Valence- and sea-quark distributions in the pion

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We apply the quark-recombination model to the low-p_T π^+ and π^- production data in π^-p interactions at 200 GeV/c. We find that the known quark distributions in the proton can account for the pion production in the backward hemisphere. We then obtain information on the valence- and sea-quark distributions in the pion using the forward-hemisphere pion production data.

Recently the quark-parton model has been applied to single-particle inclusive production in the low-p_T region.[1,2] According to this model, low-p_T meson production proceeds predominantly via the quark-antiquark-recombination process; e.g. in baryon fragmentation to mesons a valence quark q picks up a sea antiquark $\bar{q}$ to form a meson. This mechanism has by now been extensively used to explain the production of various hadrons in pp collisions.[3] The most attractive feature of the model is that it is simple and that it can predict[4] some significant features in the hadron production at low p_T. Some of these predictions have been already verified[5] by experimental data, and other experiments are now being undertaken for testing the model in detail.

So far, the model has not been applied to low-p_T hadron production in the pion fragmentation region. In this paper, we apply the quark-recombination model to $\pi^\pm$ production in π^-p interactions at 200 GeV/c. We show that the proton-fragmentation data are consistent with the model and then, using the model, we obtain information about the quark distributions in the pion from $\pi^\pm$ production data in the forward hemisphere.

The data sample used in this paper was obtained at Fermilab using the facilities of a hybrid system[6] consisting of the Fermilab 30-in. hydrogen bubble chamber in combination with a set of wide-gap optical spark chambers. The events containing fast tracks in the forward direction trigger the spark chamber system. The momenta of these fast-forward tracks are determined from the combined bubble-chamber and spark-chamber measurements yielding $\Delta p/p \approx 10\%$ at $p = 200$ GeV/c. The data sample consists of ~17 000 events of all topologies (ranging from 2 to 22 outgoing charged tracks) in π^-p interactions at 200 GeV/c. Particles having no obvious kinks and with momentum greater than 1.4 GeV/c are assumed to be pions. For positively charged particles with $p < 1.4$ GeV/c, ionization information was used to discriminate between protons and pions.

We discuss here the inclusive pion production data in terms of the model of Das and Hwa.[1] According to this model, the production of a meson as a function of Feynman $x = 2p_\parallel/\sqrt{s}$ is given by

$$f(x) \equiv \frac{E d\sigma}{\sigma_T dp_\parallel} = c\left(\frac{1-x}{x}\right)\int_0^x F_q(x')F_{\bar{q}}(x-x')dx' , \qquad (1)$$

where $F(x')$ is the x distribution of the quarks in the incident hadron. For pion production in the backward hemisphere ($x<0$, F_q and $F_{\bar{q}}$ correspond to quark and antiquark distributions in the proton. For forward pion production ($x>0$), these functions correspond to appropriate quark and antiquark distributions in the pion.

First, we investigate whether the pion production in the backward (proton-fragmentation) hemisphere in π^-p reactions can be adequately described by the quark-parton model. In this case, the functions $F_q(x')$ and $F_{\bar{q}}(x')$ are treated as completely known. For valence u and d quarks in the proton, we use the quark functions given by Field and Feynman[7] (derived from deep-inelastic ep scattering data). We assume the sea-quark [both $u(\bar{u})$ and $d(\bar{d})$] distributions to be given by the form $F_s(x') = 1.2(1-x')^8$ consistent with the results of Duke and Taylor[3] obtained from the

