Multiplicity of secondary particles in inelastic proton-neon interactions at 300 GeV/c

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(Received 29 December 1980)

The data on the total inelastic and partial cross sections in pNe interactions at 300 GeV are presented. It is found that the total cross section, $\sigma_{\text{in}}(p\text{Ne}) = 356 \pm 13$ mb, and multiplicity distributions of the number of negative and relativistic charged particles are in good agreement with predictions of a multiple-scattering model based on Glauber's approach. The multiplicity of negative particles obeys the Koba-Nielsen-Olesen (KNO) scaling, but it is observed that the KNO function depends on the atomic mass number of the target. From an analysis of the average multiplicities of secondary particles, it is shown that approximately 10 percent of the fast ($p \gtrsim 1.2$ GeV) positive secondaries are protons, which are derived from the nucleons in the neon nucleus.

I. INTRODUCTION

It has been pointed out by several authors in the last few years that in a study of hadron-nucleus (hA) interactions at high energies one can obtain information on the space-time structure of multiparticle production.[1] From this point of view the most important data will come from experiments in which specific nuclear targets and high primary energies are used. In this context experiments performed with the use of bubble chambers filled with heavy liquids (D_2, NeH_2, C_3H_8, Xe, etc.) have some advantages: complete angular detection, a target of specific nuclei, and the ability to measure the charges and momenta of secondaries. In addition, one can also detect with good efficiency neutral particles such as γ's, V^0's, and neutrons.

In this paper we present the first experimental data on the study of multiparticle production in inelastic pNe interactions at 300 GeV/c. The separation of hydrogen and neon interactions will be discussed and the p-neon cross sections presented. The multiplicity of secondary pions and protons ejected from the nucleus should serve as a probe of the type and number of interactions occurring within the nucleus. Some details of this connection will be discussed in the context of various specific models.

The A dependence of high-energy interactions can help illuminate details of the space-time structure of strong interactions which are not accessible to p-nucleon interactions. In this respect we have investigated the recoil protons and the secondary pions and found significant differences from p-nucleon data. We do observe Koba-Nielsen-Olesen (KNO) scaling in neon at high energies, but it differs from the pp KNO scaling at the same energy.

One source of experimental uncertainty is the misidentification of fast protons as secondary pions and the loss of slow protons. This loss can, of course, be circumvented by considering only negative particles. But, more importantly, this loss of protons can often be factored out of relevant variables (for example, by considering ratios, by adjusting models, etc.). Hence the conclusions we reach should be independent of this proton loss.

II. EXPERIMENTAL PROCEDURE

The data come from an exposure of the 30-in. Fermilab bubble chamber to a diffractive proton beam with momentum 300 GeV/c. Contamination of π^+, K^+, and μ^+ in the beam is estimated to be less than 0.2%.

The bubble chamber was filled with a light neon-hydrogen mixture (30.9 ± 0.7% molar Ne). The density and the radiation length of this mixture are 0.249 g/cm^3 and 128.1 cm, respectively. The average number of incoming primary protons is found to be 2.66 ± 0.01 per frame.

The data presented below were obtained from the double scanning of 29 134 frames of which 5765 were rejected due to interactions of primary protons upstream of the chosen fiducial volume. The double-scan efficiency was greater than 99% except for low-prong events ($n_{\text{ch}} \leqslant 3$), for which the average efficiency was (87 ± 3)%. The one-prong events were detected only for scattering angles greater than $\gtrsim 2°$ and, thus, elastic and nearly all quasielastic scattering events of primary protons on neon nuclei are not recorded. Therefore, the sample of observed events is the sum of inelastic proton-neon interactions and proton collisions on free hydrogen. For the latter there is a partial loss of elastic events due to missing recoil protons (see below).

For each event recorded we define the following numbers:

n_- = number of negatively charged particles including slow π^- and K^- mesons.

n_+ = number of positively charged lightly ionizing particles. This number also includes slow π^+ and K^+ mesons identified by their ionization or decay in the visible volume of the bubble chamber.

$n_\pm = n_+ + n_-$ = number of relativistic charged secondaries.

n_p = number of secondary protons identified by range and ionization.

n_γ, n_{V^0}, and n_{N^*} = number of γ's, V^0's, and neutral stars, respectively, associated with primary interaction. The neutral particles were detected within the entire visible volume of the bubble chamber.

For our NeH_2 mixture protons can be identified by their range and ionization in the momentum range $0.13 \lesssim p \lesssim 1.2$ GeV/c. Previous experiments indicate that contamination of heavier fragments $(d, t, \mathrm{He}, \ldots)$ among these protons does not exceed $(9\pm3)\%$.[2]

Using the measurements of the mean multiplicities of secondary particles produced in pp interactions at 300 GeV,[3] we estimate that the contamination of K^- mesons and antiprotons among negatively charged particles is less than 5% and 1.4%, respectively. That is, approximately 94% of negative particles produced in pNe and pp interactions are π^- mesons. The positively charged tracks (except identified protons) consist of π^+ and K^+ mesons and fast ($p \gtrsim 1.2$ GeV/c) unidentified protons. Similarly, the fraction of K^+ mesons among n_+ particles is estimated to be less than 6%.

The data obtained from the scan were corrected for Dalitz pairs, close Compton electrons, γ conversion, neutral strange particles, neutral stars, and secondary interactions which were closer than 0.5 cm to the primary vertex. In 8.4% of the recorded events it was impossible to determine the multiplicity and charges of all secondaries mainly because of close ($0.5 \leq L \leq 8$ cm) secondary interactions. The corrections for these events were made using a Monte Carlo program based on the results obtained for events with determined multiplicities of negative and positive secondaries. After all corrections, the number of analyzed events (sum of pNe and pp interactions) is found to be $N_{\mathrm{tot}}(p\mathrm{NeH}_2) = 9296 \pm 140$.

