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Scaling Behavior of Spectra of Protons, Deuterons, and Tritons Produced with High Transverse Momenta in *pA* and ^{12}C*A* Collisions

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The first data on the yield of the lightest nuclear fragments (protons p, deuterons d, and tritons t) with high transverse momenta p_T at an angle of 40° in the laboratory reference frame from nuclear targets bombarded by 50-GeV/c protons and 20A-GeV/c carbon nuclei obtained in the SPIN experiment (IHEP, Protvino, Russia) have been reported. It has been shown that the pA and CA data can be described within a common scaling approach, which possibly indicates that the mechanism of formation of high-p_T nuclear fragments is common for these reactions.

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In this work, we continue the study of features of the formation of cumulative particles with high transverse momenta in the SPIN experiment. Cumulative particles produced in collisions of two objects at least one of which is a nucleus are particles with kinematic parameters forbidden for collisions with free nucleons. Study of the production of cumulative particles with high transverse momenta is one of the ways to obtain information on the properties of nuclear matter at high energy and momentum transfers.

Details of the experiment, as well as data on the detection of cumulative particles with $p_T > 2$ GeV/c emitted at an angle of 35° in the laboratory frame in pA collisions at a beam momentum of 50 GeV/c, can be found in [1–4]. According to the analysis of features of production of cumulative particles [3, 4] in the kinematic range under study, deuterons and tritons are directly knocked out from a nucleus, which indicates the existence of a cold dense multinucleon (multiquark) component.

In this work, we report data on the emission of the lightest nuclear fragments (protons p, deuterons d, and tritons t) at an angle of 40° in the laboratory reference frame from nuclear targets bombarded by 50-GeV/c protons and 20A-GeV/c carbon nuclei. Carbon, aluminum, copper, and tungsten targets were bombarded by the proton beam, whereas only carbon and tungsten targets were used for the carbon beam. For this reason, only data obtained with carbon and tungsten targets were used for the comparative analysis of pA and CA collisions. A great advantage of this comparison is that pA and CA data were obtained on the same setup under close experimental conditions.

Figure 1 shows the spectra of p, d, and t emitted at an angle of 40° in pC, pW, CC, and CW collisions. The maximum transverse momentum of particles was $p_T \approx$ 2.7 GeV/c. The dashed vertical straight lines in Fig. 1 indicate the limits for elastic nucleon–nucleon scattering at an angle of 40°. As seen in Fig. 1, the spectra of particles were measured in both pre-cumulative and cumulative kinematic ranges. An increase in the relative yields of deuterons and tritons with the momentum is characteristic of all four sets of data, which can indicate that the mechanism of production of protons and light nuclear fragments is common for these reactions.

The scaling approach proposed in [5, 6] can be used to comparatively analyze pA and CA collisions differing in energy and type of incident beam. In this approach, the production of particles with high p_T values is attributed to the hard quasibinary process involving components carrying the fractions X_1 and X_2 of the 4-momenta P_1 and P_2 of the incident particle

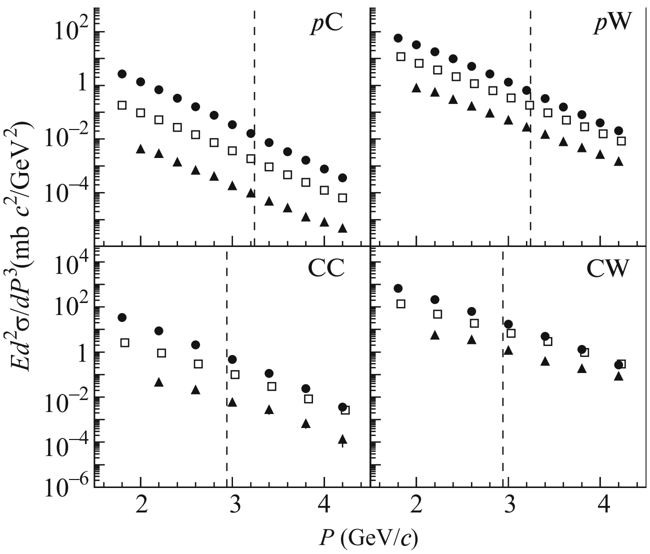

Fig. 1. Spectra of (circles) protons, (rectangles) deuterons, and (triangles) tritons in four different collisions. The vertical dashed straight lines indicate the kinematic limit of elastic nucleon–nucleon scattering at 40°.

