The Study of Charged Hadrons and Nuclear Fragments Forward Production in CC Collisions at Beam Energy 20.5 GeV/nucleon

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The 70th International Conference “NUCLEUS – 2020. Nuclear physics and elementary particle physics. Nuclear physics technologies”, St Petersburg, October 11-17, 2020.

Introduction

The U-70 Accelerator Complex (National Research Center Kurchatov Institute – Institute for High Energy Physics, Protvino, Russia), originally used to accelerate protons, has undergone a major modification to be able to accelerate light nuclei for using in experiments of fundamental physics, applications in modern technologies and nuclear medicine. Now it can provide ^{12}C beams with full energy of incident ions up to 300 GeV.

New possibilities for researches in relativistic nuclear physics are opened. The experimental programs can be aimed to define the yields of 2ry hadrons and nuclei (including unstable nuclei) in AA-interactions, clarifying of the nuclear structure, study of cumulative processes (forbidden by kinematics of NN-collisions). Measurements of forward scattering on an angle of 0^o are possible. They are free from ambiguities in the interpretation of the cumulative effect in standard experiments on backward production. It allows to understand unambiguously the internal quark-cluster structure of nuclei. For this goal it is proposed to use at the U-70 the combine spectrometer consisting of beam line no. 22 and detectors of the modified setup FODS.

This talk is overview of the results obtained in experiment devoted to study of hadrons and nuclei forward production ($Z<7$, $A<11$, $A/Z<3.4$) including cumulative region in CC-collisions at full energy of ion beam 246 GeV. This energy is maximal one for such experiments at a fixed target.

The main parameters of the experiment

Beam: ^{12}C, 20.5 A GeV.

Beam extraction:

Stochastic slow extraction (10^9 per spill)
Extraction with bent crystal (10^7 per spill)

Total length of the setup ~120m.

Angular acceptance: ~6 mrad.

Targets: Carbon (~1.8 cm length, 3 cm diameter) and empty target.

Beam line rigidity Pc was varied from 7 to 70 GeV/c, but interval 36< Pc<46 GeV/c is forbidden by technical reasons, that leads to gaps in measured momentum distributions corresponding to this interval.

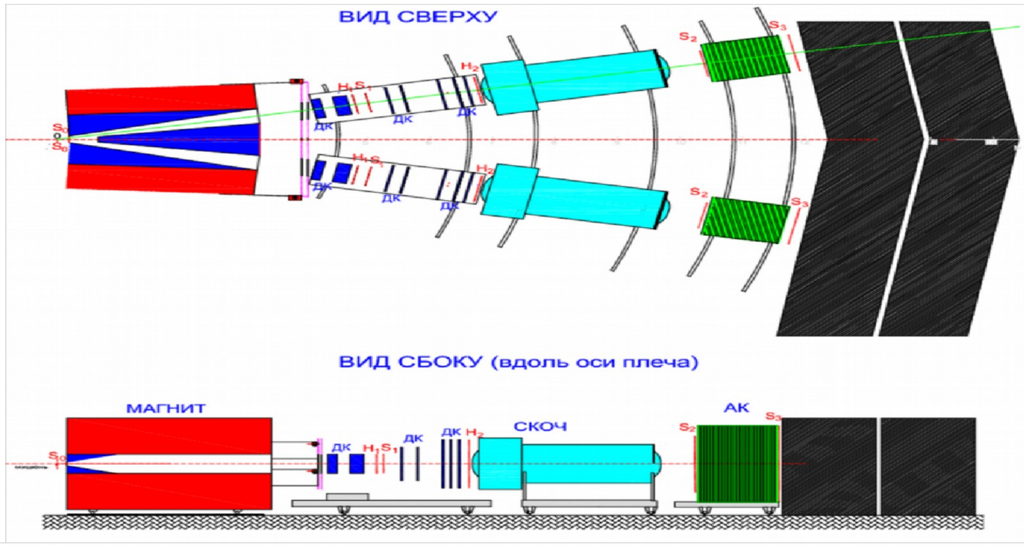
Beam intensity measuring:
Beam intensity (spill duration of 1.2 s) was measured by the Secondary Emission Chambers (SEC). The absolute calibration of the SEC was done with a current transformer (CT). The CT was easily calibrated in absolute units using a reference electric charge. At the beginning of measurement runs beam parameters and absolute beam intensity were defined by means of a radiochromic dosimetric film. The periodic control was performed with a mobile scintillation counter.

Beam size:
In the region of target the beam had dimensions approximately 4 mm in vertical and 12 mm in horizontal axes.

