Quark cluster contribution to cumulative proton emission in fragmentation of carbon ions.

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In the FRAGM experiment at heavy ion accelerator complex TWAC-ITEP, the proton yields at an angle 3.5° have been measured at fragmentation of carbon ions at \( T_0 = 0.6, 0.95 \) and 2.0 GeV/nucleon on beryllium target. The data are presented as invariant proton yields on cumulative variable \( x \) in the range \( 0.9 < x < 2.4 \). Proton spectra cover six orders of invariant cross section magnitude. They have been analyzed in the framework of quark cluster fragmentation model. Fragmentation functions of quark-gluon string model are used. The probabilities of the existence of multi-quark clusters in carbon nuclei are estimated to be 8–12% for six-quark clusters and 0.2–0.6% for nine-quark clusters.

**Introduction.** Since the discovery of cumulative effect in seventies [1, 2], the question of the nature of cumulative particles is still under discussion. Cumulative particles are produced in interactions with nuclei in kinematic region forbidden for interaction with free nucleon. Few hypothesis of their origin have been considered. Among them there are fluctuations of nuclear matter [3], clusters [4], few-nucleon correlations [5], excited dibaryons [6], etc. It was pointed out [7, 8] that multiple scattering in nuclear matter can also contribute. Modern theoretical approaches (see, e.g., [9]) connect the cumulative effect with contribution from multi-quark states. These states (first of all, six-quark states) are considered for nuclear matter phase transitions at high densities. At intermediate energies [10], the existence of multi-quark clusters in cold and hot baryonic matter blurs the boundary between hadronic and quark-gluon phases. Probability of the two-nucleon fluctuation in \(^{12}\text{C}\) nucleus was for the first time estimated in [11] based on the experimental data on cumulative pion production. It is in qualitative agreement with theoretical prediction, which was obtained later within quark cluster model [12]. Similar approach, in which fragmentation functions of quark clusters were calculated within the quark-gluon string model, was successfully used in [4] for the description of \( K^-\), \( \pi^-\) and antiproton inclusive spectra in hadron-nucleus interactions.

Ion beams open new ways for the cumulative effect study. One of the authors of [4], A.B. Kaidalov, suggested to use the data from our experiment FRAGM [13][14] for the experimental estimation of the admixture of the multi-quark cluster state in nuclear matter. In this experiment, cumulative protons are measured in inverse kinematics, i.e. in the fragmentation region of projectile nucleus. Such measurement has definite advantages over measurements in the target fragmentation region. First, relativistic boost of forward going protons increases considerably proton detection solid angle in the rest-frame of fragmented nucleus at fixed acceptance of a detection system in laboratory frame. Second, in the inverse kinematics there are no problems with a detection of protons which are at rest in projectile rest frame because they have lab momentum close to momentum per nucleon of the projectile. This allows to clearly observe nucleon-nucleon component of the projectile and use it for normalization that is impossible for target fragmentation. However inverse kinematic creates additional problems, connected with measurements of the protons with momentum few times higher than momentum per nucleon of the projectile.

**Experiment.** In the FRAGM experiment at the accelerator complex TWAC (Tera-Watt Accumulator) ITEP, the yields of nuclear fragments are studied in carbon fragmentation on beryllium target:

\[
^{12}\text{C} + \text{Be} \rightarrow f + X. \tag{1}
\]

The main goal of the experiment is to collect data at high momenta of nuclear fragments \( f \). In this paper the proton spectra from the reaction (1), obtained at carbon kinetic energies \( T_0 = 0.6, 0.95 \) and 2.0 GeV/nucleon are analyzed. A measurement of momentum spectra at different energies gives a possibility to study energy dependence of their parameters.

Experimental set-up (Fig. 1) is comprised of two-step magneto-optical channel, placed at an angle \( \theta = 3.5^\circ \) with respect to internal ion beam of the ITEP accelerator. Narrow vertical strip of 200 \( \mu \text{m} \) Be-foil was used as a target which allows to have simultaneously both high luminosity due to multiple passage of ions through the target and small sizes of the source for

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Fig. 1. Set-up of the FRAGM experiment. TWAC MR is the TWAC main ring, M is a monitor, Q1-Q5 are quadrupoles, BM1 and BM2 are bending magnets, Co1 and Co2 are collimators, CF1, CF2, H1, C2 and C3 are scintillator counters.

full usage of high momentum resolution of the channel.

