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Verification of Monte Carlo transport codes against measured small angle p-, d- and t-emission in carbon fragmentation at 600 MeV/nucleon

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Momentum spectra of hydrogen isotopes have been measured at 3.5^o from ^{12}C fragmentation on Be target. Momentum spectra cover both the region of fragmentation maximum and cumulative region. Differential cross sections span five orders of its magnitude. The data are compared to predictions of four transport codes: QMD, LAQGSM, BC and INCL++. There are large differences between the data and predictions of some models in high momentum region. INCL++ code gives the best and almost perfect description of the data.

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1. Introduction

A study of nucleus-nucleus interactions is one of the main aims of the modern nuclear physics. During last years, apart from an investigation of fundamental properties of these interactions, special attention has been paid to precise phenomenological description of the processes used in applications such as heavy ion therapy, radiation shielding and radioactive ion beam design. On this way a few simulation programs for nucleus-nucleus interactions has been created. They demand an experimental verification as well as refinement of their basic approaches. One of the aims of the FRAGM experiment performed at TWA (Tera Watt Accumulator) heavy ion facility at ITEP was to obtain high precision data on nuclear fragmentation in the energy range accessible at this accelerator. In the framework of this experiment the data has been taken for carbon ion fragmentation on Beryllium target both in a wide energy range from 0.2 to 3.2 GeV/nucleon and in a wide energy range of the fragments from hydrogen isotopes to isotopes of the projectile nucleus. The measurements were performed in the projectile fragmentation region, i.e. in the so-called inverse kinematics. This method has substantial advantages over measurements in the target fragmentation region. At first, for the fragments moving in forward direction, a relativistic boost provides larger acceptance in the projectile rest frame in case of an equal acceptance in the laboratory frame. Secondly in inverse kinematics, there is no problems with a detection of fragments that are at rest in a projectile rest frame, because they are moving in a laboratory frame with a speed of the projectile nucleus. The data of this experiment on yields of cumulative (high energy) protons were analyzed [1] in a framework of multiquark cluster model and compared to a few models of ion-ion interactions in [2]. In this publication we give preliminary results on heavier hydrogen isotope emissions at 600 MeV incident carbon ion energy and compare them with the predictions of four transport codes.

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 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, captured in the ring and accelerated up to 600 MeV/nucleon. After that the beam was steered to the internal target of 50 μm Be foil strip providing the spill. 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 captured by the double-focus beam line 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). Fragments with different charge and mass were unambiguously selected on two-dimensional plots dE/dx vs TOF. The set up has been described in more details in [1]. The fragment momentum spectra were obtained by beam line energy scan in steps of 50-200 MeV/c and fragments were selected by above mentioned procedure. As a monitor we used a telescope of three scintillation counters that view the target at $2°$.

3. Transport codes

Recently, intermediate-energy ions have been used in various fields of nuclear physics and applications. This supports the demand both for deepening of our knowledge of fundamental properties of ion-ion interactions and for developing methods of precise simulation of these processes on up-to-date level. Both these ways need large amount of various experimental data for testing new theoretical ideas and application programs. Here we use new data of the FRAGM experiment for verification of four widely used transport codes. They are LAQGSM03.03 [3], QMD [4], BC [5] and INCL++ [6]. LAQGSM03.03 (Los Alamos Quark Gluon String Model) is supported and updated by LANL in USA. It is a main part of MCNP6 transport code [7]. The three latter, QMD (Quantum Molecular Dynamics), BC (Binary Cascade) and INCL++(C++ (5.1.14) version of the Liege Intranuclear Cascade model) are free access programs from GEANT4 package [8] supported by CERN. We used the version Geant4 10.0 (released 6 December 2013). All above mentioned codes consider ion-ion interactions as a sequence of the same processes such as intranuclear cascade, formation of excited prefragments and their successive deexcitation by evaporation, Fermi breakup and fission. But an actual realization of these steps are different in different models. A description of these differences are far beyond the scope of this publication. Short and useful information on this subject can be found in GEANT4 Physics Reference manual [8] .

