[14]Preliminary results from this experiment for the hydrogen data show good agreement of the absolute normalization with photoabsorption at low q^2 and with inelastic electron scattering at high q^2 (Ref. 4). A detailed comparison of the absolute cross sections from hydrogen for muons and electrons will be made in a future publication.

[15]The authors have previously reported (Ref. 4) 10 GeV carbon/hydrogen ratios with less statistics and greater systematic errors. Inclusion of these data, which show greater shadowing, changes $R_C(K_{\text{eff}} < 3$ GeV) to 10.7 ± 0.30. This results in slightly different A dependence and neutron/proton ratios: $\sigma_A = \sigma_p A^{0.98 \pm 0.01}$ and $\sigma_n/\sigma_p = 0.86 \pm 0.05$.

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Backward Pion Production from $\pi^- p$ Interactions*

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We have measured the cross section for backward inelastic production of $\pi^\pm$ by π^- on protons at eleven beam momenta between 2.15 and 6.0 GeV/c. We find that the laboratory cross sections $d^2\sigma/dp_\parallel dp_\perp{}^2$ at fixed transverse momentum $p_\perp$ and longitudinal momentum $p_\parallel$ have little or no dependence on beam momentum between 3.5 and 6.0 GeV/c, and are sharply peaked toward zero $p_\perp{}^2$. The backward π^+ distributions in the laboratory from our experiment are nearly identical in shape to those obtained in the beam frame from pp experiments.

Benecke et al.[1] have proposed a limiting-fragmentation model of hadron-hadron collisions in which, at sufficiently high energy, the produced particles separate in momentum space into two groups consisting of fragments of the beam and of the target, respectively. They predict that as the beam momentum becomes very large, the cross sections $d^3\sigma/d^3p$ for producing a given beam (target) fragment of momentum $\vec{p}$ should approach limiting distributions, independent of beam momentum, when viewed in the rest frame of the beam (target). There is some evidence for this in p-p collisions.[1,2]

We present here the results of a spark chamber experiment which measures differential cross sections for the reaction $\pi^- p \to \pi^\pm +$anything at relatively low beam momenta (2.15-6.0 GeV/c), for pions produced near the backward direction in the laboratory, i.e., for those produced pions which are farthest removed in momentum space from the beam. We find that the laboratory cross sections at constant $p_\parallel$ are sharply peaked towards $p_\perp{}^2 = 0$, and have very little dependence on beam momentum between 3.5 and 6.0 GeV/c. In addition a small amount of bubble-chamber data on the same reaction at 25 GeV/c is consistent with the hypothesis of little or no variation of pion production between 6.0 and 25 GeV/c. We may thus be near a limiting distribution for these very backward pions.

To investigate how these backward distributions depend on the type of bombarding particle, we have transformed the cross sections[3,4] for the reaction $p + p \to \pi^\pm +$anything into the beam frame and compared the resulting $p_\parallel$, $p_\perp$ distributions for the very high-momentum pions (candidates for fragments of the beam proton) with the distributions obtained in our experiment. We find the π^+ distribution shapes from the two different projectiles are in remarkable agreement while the $p_\parallel$ distributions for π^- are significantly different.