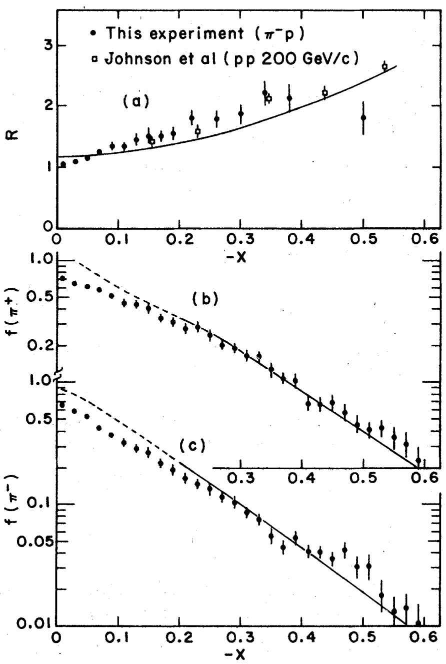

FIG. 1. (a) The ratio $R=f(\pi^+)/f(\pi^-)$ as a function of x for proton fragmentation ($x<0$) in $\pi^- p$ and pp interactions at 200 GeV/c; (b) $f(\pi^+)=(E/\sigma_T)\,[d\sigma(\pi^+)/dp_{\parallel}]$ for $x<0$ in 200-GeV/c $\pi^- p$ interactions; (c) $f(\pi^-)=(E/\sigma_T)\,[d\sigma(\pi^-)/dp_{\parallel}]$ for $x<0$ in 200-GeV/c $\pi^- p$ interactions. For $|x|<0.2$, the model calculations (shown dotted) are not reliable.

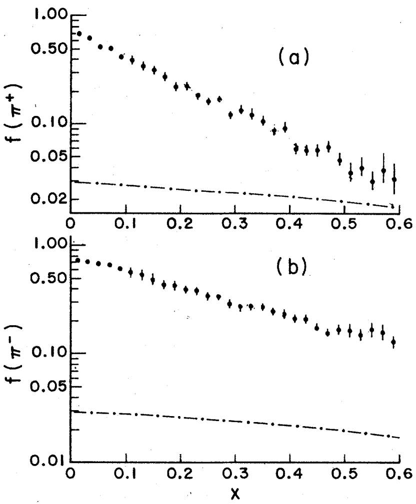

FIG. 2. (a) $f(\pi^+)$ and (b) $f(\pi^-)$ for $x>0$ in 200-GeV/c $\pi^- p$ interactions. The dot-dashed curves represent the estimated contributions from resonance production (see text).

analysis of meson production in pp interactions. Using these functions, we have computed $R=f(\pi^+)/f(\pi^-)$ as a function of x. Study of the ratio R has the advantage that factors which are not completely established, such as phase-space factors and recombination functions, are expected to be similar for π^+ and π^- production and should cancel as discussed by Duke and Taylor.[3] In Fig. 1(a), we show the π^+/π^- ratio for $\pi^- p$ data and for the pp data of Johnson *et al.*,[8] along with the calculated curve. Note that the two data sets agree reasonably well,[9] and hence it is no surprise that the same quark functions can describe both the pp and πp data. In Figs. 1(b) and 1(c), we show the experimental values of $f(\pi^+)$ and $f(\pi^-)$ in $\pi^- p$ interactions as a function of x, together with the curves calculated using Eq. (1). We find that the parton model accounts rather well for the proton fragmentation to π^+ and π^- in the region[10] $0.2 \lesssim |x| \lesssim 0.6$. We emphasize again that the curves of Fig. 1 do not represent a new fit to our $\pi^- p$ data, but are the results of the fit by Duke and Taylor[3] to pp data.

We turn now to the discussion of pion production in the forward c.m. hemisphere ($x>0$). In Figs. 2(a) and 2(b) we present the experimental $\pi^\pm$ production distributions $f(\pi^+)$ and $f(\pi^-)$ as a function of Feynman x ($x>0$). Roberts, Hwa, and Matsuda[11] have examined the possible effects of resonance production of the inclusive pion distiributions in the proton-fragmentation region. They conclude that the resonance contribution does not spoil the phenomenological success of the recombination model, although it complicates the use of the simple model of Das and Hwa. In the case of pion fragmentation, however, the effects of resonance production are of greater importance. From a study of inclusive double-charge-exchange π^- production at $x>0$ in $\pi^+ p$ interactions at 100 GeV/c, Cutts *et al.*[12] have shown that resonance contributions to inclusive $\pi^\pm$ production at large values of x are not negligible. Using their estimates for the $\pi^\pm$ production from ρ^0 and f^0 resonance production and decay we have estimated[13] the contributions from resonance decays to $f(\pi^+)$ and $f(\pi^-)$ for our data as shown by dot-dashed curves in Figs. 2(a) and 2(b). Some idea of the effects of the resonance contribution can be seen by studying our data in two different ways: (a) We will neglect resonance production and use $f(\pi^+)$ and $f(\pi^-)$ as shown in Fig. 2. (b) We will subtract out the estimated resonance contribution shown separately in Fig. 2 from the observed $f(\pi^+)$ and $f(\pi^-)$.

