Longitudinal- and Transverse-Momentum Distributions for π^- Mesons in 18.5-GeV/c $\pi^{\pm}p$ Interactions*

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New data are presented on the longitudinal- and transverse-momentum spectra of π^- mesons produced in both π^-p and π^+p interactions at 18.5 GeV/c. These distributions are studied as a function of the number of charged particles observed in the final states. The spectra are discussed in terms of relevant models and are compared with similar data from pp interactions. The data cannot be factorized into a simple product of independent functions of longitudinal and transverse momentum. The distributions suggest strongly that a simple quark-quark model is inadequate to explain multipion production.

The study of the characteristics of inelastic processes in hadron-hadron collisions at high energies is of current interest. At high energies, the inelastic processes are dominant, the production of resonances in any specific channel is small, and many particles are involved. It is of particular interest[1,2] to study processes such as

$$pp \to \pi + \text{anything},$$

$$\pi p \to \pi + \text{anything}.$$

The momentum spectra of pions produced in pp collisions have been studied rather extensively[3]; the information on the same spectra in πp collisions is limited.[4] We present new data on π^- production in the two reactions

$$\pi^+p \to \pi^- + \text{anything}, \tag{1a}$$

$$\pi^-p \to \pi^- + \text{anything}, \tag{1b}$$

at the same incident beam momentum, 18.5 GeV/c. These are, in the terminology of Feynman,[1] "inclusive processes" with no constraints on the final-state products.

Our data are based on 322 000 pictures of $\pi^{\pm}p$ interactions at 18.5 GeV/c in the Brookhaven National Laboratory (BNL) 80-in. hydrogen bubble chamber. We have measured the negative particles produced in each interaction. The analysis thus includes events with four or more visible prongs in π^+p interactions and two or more visible prongs in π^-p interactions. At present we have analyzed a total of 126 000 negative tracks, 62 000 for Reaction (1a) and 64 000 for Reaction (1b). In the following analysis we assume that all negative tracks correspond to π^- mesons. The negative tracks which are obviously strange particles from their decay were not measured. We have independently determined[5] the ratio of $\pi^+\pi^-:K^+K^-:p\bar{p}$ production in the four-body final state to be 100:3:1, and we estimate the nonpion contamination in the final sample to be at most a few percent.

Various authors[1,2] have suggested parametrizing multiparticle production processes in terms of the transverse and longitudinal momenta of the produced particles. Following Feynman, we define the quantity x as

$$x = p_{\parallel}/p_0, \tag{2}$$

where $p_{\parallel}$ is the longitudinal momentum of a secondary particle in the overall c.m. system and p_0 is the c.m. momentum of the incident pion. Here x is positive (negative) when $p_{\parallel}$ and p_0 are in the same (opposite) directions.

Distributions of the transverse momentum Q exhibit dependence on the prong number n and on x. Figure 1(a) shows distributions of Q^2 for $0.0 < x < 0.1$ as a function of prong number n in π^+p reactions; Fig. 1(b) shows Q^2 distributions for several ranges of x in π^+p interactions with $n = 4$. Steep slopes at small Q^2 are observed for all values of n when $|x|$ is small. The slopes at low Q^2 become less steep for larger $|x|$. The π^-p data exhibit virtually identical features. The distributions for other n are similar in both the π^+p and the π^-p interactions.

For small positive x, the strong peaks at low Q^2 are as prominent in π^+p as in π^-p interactions. Yen and Berger[6] have suggested that such peaks are caused primarily by peripheral production of low-mass resonances. Such resonances should be more important for low-multiplicity interactions and, in the forward direction, are expected to be predominantly of the same charge as the incident particle. The peaks should thus be smaller for forward-produced π^- from π^+p than from π^-p interactions if meson resonances are responsible, in contradiction to what is observed. We also note that Abolins *et al.*[7] have observed a sharp peak at low Q^2 in the proton momentum dis-