The experimental setup

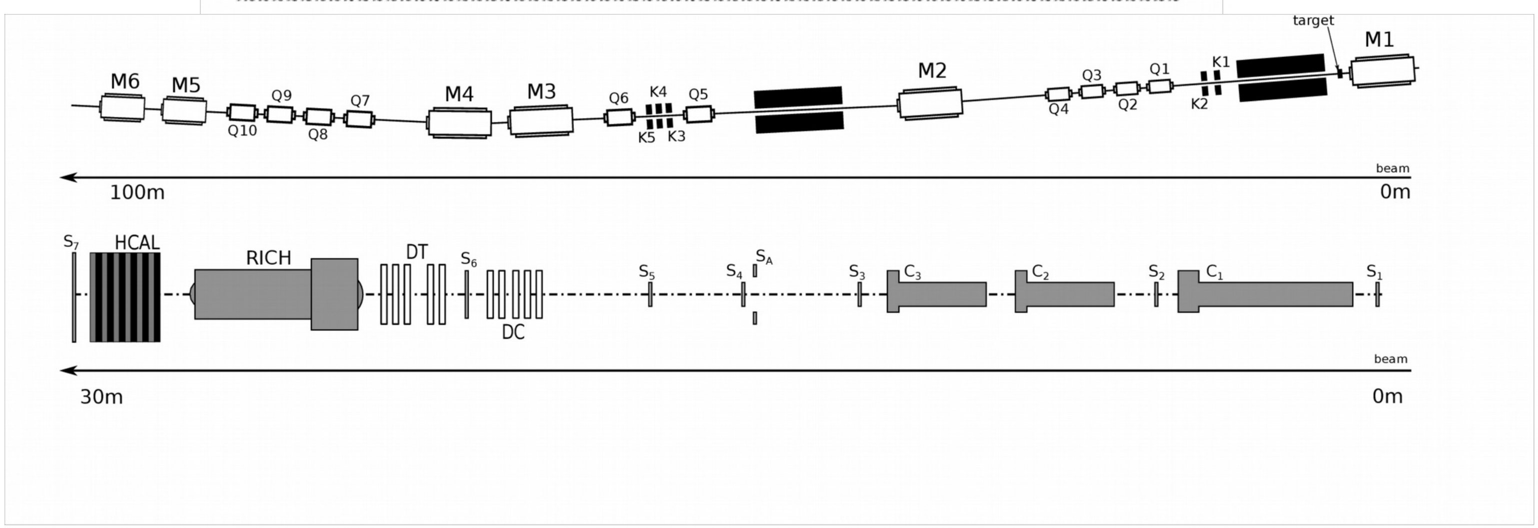
a)

b)



c)

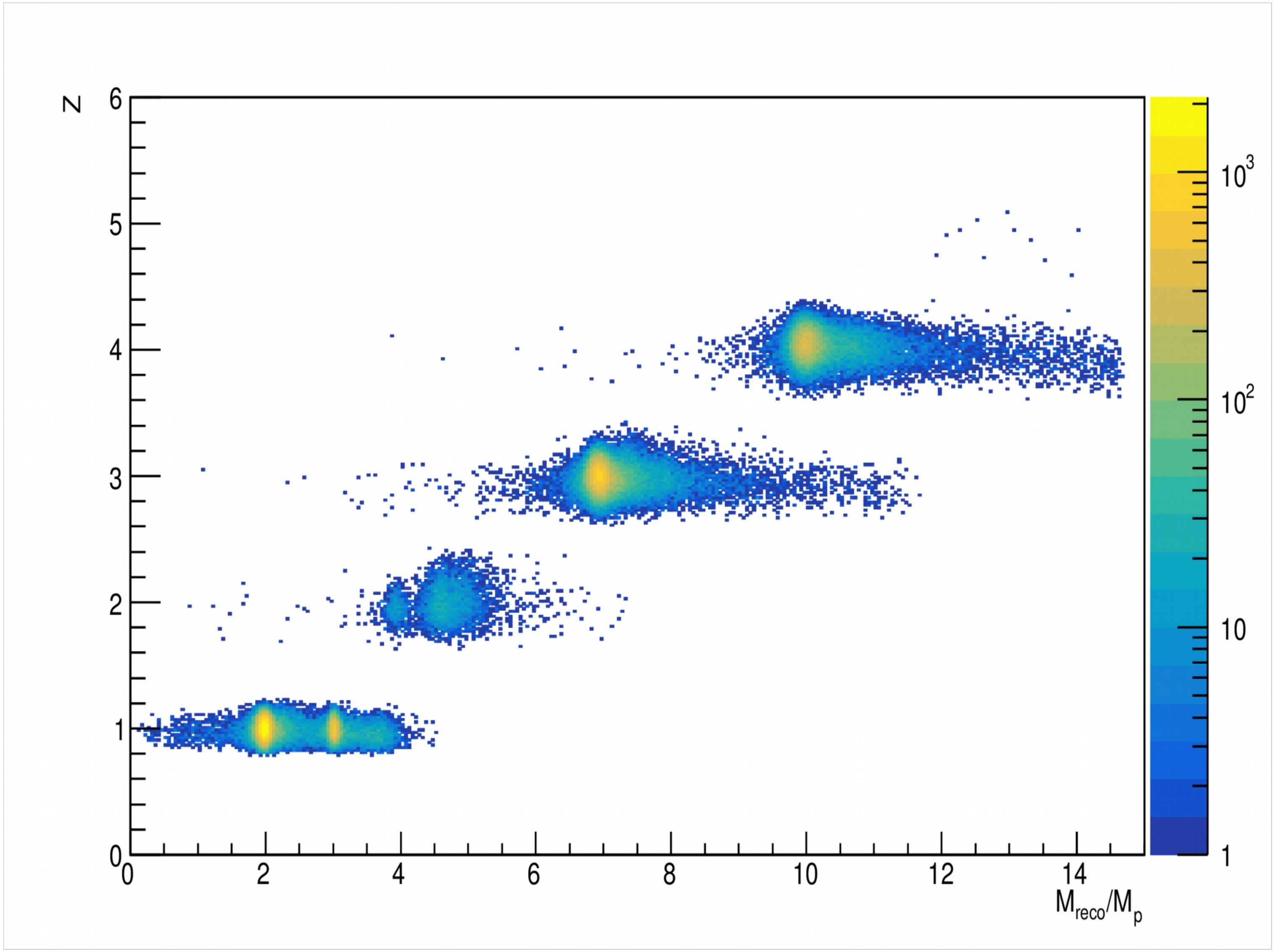
d)