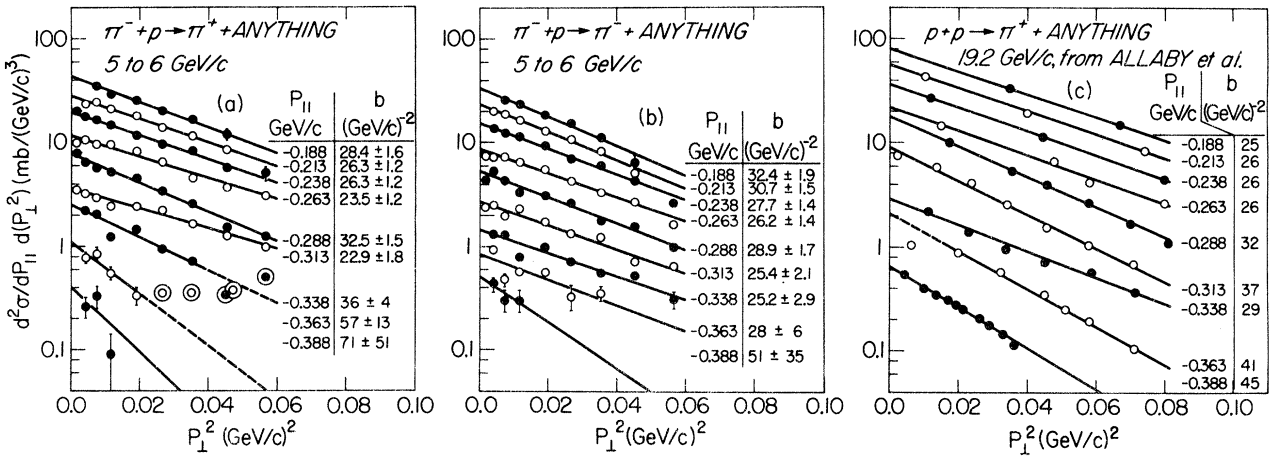

FIG. 1. Comparison with the dependence on $p_\perp{}^2$ of $d^2\sigma/dp_\parallel dp_\perp{}^2$ at fixed $p_\parallel$ for pion production from $\pi^- p$ and pp collisions. All quantities in (a) and (b) are expressed in the target rest frame, while all those in (c) are in the beam frame. The solid lines are fits to the data of the form $\exp(-bp_\perp{}^2)$; the resulting values of b are tabulated. Dashed lines indicate regions omitted from the fit. Only statistical errors are shown.

Experiment.—The data presented here are the results of an optical spark-chamber experiment performed at the Argonne National Laboratory zero-gradient synchrotron. The experimental apparatus has been described previously[5]; it is a large-aperture one-arm spectrometer which accepts pions of either charge produced at laboratory angles of 135° to 170° with momenta greater than 175 MeV/c. A total of 1.7×10^6 pictures were taken at π^- beam momenta of 2.15, 2.5, 2.8, 3.5, 3.95, 4.5, 5.0, 5.12, 5.25, 5.6, and 6.0 GeV/c. The film for beam momenta 3.5-6.0 GeV/c was scanned and measured by an improved version of the Michigan automatic scanning system (MASS)[6] flying-spot digitizer; the remainder of the film was digitized by hand. Large samples of film of varying quality were scanned and digitized by both methods to calibrate the efficiency of the automatic system. Details of the corrections to the data will be discussed elsewhere. We estimate that possible $p_\parallel$- and $p_\perp$-dependent systematic errors in our cross sections are less than ±10%. There is an additional overall normalization uncertainty of ±9%. A check of our data is provided by the general agreement of our backward elastic-scattering cross sections with the results of other experiments.

Dependence on transverse momentum.—In Figs. 1(a) and 1(b) we present our laboratory cross sections $d^2\sigma/dp_\parallel dp_\perp{}^2$ as a function of $p_\perp{}^2$ at various fixed $p_\parallel$ for combined beam momenta 5.0 to 6.0 GeV/c. We have excluded all bins of $p_\parallel$, $p_\perp{}^2$ in which the missing mass recoiling against the detected pion can be less than the inelastic threshold (1.08 GeV/c^2), so that elastic events and partially empty bins do not appear. The circled points in Fig. 1(a) contain an appreciable contamination of recoil pions from the quasi two-body backward reaction $\pi^- p \to \Delta^- \pi^+$; these points have been omitted from the fits.

The dependence of the cross section on $p_\perp{}^2$ at fixed $p_\parallel$ is seen to be fitted quite well over our region of $p_\perp{}^2$ by a Gaussian, $d^2\sigma/dp_\parallel dp_\perp{}^2 \propto \exp(-bp_\perp{}^2)$; away from threshold the fitted values of b for the 5- to 6-GeV/c data are typically in the range 22 to 33. The numbers are similar at the lower beam momenta. It should be noted that these values of b are considerably larger than those observed[3,7,8] for pion production from pp collisions at fixed $p_\parallel{}^*$ in the center of mass.[9] However, the larger values of b can also be seen when the pp data are examined in the beam frame. This is illustrated in Fig. 1(c), in which the π^+ production data from Ref. 3 have been used[10] to obtain $p_\perp{}^2$ distributions at constant $p_\parallel$. The values of b are strikingly similar to ours.

