# Carbon fragmentation at 300 MeV/nucleon vs statistical model

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**Abstract.** Momentum spectra of all long lived fragments from $^{12}$C fragmentation at 3.5$^o$ on different targets have been measured. Obtained fragmentation peak widths are compared with predictions of statistical model. An independence of these widths from target nuclei has been checked with high precision.

## 1. Introduction

The statistical model pioneered by A.Goldhaber [1] in 1980's gives a good and rather simple picture of fragmentation processes. It is widely used for estimation, simulation of fragment separators and with empirical corrections in some transport codes which pretend to precise description of ion-ion interactions. In this report we will test the model predictions on high precision data of the FRAGM [2], [3], [4] experiment on carbon ion fragmentation on few target nuclei. The statistical model associate a momentum distribution of projectile-like fragments with the intranuclear Fermi motion. This result in the following statements. 1) The momentum distributions of projectile-like fragments in the rest frame of the projectile nucleus have gaussian shapes that are independent from projectile energy and target nucleus. 2) The dispersion of longitudinal momentum distribution follow so called parabolic law

$$\sigma_{||}^2 = \sigma_0^2 \frac{A_f(A_p - A_f)}{A_p - 1}, \tag{1}$$

where $A_f(A_p)$ - atomic number of fragment(projectile), $\sigma_0 = P_F/\sqrt{5}$ and $P_F$ - the Fermi momentum. From a phenomenologic expression of the A-dependence of the Fermi momentum [5] $P_F(A) = 281(1 - A^{-0.568})$ MeV/c, $P_F = 212$ and $\sigma_0 = 95.6$ MeV/c can be calculated for $^1$2C. There were a few attempts to give a better, but more complicated, analytical expression for $\sigma_{||}$. A review of the results obtained on this way can be found in [6]. In the following these statements will be tested on the FRAGM data.

## 2. Experiment

The experiment was carried out at the heavy-ion complex TWA at ITEP which includes an ion laser source, a linac, a booster and an accelerator-accumulator ring. Ions of 200-1000 MeV/n

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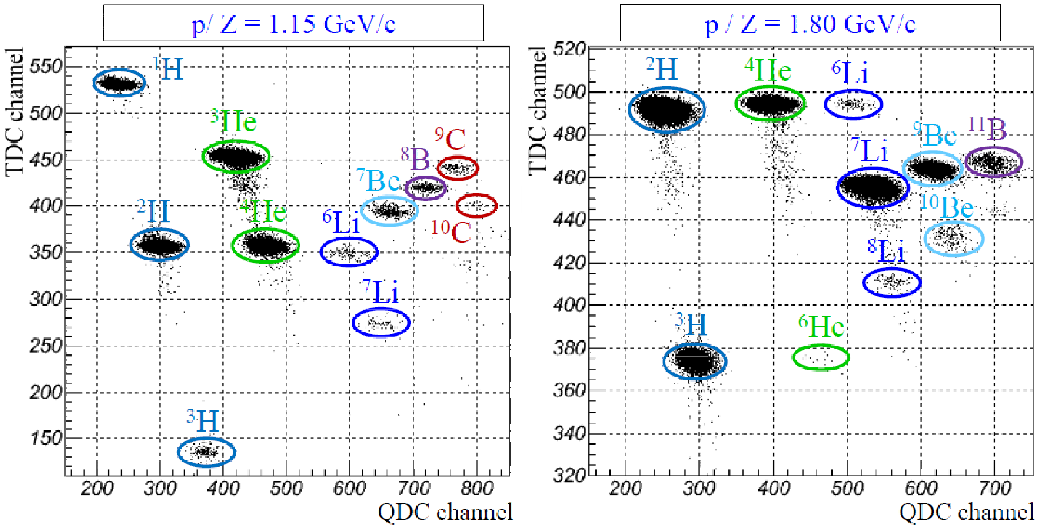



**Figure 1.** Two dimensional plots QDC vs TOF channels for two rigidities of the beam-line spectrometer demonstrate good identification of the fragments.