III. THE CROSS SECTIONS

The interaction cross section for protons in our NeH_2 mixture can be written as

$$\sigma(p\mathrm{NeH}_2) = \delta\sigma_{\mathrm{in}}(p\mathrm{Ne}) + 2(1-\delta)\sigma^*(pp)\,, \qquad (1)$$

where δ is the molar fraction of neon, $\sigma_{\mathrm{in}}(p\mathrm{Ne})$ is the inelastic cross section of pNe interactions at 300 GeV (as noted above only inelastic pNe events were recorded during the scan), and $\sigma^*(pp)$ is the "visible" total cross section for pp:

$$\sigma^*(pp) = \sigma_{\mathrm{tot}}(pp) - k\sigma_{\mathrm{el}}(pp)\,. \qquad (2)$$

Here $\sigma_{\mathrm{tot}}(pp)$ is a total pp cross section at 300 GeV,[4] and k is the fraction of elastic pp events which was not detected because of very-short-($L \lesssim 3$ mm) recoil protons.

This restriction in length implies that only protons of momentum exceeding 130 MeV/c were detected. From an analysis of the differential cross sections of elastic pp scattering at 300 GeV/c,[4] we estimate that approximately 30% of all elastic pp events on free hydrogen are lost, i.e., that the coefficient k in Eq. (2) is 0.3.

The interaction cross section $\sigma(p\mathrm{NeH}_2)$ measured in this experiment is (162.8 ± 2.5) mb. The quoted error is statistical only. The systematic error due to uncertainties in definition of the number of incoming protons and the length of fiducial volume is estimated to be less than 4%.

Using our measured value of $\sigma(p\mathrm{NeH}_2)$ and the pp cross sections $[\sigma_{\mathrm{tot}}(pp)$ and $\sigma_{\mathrm{el}}(pp)]$ at 300 GeV/c,[4] we obtain the inelastic cross section for pNe interactions:

$$\sigma_{\mathrm{in}}(p\mathrm{Ne}) = 356.0 \pm 13.0 \text{ mb}\,. \qquad (3)$$

This value is the sum of the incoherent $[\sigma_{\mathrm{prod}}(p\mathrm{Ne})]$ and the coherent $[\sigma_{\mathrm{coh}}(p\mathrm{Ne})]$ inelastic pNe interactions. Assuming that the coherent cross section, for which the nucleus remains intact, depends on the atomic mass number A as $\sigma_{\mathrm{coh}} \sim A^{2/3}$ (and is also independent of the primary energy) and using data on coherent p-emulsion interactions at 400 GeV (Ref. 5) we estimate that $\sigma_{\mathrm{coh}}(p\mathrm{Ne}) = 13.0 \pm 0.5$ mb. It follows that $\sigma_{\mathrm{prod}}(p\mathrm{Ne}) = 343.0 \pm 13.0$ mb.

The data on $\sigma_{\mathrm{in}}(p\mathrm{Ne})$ and $\sigma_{\mathrm{prod}}(p\mathrm{Ne})$ are in good agreement with recent measurements[6,7] of inelastic cross sections of pA and nA interactions at energies close to 300 GeV and also with data at lower energies.[8] For example, an interpolation of the data in Ref. 6 to 300 GeV gives $\sigma_{\mathrm{prod}}(p\mathrm{Ne}) = 344 \pm 16$ mb. In neutron-nucleus interactions[7] we interpolate $\sigma_{\mathrm{in}}(n\mathrm{Ne}) \simeq \sigma_{\mathrm{in}}(p\mathrm{Ne}) = 349 \pm 5$ mb, since the neon nucleus is an isoscalar target. For smaller incident energy (20–60 GeV),[8] $\sigma_{\mathrm{in}}(p\mathrm{Ne}) = 360 \pm 5$ mb.

The measured values of $\sigma_{\mathrm{in}}(p\mathrm{Ne})$ and $\sigma_{\mathrm{prod}}(p\mathrm{Ne})$ also agree well with Shabelsky's calculations[9] that were made in the framework of a multiple-scattering model which is based on Glauber's approach. According to these calculations, $\sigma_{in}(p\mathrm{Ne}) = 348$ mb and $\sigma_{prod}(p\mathrm{Ne}) = 338$ mb, which agree with our experimental results within statistical errors.

We deduce from the measurements of $\sigma(p\mathrm{NeH_2})$ and $\sigma(p\mathrm{Ne})$ that $(67.5 \pm 1.8)\%$ of the $p(\mathrm{NeH_2})$ interactions involve neon nuclei. To study pNe interactions, hydrogen events must be removed. This was done by two methods. In the first the total number and the multiplicity distributions of pNe events were obtained by subtracting pp interactions using the measured cross sections of pNe and pp interactions and the multiplicity distribution of charged secondaries in pp collisions at 300 GeV/c.[4,10]

The second method allows determination of the total number of pNe events and the multiplicity distributions in these events from the classification made during the scan[11]:

$$N(p\mathrm{Ne}) = N(\text{“}p\mathrm{Ne}\text{”}) + N(\text{“}pn\text{”}) + \alpha N(\text{“}pp\text{”}) \,, \qquad (4)$$

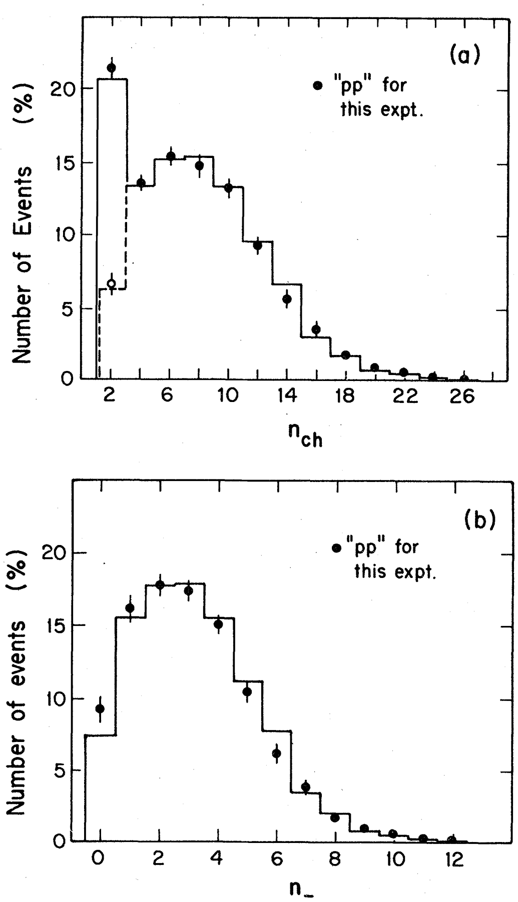

FIG. 1. The distributions of the number of all charged (a) and negative (b) secondaries for events classified as "pp" in this experiment and pp interactions at 300 GeV/c (Ref. 4).

where $N(\text{“}p\mathrm{Ne}\text{”})$, $N(\text{“}pn\text{”})$, and $N(\text{“}pp\text{”})$ are numbers of events classified as "pNe", "pn", and "pp".