Dependence on beam momentum.—Cross sections $d^2\sigma/dp_\parallel dp_\perp{}^2$, extrapolated to $p_\perp{}^2 = 0$ for several fixed $p_\parallel$ at each of our beam momenta p_{BM}, are presented in Figs. 2(a) and 2(b). The solid lines show the average cross sections from 3.95 to 6 GeV/c, while the dashed extensions are drawn to guide the eye. For the more positive values of $p_\parallel$ the cross sections fall by a factor of 2 to 4 with increasing p_{BM} between 2.15 and 3.5 GeV/c and then level off; within our relative normalization errors (±6%) and statistical errors there is no p_{BM} dependence between 3.5 and

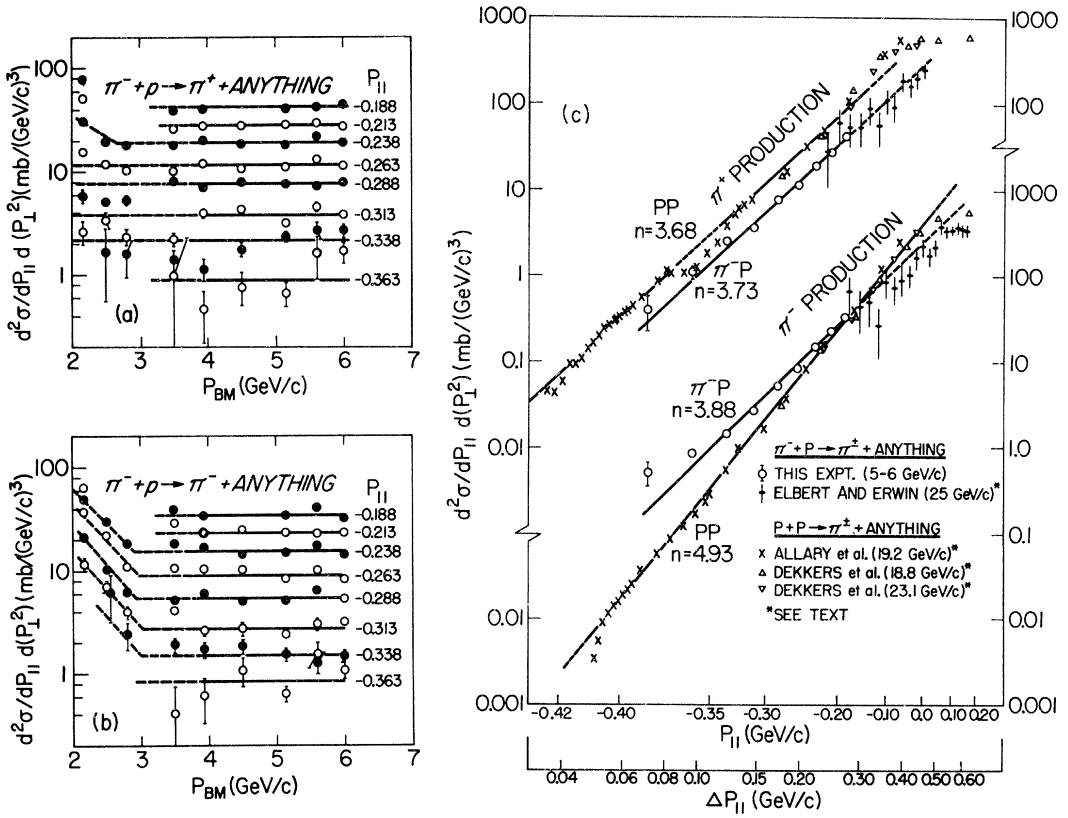

FIG. 2. Dependence on p_{BM} and $p_{||}$ of the laboratory cross sections $d^2\sigma/dp_{||}dp_\perp^2$ for pion production at $p_\perp^2 = 0$. (a), (b) Dependence on p_{BM} of $\pi^\pm$ production from $\pi^- p$ collisions, 2.15-6 GeV/c. The solid lines indicate the average cross section at fixed $p_{||}$ for $p_{BM} = 3.95$-6.0 GeV/c; the dashed curves are drawn to guide the eye. (c) Comparison of $p_{||}$ dependence of $d^2\sigma/dp_{||}dp_\perp^2$ at $p_\perp^2 = 0$ for pion production in $\pi^- p$ and pp collisions. Discussion of this figure appears in the text. Solid lines are fits to the data of the form $(\Delta p_{||})^n$; a dashed line indicates a region omitted from the fit. Only statistical errors are shown.

6 GeV/c. For the most negative $p_{||}$ the cross section rises as p_{BM} increases; this is expected, since this bin in very close to inelastic threshold at the lower p_{BM}.

