A possibility to register associated pair production of hadrons and light nuclei in a kinematically forbidden region in AA-interactions on the FODS double arm spectrometer at the U-70 accelerator complex (the Monte Carlo simulation)

M.Yu. Bogolyubsky, A.A. Volkov, D.K. Elumakhov, A.A. Ivanilov,
A.Yu. Kalinin, A.N. Krinitsyn, K.A. Romanishin

National Research Center Kurchatov Institute - Institute for High Energy Physics,
Protvino, Moscow region, 142281, Russia

The LXXI International Conference “NUCLEUS – 2021. Nuclear physics and elementary particle physics. Nuclear physics technologies”, St Petersburg, Sep. 20-25, 2021.

Introduction

The U-70 Accelerator Complex (National Research Center Kurchatov Institute – Institute for High Energy Physics, Protvino, Russia) can accelerate light nuclei for experiments in fundamental physics, applications in modern technologies and nuclear medicine. It provides ^{12}C beams with full energy of incident ions up to 300 GeV.

The physical programs are 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).

Our measurements in forward direction at an angle of 0^o had been fulfilled on the FODS setup (double arm spectrometer) at energy of carbon beam 20.5 GeV/n. This is the maximal energy for such experiments at a fixed target.

The measurements in forward direction are free from ambiguities in the interpretation of the cumulative effect like in standard experiments on backward production. It allows to understand unambiguously the internal quark-cluster structure of nuclei. This structure is manifested in an experimentally observed strong cumulative effect in the forward direction for both secondary hadrons and secondary nucle with reaching values of Feynman variable x=2.5.

Introduction (continue)

In our mentioned experiments to study scattering in the forward direction only one FODS arm was used. Further, we analyze in the framework of the Monte-Carlo simulation variant of the next development of the experiment with activation of both arms.

The arms are installed asymmetrically at angles of 128.9 mrad and -268.9 mrad relatively to propagation of the ion beam for South and North arms respectively. This gives ability to register cumulative processes with emission of the secondary nucleons and nuclei into forward and backward hemispheres in the center of mass. The purpose of such an experiment is to explicitly reveal the cases of binary interactions, showing the cluster structure of nucleus.

Next slides: a) main parameters of the experiment, b) schematic view of the FODS setup (two arm spectrometer) and c) some our results that show the strong cumulative effect in forward direction in CA-interactions for secondary hadrons and nuclei with demonstration the cluster structure of the fragmenting nucleus.

The main parameters of the experiment

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

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Beam extraction:

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

Targets: Carbon

Full opening angle between two arms of the FODS spectrometer (fixed): 7.233^o

(that corresponds to emission angle of 2ry particles in c.m. system 90^o in NN-collisions at 50 GeV/c)

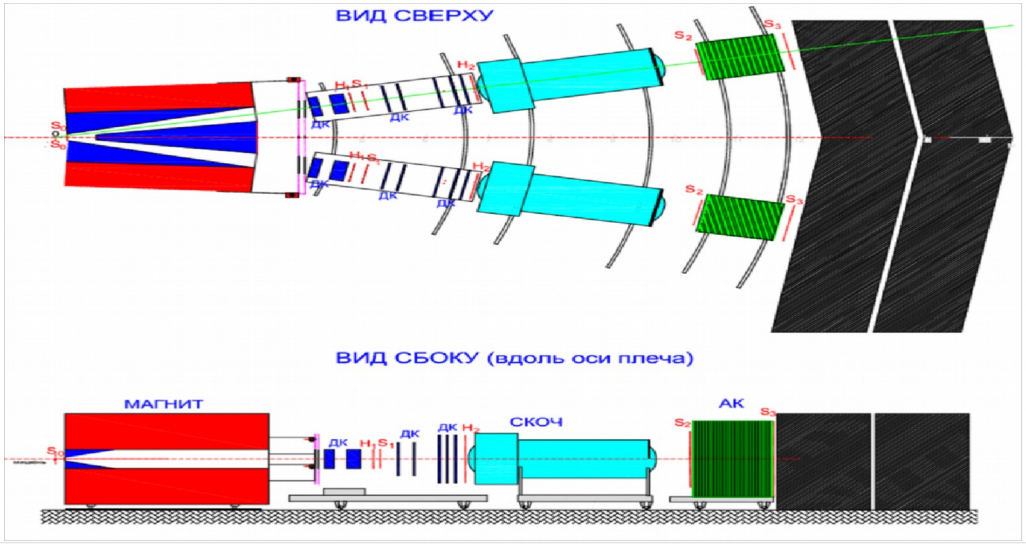
Beam intensity measuring:

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.

