Nuclear fragmentation study at ITEP heavy ion facility

B M Abramov, P N Alekseev, Yu A Borodin, S A Bulychjov, I A Dukhovskoy, A B Kaidalov¹, A I Khanov, A P Krutenkova, V V Kulikov, M A Martemianov, M A Matsyuk and E N Turdakina
Institute for Theoretical and Experimental Physics (ITEP), Moscow, 117218, Russia
E-mail: anna.krutenkova@itep.ru

Abstract. In an experiment performed at ITEP TWA heavy ion accelerator, the yields of hydrogen (p,d,t) and helium (from $^3$He to $^8$He) isotopes at 3.5° from fragmentation of $^{12}$C at $T_0 = 0.2 - 3.2$ GeV/nucleon on a Be target have been measured. Momentum spectra of the fragments in the projectile rest frame have been obtained in larger momentum intervals than in the previous experiments with heavy ion beams. The main attention was given to the region of high momentum where fragment velocity exceeds the velocity of the projectile nucleus. The obtained data cover about 6 orders of the differential cross section magnitude. It made possible the observation of a transition from the Gaussian shape of the longitudinal momentum spectra in projectile rest frame, expected for the evaporation mechanism, to the exponential shape, typical for the cumulative (pre-equilibrium) processes. The Feynman $x$ distributions for protons are analyzed in the framework of quark-gluon string model. The probabilities of existence of six- and nine-quark clusters are estimated and compared with the results on two- (three-) nucleon short range correlations in nuclei measured at Jefferson Laboratory.

1. Introduction
Nuclear fragmentation has been widely studied experimentally at different heavy ion facilities. It was observed that for some fragments produced at small angles the projectile momentum spectrum has a Gaussian evaporation peak and an exponential tail. The origin of the peak is well understood and it lies in momentum distribution of nucleons in a nucleus [1, 2, 3]. It can be reasonably described within statistical models. The origin of the high energy tail (pre-equilibrium or cumulative part of the spectrum) is not so clear and is under discussion up to now. Some theoretical approaches connect the interpretation of the cumulative effect to the contribution of multiquark states in nuclei (see, for example [4] and references therein). Such states arise while considering the transition from hadron to quark-gluon degrees of freedom in nuclear matter at high densities [5]. We have performed the experiment FRAGM [6] at ITEP TWA (Tera Watt Accumulator) heavy ion accelerator complex with the main goal to take data at high momenta of nuclear fragments. The production of cumulative particles in hadron-nucleus interactions was considered previously in [7] in the framework of the quark-gluon string model (QGSM). The distribution of quarks in the nucleus was derived under the assumption that coherent clusters exist in the nucleus and their structure functions have Regge asymptotic

¹ Deceased

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behaviour. The spectra of cumulative hadrons (K-mesons, π-mesons and ¯p) were successfully obtained for high energy projectiles. The probabilities \( w_k \) of the existence of \( k \)-nucleon (3\( k \)-quark) clusters in the nucleus were calculated according to Blokhintsev flucton model [8].

The use of heavy ions at intermediate energies opens new possibilities to study the cumulative effect. It is important, that for fragmentation processes it becomes possible to study both cumulative and evaporation momentum regions simultaneously. We have measured the yields of protons from fragmentation of \(^{12}\text{C}\) at initial kinetic energy \( T_0 \) in the range 0.2 – 3.2 GeV/nucleon on a Be target. The data obtained were analyzed as in [7] in the framework of QGSM suggesting the existence of multiquark configurations in nuclei. The probabilities of their existence were estimated and compared with the available theoretical calculations and experimental data.

2. Experiment

The experiment FRAGM [6] was carried out at the heavy-ion complex ITEP TWA which includes an ion laser source, a linear accelerator, a booster ring and the 4 GeV/nucleon accelerator main ring. The fragments of the carbon nucleus produced at an internal thin Be target at 3.5\(^\circ\) were momentum analyzed by the two-step beam channel with intermediate and final focuses at 16 and 32 meters from the target. A few scintillation counters were placed in each focus for multiple measurement of ionization losses and time-of-flight. At the intermediate focus a scintillator hodoscope of 20x8 elements was used to control the beam size and to improve momentum resolution. Each scintillator was viewed by two photomultipliers from the opposite sides. The PM signals were sent to the electronics crates through 50 m long cables and passively split into two parts. One was sent to the inputs of 16-channel CAMAC-QDCs. The other part was sent to threshold discriminators for time-of-flight measurements and for the trigger. The coincidence between the signals from two counters from different focuses was used as a trigger to initialize the read out of amplitude and time information to a LINUX computer. The information from the scalers, monitor and beam channel control system were also read out. A coincidence of three scintillation counters which directly view the target at an angle of 2\(^\circ\) was used as a monitor. A ROOT based package was written for the data acquisition and data analysis.