(i) "pp" interactions are events in which the net charge of all secondaries is $\sum_i Q_i = +2$; the number of charged particles n_{ch} is even; the number of identified protons n_p is 0 or 1; and the laboratory angle of emission of an identified proton is less than 90°, i.e., $n_p^{\mathrm{backward}} = 0$.

(ii) "pn" interactions are events in which $\sum_i Q_i = +1$; n_{ch} is odd; $n_p = 0$ or 1 and $n_p^{\mathrm{backward}} = 0$.

(iii) "pNe" interactions are the remaining events which do not satisfy the criteria for "pp" or "pn" interactions.

The coefficient α in Eq. (4), which measures the fraction of "pp" interactions on quasifree nucleons in neon, can be determined by means of the cross sections of pp and $p\mathrm{NeH_2}$ interactions[11]:

$$\alpha = 1 - \frac{2(1-\delta)\sigma^*(pp)}{\sigma(p\mathrm{NeH_2})} \frac{N_{tot}(p\mathrm{NeH_2})}{N(\text{“}pp\text{”})}$$
$$= 0.24 \pm 0.01 \,. \qquad (5)$$

We find that, within statistical errors, both methods give similar results for multiplicity distributions.

Events classified as "pp" or "pn" interactions have multiplicity distributions similar to those obtained in hydrogen and deuterium for pp and pn collisions at 300 GeV.[4,10] In Figs. 1(a) and 1(b) we show our "pp" distributions compared to those in pp interactions. This demonstrates the similarity of pp and the interaction of protons with the quasifree nucleons in neon.

After all corrections and subtraction of interactions on free hydrogen the number of analyzed pNe events is found to be $N(p\mathrm{Ne}) = 6263 \pm 175$.

IV. MULTIPLICITY OF SECONDARY IDENTIFIED PROTONS

The multiplicity distribution of identified protons with momenta of $0.13 \lesssim p \lesssim 1.2$ GeV/c in pNe interactions is shown in Fig. 2. The solid line represents a model calculation in which it is assumed that secondary protons in hadron-nucleus interactions are independently emitted in subsequent intranuclear rescattering.[12,13] In this model, the distribution of the number of observed protons, $P(n_p)$, can be related to the probability of ν inelastic collisions inside the nucleus, $P(\nu)$, by

$$P(n_p) = \sum_\nu P(\nu) \binom{n_p + \nu - 1}{n_p} (1-x)^\nu x^{n_p} \,, \qquad (6)$$

where

TABLE I. The average number of inelastic intranuclear collisions $\langle\nu\rangle$ as a function of the number of identified protons n_p in pNe interactions at 300 GeV/c. (Calculations according to a model described in text.)

n_p	$\langle\nu\rangle$
0	1.33
1	1.72
2	2.09
3	2.34
4	2.82
5	3.17
6	3.54
7	3.87
8	4.17
9	4.48
10	4.80
all	2.00

$$x=\frac{\langle n_p\rangle}{\langle n_p\rangle+\langle\nu\rangle},\quad \sum_{n_p}P(n_p)=\sum_{\nu}P(\nu)=1,$$

$$\langle\nu\rangle=\frac{\sum_\nu \nu P(\nu)}{\sum_\nu P(\nu)}$$

$\langle\nu\rangle$ is the average number of inelastic collisions or the mean number of nucleons involved in hA interaction and $\langle n_p\rangle$ is the average number of identified protons defined from experiment. In order to determine $P(\nu)$ we need Glauber's model according to which (see, e.g., Ref. 14)

$$P(\nu)=\frac{\sigma(\nu)}{\sum_\nu\sigma(\nu)}=\frac{\binom{A}{\nu}\int_0^\infty d^2b[\sigma_N T(b)]^\nu[1-\sigma_N T(b)]^{A-\nu}}{\sum_\nu\sigma(\nu)},\qquad(7)$$

where $\sigma_N\equiv\sigma_{\text{in}}(hN)$ is the inelastic hadron-nucleon cross section (we use 32 mb); A is a total number of nucleons in a given nucleus. $T(b)$ is an "optical thickness" which depends on a nuclear density, $\rho(b,z)$: $T(b)=A\int_{-\infty}^{\infty}\rho(b,z)dz$. To calculate $T(b)$ we used for $\rho(b,z)$ the Gaussian distribution $\rho(b,z)\sim\exp[-(b^2+z^2)/a^2]$, which is valid for nuclei with $A\lesssim 30$. The parameter a was chosen to fit the data for electron-nucleus scattering.[15]

The distribution obtained for $P(\nu)$ is shown in Fig. 2 as dashed curve (upper scale). The average number of interactions is $\langle\nu\rangle_{p\text{Ne}}=2.00$. We also show in Table I the average number of inelastic collisions for pNe interactions with a given number of identified protons. As can be seen in Fig.

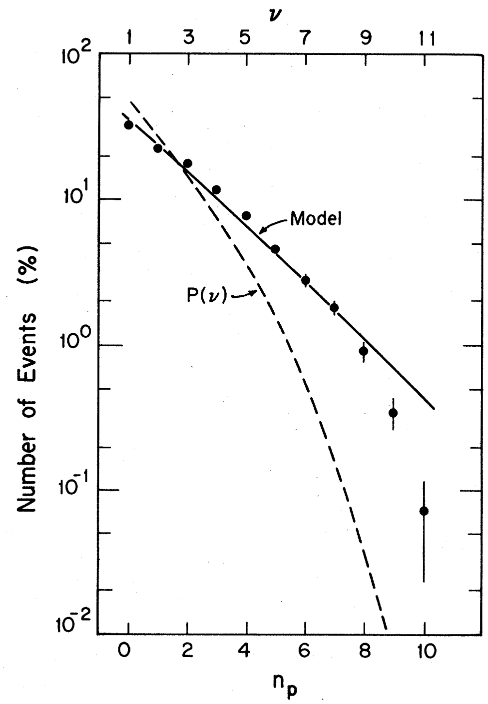

FIG. 2. The distribution $P(n_p)$ of the number of identified protons with momenta $0.13\lesssim p\lesssim 1.2$ GeV/c. The solid curve is a calculation of $P(n_p)$ according to an independent emission model as described in text. The dashed line corresponds to a Glauber-type calculation of the distribution of the number of inelastic intranuclear collisions ν (upper scale).

