Multiple Pion Production in π-Ne Collisions at 10.5 and 200 GeV*

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We have measured the multiplicities of pions produced in the collisions of π mesons with neon nuclei at bombarding momenta of 10.5 and 200 GeV/c. The diffractive production of pions is clearly separable. If one excludes the diffractive part, the pion multiplicity obeys the same Koba-Nielsen-Olesen scaling as found previously for π^--p collisions. This fact would seem to indicate the validity of an energy-flux or collective-variable description of the production process. A surprisingly large number of energetic protons (> 1 GeV/c lab momentum) are found to be produced in π-Ne collisions.

We report results obtained from the study of π^--Ne collisions at 10.5 and 200 GeV/c. The studies were done in the 82-in. Stanford Linear Accelerator Center chamber at 10.5 GeV/c and the MURA-Fermilab 30-in. chamber at 200 GeV/c. In each case the bubble chamber was filled with a mixture of Ne and H_2 consisting of about 30 mole % Ne. The results presented are based on the analysis of 11 600 and 1600 events at 10.5 and 200 GeV/c, respectively.

Recently, several interesting facts have emerged from the study of hadron-nucleus collisions.[1] Of paramount importance is the fact that the ratio R_A, the multiplicity of pions produced in hadron-nuclear collisions as compared to hadron-nucleon collisions, is a small number, varying from 1.1 to 2.0 as the atomic number A changes from 10 to 200. Our results on π-Ne generally agree with and extend the previous proton-nuclear-emulsion (Ag, Br, C, N, and O) studies. The bubble-chamber technique has the advantages of a magnetic field and a single nuclear target.

Each event in the bubble chamber has N_h visually identified heavily ionizing proton tracks and n_s "shower" tracks (lightly ionizing or identified pions) making a total of N_h+n_s tracks that are separated in charge by the magnetic field. Heavy proton tracks are visually identifiable in the momentum interval from 0.1 to 1.0 GeV/c corresponding, respectively, to a track length greater than ~1 mm or to a track density greater than twice minimum. Protons above 1.0 GeV/c are removed from the shower tracks by considerations discussed below. The corrected shower tracks are then expected to be mainly mesons (~97% π mesons and 3% K mesons at 10.5 GeV/c). Events from π-p collisions, which occur only with an even number of tracks and with $N_h=0$ or 1, are subtracted from all distributions shown in this paper. This subtraction is easily done by using the known chamber-liquid composition and the known π-p multiplicities.

An unexpected phenomenon found in the π-Ne collisions is the production of many more lightly ionizing protons than would be expected if all protons were produced either by peripheral scattering of the incident pion or by the Fermi motion retained following the breakup of the nucleus. Evidence for energetic protons having laboratory momenta above 1 GeV/c is found by examining the net charge of the shower particles for each event. The net charge of the shower tracks is n_+-n_-, where n_+ and n_- are the numbers of positive and negative shower tracks, respectively. Figure 1 shows values for the average net charge, $\langle n_+-n_-\rangle$, versus n_s for the 10.5-GeV/c data; $\langle n_+-n_-\rangle$ is seen to grow linearly from near -1 for $n_s=2$ to ~0.8 for n_s=10. A preliminary study of the 200-GeV/c data gives the same results provided that $\langle n_+-n_-\rangle$ is plotted against the scaled multiplicity $n_s/\langle n_s\rangle$. If there were no fast protons among the shower tracks, then $\langle n_+-n_-\rangle$ would be expected to be near -1, the charge of the incident pion.[2] For n_s less than 6, the number of fast protons per event is small and an alternation in $\langle n_+-n_-\rangle$ is seen between even and odd values of n_s; these results are characteristic of π collisions with single protons or neutrons in the Ne