The fragment yields were measured by scanning the beam momentum with a step of 50-100 MeV/c and counting the number of events corresponding to different fragments and normalizing to the monitor. The relative cross sections \( d\sigma/\left(d\Omega dp/p\right) \) where \( p \) is the fragment momentum in a laboratory frame were calculated. They are shown in Fig.1 for hydrogen and helium isotopes. Smooth curves are drawn through the measured points for each fragment to guide the eye. This data presentation is convenient for direct determination of the isotopic composition of the beam.

![Figure 1. Relative yields of hydrogen and helium isotopes from \(^{12}\text{C}\) fragmentation at 300 MeV/nucleon. Horizontal axis – fragment momentum \((p)\) divided by its charge, vertical axis – differential cross section \(d\sigma/\left(d\Omega dp/p\right)\) in arbitrary units.](image-url)
3. Data analysis

For the physics analysis, the distributions of invariant cross section with longitudinal momentum in the fragmenting nucleus rest frame is usually used. In Fig.2 the results of this experiment are shown. Our measurements cover the momentum range up to 0.8 GeV/c and 5 - 6 orders of magnitude in the cross section. The upper limits of these ranges are much larger than in previous experiments with heavy ion beams. The proton momentum distribution can be well described by Gaussian in the -0.15 to +0.15 GeV/c interval. At higher momenta a large deviation from Gaussian clearly shows a transition to exponential dependence typical for cumulative processes. A significant deviations from Gaussian is also present for deuterons with the momentum higher than 0.4 GeV/c. For tritons and heavier fragments the Gaussian distribution describes well the experimental data in the whole longitudinal momentum range.

For the analysis of high momentum part of the spectrum it is convenient to use the dependence on the fragment kinetic energy $T$ in the $^{12}$C rest frame. The cross section decreases with $T$, and on a log scale two regions are well distinguished: the evaporation region below $T \approx 20$ MeV and the cumulative region at $T > 50$ MeV, each having its own constant slope parameter. At each projectile energy the spectra were parametrized by the sum of two exponents

$$Ed^3\sigma/d^3p \sim A_S exp(-T/T_S) + A_C exp(-T/T_C),$$

where $A_S$ and $A_C$ are normalization factors for the evaporation and cumulative regions, and the slope parameters $T_S$ and $T_C$ are temperatures in these regions.

The measured values $T_S$ are in a good agreement with the widths of the Gaussians from the momentum distributions and do not depend on projectile momentum within experimental errors.

The $T_C$ values increase with the projectile energy (see Fig.3). Other available data are also shown in Fig.3: ALADIN data [9] from GSI at 1 GeV/n for Au + Au collisions and data for C + C collisions from Dubna [10] at 3.6 GeV/n. They are in reasonable agreement with our measurements. The energy dependence of $T_C$ means that we are far from scaling behaviour at the energies studied.

4. Feynman $x$ spectra

Laboratory momentum spectra of protons have been analysed in the QGSM. In this model a variable $x = p_{lab}/p_0$ is usually used, where $p_{lab}$ is proton momentum in laboratory frame, $p_0$ is projectile momentum per nucleon. In the QGSM [7] the production of cumulative protons is considered as a result of fragmentation into protons of the massive clusters, consisting of $3k \ (k$
= 1, 2, 3,...) valence quarks. Let us denote the probability of the existence of such clusters in a nucleus composed of \( A \) nucleons as \( w_k \), where \( \sum_{k=1}^{A-1} w_k = 1 \) (\( k = 1 \) corresponds to usual nucleon component). As the contribution of clusters decreases with increasing \( k \), we’ll confine ourselves to \( k = 1, 2, 3 \) and represent the invariant cross section as a sum of three terms.