a), b) – the FODS (two arms, top and lateral views), c) – beamline 22 with target, d) – one used arm of the FODS with Cherenkov threshold counters. Notations: **S_i-scintillator counters, $\check{C}_i$- Cherenkov threshold counters, SCOCH – Ring Imagine Cherenkov detector (RICH), HCAL - hadron calorimeter, DT – drift tubes, DC – drift chambers.**

Nuclei selection: Example of Z vs M -plot

(Mreco – reconstructed mass in the RICH, Mp – proton mass)



Theory and Models

The following models were chosen for application:

Model FTFP-BERT-EMV (primary interactions and/or transport code, imbedded into Geant4) - it is built from a number of components, such as the Fritiof model of AA interaction (FTFP) with the support of initial strings formation and their fragmentation into hadrons in the Lund model within Bertini cascades (BERT) and removing the excation of secondary nuclei at the precompound stage. The simulating algorithms of the electromagnetic processes (EMV) were CPU-optimized.

Model QGSP-FTFP-BERT-EMV (primary interactions and/or transport code, imbedded into Geant4) – this model is expansion of the previous one with additional including of the quark−gluon string model of hA interactions with precompound (QGSP).

Quark-cluster model (QCM) – it is used for data analysis in cumulative region. In the model a nucleus is considred consisting of clusters with i nucleons (i=1,2,3 ..) [A.V. Efrermov at al, *Phys. of Atom. Nucl.* **57, 874 (1994)].**

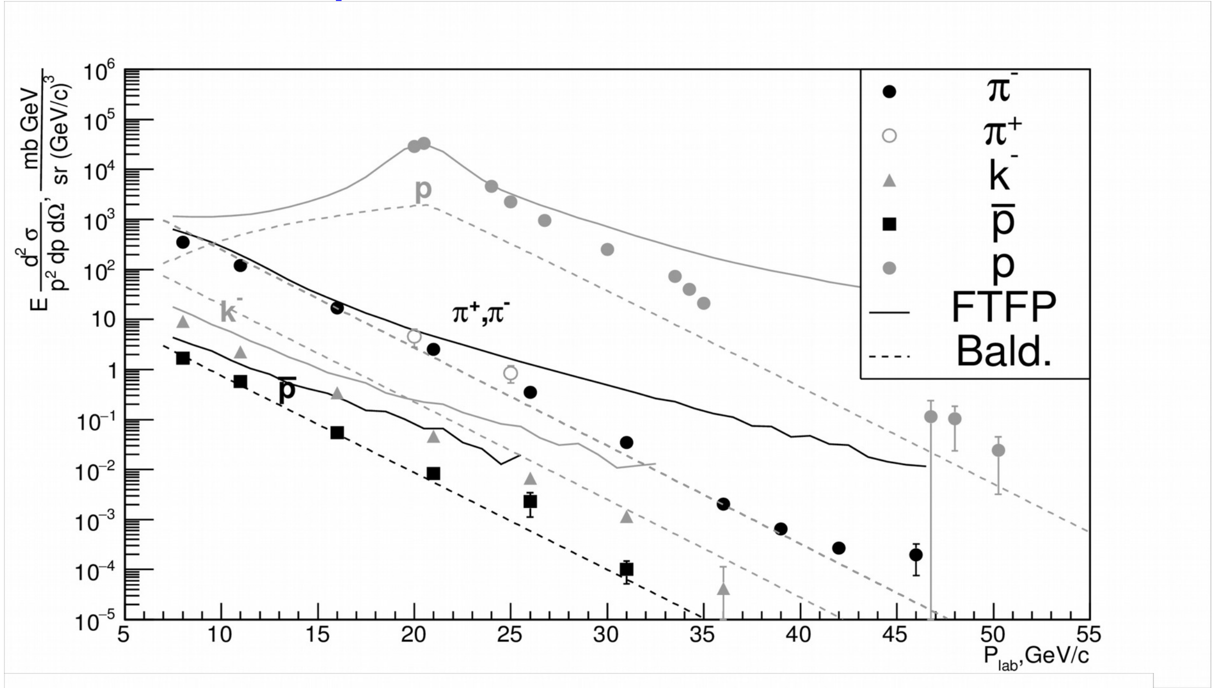
Baldin's formula for invariant cross sections on the base of Stavinsky scaling variable Smin which is minimal squared energy of colliding constituents to produce observed particle (hot processes) [A.A. Baldin, Sov. J. Nucl. Phys. 56, iss.3 (1993) p. 385].

