Average Charged Multiplicity in $\pi^- + p \to \pi_{\text{fast}}^- + X$ at 147 GeV/c and Comparison with Other Reactions*

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The average charged multiplicity, $\langle n_x \rangle$, has been determined for $\pi^- + p \to \pi_{\text{fast}}^- + X$ at 147 GeV/c and is found to increase linearly with $|t|$ as well as $\ln M_x^2$. The coefficient of the $\ln M_x^2$ term is approximately equal to that for other reactions, but the absolute value of $\langle n_x \rangle$ is significantly smaller even when it is analyzed in terms of the energy available. This result is discussed in the framework of a simple model.

In this paper we present for the first time data on the dependence of the average charged multiplicity, $\langle n_x \rangle$, of the system X in the inclusive reaction

$$\pi^- + p \to \pi_{\text{fast}}^- + X \tag{1}$$

on the square of the invariant mass of X, M_x^2, and on the square of the four-momentum transfer, t, between the incoming and fast outgoing π^-. We have observed a statistically significant linear increase of $\langle n_x \rangle$ with $|t|$ as well as with $\ln M_x^2$. The coefficient of the $\ln M_x^2$ term is approximately equal to that for other reactions. However, differences are observed between the absolute values of the average charged multiplicity for different reactions even when the comparison is made in terms of the energy available. This result is discussed in the framework of a simple model.

The dependence of $\langle n_x \rangle$ on M_x^2 in inclusive reactions of the type $a + b \to c + X$ has previously been studied both theoretically and experimentally. A linear dependence of $\langle n_x \rangle$ on $\ln M_x^2$ has been predicted within several theoretical models.[1,2] The slope of this dependence is expected to be independent of s, t, and the type of the incident particle; and it is also expected to be identical to the slope of the linear increase with $\ln s$ of the average total charged multiplicity, $\langle n_c \rangle$, in hadron-hadron reactions.[2] These predictions have previously been verified for the reaction

$$p + p \to p + X \tag{2}$$

at energies equivalent to laboratory momenta between 100 and 1100 GeV/c at Fermilab[3] and the CERN intersecting storage rings (ISR),[4] and for the reaction

$$\pi^- + p \to p + X \tag{3}$$

at 205 GeV/c.[5] It is not possible to fit $\langle n_c \rangle$ for

$$p + p \to X \tag{4}$$

by a $\ln s$ term alone from $s = 20$ to 2800 GeV^2 but $\langle n_c \rangle$ for

$$\pi^- + p \to X \tag{5}$$

can be fitted by a $\ln s$ dependence for $s = 20$ to 750 GeV^2.[5,6] The various models also suggest a dependence of $\langle n_x \rangle$ on t but do not predict a unique functional form.[1,2] Studies of Reaction (2) at 205 GeV/c and $s = 1995$ GeV^2 and of Reaction (3) at 205 GeV/c indicated that $\langle n_x \rangle$ has a weak or no t dependence in these reactions.[4,7] It has previously been pointed out that when $\langle n_c \rangle$ is plotted for $p + p \to X$, $\pi^\pm + p \to X$, and $K^\pm + p \to X$ as a function of the energy, $Q = \sqrt{s} - m_a - m_b$, available for the reaction $a + b \to X$, all values lie approximately on a universal curve.[8] Whitmore and Derrick[9] have extended this idea to inclusive reactions of the type $a + b \to c + X$, where c is produced in the fragmentation region of the incoming particle a, and have plotted $\langle n_x \rangle$ as a function of $Q = M_x - m_b$. A roughly universal dependence of $\langle n \rangle$ on $\ln Q^2$ has been obtained for Reactions (2)–(5).[9]

This experiment was performed with a beam of 147-GeV/c π^- mesons resulting in an exposure of 105 000 pictures in the Fermilab 30-in. bubble-chamber–proportional-wire-chamber hybrid spectrometer. Details of the experimental arrangement and of the data reduction in this experiment have already been published.[6,10] From the total sample of 7218 inelastic events we have obtained a sample of 1867 inelastic events with a fast π^-, for which $x(\pi^-)$ [11] is greater than 0.5. This study was possible because of the momentum resolution ($\Delta p/p \lesssim 0.09$) of the hybrid system for fast forward particles. The details of this analysis will be presented in a later publication.

