Production of charged hadrons with large transverse momenta in 70-GeV proton-deuteron collisions

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Measurements of the invariant cross sections for $\pi^\pm$, $K^\pm$, p, and $\bar{p}$ production in pd collisions at 70 GeV are reported over the transverse-momentum interval $1.55 \leqslant P_T \leqslant 4.22$ GeV/c at a c.m. angle of 90°. There is a substantial deviation from the sum of the free-nucleon cross sections.

The reaction $p + d \rightarrow h + X$ has been studied over the transverse-momentum interval $1.55 \leqslant P_T \leqslant 4.22$ GeV/c at an angle of 90° in the c.m. frame of the two nucleons at an energy of 70 GeV ($h = \pi^\pm$ mesons, $K^\pm$ mesons, p, and $\bar{p}$). The production of hadrons with large values of P_T has been studied previously at $\sqrt{S} = 27.4$ GeV and at $X_T = 2P_T/\sqrt{S}$ below 0.50 (Ref. 1). The experiments were carried out on the focusing two-arm spectrometer of the Institute of High-Energy Physics.[2] They constitute a continuation of an earlier study[3] in a beam slowly extracted from an accelerator.

Table I lists the invariant cross sections $E(d^3\sigma)/(d^3p)$ for the production of hadrons h in collisions with the deuteron; below we will use the briefer notation $\sigma(h)_d$ for

TABLE I. Invariant cross sections $Ed^3\sigma/d^3p$ (mb/GeV^2) for the production of positively charged hadrons (upper row) and negatively charged hadrons (lower row) in pd collisions at 70 GeV.

P_T, GeV/c	π	K	P
1.550	$(0.261 \pm 0.002)\cdot10^{-1}$ $(0.232 \pm 0.002)\cdot10^{-1}$	$(0.732 \pm 0.009)\cdot10^{-2}$ $(0.259 \pm 0.006)\cdot10^{-2}$	$(0.233 \pm 0.002)\cdot10^{-1}$ $(0.888 \pm 0.024)\cdot10^{-3}$
1.993	$(0.244 \pm 0.002)\cdot10^{-2}$ $(0.207 \pm 0.002)\cdot10^{-2}$	$(0.790 \pm 0.009)\cdot10^{-3}$ $(0.256 \pm 0.005)\cdot10^{-3}$	$(0.295 \pm 0.002)\cdot10^{-2}$ $(0.818 \pm 0.024)\cdot10^{-4}$
2.889	$(0.192 \pm 0.002)\cdot10^{-4}$ $(0.145 \pm 0.001)\cdot10^{-4}$	$(0.711 \pm 0.013)\cdot10^{-5}$ $(0.160 \pm 0.008)\cdot10^{-5}$	$(0.358 \pm 0.002)\cdot10^{-4}$ $(0.325 \pm 0.014)\cdot10^{-6}$
3.256	$(0.266 \pm 0.005)\cdot10^{-5}$ $(0.195 \pm 0.003)\cdot10^{-5}$	$(0.103 \pm 0.005)\cdot10^{-5}$ $(0.180 \pm 0.022)\cdot10^{-6}$	$(0.579 \pm 0.004)\cdot10^{-5}$ $(0.370 \pm 0.025)\cdot10^{-7}$
4.220	$(0.641 \pm 0.020)\cdot10^{-8}$ $(0.432 \pm 0.013)\cdot10^{-8}$	$(0.316 \pm 0.022)\cdot10^{-8}$ $(0.194 \pm 0.053)\cdot10^{-9}$	$(0.248 \pm 0.004)\cdot10^{-7}$ $(0.379 \pm 0.240)\cdot10^{-10}$

these cross sections. The indicated errors are statistical only. The accuracy of the absolute values of the cross sections is $\pm$ 15%; this figure also incorporates the error ($\pm$ 6%) in the absolute normalization of the monitors. The present results agree well with the results of our previous measurements[3] over that part of the P_T scale where there is an overlap of results. The invariant cross section for the production of pions in collisions with a "neutron" was found as the difference between the invariant cross sections for *pd* and *pp* collisions.