2 the model discussed above describes the data well except at $n_p=0$ and $n_p\gtrsim 9$. This disagreement can be due to the impossibility (in our experiment) of detecting slow ($p\lesssim 0.130$ GeV/c) or fast ($p\gtrsim 1.2$ GeV/c) protons or the misidentification of heavy fragments (d, t, He, etc.) as protons. We estimate that these heavy fragments contribute less than 10% to the n_p distribution.[2] A more detailed analysis of the multiplicity distributions of protons (including data for π^-C and π^-Ne interactions) will be presented elsewhere.[16]

The average multiplicities and dispersions, $D=(\langle n_p^2\rangle-\langle n_p\rangle^2)^{1/2}$, of secondary identified protons in pNe, "pp", "pn", and "pN" interactions at 300 GeV/c are given in Table II. Data for proton-nucleon interactions were obtained by averaging results for inelastic "pp" and "pn" events, from which we removed coherent pNe interactions. Also in Table II the ratios $R(n_p)=\langle n_p\rangle_{p\text{Ne}}/\langle n_p\rangle_{pN}$ are given. Assuming a power-law A dependence of $R(n_p)$, we find that $\beta=0.64\pm0.02$ which is consistent with the dependence $\langle n_p\rangle_{pA}=A^{2/3}\langle n_p\rangle_{pN}$.

Using data on $\langle n_p\rangle_{pp}$ and $\langle n_p\rangle_{pn}$ we can also determine the probability of inelastic charge exchange $p\to n$,[17] with the assumption that $d\sigma/dt(p\to n)$ is

TABLE II. The mean multiplicities $\langle n_p \rangle$ and dispersions D_p of identified secondary protons in pNe and pN interactions at 300 GeV/c.

Type of interaction	$\langle n_p \rangle$	D_p	$R = \frac{\langle n_p \rangle_{p\mathrm{Ne}}}{\langle n_p \rangle_{pN}}$
pNe (inelastic)	1.77 ± 0.03	1.90 ± 0.04	6.56 ± 0.27
pNe (incoherent)	1.84 ± 0.03	1.90 ± 0.04	6.81 ± 0.23
"pp" (inelastic)	0.34 ± 0.02	0.49 ± 0.02	
"pn" (inelastic)	0.19 ± 0.01	0.36 ± 0.02	
$pN = \frac{1}{2}$("pp" + "pn") (inelastic)	0.27 ± 0.01	0.44 ± 0.02	

equal to $d\sigma/dt(p \to p)$.

$$W(p \to n) = \frac{\langle n_p \rangle_{pn}}{\langle n_p \rangle_{pp} + \langle n_p \rangle_{pn}} = 0.36 \pm 0.02 .$$

This result is in an excellent agreement with data from other experiments.[3,17,18]

The fact that we obtain $\langle n_p \rangle_{pN} = 0.27 \pm 0.01$ instead of the expected value from charge symmetry

$$\langle n_p \rangle_{pN} = \tfrac{1}{2}[1 - W(p \to n) + W(n \to p)] = 0.5$$

means that there are protons lost due to very low momenta ($p \lesssim 0.13$ GeV/c) or because they are fast ($p \gtrsim 1.2$ GeV/c). The average multiplicity of the latter according to our estimate is $\langle n_p^f \rangle_N^T \simeq 0.2$, neglecting $N\bar{N}$ production.

V. THE MULTIPLICITY OF $n_\pm$ PARTICLES

The distributions of the number of secondary $n_\pm$ and negative particles produced in inelastic pNe interactions are shown in Figs. 3 and 4. Shaded areas correspond to estimates of contribution of coherent channels: $p\mathrm{Ne} \to \mathrm{Ne} + (1,3,5,7,9$ prongs).[5] The curves are results of calculations according to the Shabelsky multiple-scattering model[9] which gives predictions[19] similar to the additive quark model of hA interactions.[20,21] As one can see from Figs. 3 and 4 experimental data are in reasonable agreement with predictions of this model. Peaks in $n_\pm$ distributions (after subtraction of coherent channels) at odd values of $n_\pm$ are probably due to the contribution of incoherent inelastic diffractive scattering of protons off nucleons of neon.

The average multiplicities $\langle n_{\pm,-} \rangle$ and ratios $\langle n_{\pm,-} \rangle / D_{\pm,-}$, where $D_{\pm,-} = (\langle n_{\pm,-}^2 \rangle - \langle n_{\pm,-} \rangle^2)^{1/2}$, for $n_\pm$ and negative particles are given in Table III. Also in the same table are the predictions of the multiple-scattering model.[9]

Data for proton-nucleon interactions (see Table III) were obtained by averaging results which came from a study of inelastic pp and pn collisions at 300 GeV/c (Refs. 4 and 10) (hydrogen and deu-

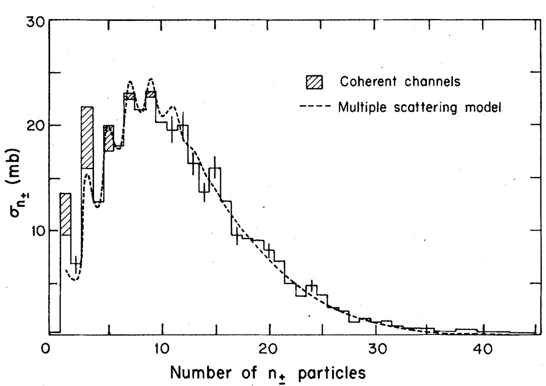

FIG. 3. The multiplicity distribution of $n_\pm$ particles in inelastic pNe interactions. The curve is a prediction of the multiple-scattering model (Ref. 9). The shaded areas correspond to the estimate of coherent pNe interactions.