In Fig. 1 we present $\langle n_x \rangle$ as a function of $|t|$ for various M_x^2 intervals; significant increases in $\langle n_x \rangle$ as a function of $|t|$ are observed in all M_x^2 regions. The data for $M_x^2 > 20$ GeV^2 can all be fitted with a linear dependence on $|t|$; and within our uncertainties, the slopes of this dependence are independent of M_x^2. The dependence of

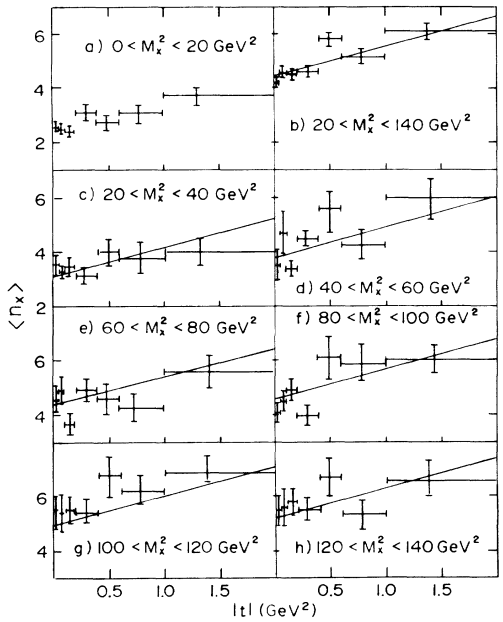

FIG. 1. The average charged multiplicity of the system X for Reaction (1) as a function of $|t|$ for (a) 0 GeV^2 $< M_x^2 <$ 20 GeV^2, (b) 20 GeV^2 $< M_x^2 <$ 140 GeV^2, and (c)–(h) various M_x^2 (>20 GeV^2) intervals. The straight lines are plotted from the two-dimensional function described in the text.

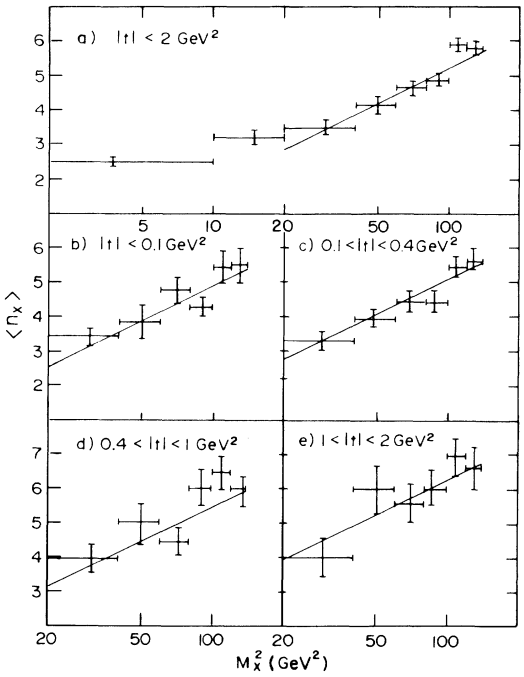

FIG. 2. The average charged multiplicity of the system X for Reaction (1) as a function of M_x^2 for (a) $|t|$ <2 GeV^2 and (b)–(e) various $|t|$ intervals. The straight lines are plotted from the two-dimensional function described in the text.

$\langle n_x \rangle$ on $\ln M_x^2$ for various t intervals is shown in Fig. 2; it is consistent with the linear behavior found previously[3-5] in Reactions (2) and (3) and predicted theoretically.[1,2] Within our uncertainties the slope of the dependence on $\ln M_x^2$ is independent of t. We have therefore carried out a two-dimensional fit to all the data for Reaction (1) in the kinematical region $|t| < 2$ GeV^2 and 20 GeV^2 $< M_x^2 <$ 140 GeV^2 with the expression $\langle n_x \rangle = A + B \ln M_x^2 + C|t|$. The best fit yielded the parameters $A = -1.77 \pm 0.61$, $B = 1.43 \pm 0.15$, and $C = 1.06 \pm 0.19$ with a χ^2 probability of 26%. The solid lines in Figs. 1 and 2 represent the fitting function; as one can see, all the data in Figs. 1 and 2 are satisfactorily described by this parametrization.

We have also carried out a two-dimensional fit to the data for Reaction (3) from this experiment and obtained the preliminary result $B = 1.47 \pm 0.15$. Our results for B in Reactions (1) and (3) may be compared with the values of the coefficient of the $\ln M_x^2$ or $\ln s$ terms from previous fits to $\langle n \rangle$ ($\langle n_x \rangle$ or $\langle n_c \rangle$, respectively) for Reactions (2)–(5); and the agreement is good.[7-9,12] The preliminary value of C we have obtained for Reaction (3) indicates that there is little dependence of $\langle n_x \rangle$ on t for this reaction, in agreement with previous results[7] and in contrast to the significant t dependence obtained for Reaction (1).

