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Observation of the Independence of the p/π Ratio from the Nuclear Size for Hadrons Knocked out with Large Transverse Momenta from a Nuclear Target by 50-GeV Protons

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The yields of cumulative protons and $\pi^{\pm}$ mesons emitted at a laboratory angle of 40° from carbon and heavier nuclear targets irradiated by a proton beam from the U70 accelerator (Institute for High Energy Physics, Protvino) have been studied in the SPIN experiment. It has been found that the effect of the target nucleus on the yield of particles with large transverse momenta is weakened.

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The aim of the SPIN experiment is to study the spectra and composition of secondary particles produced with large transverse momenta ($p_T > 1$ GeV/c) in the so-called cumulative region in order to obtain information on both the mechanism of production of such particles and the structure of baryonic matter in a nucleus. The cumulative region is a region of momenta kinematically forbidden for collisions of free nucleons. Particles produced in collisions with nuclei in the cumulative part of the spectrum are referred to as cumulative.

According to theoretical estimates [1], the main contribution to the kinematic region that is studied in the SPIN experiment comes from hard collisions with multinucleon configurations in a nucleus. The data obtained in this experiment on the production of $\pi^{\pm}$, p, and light nuclear fragments d and t with large p_T values emitted at a laboratory angle of 35° from C, Al, Cu, and W thin nuclear targets irradiated by 50-GeV/c protons were previously reported in [2–5]. The observation of cumulative particles with transverse momenta above 2 GeV/c was first reported in [2, 3], where the schematic of the setup and details of the experiment were also described. The analysis [4, 5] of spectra of cumulative light nuclear fragments (d, t) indicates that the direct knockout of deuterons and tritons from a nucleus is detected in the studied kinematic region.

In the energy range ($\sqrt{s} \sim 10$ GeV) available the SPIN detector, data on the yields of $\pi\pm$, $K\pm$, p, and $\bar{p}$ emitted with transverse momenta from 1 to 4.65 GeV/c at a c.m. angle of 90° from C, Al, Cu, Sn, and Pb nuclei bombarded by a 70-GeV proton beam were obtained in the FODS (FOcusing Double-arm Spectrometer) experiment (Institute for High Energy Physics, Protvino) [6]. The production of charged hadrons with large transverse momenta p_T at a c.m. angle of ~90° in pA collisions with a proton beam with a higher momentum of 300–400 GeV/c was studied at the Fermi National Accelerator Laboratory [7, 8].

The aim of this work is to estimate the contribution of secondary interactions by comparing the ratio of yields of protons and π mesons from different nuclei. These measurements were initiated by our previous interesting observation [3] for cumulative particles produced at a laboratory angle of 35° in pA collisions: the ratio of yields of charged particles with different signs, h^+/h^-, measured at $p_T > 2$ GeV/c depends slightly on the atomic number of a nucleus: it is almost the same for tungsten and aluminum. In this work, we analyze the spectra of protons and π mesons produced at a laboratory angle of 40° with respect to a 50-GeV

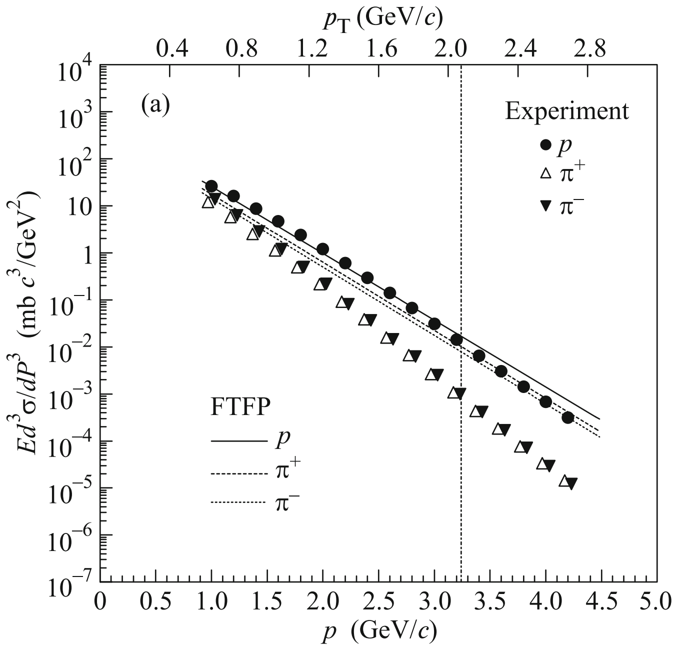

Fig. 1. Momentum spectra of charged π mesons and protons emitted at a laboratory angle of 40° from the (left panel) carbon and (right panel) tungsten targets. The dashed vertical straight lines indicate the kinematic limit for nucleons in the case of elastic nucleon–nucleon scattering. The upper horizontal axis shows the transverse momentum. The lines are the calculations within the FTFP model.