The experimental setup

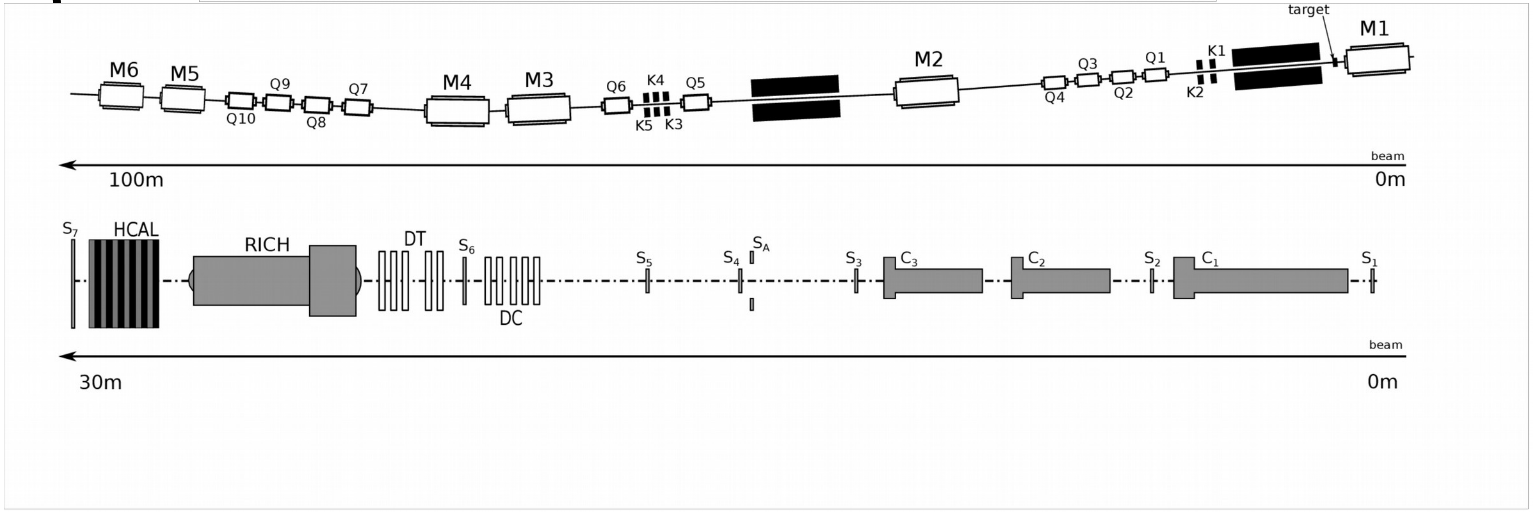
a)

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.**

Variants of the arms setting

a) symmetric (relatively to the incident particles flow) setting.
It is used to study the processes with production of particles in the region of high Pt.

b) asymmetric setting.
It can be used to observe associated particle production in backward and forward hemispheres in c.m. system. The aim of this work is to study a possibility to register the process of binary interaction ab->ab, where a and b are quark-nucleon clusters from beam and target nuclei.

c) zero angle setting of one of arms.
It is used to study production of particles and nuclei in forwards direction.

In the next slides we present some our results that show the strong cumulative effect in forward direction in CA-interactions for secondary hadrons and nuclei with demonstration the cluster structure of the fragmenting nucleus.

Hadrons and nuclei (forward production)

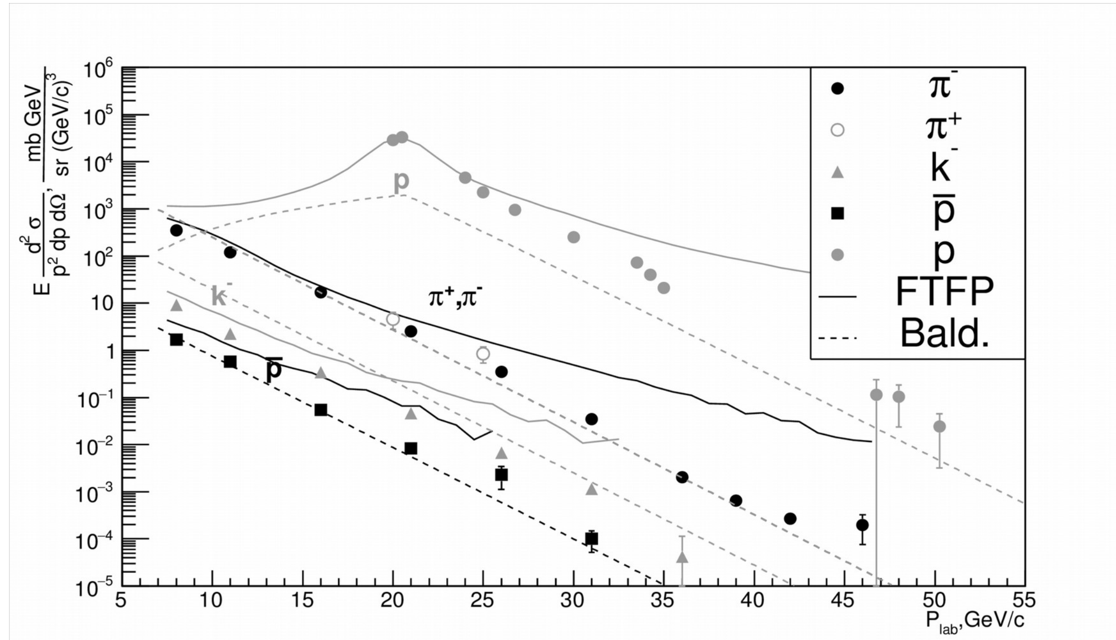
Invariant cross sections dependence on Plab