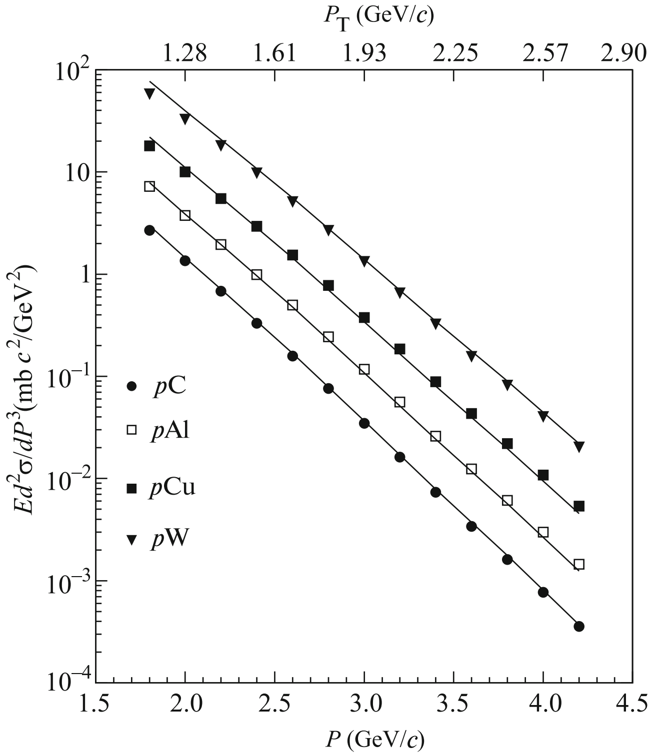

Fig. 2. (Points) Measured invariant cross sections for production of protons at an angle of 40° in C, Al, Cu, and W targets bombarded by 50-GeV/c protons and (lines) calculations by Eq. (1). The upper horizontal axis shows the transverse momentum.

and target, respectively. The values X_1 and X_2 can be determined from the requirement of the minimum invariant energy of the quasibinary reaction. A dimensionless scaling variable $\Pi = \sqrt{S_{\min}}/2m_N$, where $S_{\min}$ is the minimum energy of the quasibinary reaction for this inclusive process and m_N is the mass of the nucleon, was introduced in [6] to describe the behavior of inclusive spectra. The analysis of a rich set of experimental data on the production of particles in the cumulative and subthreshold regions showed [6, 7] that the invariant production cross sections of particles in A_1A_2 nuclear collisions can be described by the expression

$$f_{A_1+A_2} = E\frac{d^3\sigma}{dp^3} = C_1 A_1^{\alpha(X_1)} A_2^{\alpha(X_2)} \exp(-\Pi/C_2), \qquad (1)$$

where A_1 and A_2 are the atomic mass numbers of colliding nuclei, C_1 and C_2 are constants, and $\alpha(X)$ is a function of X assumingly the same for A_1 and A_2.

The description of p, d, and t spectra shown in Fig. 1 by Eq. (1) with the same slope parameter C_2 and the same A dependence would indicate that the mechanism of production of high-p_T particles is common for pA and CA collisions.

