ISSN 0021-3640, JETP Letters, 2016, Vol. 104, No. 10, pp. 662–665. © Pleiades Publishing, Inc., 2016.
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FIELDS, PARTICLES, AND NUCLEI

Knockout of Deuterons and Tritons with Large Transverse Momenta in *pA* Collisions Involving 50-GeV Protons

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Received October 4, 2016; in final form, October 11, 2016

Formation of the d and t cumulative light nuclear fragments emitted from the nucleus with large transverse momenta at an angle of 35° in the laboratory frame is investigated. The data on collisions of 50-GeV protons with the C, Al, Cu, and W nuclei are collected using the extracted proton beam of the IHEP accelerator and the SPIN detector. The results indicate that the dominant contribution to formation of nuclear fragments comes from the local process of direct knockout from the nucleus.

DOI: 10.1134/S0021364016220045

The data [1] on direct deuteron knockout from light nuclei with energy transfer near 500 MeV suggested the existence of quantum nuclear states in which several nucleons occupy a volume comparable to the nucleon size [2]. Theoretical description of this process is complicated by the smallness of nucleon binding energy within the deuteron compared to the energy transfer. The mean size of the deuteron, determined by the 2.22-MeV binding energy, is greatly in excess of the distances corresponding to energy transfers of hundreds of MeV. By probing the kinematic region corresponding to interactions with more than one constituent nucleon, one may obtain unique data on unusual properties of these multinucleon systems. In the collisions involving atomic nuclei, the processes in which the kinematics of nucleon–nucleon scattering is violated are commonly referred to as cumulative [3, 4].

In this paper, we analyze the new data for formation of the d and t cumulative nuclear fragments with momenta up to 6.4 GeV/c emitted in pA collisions at an angle of 35° in the laboratory frame. The data have been obtained at IHEP (Protvino) by exposing the SPIN detector to the U70 50-GeV proton beam with an intensity of 5×10^{12} p/s. The SPIN detector is a narrow-aperture one-arm spectrometer, which comprises a target station, seven magnetic-optics elements, wire chambers, a time-of-flight system, and a threshold Cherenkov detector. By varying the positions of magnetic elements, one may accept particles emitted from the target at a laboratory angle in the range of 22°–55°. Secondary particles are momentum-analyzed to a precision of $\Delta p/p \approx 3\times10^{-3}$ using a system of wire chambers upstream and downstream of the analyzing magnet. The angular acceptance amounts to $\Delta\varphi \approx 100$ mrad and $\Delta\theta \approx 40$ mrad in the azimuthal and polar angles, respectively. The momentum acceptance varies from 5.5% for 1 GeV/c to 3.5% for 6 GeV/c. The spectrometer is tuned to a required secondary-particle momentum by appropriately setting the magnet currents. Particles are identified using the time-of-flight system and the Cherenkov counter. The momenta of detected particles may either comply with or violate the kinematics of the nucleon–nucleon collision (the latter case corresponds to the region of cumulative processes). Further details on the detector and the experimental procedure may be found in [5].

Momentum spectra of cumulative charged particles with large p_T up to 3.5 GeV/c in the $pA \to h^{\pm} + X$ reaction were for the first time obtained in previous measurements with the SPIN detector [5, 6]. A strong dependence of the inclusive cross section on the nucleus atomic number and indication to the local character of the formation mechanism of $h^{\pm}$ particles [6] suggested that the $h^{\pm}$ formation picked a significant

† Deceased.

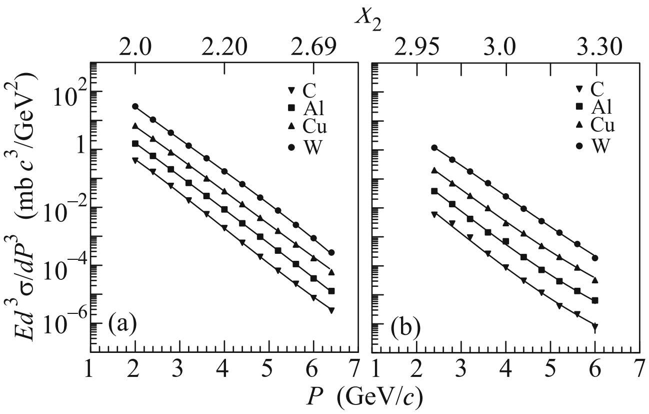

Fig. 1. Measured cross section for the (a) deuteron and (b) triton formation on four different targets. The upper horizontal axes show the X_2 variable [8]. The curves running through the experimental points are aimed at better perception of the data.