Models QGSP-FTFP-BERT-EMV, QCM allow to describe the main features of cumulative productions for hadrons and nuclei.

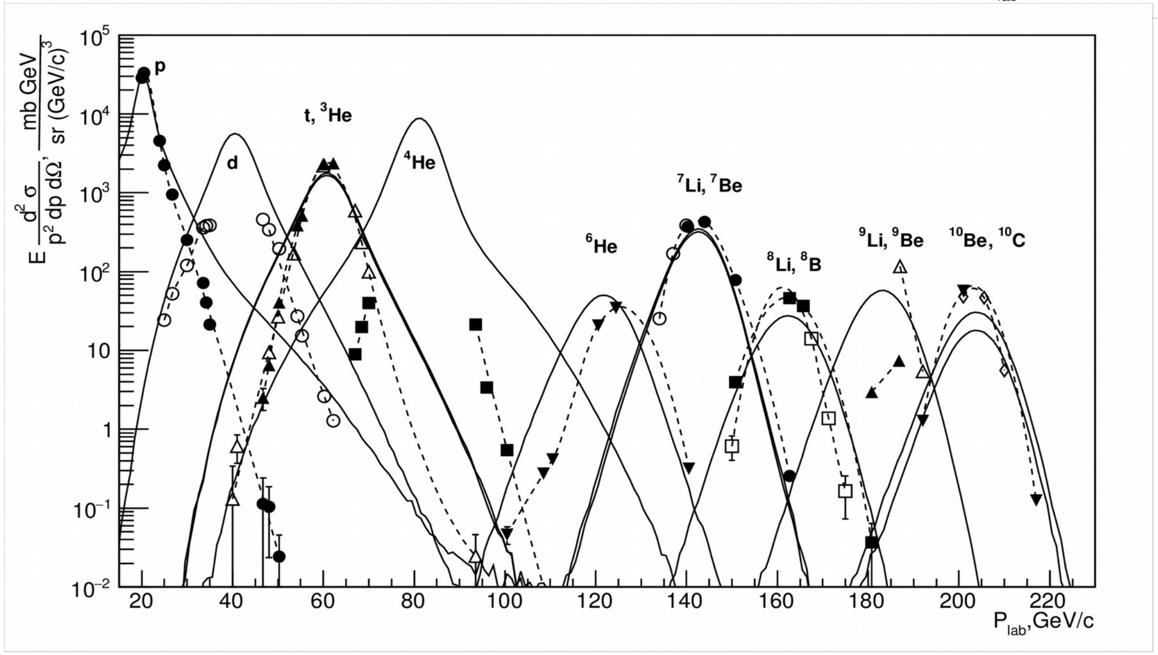
Hadrons and nuclei

Invariant cross sections dependence on Plab

Hadrons forward production:
For every particle there is essential contribution in cumulative region Plab>20.5 GeV/c.
Models: solid curves – FTFP, dotted lines - Baldin's hot formula (the observed object is produced due to collisions of the constituents).
A.G. Afonin et al., Phys. of Atom. Nucl., 2020, Vol. 83, No. 2, pp. 228-236.



Nuclei forward production:
For every nucleus there is essential contribution in cumulative region Plab>20.5*A GeV/c.
Models: solid curves – FTFP, Baldin's hot formula is omitted because it does not describe the data (on many orders of magnitude). Therefore, the nuclei forward production occurs due to the cold processes (the observed object is initially presented in the fragmented carbon nucleus).
Dotted curves are drawn to guide the eye.
A.G. Afonin et al., Nuclear Physics A997 (2020) 121718.