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).**

Data from our work *A.G. Afonin et al., Phys. of Atom. Nucl., 2020, Vol. 83, No. 2, pp. 228-236. https://link.springer.com/article/10.1134/S1063778820020015*



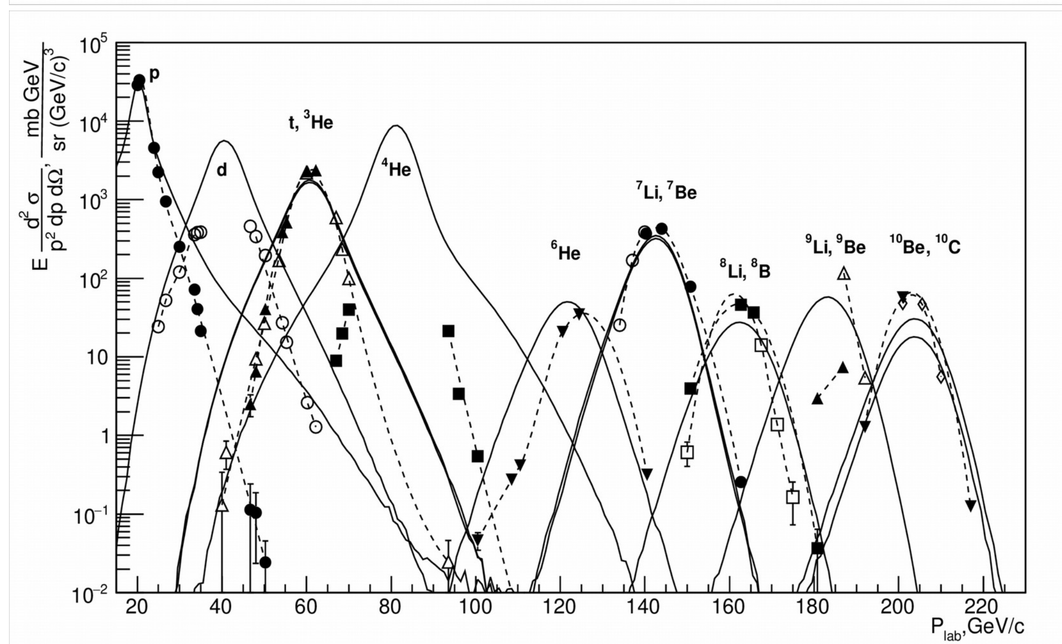
Nuclei forward production:

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.

Data from our work *A.G. Afonin et al., Nuclear Physics A997 (2020) 121718. https://doi.org/10.1016/j.nuclphysa.2020.121718*

