CUMULATIVE PROTONS PRODUCTION DURING THE CARBON NUCLEUS FRAGMENTATION ON THE BERYLLIUM TARGET

D.M. Larionova, M.M. Larionova, Yu. M. Mitrankov, V.S. Borisov, V.N. Solovev, A.Ya. Berdnikov

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

The collision of carbon nuclei with beryllium targets has been simulated in the framework of the Liège Intranuclear Cascade model at the carbon nuclei initial kinetic energies of 0.60, 0.95, 2.00 GeV / nucleon. Proton production invariant cross-sections at the nuclei collision angle of 3.5 degrees were obtained. It was shown that the dependence of experimental invariant cross-sections on the cumulative variable x in the range $0.9 < x < 2.4$ could be interpret on the basis of taking into account the Fermi motion of nucleons in nuclei, multiple scattering processes, and the formation of delta resonance. The calculation results were compared with experimental data and findings of investigation where data was analyzed in the context of the quark cluster model.

Key words: cumulative particle, delta resonance, Liège Intranuclear Cascade model, beryllium target.

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Introduction

Cumulative production of particles means that particles are generated in nucleus-nucleus collisions in the region kinematically forbidden for free nucleon-nucleon collisions [1, 2].

A dimensionless quantity x, also called the dimensionless variable, is introduced to characterize the cumulative particles [3].

There are different definitions for this quantity [1, 2]; in this paper, the cumulative variable x is used as a ratio of the momentum p of the detected proton to the momentum p_0 of the nucleon in the carbon nucleus [4], in the laboratory frame of reference (rest frame of the ^{9}Be target):

$$x = p / p_0.$$

Currently, there are two fundamentally different models describing the production of cumulative particles.

The first model takes into account the Fermi motion, multiple scattering within the nucleus as the hadron projectile or its fragmentation products experience several successive rescatterings [1], and the processes associated with the formation of resonances. As a result, a particle can be produced in the last intranuclear collision in a region that is kinematically forbidden in scattering by a single free nucleon.

The second model is based on the processes occurring at distances that are much smaller than the characteristic nuclear distances [5]. The most common models describing such processes are the fluctuon model [5] and the nmodel of nucleon correlations at short distances [6, 7].

The flucton models are divided into two classes: “cold” and “hot”. The former assume that fluctuons always exist in the initial nucleus [1, 5, 8, 9], while according to the latter, fluctons are formed during the collision [10].

The FRAGM experiment at the TWAC-ITEP heavy ion acceleration-accumulation facility at the Institute for Theoretical and Experimental Physics (Moscow, Russia) [11] measured proton yields at an angle of 3.5°

with the fragmentation of carbon ions with energies of 0.60, 0.95, and 2.00 GeV/nucleon on a beryllium target. The obtained data are presented as invariant cross-sections of the proton yield versus the cumulative variable x in the range $0.9 < x < 2.4$.

The experimental data from Ref. [11] were analyzed in [4] based on the quark cluster model [8]. According to this model, the nucleus contains clusters consisting of $3k$ ($k = 1, 2, 3$) valence quarks. The value $k = 1$ corresponds to ordinary nucleons.

However, Ref. [4] did not take into account the contribution of the processes that are not related to formation of quark clusters, namely, the Fermi motion of nucleons in the nucleus, multiple scattering, and the formation of resonances.

The goal of this study was to calculate the cross-sections for the production of cumulative protons in an inclusive reaction

$$^{12}C + {}^{9}Be = {}^{1}p + X, \qquad (1)$$

where ^{1}p is the proton, X is the remaining products of the reaction.

Initial kinetic energies of carbon ions were taken to be 0.60, 0.95, and 2.00 GeV/nucleon. The computational model took into account the Fermi motion of nucleons, multiple rescattering, and the formation of resonances. The hypothesis of quark clusters was not included in the model.

Simulation procedure

We used the Extension of the Liиge Intranuclear Cascade Model [12] to assess the contribution from Fermi motion, multiple scattering and the formation.

According to the Intranuclear Cascade Model, the collision of two nucleons leads either to elastic or to inelastic scattering.