Since the valence-quark distributions in the pion are not as well determined as those in the proton, we will use the following procedure for our analysis of pion production in the forward (pion fragmentation) hemisphere. For the valence quarks (d and $\bar{u}$) in the incident π^-, we will assume a certain distribution and for each of the sea quarks and antiquarks (d, $\bar{d}$, u, $\bar{u}$), we will use a form $F_s=A(1-x')^N$. We will then vary both A and N to obtain the best description of the π^+/π^- ratio R as

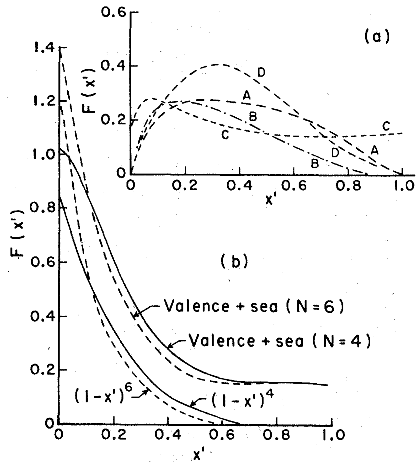

FIG. 3. (a) Pion valence-quark distributions A–D as defined in Table I are plotted as functions of x'. (b) Pion sea-quark distributions of the form $A(1-x')^N$, normalized to saturate the momentum sum rule when combined with Field-Feynman valence-quark distributions C. Also shown are the corresponding (valence+ sea) distributions for a $\bar{u}$ or d quark in a π^- meson.

a function of x. However, the choice of A and N is not entirely arbitrary. If the total momentum fraction carried by the valence quarks is f_v, then the momentum fraction carried by the sea quarks must be $\leqslant 1-f_v$, and hence (neglecting strange sea quarks which are not expected to carry a significant fraction of the momentum of a pion) we have the constraint that

$$f_s = 4\int_0^1 F_s(x')dx' = 4A/(N+1)$$

must be $\leqslant 1-f_v$.

In Fig. 3(a) we show the variation with x' of the four functions we have used to represent the valence-quark distributions $F_v(x')$ of the pion. Further information on these functions is presented in Table I. Distributions A and B correspond to simple functions of x' having forms which are physically not unreasonable. Distribution C represents the Field-Feynman parametrization for the pion valence-quark distributions which approaches a constant value at large x', in contrast to the Field-Feynman distributions for proton valence quarks which vary as $(1-x')^3$ for u quarks and $(1-x')^4$ for d quarks as $x' \to 1$. Distribution D represents a parametrization suggested by Dao *et al.*[14] on the basis of data for dimuon production in πp interactions and an assumed Drell-Yan production mechanism. In calculating distributions of R with the model, each assumed valence-quark distribution is normalized so that $\int_0^1 [F_v(x')/x']dx' = 1$. The total momentum fraction f_v carried by the valence quarks is given by $2\int_0^1 F_v(x')dx'$. Using each assumed valence distribution we vary A and N in the sea-quark distributions subject to the constraint imposed by the momentum sum rule. The limits on the allowed sea-quark momentum fraction f_s are shown in Table I. Using each valence distribution we have calculated distributions of R for values of N varying from 2 to 6 in steps of $\Delta N = 1$. The value of A has been varied within allowed limits to give the best fit to the data. In every case the best agreement with the experimental R values was obtained using the maximum allowed value of A, A_{max}. In Fig. 3(b) are shown typical sea-quark distributions for $N=4$ and $N=6$ as well as corresponding (valence + sea) distributions for $\bar{u}$ or d quarks in the π^-. The Field-Feynman distributions have been used, with the corresponding $A = A_{max}$ for the sea quarks.