could be accumulated in this ring for successive use in experiments on high-energy-density physics or accelerated to maximal energy of 4 GeV/nucleon. During our measurements each four seconds the carbon ions $C^{+4}$ were accelerated in the booster up to 300 MeV/nucleon. Then while injection to the accelerator-accumulator ring they were totally stripped and captured in the ring. After that the beam was steered to the internal target of 50 $\mu$m foil strip providing the spill. Foils from Be, Al, Cu and Ta were used. It made simultaneously possible to have both a high luminosity due to multiple passage of the ions through the target and a small size of the source needed for a high momentum resolution of the subsequent magnetic analysis. The products of the carbon nucleus fragmentation outgoing at $3.5^{o}$ were momentum analyzed by the double-focus beam-line spectrometer of 42 meters long. Sets of few scintillation counters were placed at intermediate and final focuses for multiple measurements of dE/dx and time of flight (TOF). The set up has been described in more details in [3]. Fragments with different charge and mass were unambiguously selected on two-dimensional plots dE/dx vs TOF. Two examples of this selection are given in figure 1 for different rigidities of the beam-line. The left for 1.15 GeV/c near maximal emission of fragments with A/Z = 1.5 such as $^{3}$He and $^{9}$C and the right for 1.80 GeV/c near the maximal yield of fragments with A/Z = 2.3 such as $^{7}$Li,$^{9}$Be and $^{11}$B. The fragment momentum spectra were obtained by beam line energy scan in steps of 50 MeV/c. As a monitor we used a telescope of three scintillation counters that viewed the target at 2°. An absolute normalization procedure has been described in FRAGM [2]. The preliminary results for carbon fragmentation on Be target are presented in figure 2.

### 3. Comparison of statistical model predictions with experimental data

As it can be seen from figure 2, the momentum spectrum of a fragment emission represents a peak of almost gaussian shape centered at the momentum corresponding to the velocity of the projectile. To obtain $\sigma_{||}$ we used the region where differential cross section is larger than 20% of the value at the peak maximum. The fit has been done in the rest frame of the projectile. The values of $\sigma_{||}$ are given in figure 3 by red points. The data of [7] obtained at 1 GeV/nucleon are given by blue points. The $\sigma_{||}$ values for the fragments with the same atomic number but with different charges are sightly shifted along the horizontal axis to get rid of overlaps. It can be seen that $\sigma_{||}$ for fragment with the same A are equal within the errors in good agreement

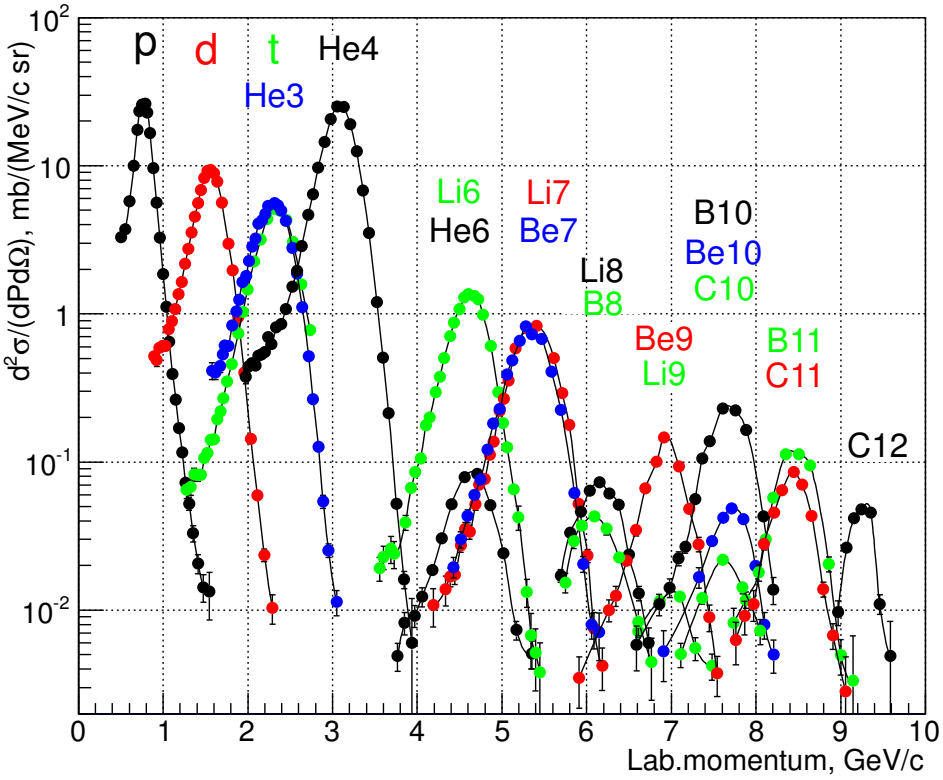



**Figure 2.** Laboratory momentum spectra of fragments emitted at $3.5^o$ from carbon fragmentation at 300 MeV/nucleon. Smooth lines are drawn though data points just to guide the eye.