4. Comparison of model predictions with experimental data

Differential cross sections $d^2\sigma/dpd\Omega$ in a laboratory frame for proton, deuteron and triton yields at an angle of 3.5° and results of the simulations with above mentioned models are given in

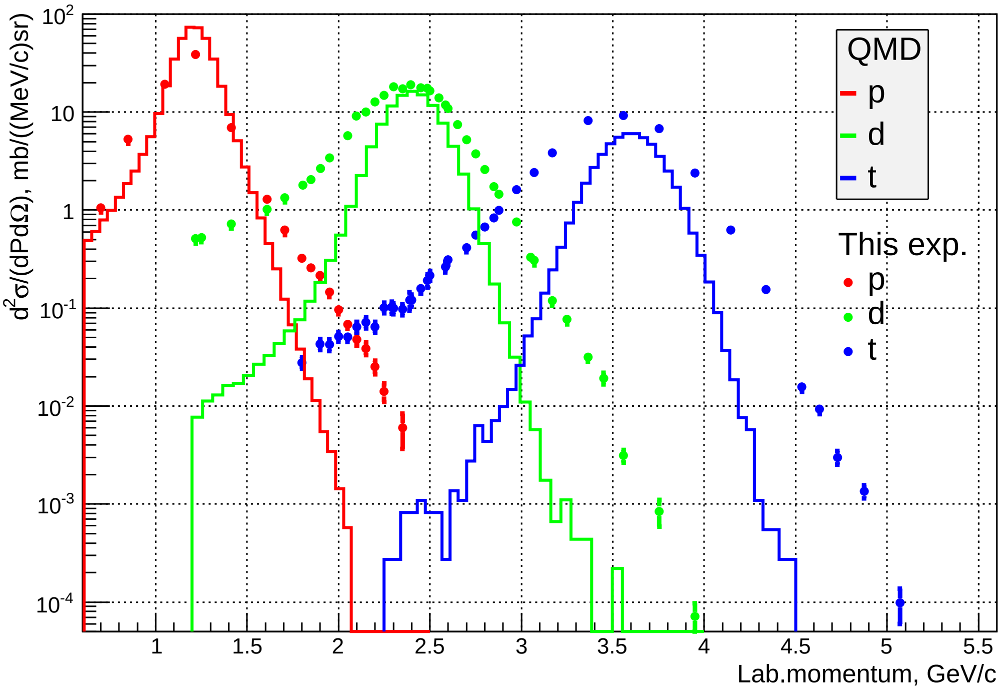

Figure 1: Laboratory momentum spectra of protons (full red points at the left), deuterons (full green points at the center) and tritons (full blue points at the right) emitted at 3.5^o from fragmentation of 600 MeV/nucleon carbon ions on Be target in comparison with the predictions of QMD model (red, green and blue histograms, correspondingly).

Fig.1—4 in logarithmic scale as a function of laboratory momentum of fragments. For normalization of calculations, the total inelastic cross section of ^{12}C + ^{9}Be interactions equal to 823.8 mb was used in accordance with prescription of LAQGSM03.03. The data of the FRAGM experiment were normalized to the BC predictions at fragmentation peak maximum for protons. The BC was chosen because the shape of the fragmentation peak is in a good agreement with observed in the experiment. It can be seen from Fig.4 that this normalization is of the same quality for INCL++ model. For each fragment the spectrum demonstrate the ∼so called fragmentation peak with maximum at fragment velocity approximately equal to that of the projectile carbon ion. For protons the peak maximum is at ∼1.2 GeV/c, for deuterons - at ∼2.4 GeV/c and for tritons - at ∼3.6 GeV/c. The experimental points go down at higher momentum (in so called cumulative region) by 5 orders of differential cross section magnitude and show less seep fall to lower momentum (midrapidity) region. As expected, all models give reasonable qualitative description of the data. But there are substantial quantitative differences between the data and model predictions as well as between the different models.

The QMD model (see Fig.1) gives good predictions for differential cross sections at fragmentation maxima, but the widths of the peaks for all fragments are too narrow. To give quantitative results we fitted these peaks of longitudinal momentum distributions with gaussians near their