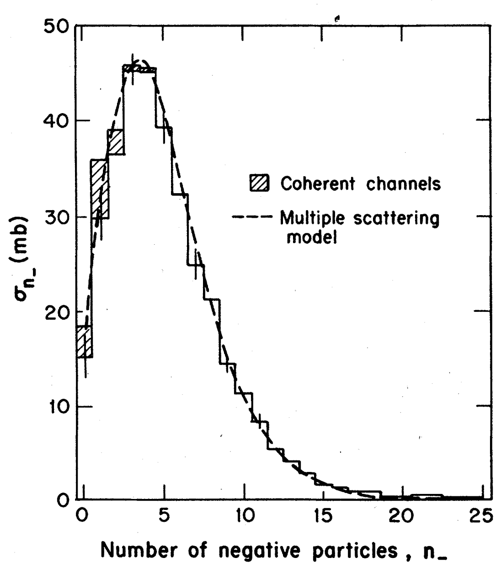

FIG. 4. The distribution of the number of negative particles in inelastic pNe interactions. The curve is calculated from the multiple-scattering model (Ref. 9).

TABLE III. The mean multiplicities and related characteristics of secondary $n_\pm$ particles in pNe and pN interactions at 300 GeV/c.

Quantity	pNe, this experiment inelastic	pNe, this experiment incoherent	pNe, model (Ref. 9) (incoherent)	$pN=\frac{1}{2}(pp+pn)$ (Refs. 4,10) (inelastic)
$\langle n_\pm\rangle$	11.51 ± 0.09	11.83 ± 0.10	11.74	7.67 ± 0.10
$\langle n_-\rangle$	4.91 ± 0.05	5.06 ± 0.05	5.07	3.34 ± 0.05
$\langle n_+\rangle$	6.60 ± 0.06	6.77 ± 0.06	6.67	4.33 ± 0.06
$\langle n_\pm\rangle/D_\pm$	1.60 ± 0.03	1.66 ± 0.03	1.75	
$\langle n_-\rangle/D_-$	1.39 ± 0.02	1.44 ± 0.02	1.57	1.56 ± 0.02
$r_\pm$	1.21 ± 0.02	1.21 ± 0.02	1.19	1.10 ± 0.01

terium bubble chambers):

$$\langle n_-\rangle_{pN}=\tfrac{1}{2}(\langle n_-\rangle_{pp}+\langle n_-\rangle_{pn}), \quad (8)$$

$$\langle n_\pm\rangle_{pN}=\tfrac{1}{2}(\langle n_{\mathrm{ch}}\rangle_{pp}+\langle n_{\mathrm{ch}}\rangle_{pn}-1), \quad (9)$$

where $\langle n_{\mathrm{ch}}\rangle_{pp}$ ($\langle n_{\mathrm{ch}}\rangle_{pn}$) is the average multiplicity of all secondaries produced in inelastic pp (pn) interactions. From charge symmetry the average multiplicity of recoil protons in p-nucleon interactions should be 0.5, which must be subtracted from the charged tracks.

The ratio of the mean negative-particle multiplicities $\langle n_-\rangle$ produced in incoherent pNe and inelastic pN interactions is

$$R(n_-)=\frac{\langle n_-\rangle_{p\mathrm{Ne}}^{\mathrm{incoh}}}{\langle n_-\rangle_{pN}}=1.51\pm0.03\,.$$

Within errors the value of $R(n_-)$ is consistent with dependence

$$R=\tfrac{1}{2}(1+\langle\nu\rangle)=1.5 \quad (10)$$

predicted by the two-phase model[22] but inconsistent with

$$R=\tfrac{1}{3}(2+\langle\nu\rangle)=1.33\,. \quad (11)$$

Gottfried's model[1] and is marginally consistent with

$$R=\frac{\langle\nu\rangle}{2}+\frac{\langle\nu\rangle}{\langle\nu\rangle+1}-\frac{0.2(\langle\nu\rangle-1)}{\langle\nu\rangle+1}=1.6 \quad (12)$$

which follows from the quark-parton model by Brodsky *et al.*[23] In each case we used $\langle\nu\rangle_{p\mathrm{Ne}}=2$ as obtained in Sec. IV from the $P(\nu)$ distribution to calculate R.

If one can parametrize ratio $R(n_-)$ in the form $R(n_-)\sim A^c$, where A is the atomic mass number, then it follows from our data that $c=0.14\pm0.01$, which contradicts the prediction of the hydrodynamic model, $c=0.19$.[24]

We now return to the question of the composition of n_+ particles. It was noted in Sec. II that positively charged fast secondaries consist of fast unidentified protons and π^+/K^+ mesons. For the average multiplicity of n_+ particles we can write

$$\langle n_+\rangle=\langle n_{\pi^+}\rangle+\langle n_p^f\rangle\,,$$

where $\langle n_{\pi^+}\rangle$ is mean multiplicity of positive mesons ($\pi^+ + K^+$) and

$$\langle n_p^f\rangle=\langle n_p^f\rangle^P+\langle n_p^f\rangle^T\,,$$

where $\langle n_p^f\rangle^P$ is the average multiplicity of secondary protons which are correlated with the primary proton (so-called "leading protons") and $\langle n_p^f\rangle^T$ is the average multiplicity of those protons which are nucleons from the neon target and have momenta greater than $\simeq1.2$ GeV/c so they cannot be identified at the scanning table.

According to our data (see Sec. IV) and Refs. 2, 17, and 18,

$$\langle n_p^f\rangle^P=1-W(p\to n)=0.64\pm0.02\,. \quad (13)$$

Within errors this value does not depend on the target nucleus.