Slightly different functions $\alpha(X)$ were proposed in [6, 7]. To refine the A dependence in application to our data, we used spectra of protons emitted at an angle of 40° from C, Al, Cu, and W nuclear targets bombarded by protons. These experimental spectra are shown by points in Fig. 2. For each momentum value, we calculated the X_1 and X_2 values, then determined the C_1 and C_2 values and the function $\alpha(X_2)$ that ensure the best description of experimental data. Lines in Fig. 2 are calculated by Eq. (1) with the found optimal parameters. The best description of the data is achieved with the function $\alpha(X_2) = (k + X_2)/3$, where $k = 2.40$, which is close to $k = 2.45 \pm 0.05$ obtained in our previous work [2] for the production of π mesons at an angle of 35° in the laboratory reference frame from the same targets bombarded by 50-GeV/c protons. For the data shown in Fig. 2, the dimensionless slope parameter C_2 is 0.172 ± 0.003 and the parameter C_1 specifying the dimension of cross sections is (546 ± 18) mb c^3/GeV^2.

According to Eq. (1), the ratio of the inclusive production cross sections for any particle on different targets irradiated by the proton beam multiplied by the inverse A dependence should be unity:

$$R = \frac{f_{p+A_{2a}}}{f_{p+A_{2b}}}\left(\frac{A_{2b}}{A_{2a}}\right)^{\alpha(X_2)} = 1. \qquad (2)$$

Here, A_{2a} and A_{2b} are the atomic mass numbers of two different targets. The points in Fig. 3 are R values

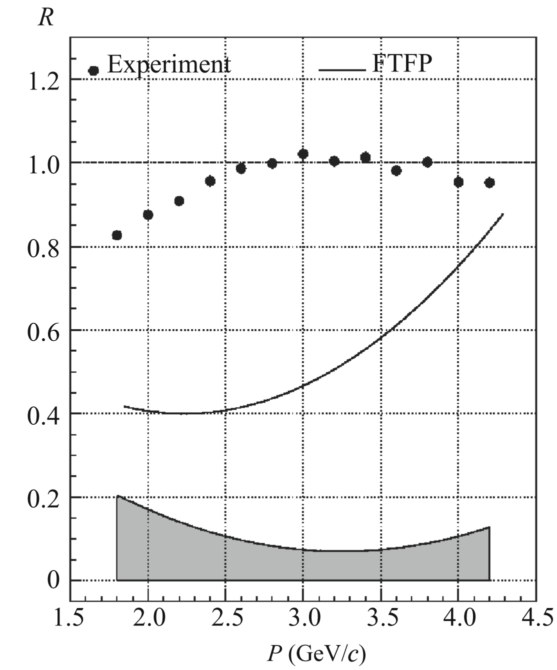

Fig. 3. Ratios R calculated for (points) experimental data and (line) values simulated by the FTFP algorithm [8]. The width of the gray band at the bottom represents the possible systematic error in the measured R values.

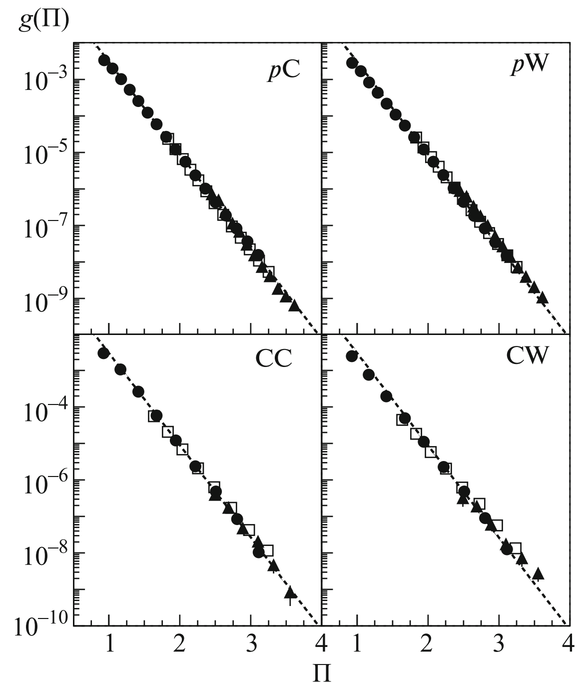

Fig. 4. Exponential dependence of the cross sections on Π for (circles) protons, (squares) deuterons, and (triangles) tritons. The dashed lines represent the function $\exp(-\Pi/0.172)$.