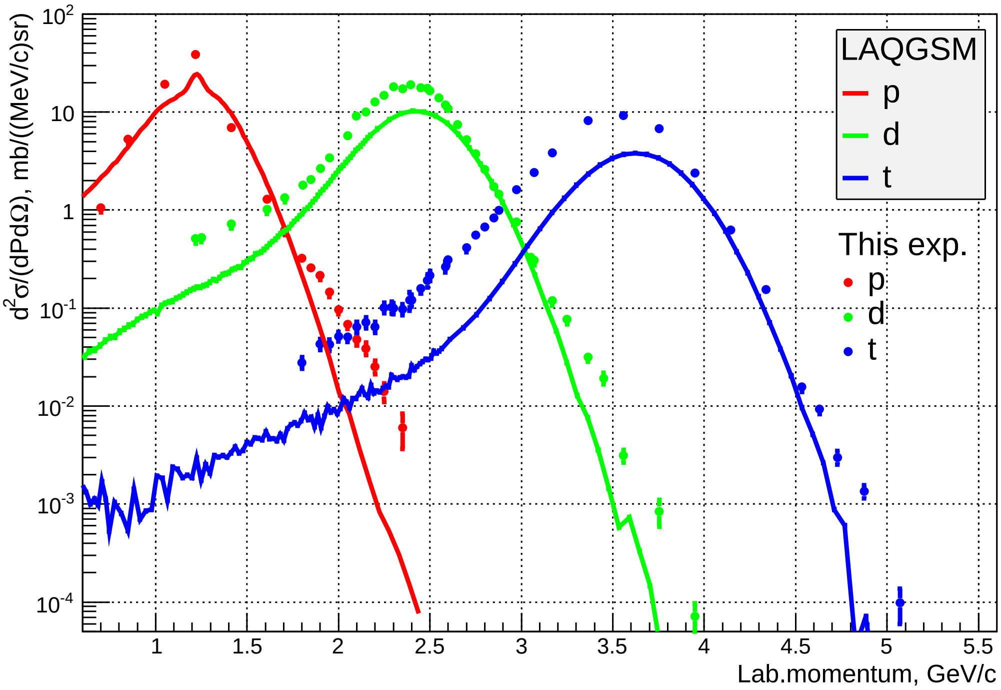

Figure 2: The same experimental data as in Fig.1 but in comparison with the predictions of LAQGS03.03 model

maxima in projectile rest frame. For this experiment the r.m.s of the peaks are 72±5, 134±3 and 160±4 MeV/c for protons, deuterons and tritons, respectively. While for QMD, these values are 56, 88 and 100 MeV/c. Here and later the errors for model calculations will not be given because they always can be made much smaller than experimental ones. The data of our experiment are in reasonable agreement with existing measurement [9] 63±4, 113±11 and 162±14 MeV/c. The narrow widths of the fragmentation peaks predicted by QMD result partly in a large underestimation of the differential cross section in cumulative and midrapidity regions. The differences exceed two orders of magnitude at the edges of studied momentum intervals. For LAQGSM03.03 (see Fig.2) the widths of the fragmentation peaks for deuterons and tritons are in reasonable agreement with the data. They are 147 and 159 MeV/c in projectile rest frame, respectively. For protons the predicted shape of the peak is not gaussian one. Unfortunately the momentum step of our data are too large to check this prediction. LAQGSM03.03 underestimate the differential cross section at fragmentation peak maxima by a factor of 2 and does not reproduce cumulative tail of proton spectra at 2.0-2.5 GeV/c laboratory momentum region, but shapes of deuteron and triton momentum spectra in midrapidity region are reproduced well.

The BC model (see Fig.3) gives slightly smaller values for fragmentation peak widths than LAQGSM03.03. The r.m.s. valuers are 62, 122 and 140 MeV/c for protons, deuterons and tritons in projectile rest frame. The BC underestimates differential cross sections in cumulative and midrapidity region for deuterons and tritons, but give reasonable description of the proton cumulative tail.