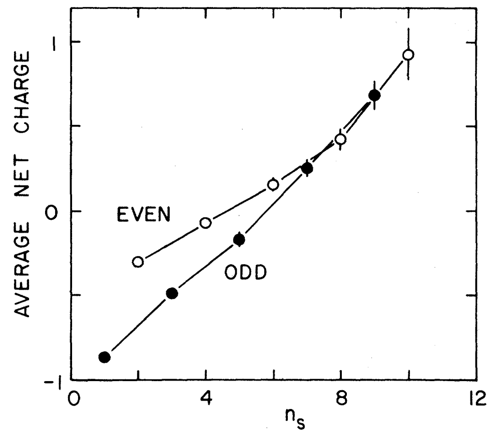

FIG. 1. The average net charge $\langle n_+ - n_- \rangle$ carried by "shower particles" (identified pions and lightly ionizing tracks) versus the number of shower particles n_s for 10.5-GeV/c π^- on neon. The average number of protons per event with momenta above 1.0 GeV/c is given approximately by $\langle n_+ - n_- \rangle + 1$ (see text).

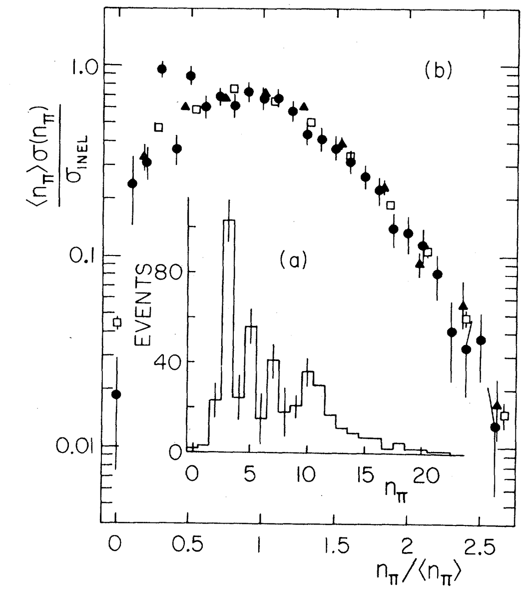

FIG. 2. (a) Distribution of charged-pion multiplicities for events having no protons. The error bars include the uncertainties in the removal of π^--p events and in the removal of events with energetic proton tracks. (b) Scaled pion multiplicity cross section for π^--Ne collisions at 200 GeV/c (solid circles) and 10.5 GeV/c (open squares). Also shown for comparison are the 200-GeV/c π^--p results of Ref. 5 (triangles). The Ne results have been corrected for the presence of energetic proton tracks. The π^--p multiplicities have also been adjusted by assuming that on the average there is 0.6 proton per event.

nucleus. As n_s is increased, the number of energetic protons per event steadily grows and reaches nearly 2 per event for $n_s = 10$. We stress that such a large number of fast protons cannot be explained by the kinematics of high-multiplicity π collisions with single nucleons. Rather it would appear that a large fraction of the energetic protons arise from multiple nucleon collisions in the Ne nucleus. To our knowledge, the production of energetic protons in nuclear collisions has not been discussed previously.[3]

We now turn to the multiplicity study of π-Ne collisions. In what follows we have corrected for the presence of unidentified protons using the above information on excess positive charge. All distributions are then in terms of the variables n_π, the number of charged pions per event, and N_p, the number of protons per event.[4] Figure 2(a) shows the n_π distribution for $N_p = 0$ in π^--Ne collisions at 200 GeV/c. The prominent features are the peaks at 3, 5, and 7 charged pions. Most of these events are the result of diffraction dissociation of the incident pion although the fraction of the events that leave the nucleus in the ground state is not known. At 200 GeV/c, the diffractive cross sections $\sigma_{\mathrm{diff}}(\pi^- \to n_\pi)_{\mathrm{Ne}}$, are found to be 14.5 ± 1.9, 6.0 ± 1.6, and 2.9 ± 1.6 mb for $n_\pi = 3$, 5, and 7, respectively, where a value of 270 mb for the π^--Ne inelastic cross section[6] has been used for normalization. The corresponding values at 10.5 GeV/c are 11.7 ± 2.3, 4.5 ± 1.9, and 1.0 ± 0.6 mb. We note that the diffraction cross section for $n_\pi = 3$, 5, and 7 at 200 GeV/c totals 23.4 ± 3.0 mb, as compared with an elastic π^--Ne cross section of 70 mb.[7] The ratio $\sigma_{\mathrm{diff}}(\pi^- \to n_\pi = 3, 5, 7)_{\mathrm{Ne}} / \sigma_{\mathrm{el}}(\pi^-\mathrm{Ne})$ is 0.35 ± 0.1, which within errors is equal to the same ratio for π^--p collisions at 200 GeV/c,[8] 0.41 ± 0.06.