When we compare our results for $\langle n \rangle$ as a function of $\ln Q^2$ for Reactions (1) and (3) with the published results for Reactions (2) and (3) at 205 GeV/c [3,5] and Reactions (4) and (5) at energies corresponding to $Q^2 \leq 180$ GeV^2,[8] there are significant differences in the absolute values of $\langle n \rangle$. The data for these three pairs of reactions are shown in Figs. 3(a)–3(c), together with the results of fits with the expression $\langle n \rangle = A' + B' \ln Q'^2$ to the data for each reaction in the region of Q^2 shown. These fits were done in terms of the normalized variable $Q'^2 = Q^2/Q_M^2$, where Q_M^2 is the value of Q^2 at the center of the region fit, so that A' is equal to $\langle n \rangle$ at that point for each reaction. The systematic displacements between the fits for each of the three pairs of reactions, $\delta'(j)$, are thus given by the differences between the values of A' for each pair, and the values obtained are $\delta(\mathrm{i}) = 0.27 \pm 0.06$, $\delta(\mathrm{ii}) = 0.30 \pm 0.10$, and $\delta(\mathrm{iii}) = 0.55 \pm 0.12$ for (i) Reactions (5) and (4), (ii) Reactions (3) and (2), and (iii) Reactions (3) and (1), respectively.[13]

We have attempted to explain these differences

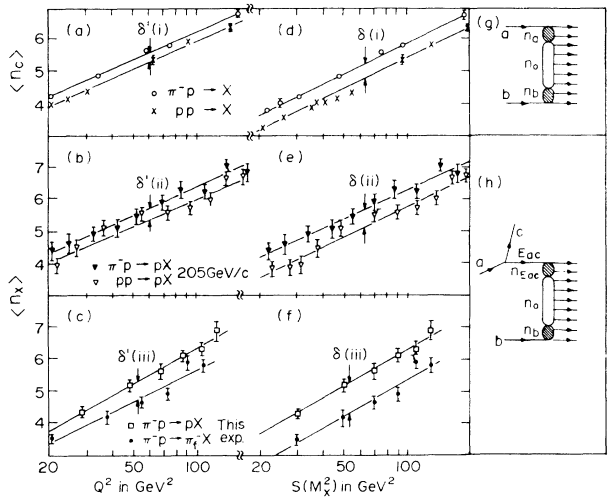

FIG. 3. (a) The average charged multiplicity as a function of $\ln Q^2$ for Reactions (4) and (5) (Ref. 8). The solid lines are calculated from the best fits of the expression $A' + B' \ln Q'^2$ to the data. The arrows labeled δ'(i) indicate the point at which the difference between the average multiplicities for this pair of reactions (i) was calculated. (b) Same as (a) for the pair (ii) of Reactions (2) and (3) at 205 GeV/c (see Refs. 3 and 5). (c) Same as (a) for the pair (iii) of Reactions (1) and (3) at 147 GeV/c; (d) The average charged multiplicity as a function of s for Reactions (4) and (5) (see Ref. 8). The solid lines are calculated from the best fits of the expression $A + B \ln E_x'^2$ to the data (see text). The arrows labeled δ(i) indicate the point at which the difference between the average multiplicities for this pair of reactions (i) was calculated. (e) Same as (d) with s replaced by M_x^2 for the pair (ii) of Reactions (2) and (3) at 205 GeV/c (see Refs. 3 and 5). (f) Same as (d) with s replaced by M_x^2 for the pair (iii) of Reactions (1) and (3) at 147 GeV/c. (g) Diagram for the total inelastic reaction $a+b \to X$ (see text). (h) Diagram for the inclusive reaction $a+b \to c+X$ (see text).

by a simple model which assumes that for any given reaction $a+b \to X$, the outgoing particles can originate from three distinct regions [Fig. 3(g)]: a central region, which is independent of particles a and b and where the average multiplicity n_0 increases with energy as $B \ln s$, and the fragmentation regions of particles a and b, where the average multiplicities n_a and n_b are presumably energy independent, but may depend on the nature of the fragmented particle.[14] Based on this description one obtains for the average charged multiplicity

$$\langle n \rangle = n_a + n_0 + n_b = n_a + B \ln s + n_b. \quad (6)$$

$\langle n_x \rangle$ for the single inclusive reaction, $a+b \to c+X$, may be described analogously where the process $E_{ac}+b \to X$ (E_{ac} is the exchanged particle) replaces $a+b \to X$ [see Fig. 3(h)]. Thus

$$\langle n_x \rangle = n_{E_{ac}} + n_0 + n_b = n_{E_{ac}} + B \ln M_x^2 + n_b. \quad (7)$$

