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Small-angle fragmentation of carbon ions at 0.6 GeV/n: a comparison with models of ion-ion interactions

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Abstract. Momentum distributions of hydrogen and helium isotopes from ^{12}C fragmentation at 3.5^o were measured at 0.6 GeV/nucleon in the FRAGM experiment at ITEP TWA heavy ion accelerator. The fragments were selected by correlated time of flight and dE/dx measurements with a magnetic spectrometer with scintillation counters. The main attention was drawn to the high momentum region where the fragment velocity exceeds the velocity of the projectile nucleus. The momentum spectra of fragments span the region of the fragmentation peak as well as the cumulative region. The differential cross sections cover six orders of magnitude. The distributions measured are compared to the predictions of three ion-ion interaction models: BC, QMD and LAQGSM03.03. The kinetic energy spectra of fragments in the projectile rest frame have an exponential shape with two temperatures, being defined by their slope parameters.

1 Introduction

The emission of light fragments (LF) is an important part of ion-ion interactions. Different reaction mechanisms contribute to this rather complicated process which hardly can be described in analytical way. The Monte-Carlo transport codes give a good approach to this problem, but they need verification against the experimental data [1]. In our experiment FRAGM [2] at ITEP TWA heavy ion accelerator, we have measured the forward-angle yields of the fragments from the reaction

$$^{12}\mathrm{C} + \mathrm{Be} \rightarrow \mathrm{f} + X, \quad (1)$$

where f stands for all fragments up to isotopes of projectile nucleus. The projectile kinetic energies were T_0= 0.2–3.2 GeV/nucleon and the fragment angle was of 3.5^o. In this report we present preliminary data at T_0= 0.6 GeV/nucleon for the LF emission. In our study we focused mostly on high momentum fragments whose velocities exceed the velocity of the projectile nucleus, because:

1. high momentum (cumulative) particles provide information on localized dense objects inside nuclei, as was emphasized as early as in 1970s [3]; but the nature of cumulative particles production is still under discussion up to now [4];

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2. there is a lack of data on fragment emission at intermediate energies in ion-ion collisions [5] that test different models of ion-ion interactions covering large kinematic region (for both the cumulative region and the fragmentation peak region);

3. this study can be useful for testing and improving transport codes often used in nuclear applications, like carbon radiotherapy [6].

2 The FRAGM Experiment

The FRAGM experiment [2] 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 from the carbon nucleus produced at an internal thin Be target at 3.5^o were momentum analyzed by the two-step beam channel with intermediate and final focuses at 26 and 42 meters from the target. A few scintillation counters were placed in each focus for multiple measurements 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. Another 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^o was used as a monitor. A ROOT-based package was written for the data acquisition and data analysis.

3 Data analysis and test of models of ion-ion interactions

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. Regions of different fragments were well separated and could be clearly selected on time-of-flight *vs* dE/dx plots. The relative cross sections $d^2\sigma/(d\Omega dp)$, where p is the fragment momentum in a laboratory frame, were calculated. They are shown for hydrogen and helium isotopes in comparison with the calculations by three models: BC (Binary Cascade) [7] in Fig. 1, QMD (Quantum Molecular Dynamics) [8] in Fig. 2 and LAQGSM (Los Alamos version of the Quark Gluon String Model) [9] in Fig. 3. The BC and QMD models were incorporated into a GEANT4-based package (version 4.9.4). Our measurements cover three-to-six orders of magnitude in the cross section, depending on the fragment. Cumulative proton emission has been studied previously in 0.3-2.0 GeV/nucleon energy range [10–12]. Near the fragmentation maximum, the shape of the proton distribution is close to a Gaussian one. At higher momentum, the cross section decreases exponentially which is typical for cumulative processes. The BC model describes the region near the fragmentation maxima rather well, strongly underestimating the yields in the cumulative region[1].