A limited amount of bubble-chamber data for $\pi^- + p \to \pi^\pm +$anything is available at $p_{BM} = 25$ GeV/c in the form $d\sigma/dp_{||}$, i.e., integrated over $p_\perp^2$.[11] To compare these data with ours, we have assumed that the form $d^2\sigma/dp_{||}dp_\perp^2 \propto \exp(-bp_\perp^2)$ describes most of the contribution to $d\sigma/dp_{||}$, so that one may write

$$(d^2\sigma/dp_{||}dp_\perp^2)_{p_\perp^2=0} \approx b\, d\sigma/dp_{||},$$

with $b = 26.5$ (30) for π^+ (π^-) production as in our data at 5-6 GeV/c. (We have tested this prescription on the pp data[3] which cover a large range of $p_\perp^2$ and find that it generally holds to better than 25% for $p_{||}$ between -0.15 and 0.0 GeV/c.) The resulting π-p cross sections at 25 GeV/c are plotted along with our data in Fig. 2(c) (described in the next section). Where the two sets of data overlap in $p_{||}$, they are consistent with being equal, and an extrapolation of our π^+ data to more positive $p_{||}$ fits the 25-GeV/c data very well; the 25-GeV/c π^- points are about 40% below the extrapolation of our data, but possibly still consistent given the uncertainties in the comparison procedure.

Dependence on longitudinal momentum.—In Fig. 2(c) we show on a log-log plot the $p_{||}$ dependence at $p_\perp^2 = 0$ of our combined 5- to 6-GeV/c data. The independent variable is $\Delta p_{||} = p_{||} - p_{||}(\infty)$, where $p_{||}(\infty) = -(M_p^2 - m_\pi^2)/2M_p \approx -0.459$ GeV/c is the limiting value of $p_{||}$ at infinite beam momentum. We have included the 25-GeV/c $\pi^- p$ data (with the treatment described above), and also the pp data of Ref. 3 (extrapolated[10] to $p_\perp^2 = 0$) and Ref. 4 (taken at $p_\perp^2 = 0$), both in the beam frame with the sign of $p_{||}$ changed appropriately. Because of an apparent normalization discrepancy between the data of Refs. 3 and 4 we have arbitrarily multiplied the points from Ref. 4 by 1.5. A straight line on this plot is of the form $d^2\sigma/dp_{||}dp_\perp^2 \sim [p_{||} - p_{||}(\infty)]^n$, which is certainly in-

correct very near threshold and also for $p_{\parallel} \gtrsim 0$, but still describes the $p_{\parallel}$ dependence of both the πp and pp data reasonably well—over nearly five decades for the pp data,[12] even quite close to the physical threshold. Our π^+ and π^- production data can be parametrized with nearly equal values of n: 3.73 for π^+, 3.88 for π^-, with statistical errors of ± 0.06; the π^+ cross section is a factor of ~1.3 higher than the π^-.

The π^+ data from the pp collisions also have essentially the same n, 3.68, with a cross section ~2 times that from the $\pi^- p$ collisions. However, the π^- data from pp have a steeper dependence by about one power of $\Delta p_{\parallel}$ than the rest of the data, $n = 4.93$.

We wish to thank the staff of the zero-gradient synchrotron for their effective operation of the accelerator and their strong supporting services during our experiment. We also want to express our appreciation to Jerome Elbert and Albert Erwin of the University of Wisconsin for sending us some of their 25-GeV/c bubble-chamber data prior to publication.

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[9]The steeper slopes at fixed $p_{\parallel}$ for backward pions in the laboratory and beam frames arise because of the falloff of the cross sections in $p_{\parallel}{}^*$, plus the fact that fixed $p_{\parallel}{}^*$ is not the same as fixed $p_{\parallel}$. We have also transformed our data into the center-of-mass frame and find $p_{\perp}{}^2$ dependences at fixed $p_{\parallel}{}^*$ consistent with those of the pp data at small $p_{\perp}{}^2$.

[10]The interpolation of the data of Ref. 3 was performed along curves of constant P_{1ab} (roughly, constant $p_{\parallel}{}^*$) as were the extrapolations to $p_{\perp}{}^2 = 0$. For high-momentum π^-, for which data exist only at $\theta_{1ab} = 12.5$ mrad, the extrapolation was performed by assuming a similar average falloff for π^- and π^+ between 0 and 12.5 mrad.

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[12]Note that the structure observed in Ref. 3 for π^+ production from pp appears on this plot as a dip near $p_{\parallel} = -0.36$ rather than as a bump at more negative $p_{\parallel}$. The same dip anomaly may also be seen in Fig. 1(c) as a deviation from the Gaussian $p_{\perp}$ dependence near $p_{\perp}{}^2 = 0$.