In order to estimate the number of fast protons knocked out of neon, we can use data on the inclusive measurements of yields of secondary particles produced in hadron-nucleus interactions at high energies.[18,25,26] According to these experiments, the ratios $\langle n_{\pi^+}\rangle/\langle n_{\pi^-}\rangle$ and $\langle n_{K^+}\rangle/\langle n_{K^-}\rangle$ at fixed Feynman variable x do not depend either on the atomic mass number of the target or the primary energy. In Table III we give the ratio $r_\pm=(\langle n_+\rangle-\langle n_p^f\rangle^P)/\langle n_-\rangle$ for pNe and pN interactions where $\langle n_p^f\rangle^P$ was taken from Eq. (13). In proton-nucleon interactions $r_\pm$ means a ratio of the mean multiplicities of π^+ and K^+ to π^- and K^- mesons.

As one can see from Table III, there is a difference between $r_\pm(p\mathrm{Ne})$ and $r_\pm(pN)$, which must be due to the presence of fast ($p\gtrsim1.2$ GeV/c), unidentified protons knocked out of the neon nucleus. Neglecting $N\bar{N}$ production, the average multiplicity of these protons can be estimated as

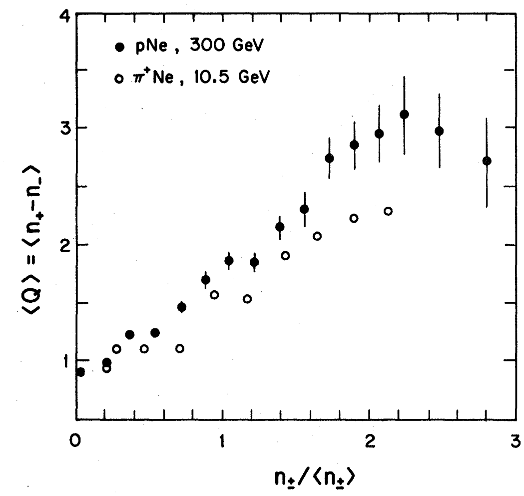

FIG. 5. The dependence of the average net charge of $n_\pm$ particles on $n_\pm/\langle n_\pm\rangle$ in pNe (this experiment) and π^+Ne (Ref. 28) interactions.

$$\langle n_p^f\rangle_{p\text{Ne}}^T \simeq \langle n_-\rangle_{p\text{Ne}}[r_\pm(pNe) - r_\pm(pN)] .$$

From the data in Table III we find $\langle n_p^f\rangle_{p\text{Ne}}^T \simeq 0.6 \pm 0.1$. We note that in π^-Ne interactions at 200 GeV/c $\langle n_p^f\rangle_{\text{Ne}}^T = 0.44 \pm 0.14$.[27]

More evidence for the presence of the relatively large amount of target fast protons comes from a study of the dependence of the mean net charge of $n_\pm$ particles, $\langle Q\rangle = \langle n_+\rangle - \langle n_-\rangle$, as a function of $n_\pm$ which is shown in Fig. 5. An increase of $\langle Q\rangle$ with $n_\pm$, observed also in π^+Ne interactions at 10.5 GeV,[28] is an indication for a rise of $\langle n_p^f\rangle^T$ with $n_\pm$.[29,30]

The difference between $\langle Q\rangle_{p\text{Ne}}$ and $\langle Q\rangle_{\pi^+\text{Ne}}$ at fixed $n_\pm/\langle n_\pm\rangle$ (see Fig. 5) is obviously connected with the fact that the average number of intranuclear collisions $\langle\nu\rangle$ (or the average number of nucleons involved in hA interactions) is higher in pNe than in π^+Ne interactions. According to calculations by formulas in Sec. IV we have $\langle\nu\rangle_{p\text{Ne}} = 2.00$ and $\langle\nu\rangle_{\pi^+\text{Ne}} = 1.65$.

In Fig. 6 we show dependence of $\langle Q\rangle_{p\text{Ne}}$ and $\langle Q'\rangle_{\pi^-\text{Ne}} = \langle Q\rangle_{\pi^-\text{Ne}} + 2$ as a function of $n_\pm/\langle n_\pm\rangle$ for events with a number of visually identified protons $n_p \geq 2$ in pNe at 300 GeV/c and in π^-Ne interactions at 10.5 and 200 GeV/c.[28-30] The value $\langle Q'\rangle_{\pi^-\text{Ne}}$ was used to compare pNe and π^-Ne interactions by taking into account the difference in the charge of the initial state.

We can see from Fig. 6 that there is a systematic difference between $\langle Q\rangle_{p\text{Ne}}$ and $\langle Q'\rangle_{\pi^-\text{Ne}}$ at high values of $n_\pm/\langle n_\pm\rangle$. Again, as discussed above, this difference could be due to different values of $\langle\nu\rangle$ in π^-Ne and pNe interactions with $n_p \geq 2$. Using formulas of Sec. IV we estimate that for events with $n_p \geq 2$ the average numbers of inelastic collisions are $\langle\nu(n_p \geq 2)\rangle_{p\text{Ne}} = 2.63$ and $\langle\nu(n_p \geq 2)\rangle_{\pi\text{Ne}} = 2.18$.

It is interesting to note that, in the framework of the additive quark model,[20,21] in pA interactions

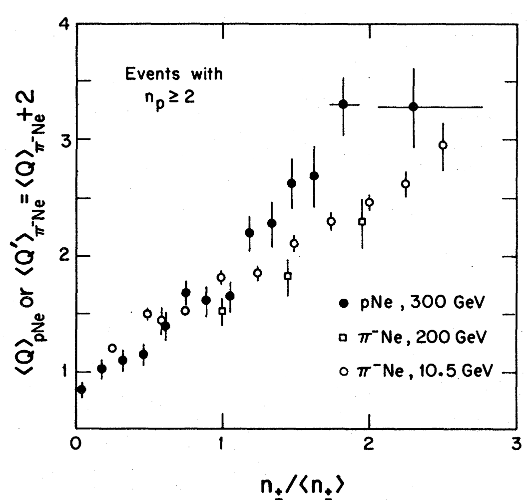

FIG. 6. The average net charge of $n_\pm$ particles in events with the number of identified protons $n_p \geq 2$ for pNe (this experiment) and π^-Ne (Refs. 28–30) interactions as a function of $n_\pm/\langle n_\pm\rangle$. The value $\langle Q'_{\pi^-\text{Ne}}\rangle = \langle Q_{\pi^-\text{Ne}}\rangle + 2$ was used to take into account a difference in the total charge of initial states in pNe and π^-Ne interactions.