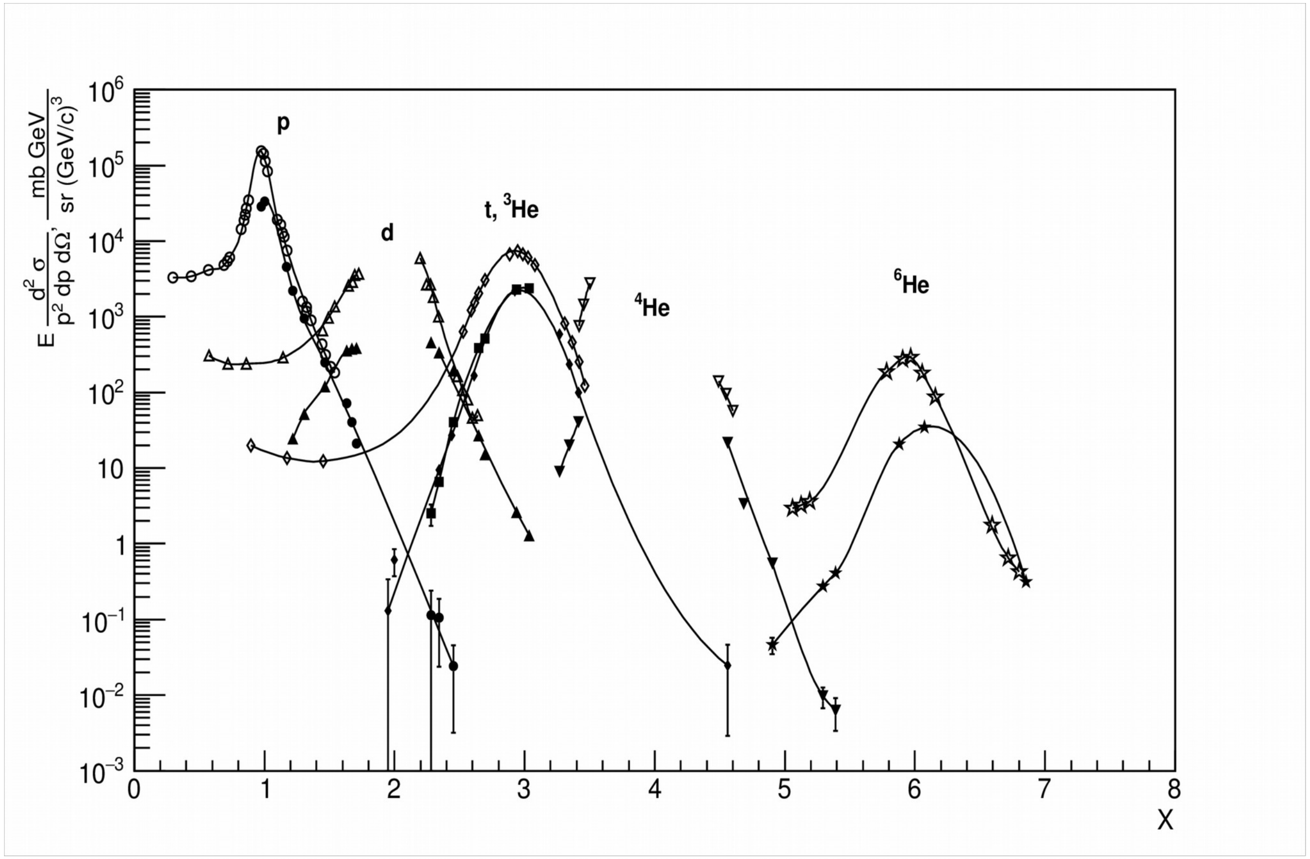


Nuclei (forward production): Comparison of our experimental data at beam energy 20.5 GeV/n (*A.G. Afonin et al., Nuclear Physics A997 (2020) 121718, https://doi.org/10.1016/j.nuclphysa.2020.121718*) and at low energy 1.05 GeV/n (L. Anderson et al., Phys. Rev. C28 No3 (1983)1224).

(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 our data at 20.5 GeV/n (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.



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

Protons (forward production)

Invariant cross-section as function of x=P/Po in the projectile frame

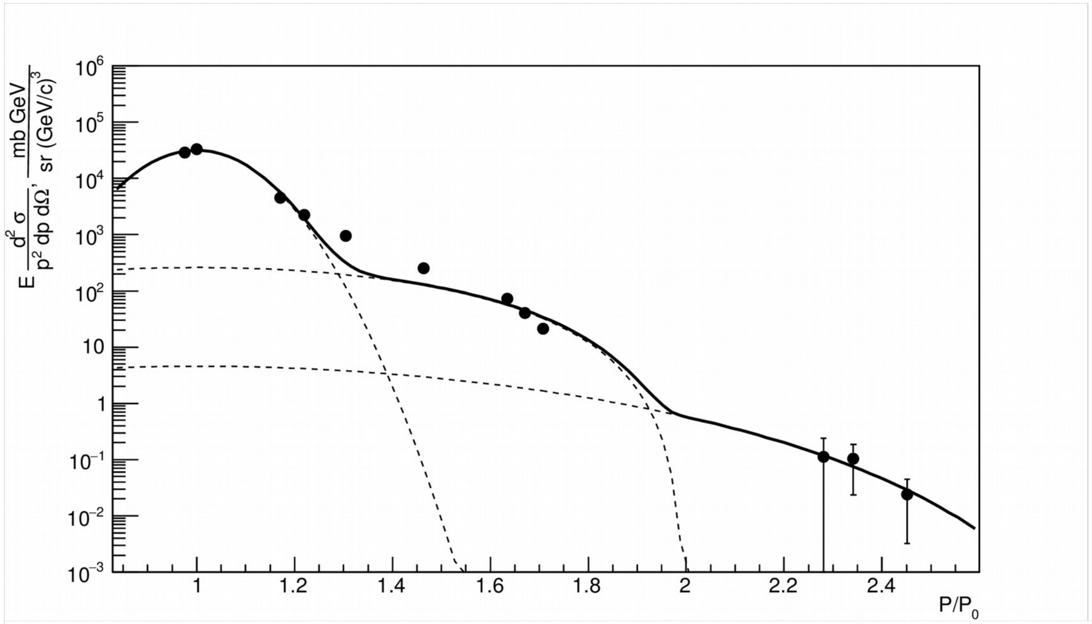
(Po is momentum of one nucleon in a beam carbon ion)

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).