The first step of the channel consists of quadrupole doublet Q1, Q2, bending magnet BM1 and achromatic correction quadrupole Q3, placed in the first focus of the channel. The second step contains bending magnet BM2 and quadrupole doublet Q4, Q5. This step refocuses the target image from the first focus to the second one, sixteen meters downstream. Scintillator hodoscope of twenty vertical and eight horizontal elements with sizes 20x1x1 cm$^3$ for beam profile measurements is placed in the first focus. This hodoscope allows to improve fragment momentum resolution up to 0.2%, using focusing properties of magneto-optical channel with full momentum acceptance of ±3%. Scintillator counters CF1, CF2 and C2, C3 for amplitude and time-of-flight (TOF) measurements are placed in the first and in the second focuses. Each counter is seen by two PMT’s from the opposite sides to use their signals in mean-time determination. Coincidence of signals from the counters of the first and the second focuses gives a trigger, which starts the data transfer from CAMAC system to a computer under LINUX. Readout software is based on ROOT [15] package. As a monitor M, a telescope of three scintillator counters, which view the target at an angle of about 2° is used.

Protons are selected on correlation plot of signal charge from one of scintillation counters (QDC) vs time-of-flight (TDC) at a base of 16 m. Projectile energy is 600 MeV/nucleon, fragment rigidity is 2.15 GeV/c.

Fig. 2 Correlation plot of signal charge from one of scintillation counters (QDC) vs time-of-flight (TDC) at a base of 16 m. Projectile energy is 600 MeV/nucleon, fragment rigidity is 2.15 GeV/c.

by momentum scan of the channel with a step 25-200 MeV c$^{-1}$. Set-up efficiency is calculated with GEANT4-based [16, 17] simulation program. The program traces particles in the magneto-optical channel taking into account multiple scattering effects, ionization losses and absorption in the detector materials.

Data analysis. The invariant cross sections of proton yield $\sigma_{inv} = (E/p_0)d^2\sigma/dxd(p_t^2)$ as a function of cumulative variable $x = p/p_0$ for projectile energies $T_0$ = 0.6, 0.95 and 2.0 GeV/nucleon are shown in Fig.3 - 5. Here $p_0$ is projectile momentum per nucleon, $p$ is proton momentum in the laboratory frame, $p_t$ is its transverse component with respect to projectile. The data cover six orders of invariant cross section magnitude. It is three orders of magnitude more than in the most sensitive previous experiment [18] at 1.05 GeV/nucleon. In the region of the maximum ($x \approx 1$) the shapes of the spectra are close to Gaussians as predicted by statistical models. However, already at $x \geq 1.3$ the spectra become exponentials, which is typical for cumulative processes.

As was already mentioned, the most successful approach to the problem of cumulative particle production is the quark cluster model [4]. This model was used to describe yields of cumulative pions, kaons and antiprotons. However, for protons such analysis was not performed. Reliable identification of one-nucleon component achievable in inverse kinematics allows to apply this analysis also for protons. In the framework of this model clusters existing in a nucleus, consist
of 3\(k\) (\(k = 1, 2, 3, \ldots\)) valent quarks. Conventional nucleon component of the nucleus corresponds to \(k = 1\). The probabilities \(w_k\) of such clusters in a nucleus with \(N\) nucleons are normalized by \(\sum_{k=1}^{N-1} w_k = 1\). As cluster contribution into observed processes falls with increasing \(k\), we limit ourselves with \(k = 1, 2, 3\) only and represent the invariant cross section as a sum of three components:

\[
\sigma_{inv} \propto G w_1 g(x, p_t^2) + w_2 b_2(x, p_t^2) + w_3 b_3(x, p_t^2),
\]

(2)

where functions \(g\), \(b_2\) and \(b_3\) are fragmentation functions of quark clusters into protons. \(g\) is a gaussian

\[
g(x, p_t^2) = \exp(-0.5(1-\Delta-x)^2/\sigma_x^2) \exp(-0.5p_t^2/\sigma_p^2),
\]

(3)

\(\Delta\) is a gaussian within quark gluon string model. We have got the invariant cross section slopes on \(p_t^2\) from the data [18] and extrapolated them to the region of our experiment, the values \(\alpha_1 = 5 \text{ GeV}^{-2}c^2\) and \(\alpha_2 = 3 \text{ GeV}^{-2}c^2\) were used.