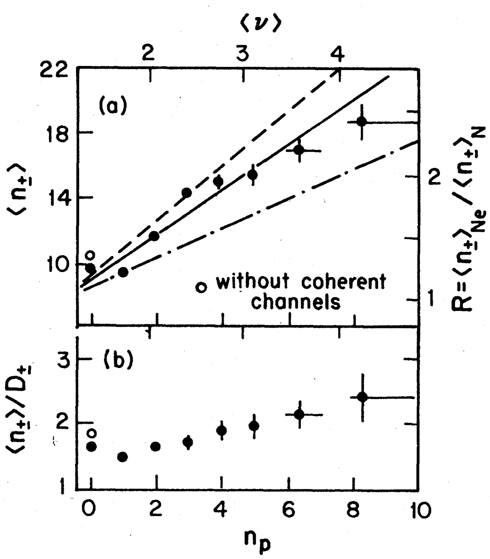

FIG. 7. The average multiplicity $\langle n_\pm\rangle$ (a) and ratio $\langle n_\pm\rangle/D_\pm$ (b) as a function of the number of identified protons in pNe interactions. The upper scale corresponds to values of $\langle\nu\rangle$ estimated from the model described in the text (see Table I). The solid line corresponds to the model described by Eq. (10), the dashed and dash-dotted lines come from Eqs. (11) and (12), respectively.

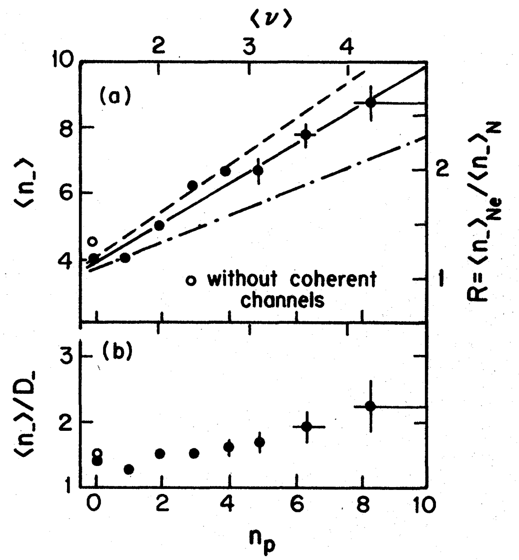

FIG. 8. The same as in Figs. 7 (a), and 7 (b) but for negative particles produced in p Ne interactions.

compared to πA there should be an additional number of recoil nucleons emitted due to processes when all three valence quarks of the incoming proton are involved in an interaction with nucleons of a nucleus. Such interactions will yield high-multiplicity events. As we saw above, pNe and π^-Ne experimental results on $\langle Q\rangle$ are in qualitative agreement with expectations from the additive quark model.

We now discuss correlations between multiplicities of negative and $n_\pm$ particles and the number of identified protons n_p. In Figs. 7(a) and 7(b) and 8(a) and 8(b) we show the dependence of $\langle n_{\pm,-}\rangle$ and $\langle n_{\pm,-}\rangle/D_\pm$ on n_p in inelastic pNe interactions at 300 GeV/c. The upper scales in both figures are the values of $\langle\nu\rangle$ estimated from calculations in Sec. IV (see also Table I). The right scales correspond to the normalized multiplicities:

$$R=\langle n_{\pm,-}\rangle_{p\mathrm{Ne}}/\langle n_{\pm,-}\rangle_{pN}\,.$$

There is an approximately linear rise of $\langle n_\pm\rangle$ and $\langle n_-\rangle$ with n_p (or $\langle\nu\rangle$): $\langle n_{\pm,-}\rangle \simeq A+Bn_p$. For negative particles the slope parameter B at 300 GeV/c is $B=0.61\pm0.03$ which is twice as large as data at 28 GeV/c which has $B=0.24\pm0.05$.[31] The same increase of B was observed in π^-C interactions in the momentum range 4–40 GeV/c.[11]

The fact should be noted that even for pNe events with $n_p=0$ the ratios $R(n_\pm)$ and $R(n_-)$ are greater than 1. This phenomenon can be understood from Table I where we see that in pNe events at $n_p=0$ the average number of intranuclear collisions $\langle\nu\rangle>1$, which automatically means $R(n_-)>1$.

The solid lines in Figs. 7(a) and 8(a) correspond to the prediction of the two-phase model [Eq. (10)]. It is seen that experimental data are close to what is expected from Eq. (10) rather than predictions of Eqs. (11) and (12).

We also note from Figs. 7(b) and 8(b) that there is a linear increase of the ratios $\langle n_{\pm,-}\rangle/D_{\pm,-}$ with n_p (or $\langle\nu\rangle$) at $n_p\geq 1$. This can be evidence that the KNO function is energy dependent (see below).

To conclude this section we would like to point out that irregularities (see Figs. 7, 8, and 10) observed in dependence of $\langle n_{\pm,-}\rangle$ on the number of protons at low values of n_p take place also in π^-C, π^-Ne, and p-emulsion interactions.[11-13,29,30,33] These irregularities become more pronounced at higher energies, $E\gtrsim 40$ GeV. At the present time, we have no reasonable explanation of this deviation from a monotonic dependence.