with prediction of statistical model (the formula 1). The data of [7] has been obtained for two projectile energies 1 and 2 GeV/nucleon at a zero emission angle. An equality of the $\sigma_{||}(A_f)$ for both energies supports the statement of the statistical model for an independence of $\sigma_{||}$ from projectile energies in these energy range. An agreement of our measurements with that of [7] for $A_f < 6$ supports a validity of this statement up to 300 MeV/nucleon. At $A_f > 6$ there are sizable disagreements between our data and the data of [7]. Larger $\sigma_{||}$ values measured in our experiment are connected with a dependence of the $\sigma_{||}$ on fragment emission angle or, that is the same, on momentum transfer to the target nucleons. It is not predicted by statistical model but predicted by more accurate transport codes. The results of $\sigma_{||}$ calculations in laboratory frame by four transport codes are given in figure 4. Additional information on these transport codes can be found in [2]. It is seen that for INCL++ and LAQGSM transport codes the dependence of $\sigma_{||}$ on the emission angle is week for light fragment and rather strong for heavy fragments. Taking into account this dependence our data are in agreement with the data of [7]. In figure 3 two curves are also given. The red one is the parabolic law (1) and the green one is the parametrization of [6]. For carbon projectile, the both curves are almost identical. They give reasonable but approximate description of the $A_f$ dependence of $\sigma_{||}$. The both of them do not take into account some additional effects which can possibly be connected with internal structure of the projectile and/or the fragments.

The $\sigma_{||}$ values has been measured on four different target nuclei: Be, Al, Cu and Ta.

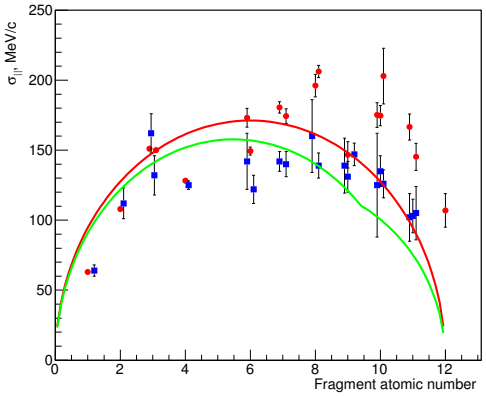



**Figure 3.** Gaussian parameter of the longitudinal momentum distribution $\sigma_{||}$ as a function of fragment atomic number. The red circles are the data of this experiment, the blue squares are data of [7] for 1 GeV/nucleon. The read line - parabolic law (1) with $\sigma_0$ = 95.6 MeV/c, green line - parametrization of [6].

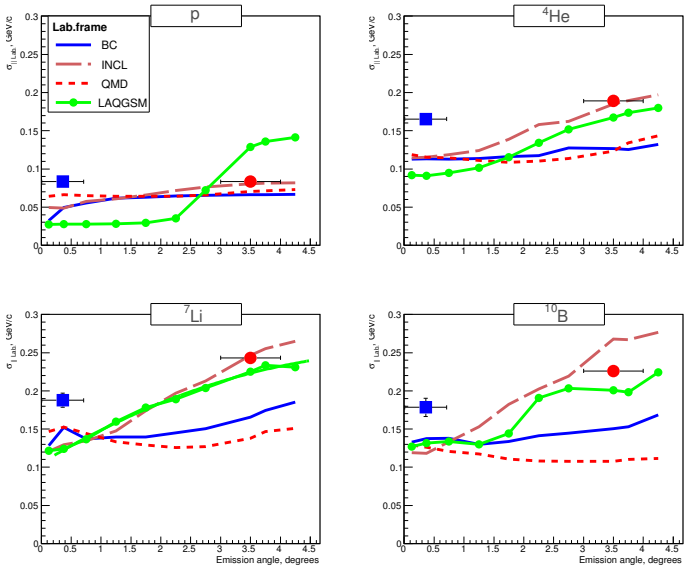



**Figure 4.** Results of the transport codes calculations in laboratory frame for $\sigma_{||}$ dependence on the fragment emission angle. The red circles are the data of this experiment for $3.5^o$, the blue squares are the data of [7] for 1 GeV/nucleon and for zero degree.