The experimental results were analyzed to extract information on the collisions of protons with neutrons and to detect manifestations of nuclear effects in the deuteron, by which we mean a difference from the sum of the cross sections for scattering by free protons and neutrons.

To detect nuclear effects we used some experimental values which are predicted by the quark-parton model[5] to be approximately equal for *pp* and *pn* collisions. First, we analyzed the sum of the cross sections for the production of π^+ and π^- mesons in collisions with protons and deuterons: $\sigma(\pi^+)_d + \sigma(\pi^-)_d$ and $\sigma(\pi^+)_p + \sigma(\pi^-)_p$. This sum is symmetric in quark composition $(ud + \bar{u}d)$, and its value would differ for *pp* and *pn* collisions only because of different contributions from interference terms. Figure 1a shows the ratio of $[\sigma(\pi^+)_d + \sigma(\pi^-)_d]$ to $2[\sigma(\pi^+)_p + \sigma(\pi^-)_p]$, which becomes greater than unity at $X_T = 0.3$ and reaches the value of 1.3 at $X_T = 0.7$. As can be

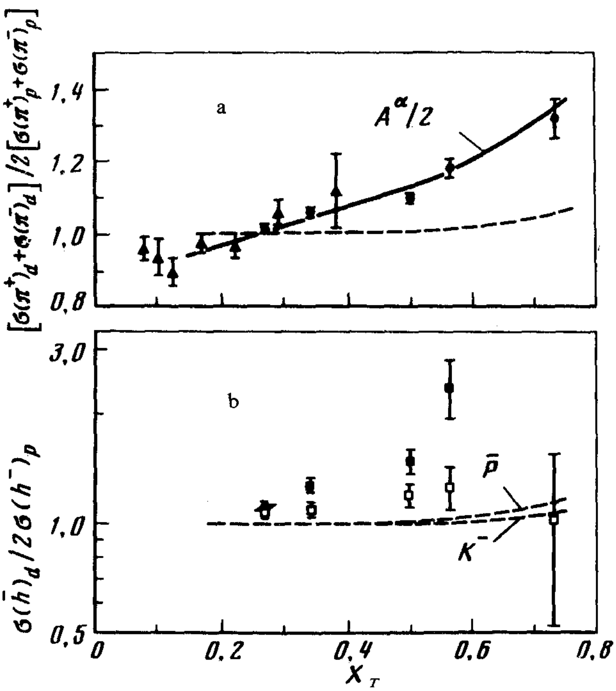

FIG. 1. Nuclear effects in the deuteron vs X_T. The dashed curves show the contribution of the Fermi motion of the nucleons in the deuteron.[6] a: The ratio $[\sigma(\pi^+)_d + \sigma(\pi^-)_d]/2[\sigma(\pi^+)_p + \sigma(\pi^-)_p]$. ●—Present study; ▲—Ref. 3. b: The cross-section ratios $\sigma(\bar{p})_d/2\sigma(\bar{p})_p$ (■) and $\sigma(K^-)_d/2\sigma(K^-)_p$ (□).

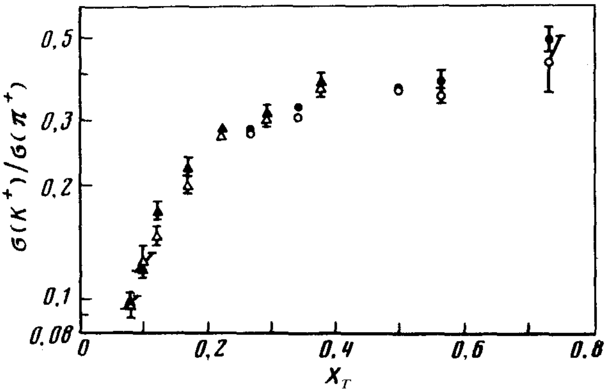

Fig. 2. Particle-yield ratio $\sigma(K^+)/\sigma(\pi^+)$ vs X_T for collisions with the proton. ○—Present study; △—Ref. 4. For collisions with the deuteron. ●—Present study; ▲—Ref. 3.

seen from this figure, the observed excess cannot be explained by Fermi motion of the nucleons in the deuteron, which was taken into account in the model of Ref. 6. On the other hand, the experimental results can be described well by a dependence $A\alpha^{(P_T)}$, where the exponent $\alpha(P_T)$ is taken to be the average of the exponents for the π^+ and π^- mesons from our measurements[7] in collisions with a pair of light nuclei: carbon and aluminum. The applicability of this description suggests a commonality between the effects in the deuteron and in more complex nuclei.