Data from our work *A.G. Afonin et al., Phys. of Atom. Nucl., 2020, Vol. 83, No. 2, pp. 228-236. https://link.springer.com/article/10.1134/S1063778820020015*



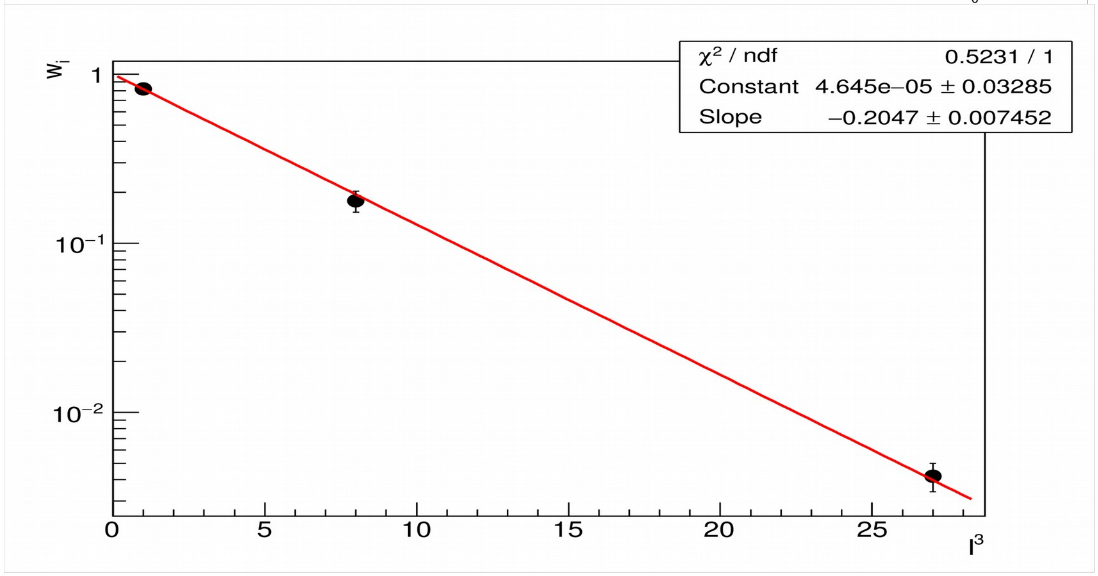


Fig.1. Dependence of Wi on argument i^3 showing exponential form, where I is number of nucleons in a cluster.

Remark to the shown our experimental results on forward production from previous slides

Our comparison of invariant cross sections for forward production in CA-collisions on light (carbon) and heavy (lead) targets in framework of the geometrical model allows us to conclude that peripheral processes with low momentum transfer dominate in the forward scattering. Thus, the observed momentum distributions of secondary nuclei (shown on previous slides) reflect their momentum distributions inside the fragmenting nucleus and demonstrate its cluster structure.

This remark follows the results of our work *A.G. Afonin et al.,* Phys. of Atom. Nucl., 2021, Vol. 84, No.4, pp. 475–482
http://link.springer.com/10.1134/S1063778821040049

The Monte-Carlo simulation

In our experiment to study the forward production in CA-interactions the detailed Monte-Carlo simulation (Gean4 10.02.p02) of the setup has been done. In this case it was used the variant with zero angle setting of the South arm of the FODS. The simulation included transportation and selection of the produced particles in the beamline used as a part of the combine spectrometer (beamline + FODS) and also definition of acceptance for the different secondary particles and nuclei with taking into account detector efficiencies, absorption in spectrometer materials and decay for unstable objects:

M.Yu. Bogolyubsky, Instrum. Exp. Tech. 57 (2014) 519-530, DOI:10.1134/S0020441214050030.

M.Yu. Bogolyubsky et al., Instrum. Exp. Tech. 62, No. 6 (2019) 731-736, DOI:10.1134/S0020441219050130

The extension of the Monte-Carlo simulation for asymmetric setting of the arms
Generator of binary processes ab->ab

To determine the possibility of registering binary processes of scattering of clusters from target and beam nuclei a generator of elastic interaction is applied with including Fermi motion. The last leads to some variation of square of total energy s of the interacting clusters in their center of mass.

The data in Fig. 1 (see slide above) show that the contribution of clusters to the nucleus structure quickly decreases with an increase of the number i of nucleons in the cluster. Therefore, in this work we limited ourselves to i≤2, i.e. protons and deuterons with analysis of processes pp->pp and dp->dp.

For the former process pp->pp the dependence of cross section on s is taken into account ($\sigma \sim s^{-3.6}$) from phenomenological parametrization [1] of the differential cross sections for big $-t>2$ GeV^2, where t is square of momentum transfer. For definition of t in the Monthe-Carlo procedure the experimental data at energies of 10–100 GeV are used. The dependence of cross section on t is taken in the form

$$d\sigma/dt \sim \exp(Bt)$$

having a character two-component structure: big B=8–9 GeV^{-2} for $0<-t<1.4$ GeV^2, and much smaller B ≈1.6 GeV^{-2} for $-t>1.4$ GeV^2 [2].

References:

[1] L. Frankfurt, E.Piasetsky, M. Sargsyan, M. Strikman, Phys.Rev. C 51,890 (1995).

[2] E. Martynov, hep-ph/0703248 (2007).

