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Production of Cumulative Particles and Light Nuclear Fragments at High p_T Values beyond the Fragmentation Region of Nuclei in pA Collisions at a Proton Energy of 50 GeV

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The first data on the production of cumulative π^+, p, and light nuclear fragments d and t emitted from a nucleus with a high transverse momentum at an angle of 35° in the laboratory system have been reported. The data have been obtained at the SPIN setup at the interaction of a 50-GeV proton beam extracted from the U-70 accelerator (IHEP, Protvino) with C, Al, Cu, and W nuclei.

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Particle production in a kinematic region forbidden for reactions with free nucleons (cumulative effect in processes involving nuclei) was actively studied in the 1970s–1980s. As a result, a number of their characteristic features were revealed (see, e.g., [1]). The complete understanding of the nature of multinucleon (multiquark) configurations in nuclei, which are presumably responsible for the existence of the cumulative effect, is still absent. Almost all existing data on cumulative particles were obtained in the nuclear fragmentation region where particles emitted into the back hemisphere in the laboratory system with momenta $p < 2$ GeV/c are detected. The estimates [2] indicate that the distortion of spectra in this region owing to the interaction in the final state is very significant. In the region of high transverse momenta p_T, for which data on the cumulative process are absent, it is assumed [3] that the main contribution to the process of the production of particles with extreme transverse momenta ($p_T/p_T^{\max} \sim 1$, where $p_T^{\max}$ is the maximum possible value) comes from hard collisions with multinucleon configurations at small distortions induced by the nucleus. For this reason, it seems important to study cumulative processes with high p_T values. Such data can improve the understanding of the mechanism of the cumulative effect.

The SPIN setup is a narrow-aperture single-arm spectrometer consisting of seven magnetic elements, wire chambers, time-of-flight system, and a threshold Cherenkov detector. The variation of the positions of the magnetic elements makes it possible to select charged particles emitted from the target in the angular range of 22°–55° in the laboratory system. In this work, we report the data obtained at a detection angle of 35°. The system of wire chambers located upstream and downstream of the analyzing magnet allows the measurements of the momentum of particles with the resolution $\Delta p/p \approx 3 \times 10^{-3}$. The angular acceptances of the setup are $\Delta\varphi \approx 100$ mrad and $\Delta\theta \approx 40$ mrad in the azimuth and polar angles, respectively. The momentum acceptance of the setup varies from 5.5% at 1 GeV/c to 3.5% at 6 GeV/c. Data collection was performed with a 50-GeV/c proton beam with an intensity of $\sim 5 \times 10^{12}$ protons passing through the target per second. The magnetic optics of the spectrometer was adjusted to the required momentum of a charged particle emitted from the target. Data collection was performed until the necessary statistical accuracy of the measurements. Thin C, Al, Cu, and W nuclear targets with a thickness of 0.7–0.9 g/cm^2 were used. The scheme of the setup and details of the experiment can be found in [4, 5].

In our preceding works [4, 5] on the measurement of the momentum spectra of positively and negatively charged particles, we observed a strong dependence of the spectra on the number of nucleons in a nucleus (A), which is a characteristic feature of the production of cumulative particles. It was demonstrated in [5] that the strong A dependence observed in the SPIN experiment is due to the processes of local interaction rather than to the multiple interaction inside the nucleus. This conclusion follows from the measurement of the ratio of the yields of positively and negatively charged