In Figs. 4(a)–4(d) we compare the distributions determined from the recombination model with the distributions for R obtained using the experimental $f(\pi^+)$ and $f(\pi^-)$. Resonance contributions are not subtracted. Even with the largest sea-quark contributions allowed by the momentum sum rule the curves obtained from the model tend to fall some-

TABLE I. Assumed pion valence-quark distributions and constraints for sea-quark distributions of the form $F_s(x') = A(1-x')^N$.

	Valence distribution[a] $F_v(x')$	Total valence momentum f_v	Constraint on total sea momentum[d] f_s	A_{max} for $N=4$	A_{max} for $N=6$
A	$(\frac{3}{4})\sqrt{x'}(1-x')$	$\frac{2}{5}$	$f_s \leqslant \frac{3}{5}$	0.75	1.05
B	$(\frac{15}{16})\sqrt{x'}(1-x')^2$	$\frac{2}{7}$	$f_s \leqslant \frac{5}{7}$	0.89	1.25
C	Field-Feynman[b]	0.32	$f_s \leqslant 0.68$	0.85	1.19
D	Dao *et al.*[c]	0.42	$f_s \leqslant 0.58$	0.72	1.02

[a] $F_v(x')$ satisfies the condition $\int_0^1 [F(x')/x']dx' = 1$.
[b] See Ref. 7.
[c] See Ref. 14.
[d] $f_s = 4A/(N+1)$.

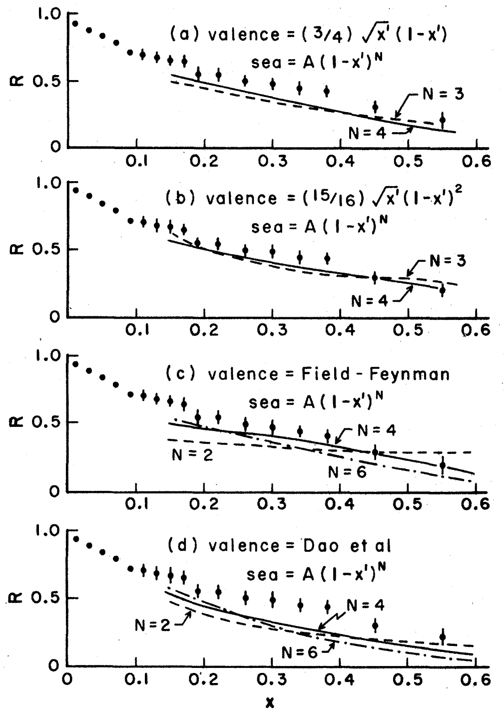

FIG. 4. (a)–(d) The ratio $R=f(\pi^+)/f(\pi^-)$ as a function of $x>0$ in 200 GeV/c π^-p interactions is compared with calculated distributions from the recombination model described in the text using valence- (A–D) and sea-quark distributions described in Table I. The values of R are calculated directly from the experimentally determined $f(\pi^+)$ and $f(\pi^-)$.

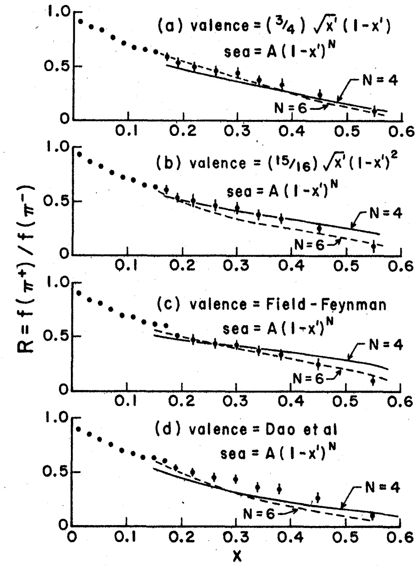

FIG. 5. (a)–(d) The ratio $R=f(\pi^+)/f(\pi^-)$ as a function of $x>0$ in 200 GeV/c π^-p interactions is compared with calculated distributions from the recombination model described in the text using valence- (A–D) and sea-quark distributions described in Table I. The values of R were calculated from data for $f(\pi^+)$ and $f(\pi^-)$ after subtraction of estimated contributions from resonance decays.

what below the experimental points, although valence-quark distributions B and C together with sea-quark distributions calculated for $N=4$, Figs. 4(b) and 4(c), provide a reasonable description of the data.