The extension of the Monte-Carlo simulation for asymmetric setting of the arms
Generator of primary interaction – the UrQMD model

We present some common results for CC-interactions in framework of the UrQMD model [3,4] at a beam energy of 20.5 GeV/n for estimation of the setup loading. This model gives the value of total cross section 850 mb for CC-interactions at energy 20.5 GeV/n.

References:

[3] http://urqmd.org

[4] S. A. Bass, M. Belkacem, M. Bleicher at al., Prog. Part. Nucl. Phys. 41, 225 (1998); ArXiv: nucl-th/9803035v2, 19 Mach 1998, revised August 1, 2011.

Results: the Monte-Carlo simulation for asymmetric setting of the arms
The UrQMD model

Totally it was generated 214 millions of events.

Table 1. The number of events registered by the FODS, where “same” and “other” mean correspondingly the number of events with several particles in the same arm or in different arms (arm0=South arm, arm1=North arm).

	arm0	arm1
all	2631621	391653
same	6699	243
other	3258	2186

Table 2. The number of particles of different types registered in the FODS tracking system (arm0=South arm, arm1=North arm).

	arm0	arm1
Proton	1367822	224354
d	40701	850
t	781	0
4He	11	0
$\pi +$	434471	57027
$\pi -$	435919	59660
K+	91663	12096
K−	16317	1918
antiproton	6496	792

Results: the Monte-Carlo simulation for asymmetric setting of the arms
The UrQMD model