Figure 2(b) shows the multiplicity spectra at 10.5 and 200 GeV/c, summed over all N_p, and plotted against the scaled multiplicity $n_\pi / \langle n_\pi \rangle$. The scaled multiplicity distributions are seen to be in excellent agreement with each other and are consistent with Koba-Nielsen-Olesen scaling[9] except for the low multiplicities where diffractive processes are important. The scaled pion multiplicities for π^--p at 200 GeV/c [5] are also plotted in Fig. 2(b). The close agreement for the different energies and targets is quite remarkable. Previously, Grishin *et al.*[1] noted a similar scaling for π^--C collisions at 40 GeV/c. Values for $\langle n_\pi \rangle$ and $D = (\langle n_\pi^2 \rangle - \langle n_\pi \rangle^2)^{1/2}$ are given in Table I.

TABLE I. Charged-pion–multiplicity distribution parameters for π^--Ne collisions at 10.5 and 200 GeV/c.

p (GeV/c)	$\langle n_\pi \rangle^a$	Dispersion[a] $(\langle n_\pi^2\rangle - \langle n_\pi\rangle^2)^{1/2}$	$R_{\rm Ne} = \dfrac{\langle n_\pi\rangle_{\pi{\rm Ne}}}{\langle n_\pi\rangle_{\pi p}}$ [b]
10.5	3.74 ± 0.06	2.04 ± 0.03	1.36 ± 0.04
			(1.20 ± 0.04)
200	10.0 ± 0.2	5.38 ± 0.15	1.35 ± 0.07
			(1.25 ± 0.07)

[a]Averaged over all N_p categories. Elastic and diffractive events removed.

[b]Values in parentheses are found if π^--p elastic events are removed in calculating $\langle n_\pi\rangle_{\pi p}$.

Close agreement is found for the ratio $\langle n_\pi\rangle/D$, 1.83 ± 0.04 and 1.86 ± 0.06, at 10.5 and 200 GeV/c, respectively. The fact that the multiplicity spectrum is close to the Koba-Nielsen-Olesen result implies that the multiplicity spectrum does not depend on whether the excitation occurs in one or several collisions. This picture agrees with the idea that the decay time required for the fireball or residuum of the incident hadron is considerably longer than the collision time. Thus the incident hadron can be excited (or possibly de-excited) by successive collisions in the nucleus.[10]

Values for $R_{\rm Ne}$ are also given in Table I. Our results on π-Ne are close to unity and are similar to those tabulated by Gurtu *et al.*[1] for proton-emulsion collisions. The small values of $R_{\rm Ne}$ are

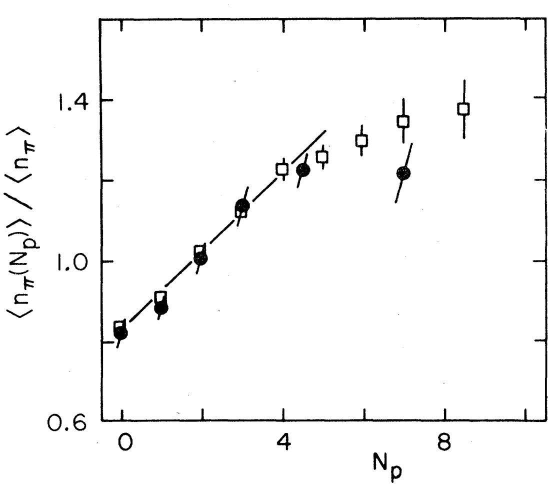

FIG. 3. Scaled values of the average pion multiplicity versus N_p, the number of protons per event, for π^--Ne interactions at 200 GeV/c (solid circles) and 10.5 GeV/c (open squares). N_p includes the energetic protons in addition to the visible protons.