\[
E \cdot \frac{d^3\sigma}{dx dp^2} = C'(w_1 g(x, p_1^2) + w_2 b_2(x, p_1^2) + w_3 b_3(x, p_1^2)),
\]

where \( p_t \) is a transverse momentum and functions \( g, b_2 \) and \( b_3 \) are known fragmentation functions for systems of 3\( q \), 6\( q \) and 9\( q \) clusters respectively. \( g(x, p_1^2) \) is a one nucleon component taken as a Gaussian of statistical models.

\[
g(x, p_1^2) = G \exp\left(-0.5((1 - \Delta) - x)^2/\sigma_x^2\right) \exp\left(-0.5p_t^2/\sigma_p^2\right),
\]

\[
b_2(x, p_1^2) = B_2(x/2)^3(1 - x/2)^3 \exp(-\alpha_1 p_t^2), b_2(x, p_1^2) = 0, \quad x \notin [0, 2],
\]

\[
b_3(x, p_1^2) = B_3(x/3)^3(1 - x/3)^6 \exp(-\alpha_2 p_t^2), b_3(x, p_1^2) = 0, \quad x \notin [0, 3],
\]

The values \( G, B_2 \) and \( B_3 \) are known normalization constants

\[
G = (4 \cdot \sqrt{2\pi} \cdot \sigma_x \cdot \sigma_p^2)^{-1}, \quad \sigma_p = \sigma_x \cdot m_p \cdot p_0/(T_0 + m_p),
\]

\( B_2 \) and \( B_3 \), are determined from the conditions

\[
\int_0^\infty \int_0^\infty B_i(x, p_1^2) dx dp_1^2 = i/2, \quad i = 2, 3.
\]

The cross section slope parameters on \( p_1^2 \), \( \alpha_1 = 5 \) (GeV)\(^{-2} \cdot c^2 \) and \( \alpha_2 = 3 \) (GeV)\(^{-2} \cdot c^2 \), are derived from the data [11].

We fitted the proton spectra with equation (2), and the result is presented in Fig.4 for \( T_0 = 0.6 \) GeV/nucleon.

The following fit parameters were obtained: the center position and root mean square for the Gaussian, \( (1 - \Delta) \) and \( \sigma_x \), the probabilities \( W_2 = w_2/w_1 \) and \( W_3 = w_3/w_1 \). In Fig.4 the full fitting curve is shown as a solid line, the contributions to the fragmentation of one nucleon component, two and three nucleon clusters are shown with dashed, dotted and dashed-dotted lines. The fitted parameters are stable at the projectile energies of our experiment 0.3, 0.6, 2.0 GeV/n, the value \( W_2 \) is found to be (10-15 \%) and \( W_3 \) is less than 1\%.

**Figure 3.** Dependence of slope parameter \( T_C \) on \( ^{12}\text{C} \) energy: full squares - this experiment, triangle - [9], empty square - [10].
Figure 4. Invariant cross section $\sigma_{\text{inv}} = E \cdot d^3 \sigma / d^3 p$ for yield of protons from $^{12}$C fragmentation at 0.6 GeV/nucleon in relative units as a function of Feynman variable $x = p_{\text{lab}} / p_0$. The solid curve describes the dependence in the QGSM (see equation (2) in the text). The contributions of one nucleon component, of two- and three-nucleon clusters are shown by the dashed, dotted and dashed-dotted lines, respectively.

5. Discussion

The obtained values $w_2$ and $w_3$ are in a reasonable agreement with the values 0.115 and 0.009, which were found for cluster radius $R_c = 0.85$ fm and used by the authors of [7]. The value $w_2$ also agrees with the values of 6-quark cluster probability 0.125, predicted in [12] for $^{12}$C based on $R_c = 0.50$ fm, but our value for $w_3$ is much smaller than 0.026 predicted in [12]. The values $w_2$ ($w_3$) could be compared with the probabilities of the existence of two (and three-nucleon) short-range correlations in nuclei, which were obtained in [13] and are $(19.3 \pm 4.1)$% and $(0.55 \pm 0.17)$% for carbon nucleus. This supports the hypothesis of Pirner and Vary [5] that short range correlations in nuclei and quark cluster approach could have the same origin.

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