Total cross-sections $\sigma_{tot,pp}$ of nucleon-nucleon scattering in millibarns (mb) were calculated using the following formulae [13, 14]:

$$\sigma^{I}_{tot,pp} = 34\left(\frac{p_{lab}}{0,4}\right)^{-2,104} \quad \text{with } p_{lab} < 0,44;$$

$$\sigma^{II}_{tot,pp} = 23,5 + 1000(p_{lab} - 0,7)^4$$

$$\text{with } 0,44 < p_{lab} < 0,80; \qquad (3)$$

$$\sigma^{III}_{tot,pp} = 23,5 + \frac{24,6}{1 + \exp\left(-\frac{p_{lab} - 1,2}{0,1}\right)}$$

$$\text{with } 0,8 < p_{lab} < 1,5; \qquad (4)$$

$$\sigma^{IV}_{tot,pp} = 41 + 60(p_{lab} - 0,9)\exp(-1,2p_{lab})$$

$$\text{with } 1,5 < p_{lab} < 3,0; \qquad (5)$$

$$\sigma^{V}_{tot,pp} = 45,6 - 219p_{lab}^{-4,23} + 0,41\log^2(p_{lab}) - 3,41\log(p_{lab})$$

$$\text{with } p_{lab} > 3,0; \qquad (6)$$

$$\sigma^{I}_{tot,np} = 6,3555\exp[-3,2481\log(p_{lab}) - 0,377\log^2(p_{lab})]$$

$$\text{with } p_{lab} < 0,446; \qquad (7)$$

$$\sigma^{II}_{tot,np} = 33 + 196\left|p_{lab} - 0,95\right|^{2,5}$$

$$\text{with } 0,446 < p_{lab} < 1,000; \qquad (8)$$

$$\sigma^{III}_{tot,np} = 24,2 + 8,9p_{lab}$$

$$\text{with } 1 < p_{lab} < 1,924; \qquad (9)$$

$$\sigma^{IV}_{tot,np} = 48,9 - 33,7p_{lab}^{-3,08} + 0,619\log^2(p_{lab}) - 5,12\log(p_{lab})$$

$$\text{with } 1,924 < p_{lab}, \qquad (10)$$

where p_{lab}, GeV/c is the momentum in the laboratory frame of reference.

The cross-sections $\sigma_{el,pp}$ for nucleon-nucleon elastic scattering are calculated in the extended model using the following formulae:

$$\sigma^{I}_{el,pp} = \sigma_{tot,pp} \text{ with } p_{lab} < 0,8; \qquad (11)$$

$$\sigma^{II}_{el,pp} = \frac{1250}{p_{lab} + 50} - 4(p_{lab} - 1,3)^2$$

$$\text{with } 0,8 < p_{lab} < 2,0; \qquad (12)$$

$$\sigma^{III}_{el,pp} = \frac{77}{p_{lab} + 1,5}$$

$$\text{with } 2,000 < p_{lab} < 3,096; \qquad (13)$$

$$\sigma^{IV}_{el,pp} = 11,2 - 22,5p_{lab}^{-1,12} + 0,151\log^2(p_{lab}) - 1,62\log(p_{lab})$$

$$\text{with } 2,096 < p_{lab}; \qquad (14)$$

$$\sigma^{\mathrm{I}}_{el,np} = \sigma_{tot,np} \text{ with } p_{lab} < 0,85; \quad (15)$$

$$\sigma^{\mathrm{II}}_{el,np} = \frac{31}{\sqrt{p_{lab}}} \text{ with } 0,85 < p_{lab} < 2,00; \quad (16)$$

$$\sigma^{\mathrm{III}}_{el,np} = \frac{77}{p_{lab} + 1,5} \text{ with } 2,00 < p_{lab}. \quad (17)$$

The cross-sections for the formation of inelastic processes can be calculated as the difference between the total cross-section of nucleon-nucleon scattering and the cross-section of elastic scattering.

Computational study

The results for the simulation of intranuclear cascade are shown in Fig. 1 as the dependence of invariant cross-section (σ_{inv}) for proton production in the given reaction versus the cumulative variable *x*. The invariant cross-section for proton production was calculated by the formula:

$$\sigma_{inv} = \frac{E}{p_0} \frac{d^2\sigma}{dx d(p_t)^2},$$

where σ is the total cross-section of the reaction; p_0 is the per nucleon incident momentum; E and p_t are the total energy and the transverse momentum of the proton in the laboratory frame of reference [4].