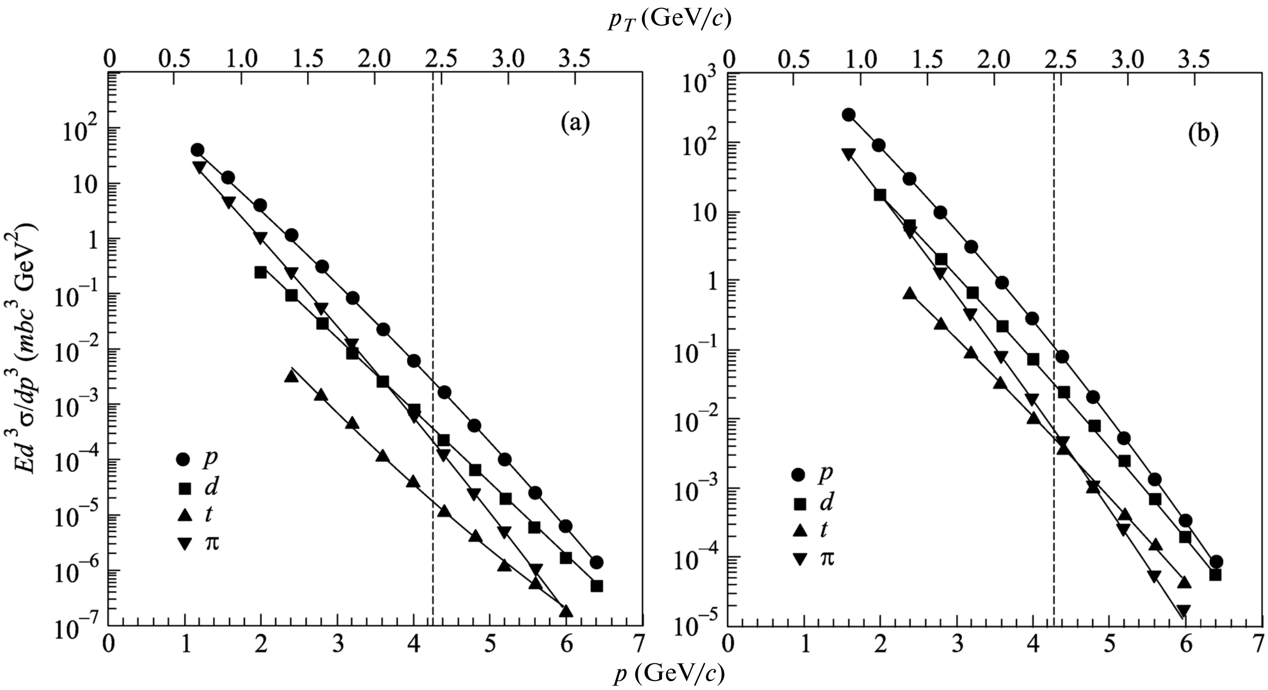

Fig. 1. Momentum spectra of positive pions, protons, deuterons, and tritons for (a) carbon and (b) tungsten target. The upper horizontal scale shows the transverse momentum. The vertical dashed straight lines correspond to the limit for the elastic nucleon–nucleon scattering. The lines connecting the experimental points are given for better representation of the data.

particles, which is almost the same for all nuclei in the cumulative region.

In this work, we report the data on the production of π^+ mesons, protons (p), deuterons (d), and tritons (t) emitted from the target with momenta up to 6.4 GeV/c. Particles were identified by the time-of-flight method. Information obtained from the threshold Cherenkov detector was used to identify π mesons. Data on K^+ mesons are not presented because of large corrections to losses and corresponding possible systematic errors, particularly at low momenta. The SPIN setup allows the detection of particles with momenta both satisfying the nucleon–nucleon interaction kinematics and beyond this kinematics, i.e., in the region of cumulative processes.

Figure 1 shows the invariant spectra of positively charged particles measured for the carbon and tungsten targets, which are the lightest and heaviest nuclei, respectively, among the targets used in the experiment. The spectra measured for the two other targets (Al and Cu) are qualitatively similar to the spectra shown in Fig. 1. The yield of π^+ mesons decreases rapidly with an increase in the momentum and becomes smaller than the yield of deuterons. At the same time, the contributions from deuterons and tritons increase.

The FODS experiment on the collision of 70-GeV protons with the Be, Cu, and Pb nuclei provided the data [6] on the yield of deuterons (at a detection angle of 9° in the laboratory system) in the transverse-momentum range of 1–4 GeV/c, which is also accessible in measurements at the SPIN setup. The measurements in the FODS experiment confirm that the production of d is completely described by the model of binding of protons and neutrons (see, e.g., [7]) produced inclusively in the pA collisions. The d/p ratio values measured in the FODS experiment are independent of p_T and are less than 0.02, whereas the SPIN data demonstrate an increase in the d/p ratio with p_T (see Fig. 1). For example, the d/p ratio obtained in the SPIN experiment for the tungsten target at p_T = 3.44 GeV/c is 0.56 ± 0.06. Difference in the behavior and magnitude of the d/p ratio between the FODS and SPIN experiments possibly indicates that the deuteron production mechanisms are different in these experiments. We emphasize that the FODS data, in contrast to the SPIN data, do not expand beyond the kinematic boundary of the nucleon–nucleon interaction. The process of direct knockout of dense multinucleon (multiquark) configurations from nuclei is likely observed in the SPIN experiment.

It was assumed in [1] that the source of cumulative particles is isotopically symmetric because the measured ratio was $\pi^-/\pi^+ \approx 1$. Figure 2 shows the π^-/π^+ yield ratio obtained in the reported experiment for the carbon and tungsten targets as a function of the momentum. The neutron-to-proton number ratio n/p for a given nucleus and valence quark ratio d/u in the given nucleus are presented in the figure. The dashed lines show the range of possible values because of the systematic error, which is associated with the error in