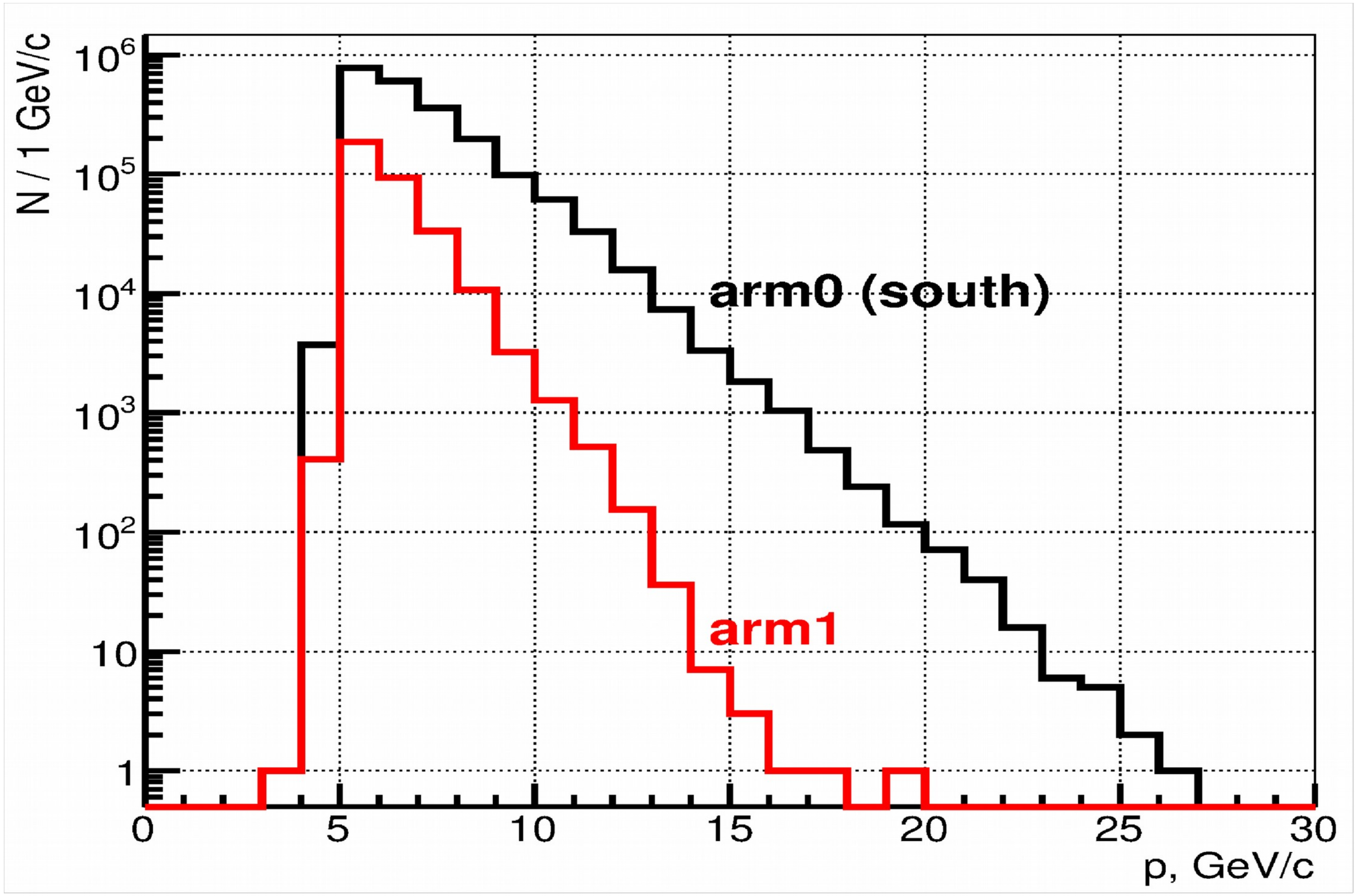
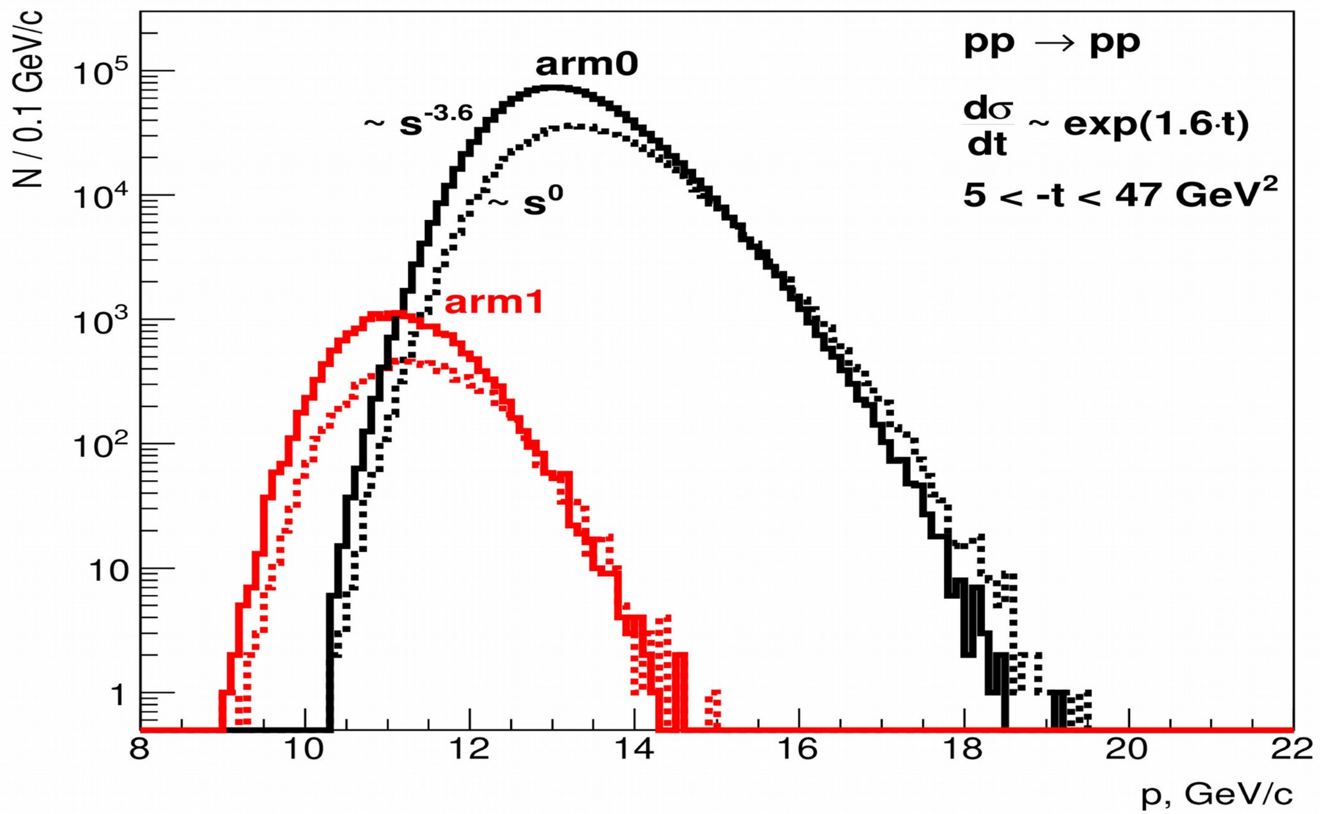


Fig.2. Momentum spectra of positive particles registered in South (arm0) and In North (arm1) arms of the FODS setup.

Results: the Monte-Carlo simulation for asymmetric setting of the arms
The generator of the binary process ab->ab

For the analysis we generated 10 millions of events for each of processes **pp->pp** and **dp->dp**, assuming that protons and deuterons are clusters forming the internal structure of colliding nuclei.