Figs. 1 – 3 show the simulation results without (i.e., exclusively due to Fermi motion and multiple scattering) and with the formation of delta resonances Δ(1232) taken into account. Figs. 1 – 3 also give a comparison of the data for the simulation of intranuclear cascade with the experimental data and the results obtained based on the quark cluster model.

Discussion

It follows from the data shown in Figs. 1 – 3 that simultaneously taking into account Fermi motion, multiple scattering and delta resonance formation leads to production of cumulative particles in the range $x > 1$.

Fig. 4 shows examples of the processes leading to the production of cumulative particles.

Example 1 (Fig. 4,*a*). Let us consider the production of a cumulative particle due to Fermi motion of nucleons in the incident nucleus and

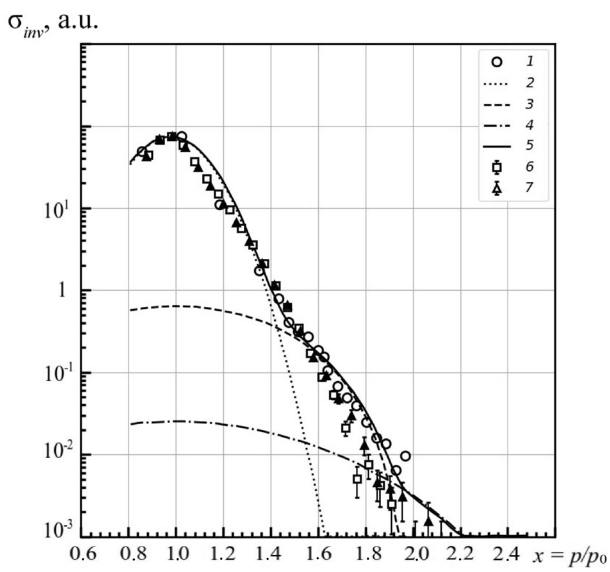

Fig. 1. Experimental (symbols *1*) [11] and simulated (*2* – *7*) curves for the cross-section of proton production in reaction (1) (angle 3.5°) versus the cumulative variable, at an initial energy of 0.60 GeV/nucleon.

The data were processed based on: the Extension of the Liиge Intranuclear Cascade Model [12], without (*6*) and with (*7*) delta resonance formation taken into account; the quark cluster model (*2* – *5*) used to assess the contributions of one- (*2*), two- (*3*) and three- (*4*) nucleon clusters and the total contribution (*5*) of quark clusters

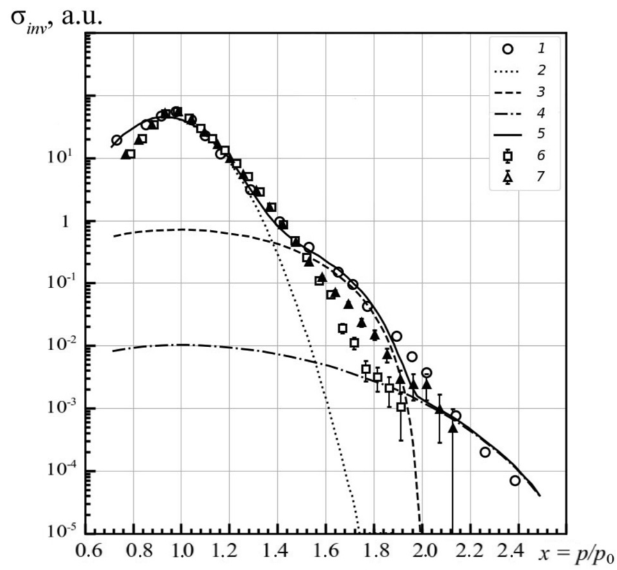

Fig. 2. The data shown are similar to those in Fig. 1 but were obtained with the initial energy of 0.95 GeV/nucleon