The results of the data fit with the formula (2) at projectile energies 0.6, 0.95 and 2.0 GeV are shown in Fig. 3 - 5. The fitted curve is shown by solid line. The contributions of one-nucleon (3q) component, two-nucleon (6q) and three-nucleon (9q) clusters are given by dashed, dotted and dash-dotted lines, respectively.

The fit parameters are mean value (1-\(\Delta\)) and r.m.s. of Gaussian \((\sigma_x)\), and also probabilities \(w_2\) and \(w_3\), connected to \(w_1\) with the relation \(w_1 + w_2 + w_3 = 1\). The obtained probabilities \(w_2\) and \(w_3\) for carbon
regions near in the quark-gluon string model only in the boundary the fragmentation functions (4) and (5) were justified uncertainties of the theoretical approach. First of all because of difficulties to take into account systematic carbon nucleus could be considered only as estimates It should be emphasized that obtained probabilities for carbon nucleus are given in the Table. The two-nucleon cluster probability, estimated at different projectile energies varies within 7.7 - 11.9%, while the three-nucleon one is within 0.2 - 0.6%. They are compatible both with given statistical errors of the fit and with expected independence of these probabilities on projectile energy. It should be emphasized that obtained probabilities for carbon nucleus could be considered only as estimates because of difficulties to take into account systematic uncertainties of the theoretical approach. First of all the fragmentation functions (4) and (5) were justified in the quark-gluon string model only in the boundary regions near \( x=0 \), \( x=2 \) and \( x=3 \). The calculation of fragmentation functions in the whole \( x \) range is still unsolved problem of the model. The fragmentation functions used here are the simplest (and widely used) ones, satisfying above mentioned boundary conditions. Moreover, in Fig.3 - 5 at \( x > 1.3 \) one can see wave-like behavior of the resulting fit curve while the data demonstrate purely exponential fall off with \( x \).

This can be considered as indication that the model does not take into account some small effects which smear fragmentation functions behavior. One of them is evident, it is internal motion of two- and three-nucleon clusters in a nucleus which has not been taken into account in this approach. It can be expected that improvement of multi-quark cluster approach will allow to overcome these difficulties. The important result of the presented analysis is the demonstration of possibility to use data on cumulative proton yield in the inverse kinematics for estimates of these probabilities. Obtained value of \( w_2 \) is close to the value of 6%, obtained in \[11\] from cumulative pion production and to theoretical predictions of 12.5% given in \[12\]. However, the value of \( w_3 \) is much smaller than 2.6% predicted in \[12\]. The values \( w_2 \) (\( w_3 \)) are not far from probabilities of two-nucleon (three-nucleon) correlations in nuclei, obtained in the TJNAF experiment on \( \Lambda(e,e') \) inclusive electron scattering on nuclei \[19\], (19.3 \( \pm \) 4.1)% and (0.55 \( \pm \) 0.17)% for carbon nucleus. Reasonable agreement of the results of these experiments can be considered as evidence for unique nature of quark clusters and short-range nucleon correlations in nuclei.

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| \( T_0 \), GeV/n | \( p_0 \), GeV/c/n | \( x_{\text{max}} \) | \( w_2 \) | \( w_3 \) |
|-----------------|-----------------|------------|------|------|
| 0.6             | 1.22            | 1.95       | .077(10) | .004(2) |
| .95             | 1.6             | 2.4        | .119(17) | .002(1) |
| 2.0             | 2.72            | 2.15       | .098(18) | .006(1) |

Table. Results from the fits of Fig.3 - 5. \( T_0 \) and \( p_0 \) are kinetic energy and momentum of the projectile per nucleon, \( x_{\text{max}} \) is maximal value of \( x \), reached in this experiment, probabilities \( w_2 \) and \( w_3 \) for carbon nucleus are defined in the text. Statistical errors of the fit are given in parentheses.

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