obtained from the ratio of the proton production cross sections in collisions of protons with tungsten and carbon. The gray band in the lower part of Fig. 3 presents the possible systematic error in the determination of R estimated by comparing the ratio of spectra measured in the experiment in different years. Within the assumed accuracy of measurements, the determined R values are in agreement with Eq. (2). For comparison, the ratio R for proton spectra from pW and pC events simulated within the Fritiof string fragmentation model (the basic FTFP generator in the Geant4 package [8]) is shown by the line in Fig. 3. It is seen that the ratio of simulated spectra is inconsistent with Eq. (2).

Figures 2 and 3 show that the production of protons in pA collisions is described by Eq. (1) with the dependence on the atomic mass number in the form $A_2^{\alpha(X_2)}$ and the same slope parameter C_2. Does the parameterization given by Eq. (1) reproduce other spectra shown in Fig. 1? According to Eq. (1), the inclusive cross section divided by $A_1^{\alpha(X_1)}A_2^{\alpha(X_2)}$ should give the exponential $\exp(-\Pi/C_2)$. Figure 4 shows distributions of the spectra of p, d, and t from pA and CA collisions over the dimensionless quantity

$$g(\Pi) = E\frac{d^3\sigma}{dp^3}\Big/\left(C_1 A_1^{\alpha(X_1)} A_2^{\alpha(X_2)}\right).$$

Here, $\alpha(X) = (2.4 + X)/3$ is taken in all cases, $A_1^{\alpha(X_1)} = 1$ for pA collisions, and constants C_1 specifying the dimension of cross sections were a priori determined when fitting Eq. (1) to experimental data and are summarized in Table 1. The dashed lines in all panels of Fig. 4 present the function $\exp(-\Pi/0.172)$. Figure 4 demonstrates a similar behavior of $g(\Pi)$ for all particles in all collisions. Parameterization (1) is valid only in the absence of secondary rescattering of the products of the quasibinary reaction on nucleons of the nucleus. Although it was shown in [2] that the final state interaction effect is weakened for cumulative particles with high p_{T} values, this effect cannot be excluded completely and is possibly responsible for the spread of points with respect to the dashed lines in Fig. 4.

Table 1. Parameters C_1 in various processes

Process	$p + A \to p + X$	$p + A \to d + X$	$p + A \to t + X$	$\mathrm{C} + A \to p + X$	$\mathrm{C} + A \to d + X$	$\mathrm{C} + A \to t + X$
C_1, mb c^3/GeV^2	546 ± 18	185 ± 15	56 ± 13	828 ± 35	367 ± 10	149 ± 17

CONCLUSIONS

New data on the yield of protons p, deuterons d, and tritons t with transverse momenta $p_T > 1$ GeV/c at an angle of 40° from carbon and tungsten targets bombarded by protons and carbon ions have been reported. The relative yields of deuterons and tritons increase with the momentum in all cases. The yield of deuterons with high p_T values from C + A collisions in the cumulative region becomes comparable to the yield of protons. The spectra of protons, deuterons, and tritons at high transverse momenta p_T in $p + A$ and C + A collisions can be described by Eq. (1) with the same dependence on the masses of nuclei involved in collisions and at similar slopes C_2. Since the parameterization given by Eq. (1) is used to describe the production of particles through hard quasibinary collisions, good agreement of this parameterization with experimental data can be considered as the confirmation of our previous conclusion [3, 4] that deuterons and tritons with high p_T values are directly knocked out from a nucleus in cumulative processes.

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