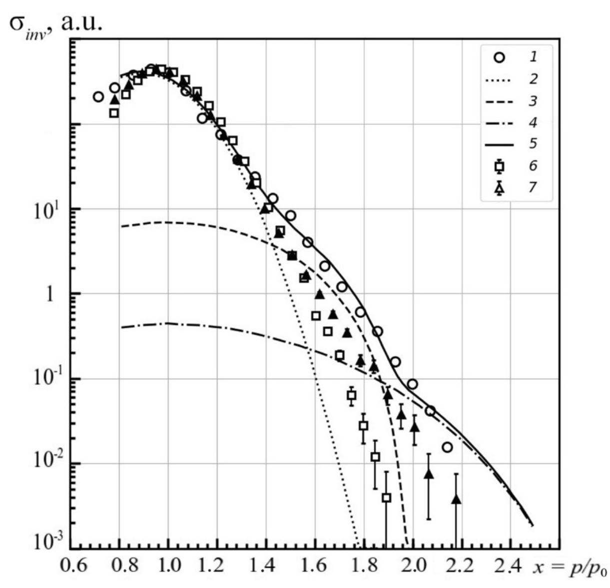

Fig. 3. The data shown are similar to those in Figs. 1 and 2 but were obtained with the initial energy of 2.00 GeV/nucleon

to multiple scattering. A cumulative proton with $x = 1.58$ was detected in this particular example of an event.

The per nucleon incident momentum can exceed the p_0 value due to Fermi motion in the given nucleus. According to the Liège intranuclear cascade model, the momenta of the nucleons in the nucleus obey the Gaussian distribution, for which the root-mean-square (RMS) value of the quantity is expressed as

$$\mathrm{RMS} = \sqrt{\frac{3}{5}}p_{\mathrm{F}},$$

where $p_{\mathrm{F}} = 270$ MeV/c is the Fermi momentum [15].

In the first stage (*1*) of the given event, proton 0, whose momentum is 1603 MeV/c, elastically collides with neutron 1; as a result, the momentum of proton 0 decreases to 1337 MeV/*c* (the proton loses energy due to elastic collision).The second stage (*2*) is the elastic collision of proton 3, whose momentum is 1421 MeV/*c*, with proton 0, whose momentum is 1337 MeV/c. Due to this collision, the momentum of proton 0 increases to 1925 MeV/*c*. This proton is the one actually detected in this event as cumulative, and the momentum of 1925 MeV/*c* corresponds to the value of the cumulative variable $x = 1.58$.

Example 2 (Fig. 4,*b*). Let us consider an event with the formation of a delta resonance. In the first stage (*1*) of such an event, proton 1, whose momentum is 1346 MeV/c, collides with proton 0; as a result, delta resonance 0 with a momentum of 1098 MeV/*c* is produced. The second stage (2) is the collision of proton 2, whose momentum is 1108 MeV/*c*, with a delta resonance. After this, proton 0, whose momentum is 1872 MeV/*c*, is produced, and it is the one detected in this event as cumulative. The momentum of 1872 MeV/*c* corresponds to the value of the cumulative variable $x = 1.53$.

It follows from expressions (4) and (5) that the cross-section of inelastic processes, including the formation of delta resonances, is zero for per nucleon momenta of carbon nuclei smaller than 0.8 GeV/($c \cdot$ nucleon).