Because of the virtual nature of E_{ac}, $n_{E_{ac}}$ (unlike n_a or n_b) may depend on the kinematic variables s, M_x^2, and t.[14] Using Eq. (6) for Reactions (4) and (5) and Eq. (7) for Reactions (1)–(3), the differences of the average multiplicities for the three pairs of reactions are predicted to be

$$\delta(\mathrm{i}) = \delta(\mathrm{ii}) = n_\pi - n_p, \quad (8)$$

$$\delta(\mathrm{iii}) = (n_\pi - n_p) + (n_{E_{pp}} - n_{E_{\pi\pi}}). \quad (9)$$

Figures 3(d)–3(f) show the data for $\langle n \rangle$ as a function of $\ln s$ or $\ln M_x^2$ for the six reactions together with the results of fits of the expression $\langle n \rangle = A + B \ln E_x'^2$ to the data. Here again the fit has been done in terms of a normalized variable $E_x'^2 = s/s_M$ [or $E_x'^2 = M_x^2/(M_x^2)_M$] where s_M [or $(M_x^2)_M$] is the value of s (or M_x^2) at the center of the region fit, so that A is equal to $\langle n \rangle$ at that point for each reaction. The systematic displacements between the fits for each of the three pairs of reactions, $\delta(j)$, are thus the differences between the values of A for each pair, and the values obtained are $\delta(\mathrm{i}) = 0.53 \pm 0.05$, $\delta(\mathrm{ii}) = 0.57 \pm 0.09$, and $\delta(\mathrm{iii}) = 0.89 \pm 0.12$. Thus, we find that within errors $\delta(\mathrm{i}) = \delta(\mathrm{ii})$, in agreement with the prediction of (8). The average of their two values gives $n_\pi - n_p = 0.55 \pm 0.05$. A similar result may be obtained from a study[15] of the reactions $\pi^+ + p \to \Delta^{++} + X$ and $p + p \to \Delta^{++} + X$ at 100 GeV/c. According to our picture, the difference between $\langle n_x \rangle$ for these reactions should also be equal to $n_\pi - n_p$. The experimental result is ~ 0.6, in good agreement with our value. From $n_\pi - n_p$ and the experimental value for δ(iii), we obtain from expression (9), $n_{E_{pp}} - n_{E_{\pi\pi}} = 0.34 \pm 0.13$.

We conclude that the average charged multiplicity $\langle n_x \rangle$ in the reaction $\pi^- + p \to \pi^-_{\mathrm{fast}} + X$ at 147 GeV/c can be parametrized as a linear function of $|t|$ and $\ln M_x^2$. The slope of the $\ln M_x^2$ dependence is very similar to those found for Reactions (2)–(5), but systematic differences are observed between the absolute values of the average charged multiplicities which persist when the data are analyzed in terms of the energy available. Comparison with the simple model described above indicates that the experimental results can be explained in terms of two differences: (1) a pion fragments on the average into more charged particles than a proton; and (2) a virtual exchanged object coupled to two protons fragments on the average into more charged particles than a vir-

tual exchanged object coupled to two pions.

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Observation of Meson-Exchange Effects in Deuteron Electrodisintegration

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Electrodisintegration of the deuteron has been measured for an incident energy of 300 MeV at 30° and 90° scattering angles. The maximum energy transfer was 116 MeV. Very good agreement with theory was achieved when the pionic-exchange currents were included. Near the threshold and for momentum transfer $\vec{q}_{c.m.}^{\,2} = 3.9$ fm^{-2}, the meson-exchange currents contribute about 40% to the total cross section.

The study of the interaction effects on electromagnetic processes in nuclei, i.e., the meson-exchange currents (MEC)[1] and nucleon off-mass-shell effects in the form of nuclear isobar configurations (IC),[2] has received considerable interest in the past years. Particular attention has been paid to few-nucleon systems,[3-7] because in these systems one can hope to keep uncertainties of the conventional nuclear structure small, which tend to cover up such interaction effects in the heavier nuclei.

The simplest system in this respect is the deuteron, which has the advantage that its structure in the nonrelativistic theory is well known. The disadvantage is that the deuteron is a rather dilute system, where interaction effects, which sensitively depend on the density, are expected to play a minor role. And in fact, very recent