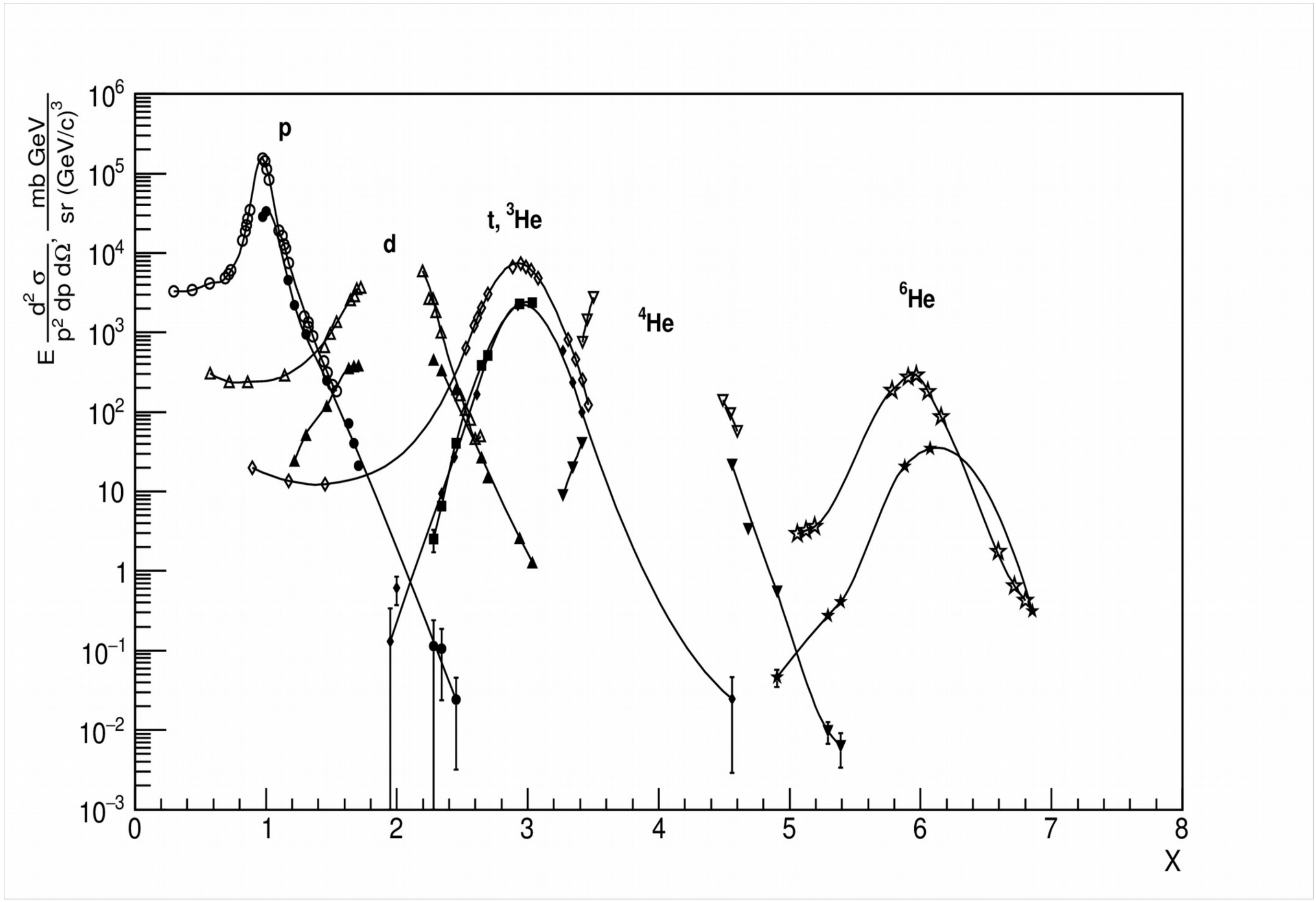


Nuclei: Comparison of these data with experiment at low energy 1.05 GeV/n (L. Anderson et al., Phys. Rev. C28 No3 (1983) 1224).

(x=Plab/p0, where p0=momentum of one nucleon in the beam)

Fig. Comparison of the inclusive invariant cross section dependence on x for zero angle production from these data (black symbols) with analogous measurements in CC collisions at lower energy 1.05 GeV/n (open symbols).

The notations are:
p(●, ○), d(▲, △), t(■, □), ^{3}He(⧫, ◊), ^{4}He(▼, ▽), ^{6}He(black star, white star).
The smooth curves are drawn to guide the eye.



Conclusion: One can see that the general dependence of cross sections on the variable x is similar, but they are noticeably lower at larger energy 20.5 GeV/n than at 1.05 GeV/n. The mentioned difference varied from a factor of 5 times near the fragmentation peak to several orders of magnitude beyond this peak

Nuclei: Comparison of these data for trituim (t) and ^{3}He with experiment at low energy 1.05 GeV/n (L. Anderson et al., Phys. Rev. C28 No.3 (1983) 1224) in terms of rapidity y in lab. system