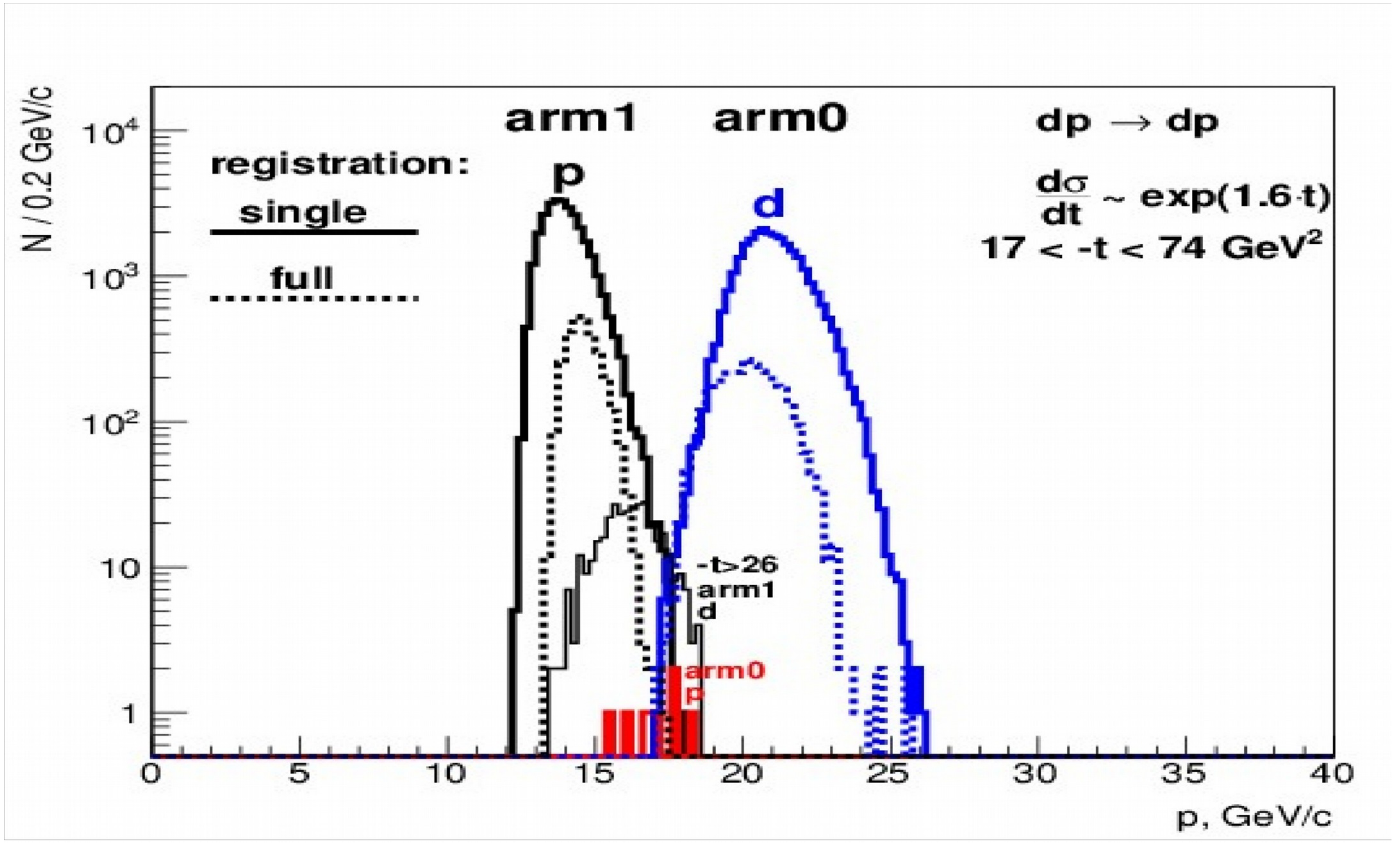
Conclusion: the simulation shows that the full registration of two protons in one event does not occur for pp->pp reaction.



Fig, 3. Momentum spectra of detected protons for pp−>pp reaction (no full registration of both protins in one event), the dotted line shows for comparison the distributions without Fermi motion).

Results: the Monte-Carlo simulation for asymmetric setting of the arms
The generator of the binary process ab->ab

In fig. 4 it is given similar data for reaction dp->dp. Momentum spectra are presented for two cases: a) single registered proton or single registered deuteron and b) simultaneously registration of both particles (proton and deuteron). Also we show the spectrum of deuterons recorded in North arm (arm1) calculated separately in the interval −t>26 GeV^2, since for −t>17 GeV^2 they are not registered.



Fig, 4. Momentum spectra of detected protons and deuterons for dp->dp reaction, the dotted curves correspond to the full registration of both particles (proton and deuteron) in one event.

Conclusion: **the simulation shows that for the dp->dp reaction it is possible simultaneously (in one event) to register both a proton and a deuteron in the FODS setup.**

Conclusions

In this article the operation of the FODS setup has been analyzed by the Monte-Carlo simulation for an asymmetric orientation of spectrometer arms relatively to the propagation of the ion beam. Loading of arms by flows of different particles and nuclei has been estimated in CC-collisions at beam energy of 20.5 GeV/nucleon. A possibility of complete registration of all particles (proton and deuteron) in dp->dp reaction has been shown. The observation of such processes in experiment will be a direct indication on scattering of nuclei clusters that determine the internal nucleus structure.