The ^{4}He yield at fragmentation maximum is very well predicted by BC, but a difference of a factor of two-to-three can be seen for d, t, ^{3}He and ^{6}He. Within the QMD model, the fragmentation peaks are too narrow, the high momentum regions are strongly underestimated. Within LAQGSM, the shapes of fragmentation peaks for p and d are reasonably well described, while for t, ^{3}He, ^{4}He, the

[1] Proton yield was normalized to the BC calculation at the maximum of the fragmentation peak. This normalization factor was used for all fragments in all figures.

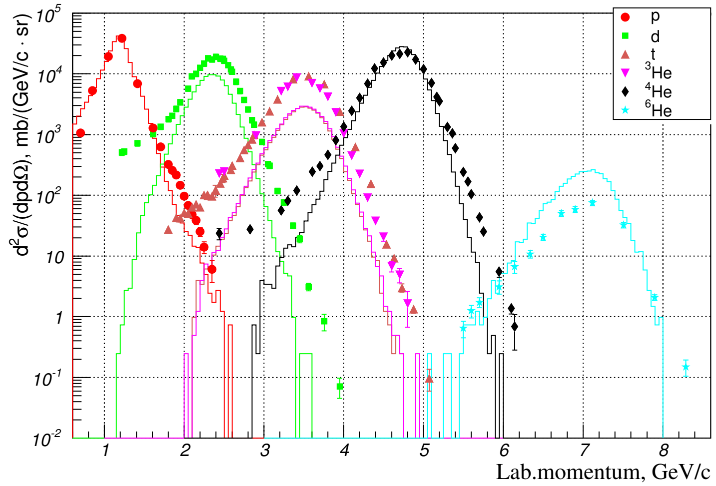

Figure 1. Relative yields of H and He isotopes in ^{12}C + Be interaction at 0.6 GeV/nucleon and at 3.5^o as a functions of fragment laboratory momenta: data *vs* BC model calculations (histograms). Note that the measured tritium and ^{3}He spectra are practically identical.

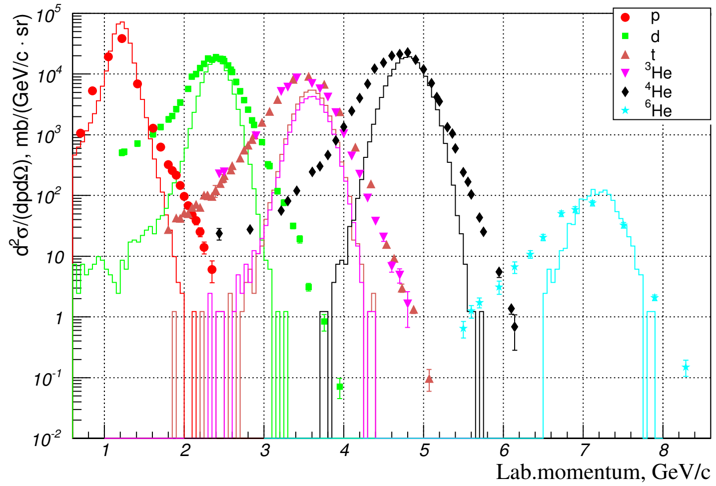

Figure 2. The same as in Figure 1, but data *vs* QMD model calculations (histograms).

fragmentation peaks are too narrow; the high momentum part is reasonably well described. Yields at fragmentation maxima look reasonable for all fragments.

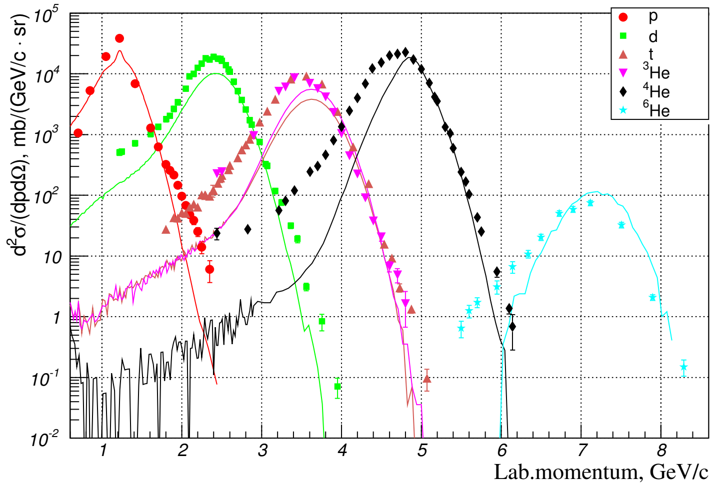

Figure 3. The same as in Figure 1, but data *vs* LAQGSM model calculations (lines).