Preliminary results on the differences between the $\sigma_{||}$ values measured on the target nucleus with atomic number A and on the Be-target are given in figure 5. For p,d and He-4 fragments, for which the statistical errors are small, we see the difference in $\sigma_{||}$ for Be and other targets on the level of 5 MeV/c. For heavier fragments up to $^7$Be the errors are on the level of 5 MeV/c and with this accuracy the independence of the $\sigma_{||}$ from target nuclei is valid. For even more heavier fragments, the accuracy limits the test of the independence hypothesis on the level of 15-20 MeV/c. So it can be summarized that the statement of the statistical model on an independence of $\sigma_{||}$ from target nucleus is valid with 5% accuracy for light fragments and 10% for heavy ones.

## 4. Conclusion

Main statements of the statistical model have been tested on new data of the FRAGM experiment on carbon fragmentation at 300 MeV/nucleon on different target nuclei. Longitudinal momentum distributions of all long lived fragments have been measured with high precision. An independence of the fragmentation peak widths from projectile energy have been found valid up to 300 MeV/nucleon and from target nucleus at 5-10% level. The dependence of $\sigma_{||}$ on fragment atomic number is only approximately described by the parabolic law (1). Deviations from this law for some fragments and for different emission angles do not have explanation in this model.

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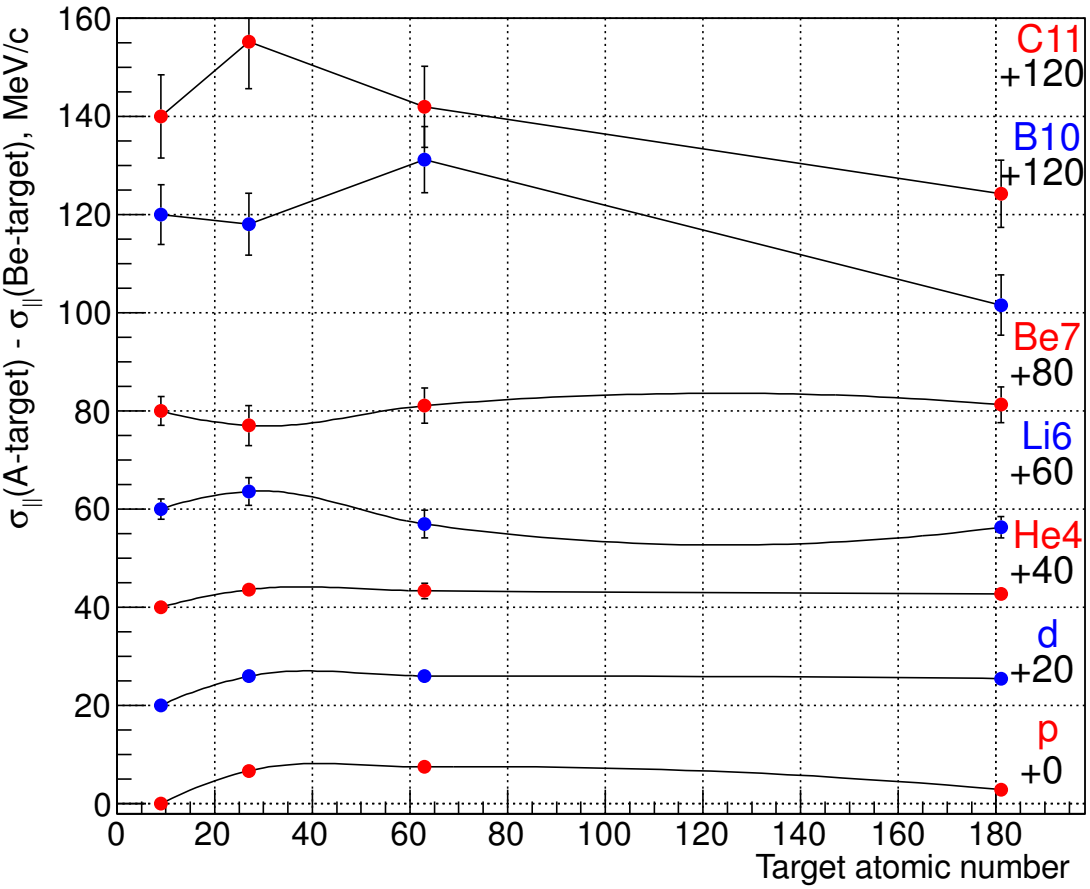



**Figure 5.** Target dependence of the difference $\sigma_{||}$(A) - $\sigma_{||}$(Be) for Be,Al, Cu and Ta target nuclei and for few fragments. For Be target this difference is always equal to zero.

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