proton beam in *pA* collisions. This particle emission angle corresponds to an angle of ~150° in the center-of-mass system of the incident proton and nuclear nucleon. We used the same thin targets (C, Al, Cu, and W) as in our preceding works [2–5].

The momentum spectra of charged π mesons and protons measured for an angle of 40° are qualitatively similar for all four targets. Points in Fig. 1 represent the spectra of negative and positive π mesons and protons for (left panel) the lightest, carbon, target and (right panel) the heaviest, tungsten, target. The spectra for Al and Cu nuclei are similar to those for C and W shown in Fig. 1. The yield of protons at high momenta from all targets becomes about a factor of 20 larger than the yield of π mesons. The dashed vertical straight lines in Fig. 1 indicate the kinematic limit for nucleons in the case of the collision of a proton with a free nucleon. *We recall that the specificity of the reported results is that the yield of particles is measured in both the pre-cumulative and cumulative kinematic regions.*

The lines in Fig. 1 are the cross sections calculated within the Fritiof string fragmentation model (FTFP model), which is one of the main components in the Geant4 package [9] for simulating hadron/ion collisions with nuclei. This model was chosen because Uzhinsky [10] demonstrated that it can describe the production of hadrons in a wide angular range (0–420 mrad) in *p*C collisions at an energy close to that available in the SPIN experiment. It is seen in Fig. 1 that the model satisfactorily describes the spectra of protons from *p*C collisions. The model reproduces the spectra of protons with momenta above 3 GeV/*c* from *p*W collisions but underestimates the yield of slow protons. The FTFP model overestimates the yield of fast π mesons from both *p*C and *p*W collisions.

When analyzing the effect of nuclear matter on any characteristic, *pp* and *pA* collisions are usually compared. In our case, the momentum spectrum includes the cumulative region inaccessible for *pp* collisions. For this reason, we compare processes on heavier nuclei to processes on the carbon nucleus. The effect of nuclear matter on the relative yield of protons and pions is estimated in terms of the double ratio $R = (p/\pi)_A/(p/\pi)_C$, where the subscripts C and *A* refer to the carbon and heavier nuclei, respectively.

Figure 2 shows the ratio $R = (p/\pi^+)_A/(p/\pi^+)_C$ measured for pairs of nuclei Al/C, Cu/C, and W/C at various p_T values. At low momenta, the larger the difference between the masses of the heavier and carbon nuclei, the larger the ratio *R*; i.e., the larger the fraction of protons among particles emitted from the heavier nucleus. However, the ratio *R* at high momenta tends to unity for all considered pairs of nuclei, which indicates the weakening of the dependence of the p/π ratio on the size of the nucleus.

Figure 2 shows experimental data with statistical error bars. The systematic error in the determination of the ratio *R* at different transverse momenta is represented by the width of the gray band in the lower part

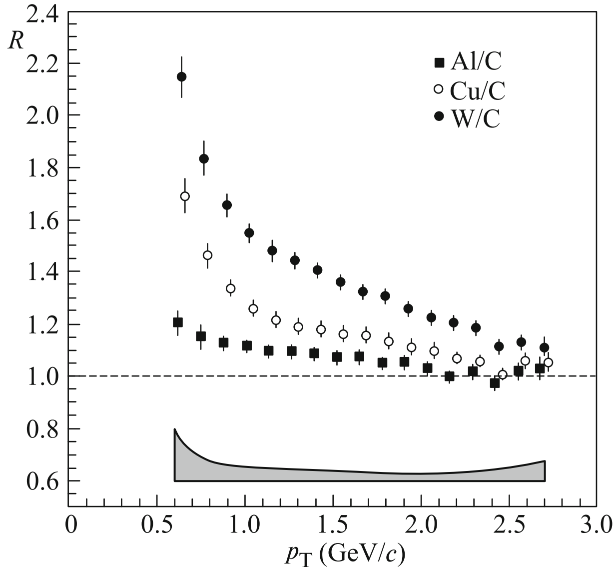

Fig. 2. Ratios of the yields from aluminum, copper, and tungsten targets to the yield from the carbon target versus the transverse momentum. The width of the gray band in the lower part of the figure corresponds to the systematic error at different p_T values.