4 Slope parameters from kinetic energy spectra

For analysis of the high momentum part of a spectrum, it is convenient to use the dependence of the invariant cross section $Ed^3\sigma/d^3p = (E/p^2)d^2\sigma/(d\Omega dp)$ on the fragment kinetic energy T in the ^{12}C rest frame. For each fragment, the cross section decreases exponentially with T and two regions can be distinguished: the fragmentation region, below $T \approx 20$ MeV, and the cumulative region, at $T > 50$ MeV, each having its own constant slope parameter (see Fig. 4). The spectra were parameterized by a sum of two exponents

$$Ed^3\sigma/d^3p \sim A_S exp(-T/T_S) + A_C exp(-T/T_C), \quad (2)$$

where A_S and A_C are normalization factors for the fragmentation and cumulative regions, and the slope parameters T_S and T_C are "temperatures" in these regions. The measured values T_S and T_C are shown in Table 1. The values of T_S are similar within errors for different fragments (except protons). They are about 8 MeV, while the values of T_C decrease with increasing of the fragment mass. Another way to estimate the temperature T_S is to calculate it from the r.m.s. σ_f of the fragmentation peak, $T_s = \sigma_f^2/m_f$. The measured values of T_S estimated in this way are also shown in Table 1. They are in a reasonable agreement with those obtained in [13] for 1–2 GeV/nucleon carbon ions, and with our data at 0.3 GeV/nucleon [14] demonstrating the energy independence of these parameters. The experimental results for T_C from [15] obtained at GSI at 1 GeV/nucleon for Au + Au collisions are also given. They are in a reasonable agreement with our results for p, d, t, ^{3}He and ^{4}He fragments[2] but have been obtained in smaller kinetic energy intervals.

In Fig. 5, the invariant cross sections as a function of kinetic energy in the ^{12}C rest frame are shown for protons, deuterons, tritons and ^{4}He together with model calculations. Circles with error bars stand for measured values, while up triangles, down triangles and squares correspond to the

[2]We took these values from Fig. 3 of Ref. [15]

calculations with the QMD, BC and LAQGSM models, respectively. Again, the BC model represents the experimental data better than the others, but all models strongly underestimate the data at large kinetic energies.

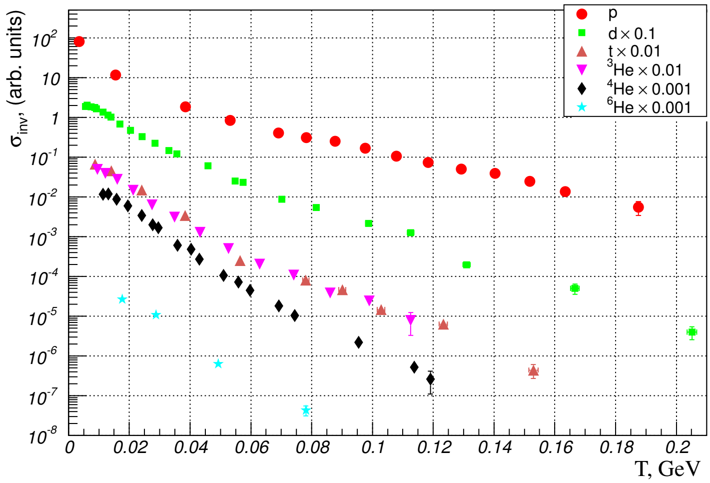

Figure 4. Invariant cross sections as functons of fragment kinetic energies in the ^{12}C rest frame.