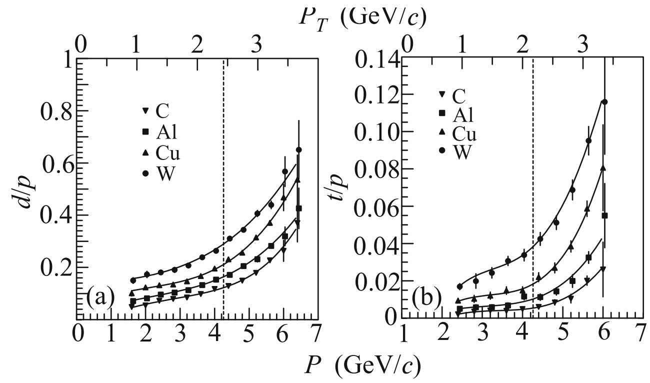

Fig. 2. Ratios of the (a) deuteron and (b) triton yields to the proton yield as functions of the particle momentum. The upper horizontal axes show the transverse momentum. Vertical dashed lines are the kinematic limits for the elastic nucleon— nucleon scattering. The curves running through the experimental points are given for better perception of the data.

contribution from proton collisions with a dense multinucleon (or multiquark) state present in nuclear matter. The analysis [7] demonstrated that measured yields of the (p, d, t) baryonic systems in the cumulative region were inconsistent with the predictions based on the model of short-range correlations [8].

The invariant cross sections for the d and t formation on the C, Al, Cu, and W nuclear targets are shown in Fig. 1 as functions of the fragment momentum (the lower horizontal axis). Stavinskii [10] proposed to describe the reactions with binary kinematics corresponding to cumulative and large-p_T processes in terms of the X_1 and X_2 variables. These variables are defined as the fractions of the four-momenta of the interacting projectile and target. In the case of the baryon-number conservation, the X_1 and X_2 values may be uniquely determined assuming a minimum value of the invariant energy required for formation of the inclusive particle. The upper horizontal axis in Fig. 1 shows the X_2 variable, which in our case is defined as the minimum target mass (in units of the nucleon mass) required for formation of a fragment with a given momentum at an emission angle of 35° in the laboratory frame. For the considered kinematic region, the data shown in Fig. 1 demonstrate that the minimum target mass required for the deuteron (triton) formation is equal to or greater than two (three) nucleon masses. Therefore, the formation of these fragments should involve proton collisions with a multinucleon (or multiquark) structure inside the nucleus.

Shown in Fig. 2 for the same four targets are the ratios of the deuteron and triton formation cross sections to that for proton emission at equal measured momenta. Corresponding values of the transverse momentum p_T are quoted on the upper horizontal axis. The d/p and t/p ratios are seen to increase with the momentum for all targets. For the pA collisions with different target nuclei at 70 GeV/c, the d/p ratio was measured in the FODS experiment at IHEP [9] over the p_T region of 1–4 GeV/c, which is similar to that probed by the SPIN experiment. The d/p ratio measured in the FODS experiment proved to be independent of p_T and amounted to less than 0.02 for all targets, including lead. That the d/p ratios measured by the FODS and SPIN experiments have different values and momentum dependences suggests that the mechanisms of deuteron formation are different in these two experiments. It should be emphasized that the SPIN and FODS experiments probe different kinematic regions. In particular, the FODS data are restricted to a kinematic region allowed for the nucleon—nucleon scattering.