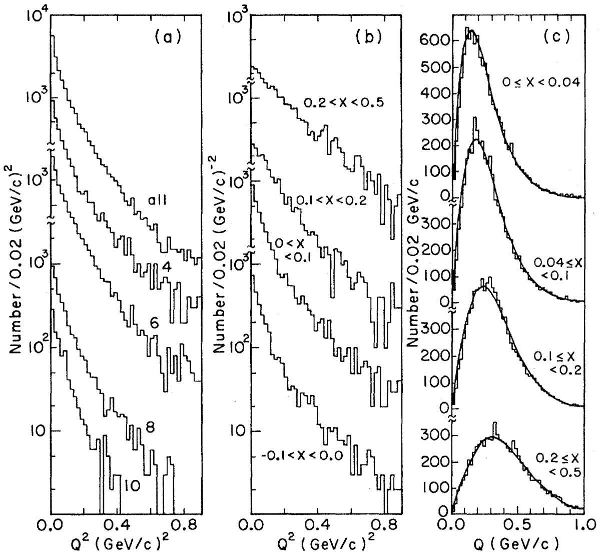

FIG. 1. Distributions of the transverse momentum Q for π^+p interactions: (a) dN/dQ^2 distributions with $0<x<0.1$ for all-, four-, six-, eight-, and ten-prong events separately; (b) dN/dQ^2 distributions for four-prong events with $0.1<x<0.0$, $0.0<x<0.1$, $0.1<x<0.1$, and $0.2<x<0.5$; (c) dN/dQ distributions for combined data (all prongs) with $0.0<x<0.04$, $0.04<x<0.10$, $0.10<x<0.20$, and $0.20<x<0.50$. The curves are described in the text.

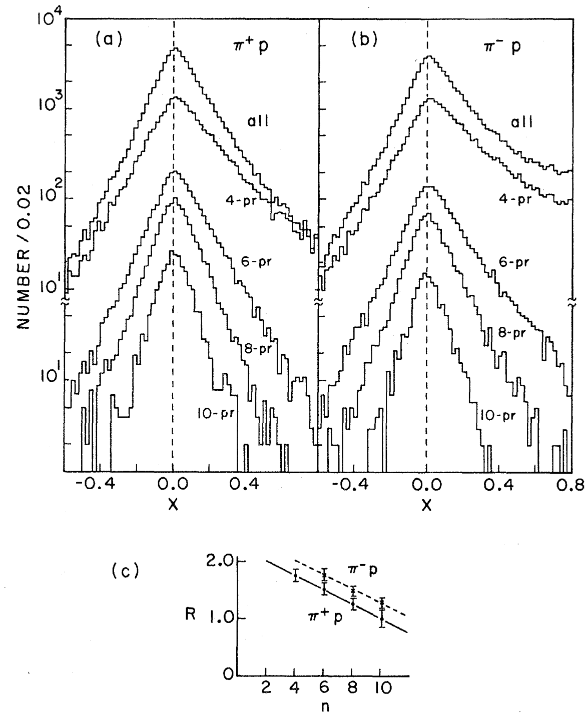

FIG. 2. Distributions in the longitudinal-momentum variable x: (a) dN/dx for π^+p data for all-, four-, six-, eight-, and ten-prong events; (b) dN/dx for π^- data for all-, four-, six-, eight-, and ten-prong events; (c) dedendence of R (see text) on prong number n for π^+p and π^-p data.

tribution in pp interactions involving K-meson production. As pointed out by these authors, the application of the Yen-Berger model to these events might imply the existence of a low-energy Z^* baryon resonance which has not been observed. However, Berger has suggested that in both experiments the peaks might be explained by peripheral production of baryon resonances.

To display the region of low transverse momentum in greater detail, we show in Fig. 1(c) Q distributions for π^+p data for all n and for different ranges of x. These distributions show a shift in the position of the peak towards higher Q and a broadening of the peak with increasing $|x|$. These features correspond to the increase in slope of the Q^2 distributions at low Q^2 observed in Fig. 1(b) for small $|x|$. According to the thermodynamical model of Hagedorn, the Q distribution should be x dependent, and in its simplest form[8] is given by

$$dN/dQ = kQ[\exp(E/T)-1]^{-1}dx, \qquad (3)$$

where $E=[Q^2+(xp_0)^2+m_\pi^2]^{1/2}$. Since the x binning of the data is broad, it was not sufficient to evaluate Eq. (3) at a mean value of x for each bin. We therefore numerically integrated over each x bin, weighting Eq. (3) by the observed x distribution of the data. The smooth curves in the figure show these fits. We find that the x dependence of the Q distributions for all n can be quantitatively described by expression (3). Acceptable values of χ^2 could not be obtained if the factor -1 was neglected. In fitting the data, good fits[9] for all of these distributions were obtained with a single value of $T=0.118$ GeV. It was not possible to obtain as good a fit to either the negative x region or the π^-p data. To what extent these fits are relevant to a thermodynamic interpretation of the data is not clear.

