Ion production in the $^{12}\text{C} + ^{9}\text{Be}$ interactions at GeV energies

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Abstract. Differential cross sections for nuclear fragment yields at an angle of 3.5$^\circ$ in the fragmentation of carbon ions with an energy of 0.95 and 2.0 GeV/nucleon on a beryllium target have been measured. The momentum spectra of the fragments were used for testing predictions of few models of ion-ion interactions.

1. Introduction
A study of nuclear fragmentation is important for solving problems of modern theory of ion-ion interactions. Data on nuclear fragmentation are also used in the application, such as heavy ion therapy, designing of radioactive nuclei beams and neutron spallation sources. Monte-Carlo simulation programs for ion-ion interactions are actively developed. They combine both the most modern and well-theoretically substantiated mechanisms of hadron interactions in nuclei, as well as hypothetical mechanisms used to describe better the experimental data. An important step in this direction is testing models on the widest possible range of experimental data. Our experiment FRAGM [1] obtained a vast amount of data on the fragmentation of carbon ions in a wide range of incident ion energies from 0.3 to 3.2 GeV/nucleon. In this report the preliminary results on fragment yields in the fragmentation of carbon ions with an energy of 2.0 GeV/nucleon on a beryllium target are presented. These results are compared with our data at 0.95 GeV/nucleon [2] and with the predictions of three models (transport codes) available in the GEANT4.10 [3] software package. These are BC (Binary Cascade [4]), INCL (Intra Nuclear Cascade Liege [5]) and QMD (Quantum Molecular Dynamics [6]) models.

2. Experiment
The FRAGM experiment was carried out at ITEP heavy-ion accelerator storage complex TWA (Tera-Watt Accumulator), which included a laser source, a linac, a booster ring of up to 1 GeV and an accelerator ring of 4 GeV/nucleon. Fragments of a carbon nucleus formed on a thin (50 $\mu$m) internal beryllium target at an angle of $3.5^\circ \pm 0.5^\circ$ to the internal ion beam in the accelerator were analyzed by a two-step beam line spectrometer with two foci at a distance of 26 and 42 meters from the target. Scintillation detectors for measuring ionization losses and time of flight were placed in each focus. The coincidence of signals from two counters of different foci gave a trigger for reading amplitude and time information. A telescope of three scintillation...
counters served as a monitor aimed directly at the target at an angle of 2° to the ion beam. A detailed description of the experimental set up is given in [1].

3. Data analysis and test of ion-ion interaction models

Our measurement of fragment momentum spectra was carried out by scanning over a rigidity of the beam line spectrometer. At each setting of the spectrometer, the fragments were identified on the correlation plots of time-of-flight (a function of the mass number of the fragment) versus amplitude of the signal from the scintillation counter (a function of the fragment charge). Two examples of correlation plots for different rigidities are given in Figure 1. The left plot shows the data obtained at the rigidity of 1.6 GeV/c, which is about 1.5 times less than the maximum of proton yield where positive pion production is clearly seen; the right one shows the data at rigidity of 5.0 GeV/c, which corresponds to the maximum yield of fragments with the charge to mass number ratio of 0.5, i.e. for $^2$H, $^4$He and $^6$Li ions. Relative yields of the fragments were calculated by normalizing the number of detected fragments to the monitor, taking into account the registration efficiency. To obtain absolute differential cross sections $d^2\sigma/dp d\Omega$, an additional normalization was performed. The relative proton yield at the maximum of the fragmentation peak was normalized to the predictions of the INCL model. This model was chosen because the shape of the proton momentum spectrum agrees well with that observed in the experiment. Although the description of the proton momentum spectrum in other models is somewhat worse, using them for the normalization leads to a similar result, consistent with systematic normalization error discussed below. The total inelastic cross section for the interaction of carbon ions with a beryllium target at 2.0 GeV/nucleon was taken to be 856 mb. Due to the lack of experimental data on inelastic $^{12}$C + $^9$Be interaction cross sections, this value was obtained from the calculation in the LAQGSM/MCNP6 model [7]. The use of older parametrization based on measurements of the cross section of nucleus - nucleus interactions at 0.87 and 2.1 GeV/nucleon [8] leads to an inelastic cross section of the $^{12}$C + $^9$Be interaction equal to 759
The cross section values cover more than five orders of magnitude. The momentum distributions for each fragment have a Gaussian shape with a maximum at a momentum per nucleon close to the momentum per nucleon of the incident carbon nucleus, i.e. the fragments are flying at a speed equal to the speed of the incident nucleus. At 2.0 GeV/nucleon, we managed to detect only six fragmentation peaks, while at 0.95 GeV/nucleon fifteen fragments were observed. This is due to two reasons. The first one is the restriction on maximum rigidity of the beam line spectrometer, which is 6 GeV/c. This rigidity is not enough to register fragments with \( \text{A}/\text{Z} > 2 \) at a carbon ion energy of 2.0 GeV/nucleon. Such fragments are \(^3\text{H}\), \(^6\text{He}\), \(^7\text{Li}\) etc. The second reason is associated with a faster decrease of the cross section with an increase in the mass number of the fragment for higher energy. At a fixed angle, this is due to the rise in the transverse momentum transmitted to the fragment. On the other hand, this is a certain
advantage, since it allows to test models at a lower level of cross sections.

For comparison with the predictions of ion-ion interactions models, $10^7$ interactions of a carbon nucleus with the beryllium target have been simulated for each of the models. Figure 3 presents a comparison of the momentum spectra for three fragments with the predictions of three models of ion-ion interactions at 0.95 and 2.0 GeV/nucleon. The INCL model gives the best description of our data for all fragments, except $^6$Li at 2.0 GeV/nucleon, where the number of simulated events turned out to be insufficient for the observed level of the cross section. The BC model gives a somewhat worse description, but it predicts well the cross section for $^6$Li at 2.0 GeV/nucleon, where all other models strongly underestimate it. The QMD model greatly narrows the fragmentation peaks and underestimates the cross sections for the yield of fragments heavier than protons.

4. Conclusion

The differential cross sections for the yields of long-lived nuclear fragments at an angle of 3.5° in the $^{12}$C + $^9$Be interactions at the energies of an incident carbon ion 0.95 and 2.0 GeV/nucleon have been measured. These data were used to test few models of ion-ion interactions. It is shown that for light fragments up to $A = 4$, all models reproduce well the fragment yields at the maxima of the fragmentation peaks. The discrepancies between the measured cross sections and the predictions of models are grow rapidly with an increase in the mass number of the fragment and the energy of the incident carbon ion. The same effect is seen for different model predictions. This means that the theoretical description of the fragment yields becomes less reliable as the transverse momentum, transferred to the fragment, increases.
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