According to the data presented in Fig. 1, we observe that two or more target nucleons are involved in deuteron formation, and three or more are involved in triton formation. However, two or more target nucleons may be involved not through a local process but rather through a chain of successive collisions with several target nucleons. Two or more nucleons arising from multiple scatterings may have similar momenta and emission angles and, therefore, may finally coalesce to form a single nuclear fragment. The formation of two protons with similar momenta through multiple scattering, including those in the cumulative region, was indeed observed in the $pA \to ppX$ [11] and $eA \to ppX$ [12] reactions. The Hanbury—Brown—Twiss (HBT) analysis of these data demonstrated that the two-proton formation region is strongly A-dependent, or directly depends on the nucleus size. Thus, the radii of the two-proton formation regions for the C and Pb targets differ by a factor of over 1.5 [12]. Therefore, should the sizes of the deu-

Mean values of the B_2 parameter

Target	C	Al	Cu	W
$B_2 \times 10^2$, GeV$^2/c^3$	1.41 ± 0.10	1.56 ± 0.08	1.51 ± 0.07	1.41 ± 0.06

teron and triton formation regions show strong A dependences in the kinematic area probed by SPIN, this would indicate that these formation processes pick dominant contributions from multiple scattering and subsequent nucleon coalescence.

The coalescence model allows one to estimate the volume of the nuclear-fragment formation region, V, from the coalescence coefficients B_A [13]. For formation of a fragment with the atomic number A, the coalescence coefficient B_A and the size of the fragment formation region are interrelated through $B_A \sim V^{-(A-1)}$, which implies $B_2 \sim V^{-1}$ and $B_3 \sim V^{-2}$ for the deuterium and tritium, respectively. In principle, the knowledge of both the proton and neutron spectra is required for investigating the effect of coalescence. In practice, the coalescence coefficient B_A is determined from the cross sections for the A fragment and proton formation under the assumption that $n/p \approx 1$:

$$\frac{E_d}{\sigma_{\text{inel}}}\frac{d^3\sigma_A}{dp_A^3} = B_A \times \left(\frac{E_p}{\sigma_{\text{inel}}}\frac{d^3\sigma_p}{dp_p^3}\right)^A. \qquad (1)$$

Here, the cross sections for the A fragment and proton formation, σ_p and σ_A, correspond to the same momenta per nucleon (i.e., the A-fragment total momentum p_A is A times larger than the proton momentum p_p), and σ_{inel} denotes the cross section for inelastic pA collisions.

The growth of the deuteron (triton) formation region at multiple scattering in a nucleus should result in a decrease in B_2 (B_3) with an increase in the size of the nucleus. The B_2 values averaged over the full range of accessible p_T values are quoted in the table. Within measurement errors, these show no dependence on the size of the target nucleus.

The extracted B_2 and B_3 values are plotted in Fig. 3 as functions of p_T. Both B_2 and B_3 are seen to increase with p_T, which implies that the fragment source region is enlarged with increasing transverse momentum. The mean B_3 values for the Al, Cu, and W targets are similar, while that for the carbon target is somewhat less. The data shown in Fig. 3 indicate that the sizes of the d and t formation regions do not increase with the size of the nucleus.

In summary, we have reported the data on formation of the lightest nuclear fragments d and t in pA collisions emitted with large transverse momenta forbidden by the kinematics of nucleon– nucleon scattering. An analysis of the extracted coalescence coefficients B_2 and B_3 suggests that these formation processes are dominated by the direct knockout mechanism. Given the binding energies of a few MeV, large energy transfers to these fragments are direct evidence for a cold and dense multinucleon (or multiquark) component in nuclei that may be probed using the direct-knockout reactions.

We are grateful to the IHEP directorate for support of this investigation and to the staffs of the accelerator and beam divisions for efficient operation of the U70 accelerator and of the eighth beam channel. A.A.B. and S.S.Sh. acknowledge partial support from the Russian Foundation for Basic Research (project no. 14-02-00896-a).

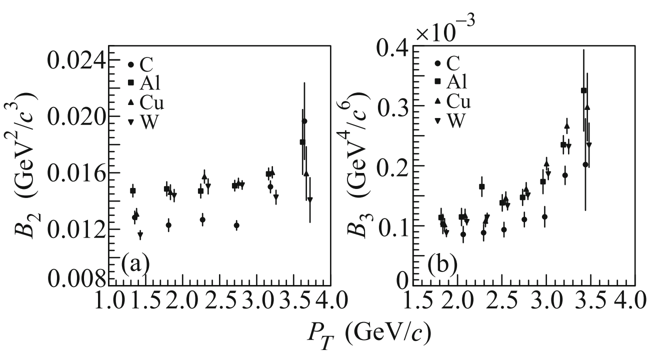

Fig. 3. Extracted values of the coalescence coefficients (a) B_2 and (b) B_3 as functions of the fragment transverse momentum.

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Translated by A. Asratyan