We present x distributions for π^+p and π^-p interactions in Figs. 2(a) and 2(b), respectively. In each case, distributions for all events as well as for four-, six-, eight-, and ten-prong events are shown. The distributions are asymmetric, being less steep for $x>0$ than for $x<0$. This effect is somewhat more pronounced for π^-p interactions but is also evident for π^+p. Thus an interpretation of the entire asymmetry in terms of a very simple "leading-particle" picture in which the beam particle continues in the forward direction will not explain the data. In both π^+p and π^-p

interactions the x distributions for high multiplicity approach symmetry about $x=0$.

The asymmetry of the longitudinal-momentum distributions is dependent on the frame of reference. This asymmetry decreases as one goes from the laboratory system to the c.m. system. This suggests that a reference frame may exist in which the longitudinal-momentum distribution is symmetric about zero. To describe such a system, we define a quantity R as

$$R = |p_t/p_{\rm in}|, \tag{4}$$

where p_t and $p_{\rm in}$ are the momenta of the target and the incident particle. (We require p_t and $p_{\rm in}$ to be collinear. Here $R=0$ defines the laboratory system and $R=1$ defines the c.m. system.) We have investigated the distributions of the longitudinal momentum p_L, in Lorentz frames corresponding to different values of R. In Fig. 2(c) we show the value of R for which the p_L distribution approaches symmetry as a function of n for π^+p and π^-p interactions. The value of R decreases monotonically for increasing n in both π^+p and π^-p interactions[10] and approaches the value 1 for large n. This suggests the relevance of the c.m. system in describing high-multiplicity events. If a simple picture of quark-quark interactions[11] is assumed to account for pion production, the value of R is expected to be $\frac{3}{2}$ for πp interactions. Although $\langle R\rangle \approx \frac{3}{2}$ for $n \geq 4$ in π^+p and $n \geq 6$ in π^-p interactions, it is clear that the dependence of R on n cannot be explained in terms of a simple quark-quark model.[12]

In order to provide a comparison with previously published results,[13] we have fitted the Q distributions with the function

$$dN/dQ = CQ^{3/2}\exp(-aQ) \tag{5}$$

and have determined a as a function of n and x. We have fitted the x distributions with the function

$$dN/dx = C\exp(-b|x|) \tag{6}$$

and have determined b as a function of n and Q^2. The fitted parameters are shown in Fig. 3. Since the x distributions are not symmetric, values of b for $x<0$ and $x>0$ are presented separately. Function (5) fits the data rather well in the region $0.06 \leq Q \leq 1.0$ (GeV/c) and function (6) fits well for $0.02<|x|<0.4$. The fitted curves deviate significantly from the data beyond these regions.

The straight lines shown in Figs. 3(a), 3(c), 3(e), and 3(g) provide reasonably good descriptions of the variation of these parameters; the curves on the other figures are shown to guide the eye.

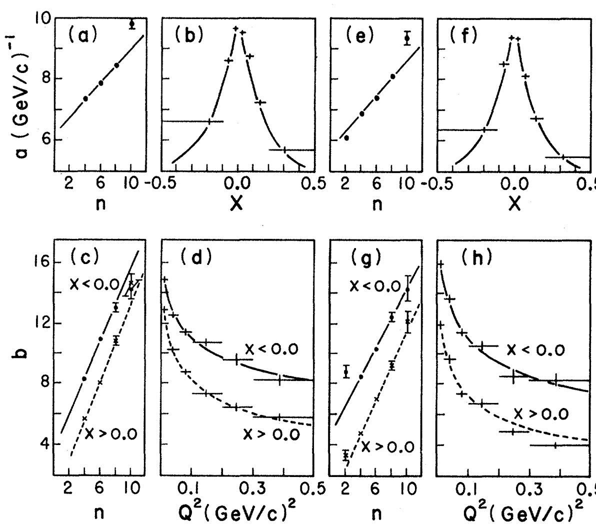

FIG. 3. Dependence of fitted parameters a and b: (a) a as a function of n, (b) a as a function of x, (c) b as as a function of n, and (d) b as a function of Q^2, all for π^+p data. The corresponding parameters for the π^-p data are shown in (e)-(h).

The dependence of a on x and of b on Q, shown in Figs. 3(b), 3(d), 3(f), and 3(h), indicates that $d^2\sigma/dx\,dQ^2$ *cannot be factorized* into independent functions of x and Q^2. We also find that $(d^2\sigma/dx\,dQ^2)E$ cannot be factorized into independent functions of x and Q^2.