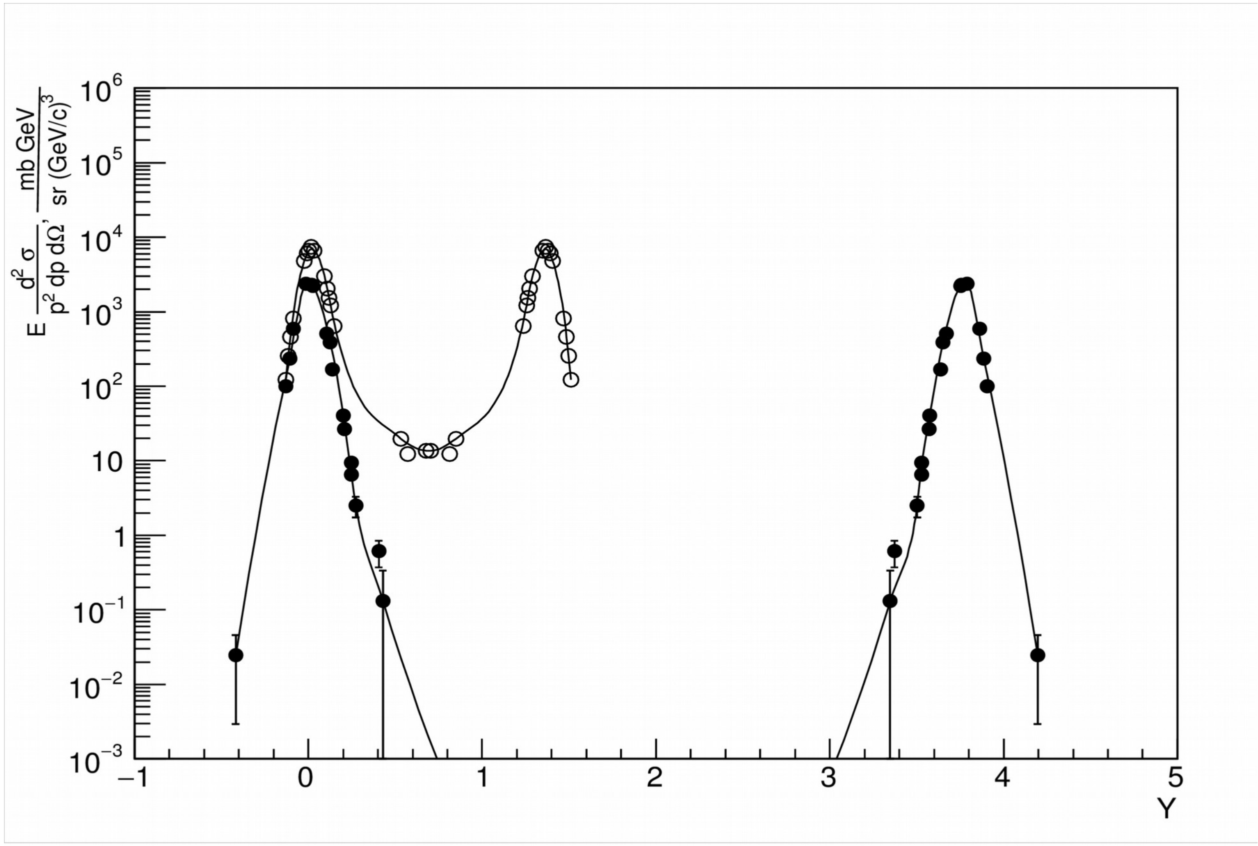


Fig. Inclusive invariant cross section versus fragment rapidity y in laboratory system for zero angle production of t and ^{3}He (the data in the target fragmentation region are obtained by the reflection procedure.

The black points (●) present data of this experiment, the open symbols (○) are given for comparison with analogous measurements in forward direction in CC collisions at lower energy 1.05 GeV/n.
The smooth curves are drawn to guide the eye.

Conclusion: At the energy of this experiment 20.5 GeV/n the clear and deep separation between projectile and target fragmentation regions is achieved. This is illustrated in the shown figure, where as a representative example the data for tritium (t) and ^{3}He are given.

Protons: Invariant cross-section on Tkin (projectile frame)

Fit of data by sum of two exponents: f(Tkin) = c1*exp(-Tkin/T1) + c2*exp(-Tkin/T2),

(Tkin is proton kinetic energy, T1 and T2 are temperatures of evaporation and cumulative processes)

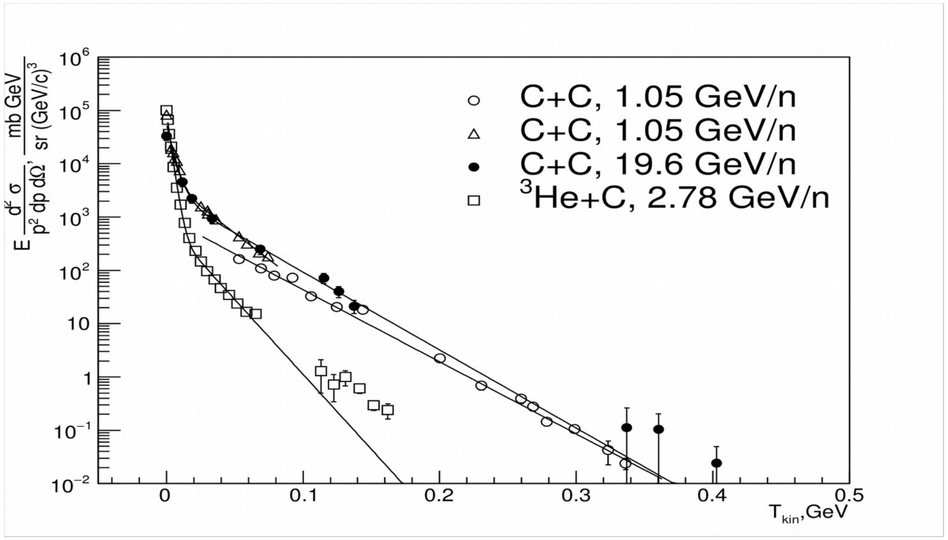


Fig. Invariant cross section for proton production in nucleus–nucleus interactions versus the proton kinetic energy in the rest frame of the fragmenting nucleus.
Black points – this experiment.
Curves – fit by summ of two exponents.