5 Conclusion

Fragment yields from the reaction ^{9}Be (^{12}C, f) X (f - fragments from p to ^{6}He) at T_0 = 0.6 GeV/nucleon were measured and compared to three models of ion-ion interactions.

- In the region of fragmentation peaks, all models give reasonable description of the data. The BC model is closer to the data than the other models;
- Kinetic energy spectra in the projectile rest frame can be parametrized as $A_s \exp(-T/T_s) + A_c \exp(-T/T_c)$, where T_s values are in reasonable agreement with predictions of the BC model, except protons;
- T_c values are higher for protons than for other fragments. Results are in agreement with those from Au-Au collisions at 1 GeV/nucleon;
- All models strongly underestimate the data in cumulative regions.

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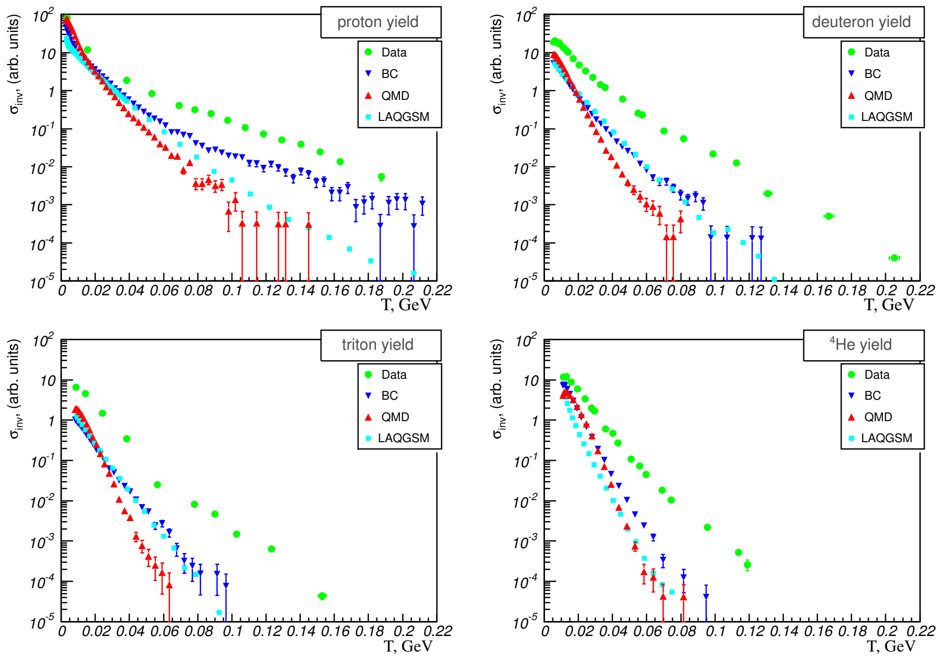

Figure 5. Invariant cross sections as functons of fragment kinetic energies in the ^{12}C rest frame: measured data *vs* model calculations.

Table 1. Slope parameters from kinetic energy spectra approximation with Eq. (2); * stands for a poor fit quality with two exponents.

f	T_s, data	$(\sigma_f)^2/m_f$, data	T_s, BC	$(\sigma_f)^2/m_f$, BC	T_c, data	T_c [15]	T_c, BC
p	5.5±0.4	5.5±0.4	9.1±0.2*	3.2±0.5	26.5±0.6	25.5±1.5	27.8±1.5
d	8.5±0.4	9.2±0.9	6.1±0.3	7.3±1.3	17.6±0.6	17.5±1.5	12.1±0.7
t	7.6±0.5	9.0±1.3	6.4±0.5	7.9±0.7	16.3±1.1	15.0±1.0	10.3±1.2
^{3}He	8.2±0.2	10.6±0.8	7.0±0.4	8.5±0.8	20.4±3.1	18.5±1.0	11.4±1.7
^{4}He	7.5±0.2	7.7±0.6	5.4±0.1	4.6±0.2	15.2±1.5	14.5±1.4	11.9±2.9
^{6}He	-	7.1±0.3	4.0±0.1	6.0±0.6	-	16.0±2.0	6.4±0.8

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