Thus, the cross-sections obtained by simu-

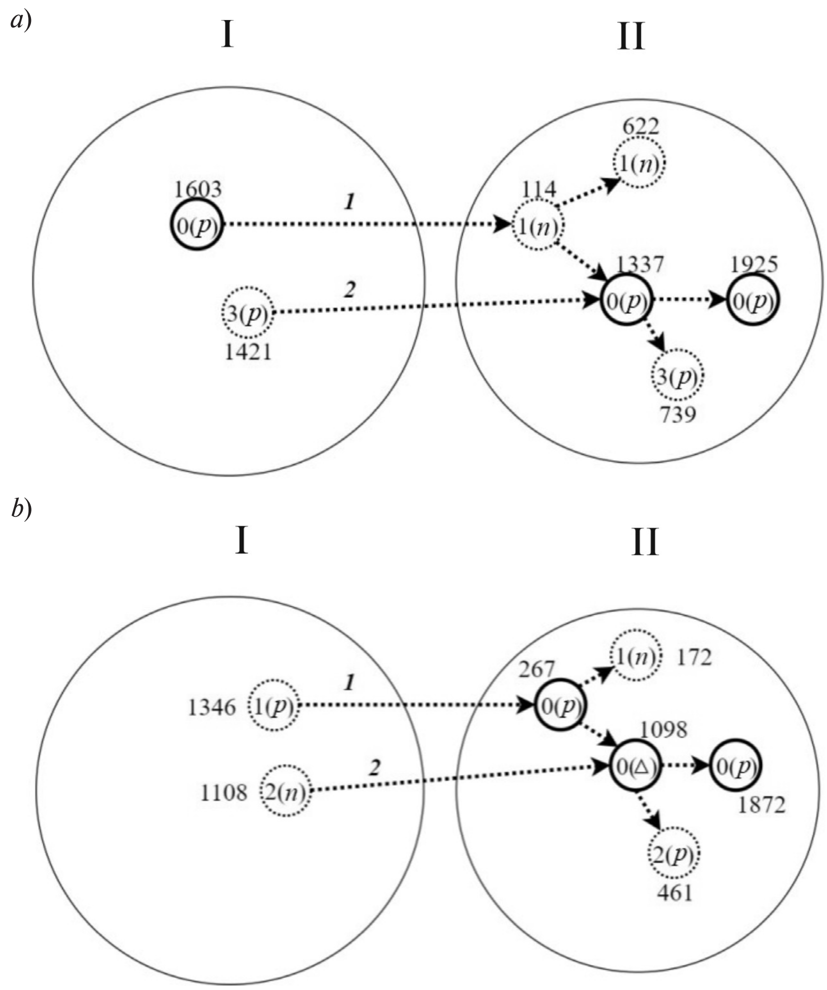

Fig. 4. Examples of events occurring in the collision of C (I) and Be (II) nuclei, without (*a*) and with (*b*) the formation of delta resonance 0(Δ); *1* and *2* are the stages of the processes. Small dashed circles indicate intranuclear nucleons, with their momenta in MeV/*c* shown beside them; (*n*) and (*p*) are the neutron and the proton; 0, 1, 2, 3 are their indices. The small solid circles indicate the cumulative particles formed in the processes

lation, both with and without the formation of delta resonances taken into account, coincide in the region $x < 0.8 / 0.6 \approx 1.3$.

If the formation of delta resonances in the region $x > 1.6$ is taken into account, the invariant cross-section increases and becomes closer to the experimental values.

Let us compare the results of the simulation carried out in our study with the predictions of the hypothesis based on the existence of quark clusters in nuclei (see Figs. 1 – 3).

Evidently, the processes of multiple scattering and formation of delta resonances in the region $x < 1.4$ are as adequate for describing the experimental data as the quark clusters approach, but yield lower values of invariant cross-sections in the region $x > 1.4$. The obtained results start to considerably deviate from the experimental data with increasing initial kinetic energies of carbon ions.

Conclusion

We have obtained the cumulative variable distributions of invariant cross-sections taking into account the processes of multiple scattering and resonance formation, without using the hypothesis of quark clusters in inclusive reaction (1)

$$^{12}C + {}^{9}Be = {}^{1}p + X$$

with initial kinetic energies of carbon ions of 0.60, 0.95, 2.00 GeV/nucleon.

We have established that the processes of multiple scattering and delta resonance formation lead to production of cumulative particles and make a significant contribution to the cross-section for the production of cumulative particles. The obtained results are in agreement with the experimental data for the initial kinetic energy of carbon ions of 0.60 GeV/nucleon.The obtained values are lower than the experimental values with increasing energy in the region x > 1.4, which indicates potential new mechanisms for the production of cumulative particles, for example, taking into account other nucleon resonances.

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THE AUTHORS

LARIONOVA Dariya M.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
dlar@bk.ru

LARIONOVA Mariya M.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
mlario@bk.ru

MITRANKOV Yuriy M.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
mitrankovy@gmail.com

BORISOV Vladislav S.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
vl-borisof@yandex.ru

SOLOVEV Vladimir N.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
hydraca39@gmail.com

BERDNIKOV Aleksandr Ya.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
alexber@phmf.spbstu.ru