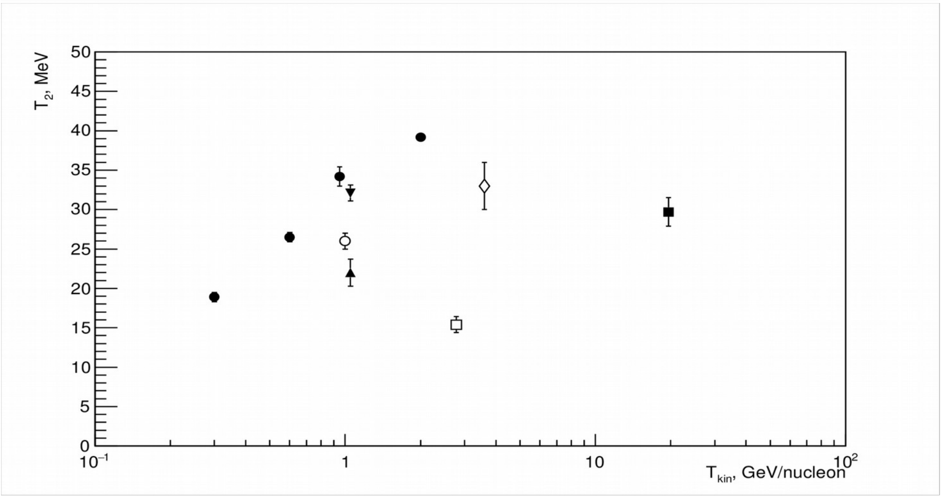


Fig. Fitted parameter T2 versus the beam kinetic energy according to the data (closed boxes) of our present study and the data on the reactions (open boxes) ^{12}C (^{3}He, p)x (0◦) from [27], (closed circles) ^{9}Be (^{12}C, p)x (3.5◦) from [31], (open circles) ^{197}Au (^{197}Au, p)x (160◦) from [30], (closed inverted triangles) ^{12}C (^{12}C, p)x (180◦) from [26], (closed triangles) ^{12}C (^{12}C, p)x (0◦) from [2], and (open diamonds) ^{12}C (^{12}C, p)x (160◦) from [29] or every nucleus

Conclusion: The temperature of cumulative processes T2 **with an increase of energy shows termination of growth with a tendency to reach a constant value.**

Protons: Invariant cross-section as function of x=P/Po,

(Po is momentum of one nucleon in a beam carbon ion)

Analysis in the quark cluster model **(A.V. Efrermov at al,** ***Phys. of Atom. Nucl.*** **57, 874 (1994)).**

Fig. Proton invariant cross section as function of x=P/P0. Wave-like form of the profile reflects the cluster structure of the fragmented carbon nucleus with seen three components. Solid curve gives fitted theoretical parametrization, dotted curves correspond to the contributions Wi of i-nucleon clusters with i=1,2,3 (W1+W2+W3=1).