In Figs. 5(a)–5(d) are shown comparisons between the recombination model distributions and values of R obtained after subtraction of the estimated resonance decay contributions from $f(\pi^+)$ and $f(\pi^-)$. Agreement with the predictions of the model is better. Descriptions of the data seem to be satisfactory with any of the valence-quark distributions A, B, or C. Sea-quark distributions with $N=6$ appear to provide the best fit when valence distributions A or C are used. The valence distribution D of Dao *et al.*[14] does not allow as good a fit to our data; even with $A=A_{max}$ the calculated values of R lie below the experimental points. We note that this parametrization has also been criticized by Georgi[15] on other grounds.

The comparison between our data and the model is expected to be most significant in the region $0.2 \leq x \leq 0.6$ where the agreement is good. In the region $|x| \leq 0.2$ the simple recombination model used here is not expected to be valid.[3] At $x \geq 0.6$ the available data do not provide stringent enough limits on R to allow a choice between valence-quark distributions A, B, and C at the present time.

We conclude that even the simple version of the recombination model can provide an adequate description of available data for π^+ and π^- meson production in the fragmentation regions in π^-p interactions. Reasonable agreement can be obtained either when resonance decay contributions are ignored or when estimated resonance contributions are removed from the data. In either case, the following is evident: (a) The $\pi^\pm$ production in the proton-fragmentation region in both π^-p and pp interactions can be described in terms of the same valence- and sea-quark distributions. A satisfactory fit in both cases is provided by the Field-Feynman proton valence-quark distributions combined with sea-quark distributions which vary approximately as $(1-x)^8$. The sea-quark distributions must be normalized so that the momentum sum rule is saturated. (b) The $\pi^\pm$ production in the π^- fragmentation region in π^-p interactions can be described with pion valence-quark distributions similar to those suggested by Field and Feynman at least in the region $0.2 \lesssim x \lesssim 0.6$. Distributions differing greatly from these will not provide a good description of the data. The pion sea-quark distributions required by our analysis vary as $(1-x)^N$ with $N=4$–6 in contrast with $N=8\pm 1$ for protons. Again the required normalization saturates the momentum sum rule.

From the results stated above we find that the most probable momenta for both valence and sea quarks in the pion are larger than the corresponding values for quarks in the proton. The saturation of the momentum sum rule required to obtain agreement with meson production data for both pion and proton fragmentation is consistent with the production of low-p_T mesons over a time span long enough to allow the production of virtual quark-antiquark pairs from gluons and the subsequent interaction of these virtual constituents. Thus, the combination of more precise data for low-p_T meson production in hadronic interactions and more detailed recombination models promises to provide information on the quark-parton structure of hadrons complementary to the information obtained from lepton-hadron interactions and from large-p_T particle production. In such studies of low-p_T hadrons one obtains a picture of an "enhanced" sea to compare with the picture of the "instantaneous" sea obtained by other means. Further detailed information may also be obtained from studies of correlations among the produced hadrons.[5]

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[9]The pp data (Ref. 8) correspond to a fixed p_T; our data are summed over all p_T. We note that to a good approximation the invariant inclusive cross section factorizes in terms of x and p_T (see discussion in Ref. 8), so a comparison can be made.

[10]The model predictions deviate from the data for $|x|\leq 0.2$; however, the model is not expected to be valid in this region. See Ref. 3.

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[13]Resonance production cross sections as a function of x are estimated in Ref. 12. for two different values of p_T. Assuming that the cross section varies as $\exp(-\alpha p_T^2)$, we have integrated the invariant cross section over p_T^2 to obtain estimates of resonance contributions to pion production as a function of x. We have assumed the ρ^0 and f^0 production to be the same in 200-GeV/c $\pi^- p$ interactions as in 100-GeV/c $\pi^+ p$ interactions. We note that recent studies of ρ^0 production in $\pi^- p$ interactions at 100, 200, and 350 GeV/c [P. D. Higgins *et al.*, Phys. Rev. D 19, 65 (1979)] indicate that the inclusive ρ^0 production cross section does not vary rapidly with energy in this range.

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