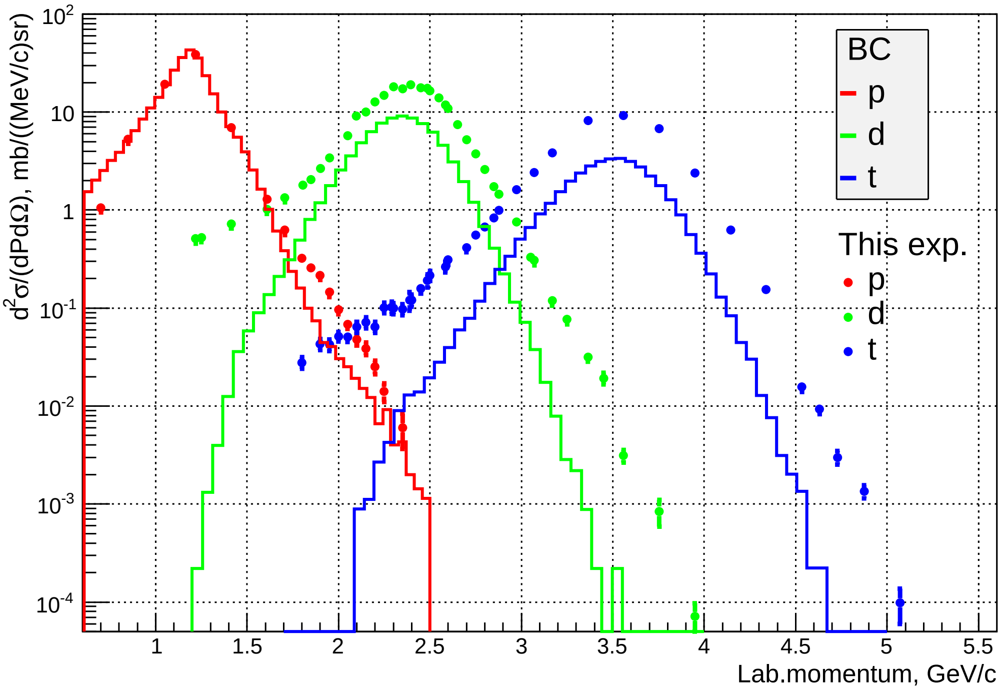

Figure 3: The same experimental data as in Fig.1 but in comparison with the predictions of BC model

Fig.4 with the results of calculations in INCL++ model demonstrate almost ideal agreement with the data of our experiment. The r.m.s. of the fragmentation peaks in projectile rest frame equal to 66, 140 and 167 MeV/c (for protons, deuterons and tritons) are very close to our measurements. Proton spectrum is reproduced with high precision even in cumulative region. Midrapidity region is also well described. The differential cross section in cumulative regions for deuterons and tritons are even slightly overestimated while all other models underestimate them in varying degrees.

5. Conclusion

The comparison performed shows a large potential of modern transport codes to describe new high precision data on fragmentation in ion-ion interactions. Apart from QMD model, all other tested models (LAQGSM03.03, BC and INCL++) give reasonable description of proton, deuteron and triton momentum spectra at 3.5^o from 600 MeV/nucleon carbon fragmentation on Be target. Some problems arise for cumulative region where BC and LAQGSM03.03 substantially underestimate the differential cross section. In an absence of recognized theory of cumulative particle production the phenomenological mechanism of excited prefragment productions and their subsequent Fermi breakup is widely used in the transport codes. Good agreement between the data and predictions of INCL++ model show that this approach are very successful for phenomenological description of the data of our experiment on cumulative proton, deuteron and triton emission in carbon fragmentation.

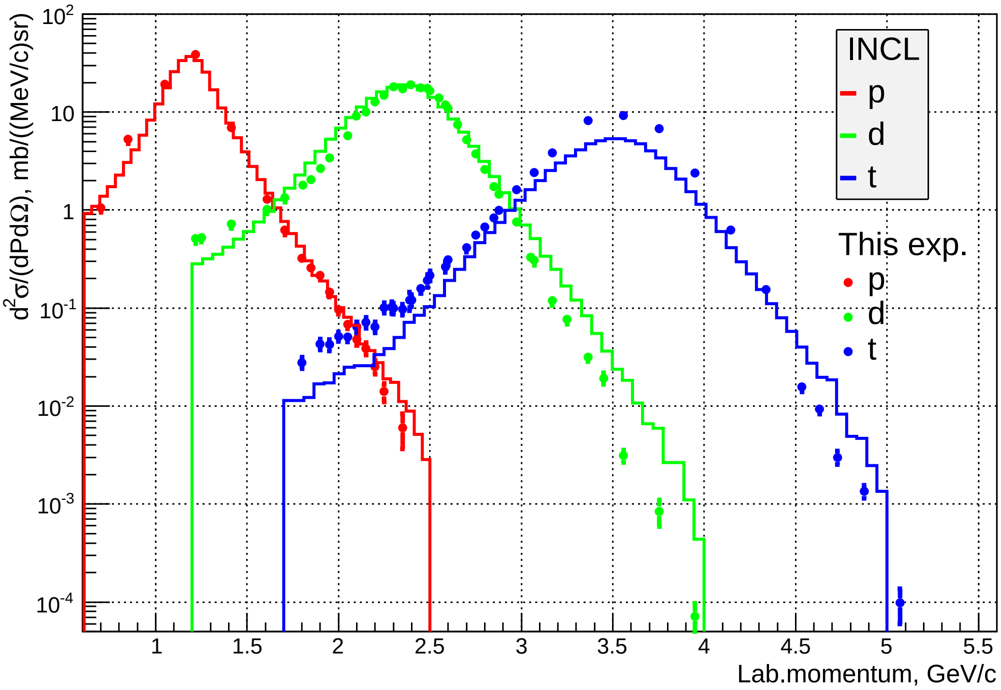

Figure 4: The same experimental data as in Fig.1 but in comparison with the predictions of INCL++ model

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