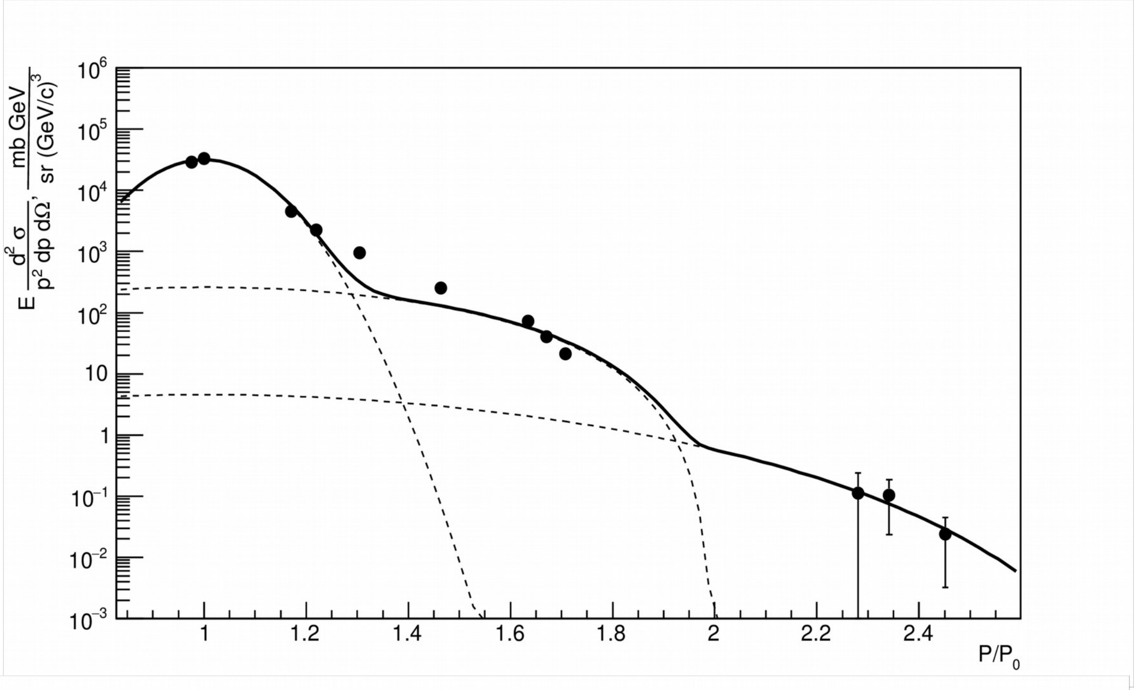
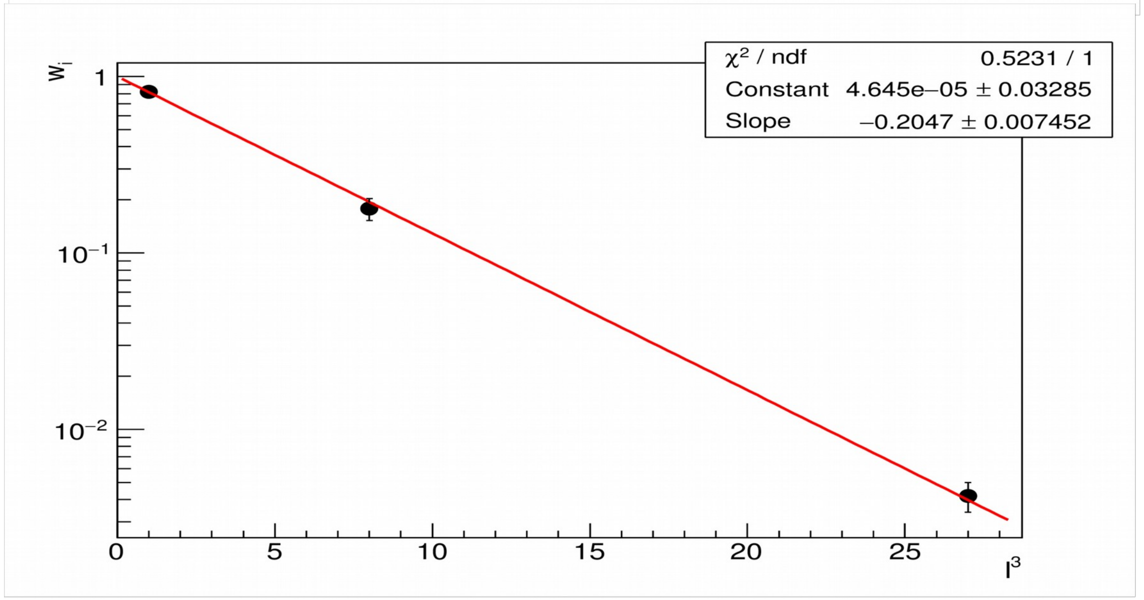


Fig. Dependence of Wi on argument i^3 showing exponential form, where I is number of nucleons in a cluster.



Conclusions

Invariant cross sections for the forward production of hadrons and nuclei are measured in CC-interaction at beam energy 20.5 GeV/n (sqrt(S_NN)=6.3 GeV). The maxima of distribution for fragments are shifted towards large momenta proportionally to its atomic number A. Hadrons and fragments are substantially produced in cumulative region (forbidden by kinematic of NN-collisions). The temperature of cumulative processes with an increase of energy shows termination of growth with a tendency to reach a constant value.

Comparison of the fragment data with results at lower energy 1.05 GeV/n shows that the general dependence of the cross section on x=Plab/p0 is similar, but yields are noticeably lower at larger energy 20.5 GeV/nucleon. The mentioned difference varied from a factor of 5 times near the fragmentation peak to several orders of magnitude beyond this peak with much more clear and deep separation at energy of this experiment between projectile and target fragmentation regions .

Comparison with Baldin's formula points out that hadrons are produced (forward direction) in hot processes (colliding of constituents) while for nuclei the main role play cold processes (the observed object are initially presented in a fragmented nucleus).

The measurements were compared with model FTFP (Fritiof) and Baldin's formula. They qualitatively describe the main features of the found spectra but nevertheless quantitatively there are noticeable discrepancies increasing with growth of hadron/fragment momentum. Analysis in framework of the quark-cluster model allowed to estimate the contribution of I-nucleon clusters (i=1,2,3) in carbon nucleus.