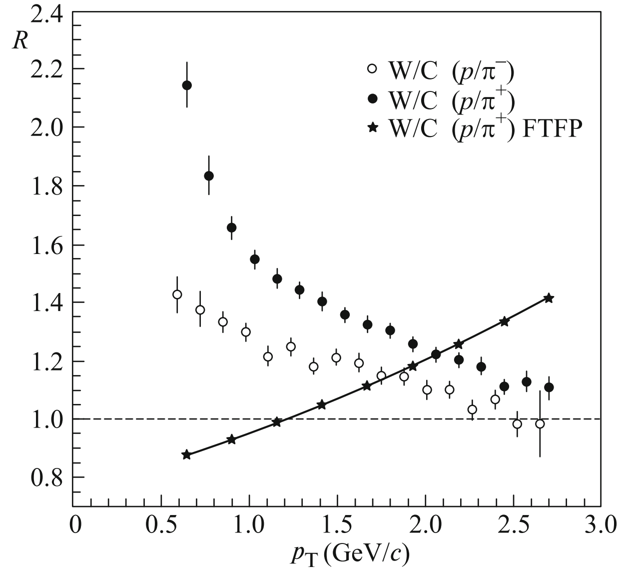

Fig. 3. W/C ratio obtained from the yields of positive and negative π mesons versus the transverse momentum. The line is the calculation within the FTFP model.

of the figure. This error is due mainly to the error in the reconstruction of invariant cross sections from raw experimental data. Furthermore, the probability of misidentification of particles increases with the momentum.

In the SPIN experiment, protons and π^+ mesons are detected in the same series of measurements under the same conditions. Data on the production of negatively charged particles were also obtained in another series of measurements. To exclude the possible systematic error associated with the difference in the conditions of measuring positively and negatively charged particles, Fig. 2 shows data only for the p/π^+ ratio. In order to demonstrate that the behavior of the p/π^- ratio is similar, Fig. 3 shows the ratios $R = (p/\pi^+)_W/(p/\pi^+)_C$ and $R = (p/\pi^-)_W/(p/\pi^-)_C$.

The W/C ratio calculated within the FTFP model is shown by the line in Fig. 3, where it is seen that the model cannot describe the experimental data.

The ratio $R = (p/\pi^+)_{Cu}/(p/\pi^+)_C$ for different transverse momenta p_T can be calculated from the FODS data [6]. The result is $R = (p/\pi^+)_{Cu}/(p/\pi^+)_C \approx 1.2$ and is hardly dependent on the transverse momentum in the range of 1–4 GeV/c; this behavior differs from the behavior of this ratio in Fig. 2. Another type of behavior of the ratio R was observed in [7, 8], where the production of hadrons in pA collisions at $\sqrt{s} \approx 27.4$ GeV was studied. The double ratio $R = (p/\pi^+)_W/(p/\pi^+)_{Be}$ calculated using data for tungsten and beryllium increases from ~1.3 to 2.0 with an increase in the transverse momentum p_T from ~0.8 to 6 GeV/c, respectively; this behavior is inconsistent with the behavior of double ratios R in Fig. 2. It is noteworthy that the data in [6–8] were obtained in the kinematic region of proton–nucleon collision without passage to the cumulative region.

CONCLUSIONS

It has been found that the dependence of the p/π^+ ratio measured in this work for various nuclei on the transverse momentum p_T differs from the dependence of the p/π^+ ratio obtained for the production of particles with large transverse momenta at a c.m. angle of 90° in pA collisions at a beam momentum of 70 GeV/c [6] and 300–400 GeV/c [7, 8]. The weakening of the dependence of the p/π ratio on the size of the nucleus possibly indicates the transparency of nuclear matter for cumulative particles with large transverse momenta. This effect is not described even qualitatively within the FTFP model, which is one of the basic components in the Geant4 package [9].

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