Other tests of nuclear effects are the cross sections for the production of K^- mesons and antiprotons—particles which have no valence quarks in the original *pp* and *pn* systems. Figure 1b shows the experimental ratios of these cross sections for collisions with deuterons to twice the cross sections for protons. According to estimates, a possible deviation from unity should be even smaller than for pions. However, despite the predictions of the quark-parton models, both ratios differ from unity and increase systematically with increasing X_T; the effect is greatest in the case of the antiprotons. As in the former case, the experimental data cannot be explained by taking Fermi motion into account.

Of particular interest in this regard is the circumstance that the cross sections $\sigma(K^+)_d/\sigma(\pi^+)_d$ are systematically higher than $\sigma(K^+)_p/\sigma(\pi^+)_p$ (Fig. 2) over the entire X_T range. The average difference is 0.039 ± 0.012. In the quark-parton models these ratios are the same for collisions with protons and neutrons. Furthermore, since the slopes are equal in the spectra of the invariant cross sections for the production of K^+ and π^+ mesons, we can rule out an effect of Fermi motion and rescattering on this ratio. It is pertinent to recall that the K^+/π^+ yield ratio increases with increasing A, the mass number of the target nucleus.[7]

Figure 3 shows the ratio of the cross sections for the production of charged pions in collisions with a "neutron" as a function of X_T. Over the entire X_T interval studied the experimental ratios agree with unity. The average value of this ratio is 0.995 ± 0.009. Nuclear effects in the deuteron affect the ratio of the cross sections for

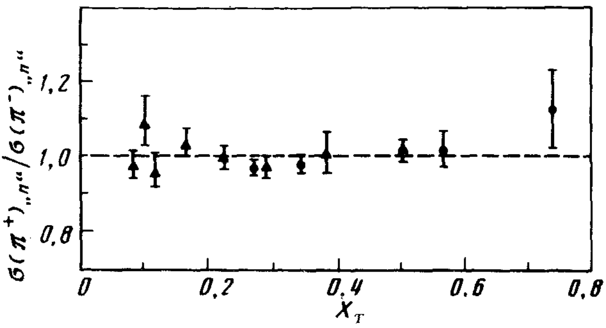

Fig. 3. The particle-yield ratio $\sigma(\pi^+)_n/\sigma(\pi^-)_n$ vs X_T for collisions with the "neutron." ●—Present study; ▲—Ref. 3.

the nucleons. Taking this effect into account, we find that the average ratio $\sigma(\pi^+)_n/\sigma(\pi^-)_n$ becomes 0.98 ± 0.01 if we adopt the quantity $[\sigma(\pi^+)_d + \sigma(\pi^-)_d]/2[\sigma(\pi^+)_p + \sigma(\pi^-)_p]$ as the characteristic magnitude of the nuclear effects. A value of unity is predicted on the basis of the isotopic invariance of the strong interactions in the detection of pions at a c.m. angle of 90°. According to the quark-parton model,[5] π^+ and π^- mesons with large P_T are produced primarily as a result of the scattering of valence u and d quarks, respectively. In this light our result acquires a deeper meaning; it essentially confirms the symmetry of the short-range interactions of u and d quarks.

Putting all these pieces of evidence together, we conclude that the experimental data differ significantly from the predictions of the quark-parton models for a free proton-neutron pair. The observed values cannot be explained by simply taking into account the Fermi motion of the nucleons in the nucleus. It is possible that in this case we are seeing manifestations of collective interactions of quarks, which are presently the subject of widespread discussion.

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