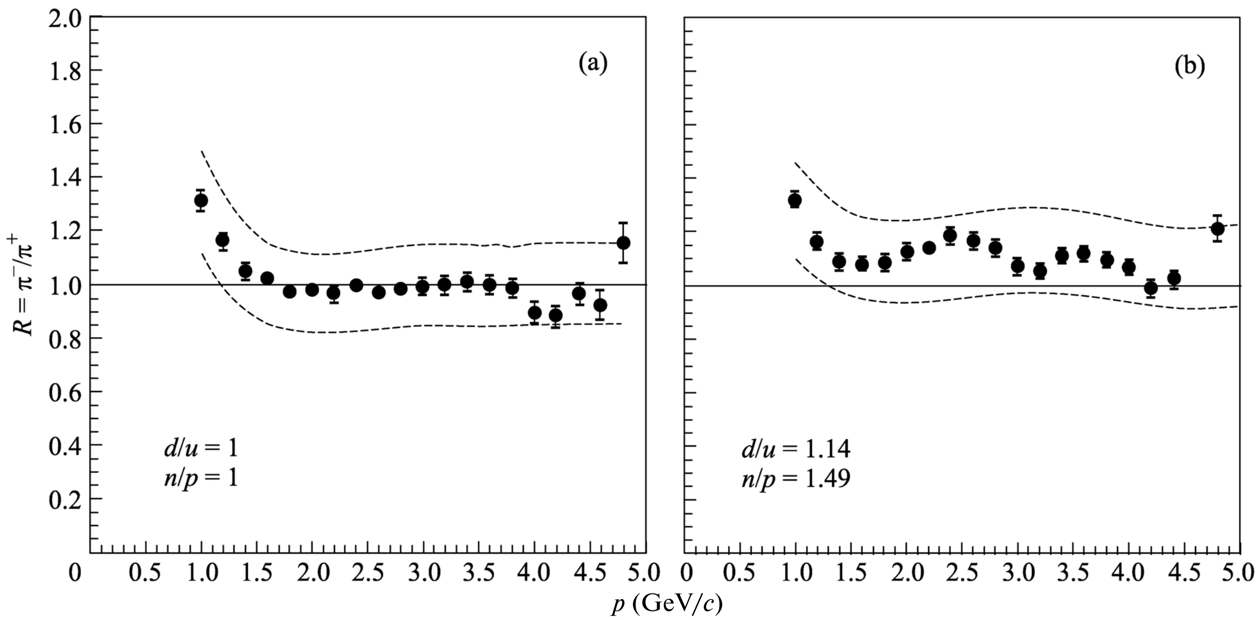

Fig. 2. Yield ratio π^-/π^+ for (a) carbon and (b) tungsten. The dashed lines indicate the region of possible values owing to systematic errors.

the measurement of the number of protons that passed through a target and is independent of the momentum. The systematic error was estimated by comparing the results obtained from the data collected at the SPIN setup in different years. Within the possible error, the measurements do not contradict the assumption that $\pi^-/\pi^+ = 1$.

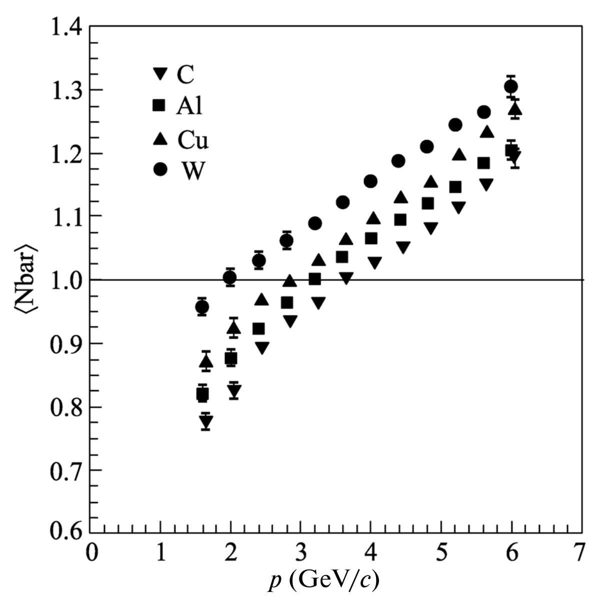

Fig. 3. Average baryon number for the detected positively charged particles versus the momentum.

The mentioned systematic error does not affect the ratios of the yields of various particles (data in Fig. 1), because particles with the same sign of the charge were identified in the same measurement.

The currently most popular models of mechanisms of the production of cumulative particles imply that nuclei include either multinucleon (multiquark) structures called fluctons [1] or configurations of point nucleons correlated at small distances (short-range correlation model) [8, 9].

The knockout of fluctons can result in an increased yield of nuclear fragments. In the case of the short-range correlation mechanism, at the knockout of correlated nucleons with high relative momenta, the average number of detected baryons should be close to unity. It is seen in Fig. 1 that the contribution of nuclear fragments increases with the momentum. Figure 3 shows the momentum dependence of the average baryon number N_{bar} for the detected particles (N_{bar} is the ratio $(\sigma_p + 2\sigma_d + 3\sigma_t)/(\sigma_\pi + \sigma_p + \sigma_d + \sigma_t)$, where σ_π, σ_p, σ_d, and σ_t are the cross sections for the production of the pion, proton, deuteron, and triton, respectively). The excess of N_{bar} above unity with an increase in the momentum can indicate that the dominant mechanism in this case is the flucton knockout mechanism rather than the short-range correlation mechanism.

Main conclusions. The first data on the high p_T production of π^+, p, d, and t in the precumulative and cumulative regions have been reported. The observed yield of protons and light nuclear fragments d and t can be treated as an indication that the processes of the interaction with multinucleon (multiquark) configurations, which can be manifestations of cold superdense baryon matter in nuclei, dominate in this kinematic region.

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