consistent with the energy-flux-cascade model of Gottfried,[11] in which $R = 1 + \frac{1}{3}(\nu - 1)$, where $\nu = 1.7$ is the mean number of collisions in neon. Other types of formulas will reproduce these results also. A formula $R_A = \sqrt{\nu}$ describes the results acceptably. Gurtu *et al.*[1] give their results in terms of $R_A = A^{0.13}$. The last two formulas would be expected if a multistep excitation picture were correct.[10] However, models in which the produced particles cascade independently in the nucleus[12] appear to be incorrect.[13]

In Fig. 3 we plot the scaled average pion multiplicities versus N_p. The scaled distributions at both energies are in good agreement with each other and may be summarized by a linear relation $\langle n_\pi(N_p)\rangle/\langle n_\pi\rangle = 0.81 + 0.10 N_p$ for $N_p \le 5$. A similar result has been found in the proton-emulsion studies.[1] This linear relationship is probably correlated to an increase in the average number of interactions within the nucleus. However, for $N_p = 5$, the multiplicity stops growing probably because of the finite size of the Ne nucleus.

In conclusion, we find the same Koba-Nielsen-Olesen scaling to hold for π-Ne and π-p collisions over a wide range of energies. We also observe the production of energetic protons in π-Ne interactions, which we believe arise from multiple collisions in the nucleus.

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J. Hébert *et al.*, Phys. Lett. 48B, 467 (1974); A. Gurtu *et al.*, Phys. Lett. 50B, 391 (1974); R. E. Gibbs *et al.*, Phys. Rev. D 10, 783 (1974); P. L. Jain *et al.*, Phys. Rev. Lett. 33, 660 (1974); V. Grishin *et al.*, Dubna Report No. 7523, 1973 (to be published).

[2]We estimate the average net charge to be -0.9 ± 0.1, on the basis of a summation over single-step (πN) and double-step (πNN) processes in the nucleus, where known π-nucleon cross sections are used. The result is quite insensitive to the details of the calculation.

[3]The momentum spectrum of the protons above 1 GeV/c may be determined by subtracting charged-particle momentum spectra obtained from the charge-symmetric π^--Ne and π^+-Ne collisions. Such measurements will be reported later.

[4]If N_{fast} is the number of fast unidentified protons per event, then $n_\pi = n_s - N_{\text{fast}}$ and $N_p = N_h + N_{\text{fast}}$. Since the fast-proton tracks are not individually identified, these corrections are made in a statistical sense to the distributions involved.

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[6]J. C. Allaby *et al.*, Yad. Fiz. 12, 538 (1970) [Sov. J. Nucl. Phys. 12, 295 (1971)].

[7]The π-Ne elastic cross section was estimated by means of an optical-model calculation. The amplitude for scattering was assumed to be purely imaginary coming from the absorption cross section of 270 mb. A radius of $1.4A^{1/3}$ was assumed to be the nuclear radius.

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[11]K. Gottfried, Phys. Rev. Lett. 32, 957 (1974).

[12]Fishbane and Trefil, Ref. 10; A. Dar and J. Vary, Phys. Rev. D 6, 2412 (1972).

[13]An independent-particle cascade was done allowing for two generations in the neon nucleus. Experimentally determined π-nucleon multiplicities and rapidity distributions were used in the calculation. The values of R_{Ne} obtained were 1.2 at 10.5 GeV/c and 6 at 200 GeV/c.