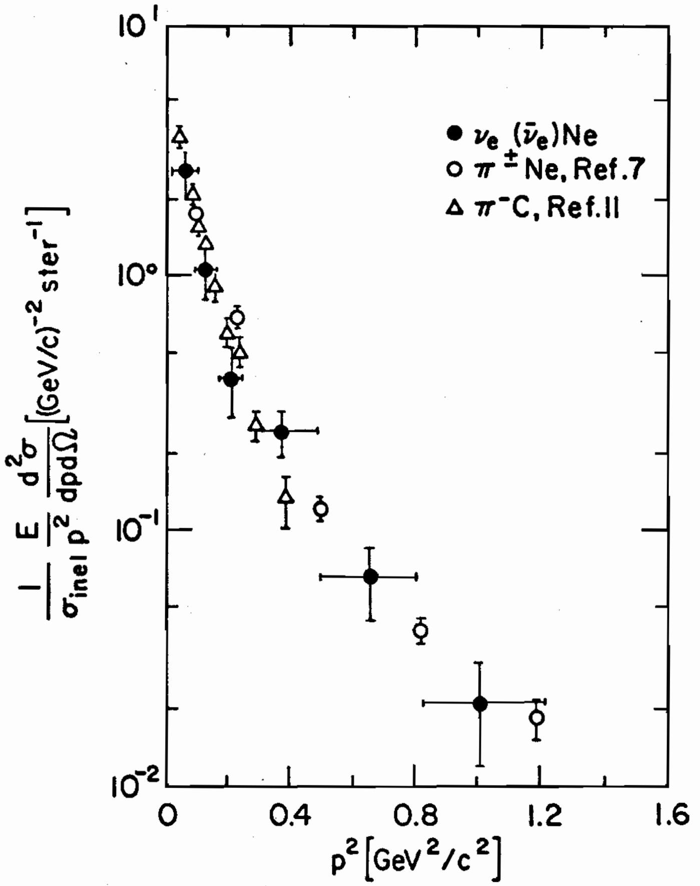

Fig.9. Inclusive cross section of identified protons in $\nu_e(\bar{\nu}_e)$Ne, $\pi^{\pm}$Ne and π^-C interactions.