VI. KNO SCALING

It is well known that within experimental errors, KNO scaling[32,33] is valid for negative particles produced in incoherent π^-A interactions.[11,34] In Fig. 9 we show our data compared to pNe interactions at 28 GeV/c.[31] As one can see there is an agreement between two experiments which indicates a validity of KNO scaling for pNe interactions in the range 28–300 GeV. For comparison, in Fig. 9 we also show data obtained in proton-nucleon interactions at 300 GeV/c. There is a

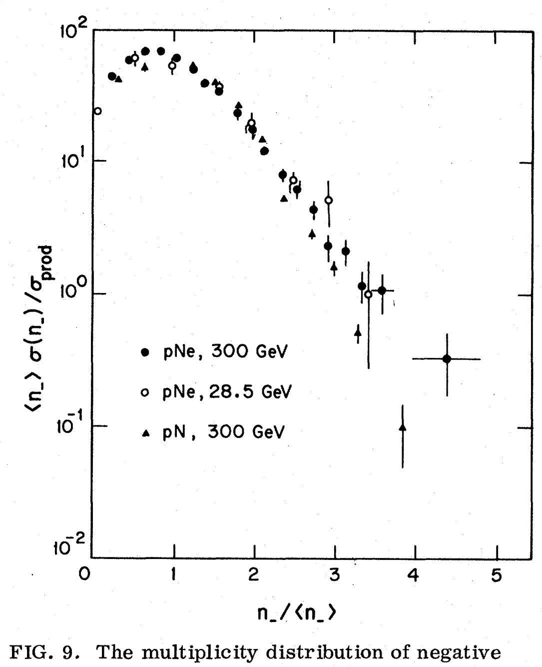

FIG. 9. The multiplicity distribution of negative particles in incoherent pNe interactions presented in the KNO variables (Refs. 32 and 33). For comparison, data for p Ne at 28.5 GeV/c (Ref. 31) and pN at 300 GeV/c (Refs. 4 and 10) are also shown.

TABLE IV. Fitted slope values for C_q, the normalized multiplicity moments, for $n_p \geq 2$. $C_q = a + bn_p$.

	$n_\pm$ particles			n_- particles		
	$q=2$	$q=3$	$q=4$	$q=2$	$q=3$	$q=4$
a	1.43 ± 0.02	2.48 ± 0.07	5.00 ± 0.22	1.52 ± 0.03	2.94 ± 0.12	6.76 ± 0.47
b	-0.034 ± 0.004	-0.125 ± 0.014	-0.368 ± 0.040	-0.038 ± 0.006	-0.149 ± 0.024	-0.491 ± 0.082
χ^2/NDF	0.25	0.9	0.18	0.06	0.08	0.1

difference ($\chi^2 = 3.8$/DOF) between pNe and pN data which indicates that the KNO distribution depends on the atomic mass number of a nucleus.

In order to verify this we studied the normalized moments of multiplicity distributions of secondary $n_\pm$ and negative particles as a function of n_p in pNe interactions. As we discussed previously in Sec. IV, the number of secondary protons produced in hA collisions can be an estimate of the average number of inelastic collisions $\langle\nu\rangle$. Then, if the KNO function does not depend on the mass number of a nucleus (this also implies independence of $\langle\nu\rangle$ because $\langle\nu\rangle \simeq A\sigma_{hN}/\sigma_{hA} \sim A^{1/3}$), the normalized moments of multiplicity distributions[32] $C_q = \langle n^q\rangle / \langle n\rangle^q$ ($q = 1, 2, \ldots$) should not change (at fixed q) with A (or $\langle\nu\rangle$). From Figs. 10(a)–10(c) we see that this is not the case. Data presented in Figs. 10(a)–10(c) show a clear evidence for dependence of C_q on the number of identified protons (or $\langle\nu\rangle$) in pNe interactions. If we assume $C_q = a + bn_p$, the fit results are shown in Table IV. Since n_p is related to $\langle\nu\rangle$ (see Table I) and $\langle\nu\rangle$ is related to $A^{1/3}$ (see above), we conclude that the dispersion of KNO distribution decreases as $\sim A^{1/3}$.

VII. CONCLUSION

In this work we have presented the first data obtained on the multiplicity of secondary charged particles produced in inelastic pNe interactions at 300 GeV/c. The main results obtained from this study are following: There is a reasonable agreement between predictions of the Shabelsky multiple-scattering model[9] and our experimental data on total inelastic and partial cross sections. The multiplicity distribution of secondary identified protons can be satisfactorily described by a model in which those protons are considered to be products of independent emission of nucleons involved in hA interactions. Within the framework of this model the number of protons can be used to estimate an average number of inelastic intranuclear collisions. It is found that among positively charged relativistic secondaries approximately 10 percent are fast ($p \gtrsim 1.2$ GeV/c) protons knocked out of the neon nucleus. We also observed that the KNO function of secondaries produced in pNe interactions depends strongly on the number of inelastic collisions. This fact is an evidence for a dependence of the KNO function on the atomic mass number of target.

ACKNOWLEDGMENTS

We express our gratitude to T.H. Burnett, V.G. Grishin, K.G. Gulamov, N.N. Nikolaev, V.M. Shekhter, and L. Vojvodic for useful discussions. We also thank Yu. M. Shabelsky who sent us his calculations according to the multiple-scattering model. We extend our appreciation to the scanning and measuring staffs at Tashkent and Wisconsin and to the 30-in. bubble-chamber crews at Fermilab. This work was supported in part by the U.S. Department of Energy.

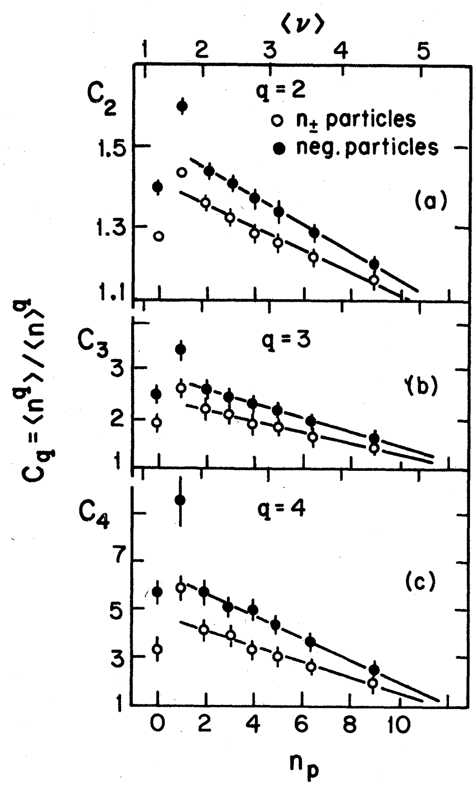

FIG. 10. The dependences of the normalized moments of multiplicity distribution for $n_\pm$ and negative particles in pNe interactions as a function of the number of identified protons. The upper scale corresponds to estimates of $\langle\nu\rangle$ (see Table I). The solid lines are linear fits to $C_q = a + bn_p$ with a and b as given in Table IV.

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