In Table I we compare our data with results for π^- production in pp collisions[14] at the same c.m. incident momentum. The values of b for $x<0$ in both π^+p and π^-p interactions are in qualitative agreement[15] with values for the pp data.

In summary, we present extensive new data on π^- production in π^+p and π^-p interactions at the high energies studied. We have studied the transverse-momentum distribution as a function of prong number and of longitudinal momentum, and the longitudinal-momentum distribution as a function of prong number and of transverse momentum. We point out that (a) the *backward* π^- production data in $\pi^\pm p$ interactions are in rather good agreement with pion production in pp interactions indicating that fragmentation of the proton is similar for πp and pp interactions. (b) The dependence of a on x and of b on Q indicates that $d^2\sigma/dx\,dQ^2$ does not factorize in any simple way. (c) In π^+p interactions there is a strong peak at low Q^2 for negative pions with small positive longitudinal momentum; this peak is as large as the peaks in corresponding distributions for π^-p

Table I. Values of b in the expression $dN/dx = C\exp[-b|x|]$ for $x<0$.

Number of prongs, n	π^-p	b π^+p	pp[a]
All	9.83 ± 0.08	10.29 ± 0.07	
2	8.82 ± 0.34		
4	8.44 ± 0.10	8.36 ± 0.10	7.29 ± 0.10
6	10.32 ± 0.14	10.89 ± 0.12	10.08 ± 0.20
8	12.44 ± 0.26	13.02 ± 0.23	12.80 ± 0.34
10	14.30 ± 0.79	14.24 ± 0.60	

[a]The values for the pp data have been interpolated to yield values corresponding to the same c.m. momentum as that of the πp experiment.

interactions and cannot be explained by peripheral production of meson resonances. (d) The Q distributions can be quantitatively described by the function (3) for a wide range of x.

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[1]R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969).

[2]J. Benecke, T. T. Chou, C. N. Yang, and E. Yen, Phys. Rev. 188, 2159 (1969).

[3]Experiments performed at the Argonne National Laboratory, BNL, CERN, and Serpukhov have been summarized by S. D. Drell, summary talk in the *Proceedings of the International Conference on Expectations for Particle Reactions at New Accelerators, Madison, Wis., April 1970* (Physics Department, University of Wisconsin, Madison, Wis., 1970).

[4]A. R. Erwin, in *Proceedings of the International Conference on Expectations for Particle Reactions at New Accelerators, Madison, Wis., April 1970* (Physics Department, University of Wisconsin, Madison, Wis., 1970); J. W. Elbert, A. R. Erwin, S. Mikamo, D. Reeder, Y. Y. Chen, W. D. Walker, and A. Weinberg, Phys. Rev. Lett. 20, 124 (1968).

[5]E. A. Harrington, thesis, University of Notre Dame, 1971 (unpublished); see also Proceedings of the Fifteenth International Conference on High Energy Physics Kiev, U.S.S.R., 1970 (Atomizdat., Moscow, to be published).

[6]E. Yen and E. L. Berger, Phys. Rev. Lett. 24, 695 (1970).

[7]M. A. Abolins, G. A. Smith, Z. M. Ma, E. Gellert, and A. B. Wicklund, Phys. Rev. Lett. 25, 126 (1970).

[8]R. Hagedorn, Nuovo Cimento, Suppl. 3, 147 (1965).

[9]A total χ^2 of 204 for 192 degrees of freedom is obtained for the composite of the four fits shown.

[10]The values of R for $n=2$ and $n=4$ for the π^-p data have not been plotted in Fig. 2(c) since the x distribution cannot be made symmetric about zero. This is presumably associated with the presence of leading particles in these final states.

[11]H. Satz, Phys. Lett. 25B, 220 (1967).

[12]J. W. Elbert, A. R. Erwin, and W. D. Walker, to be published.

[13]D. B. Smith, R. J. Sprafka, and J. A. Anderson, Phys. Rev. Lett. 23, 1064 (1969).

[14]The pion spectra from pp data have been fitted (see Ref. 13) to the expression $dN/dp_{\parallel} = C\exp[-b'p_{\parallel}]$. The quantity b' is related to b of expression (6) by $b' = b/p_0$.

[15]In a recent preprint, W. Ko and R. L. Lander study the reaction $K^+p \to \pi^-$+anything, at 11.8 GeV/c, and for $x<0$ fit dN/dx with the slope $b = 10.6\pm0.7$, in good agreement with our value $b=10.29\pm0.07$ for the π^+p interaction (all prongs).