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Simulation of the reaction of deuteron fragmentation into cumulative and twice cumulative pions

A.G. Litvinenko*
Joint Institute for Nuclear Research, Russia, 141980 Moscow region, Dubna, JINR
Dubna University, Russia, 141980 Moscow region, Dubna, JINR

E-mail: *alitvin@jinr.ru*

E.I. Litvinenko
Joint Institute for Nuclear Research, Russia, 141980 Moscow region, Dubna, JINR
E-mail: *litvin@nf.jinr.ru*

The paper discusses the features of the behavior of pion production cross section as a function of the atomic mass of the target nucleus for the reaction of fragmentation of the incident deuterons in the pions produced in the so-called "twice-cumulative" kinematic region. A distinctive feature of the twice cumulative pions is that for the production of their target nucleus must be heavier than hydrogen. The simulation results show that the dependence of the cross sections for pion production in the twice cumulative region differs from the analogous dependence for the cumulative region. The paper discusses the reasons for such differences.

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1. Introduction

To clarify the purpose of the work, dwell briefly on the definition of the cumulative particle (see for example [1-4]). For this we consider production the pion in the collision of two nuclei in the following kinematic regions:

1. Pion is produced in the backward hemisphere:

$$A_b + A_t = \pi(\theta > 90^o) + X, \quad (1)$$

here A_b and A_t are the beam and the target nuclei, respectively, θ is the angle between the momentum of the pion production and the direction of the beam. If the energy of the pion is greater than the energy achievable in the collision of free nucleons, the pion is called cumulative, produced in the fragmentation of the target (as it is detected in the backward hemisphere $\theta > 90^o$).

2. Pion is produced in the forward hemisphere

$$A_b + A_t = \pi(\theta < 90^o) + X, \quad (2)$$

If the energy of the pion is greater than the energy achievable in the collision of free nucleons, the pion is called cumulative, produced in the fragmentation of the beam (as it is detected in the forward hemisphere $\theta < 90^o$).

At production of the cumulative pion in the backward hemisphere the target nucleus must be heavier than a proton $A_t > 1$, and at production of the cumulative pion in the forward hemisphere the beam particles must be heavier than a proton $A_b > 1$.

This definition includes the colliding nuclei asymmetrically. In the experiment, this asymmetry leads to different cross sections depending on the atomic weight of the target nucleus when fragments beam [5] and when a target fragments [6].

The corresponding experimental data are shown in Fig.1 and Fig.2. From these figures it can be seen that in the case of fragmentation of the incident deuterium into cumulative pion the cross section of the atomic mass of the target nucleus for medium and heavy nuclei $A_t > 12$ close to the peripheral $d\sigma \propto A_t^{0.4}$ [5]. And in the case of the fragmentation of the target nucleus into the cumulative pion the cross section is proportional to the atomic mass of the target nucleus $d\sigma \propto A_t^{1.1}$ for medium and heavy nuclei $A_t > 12$.

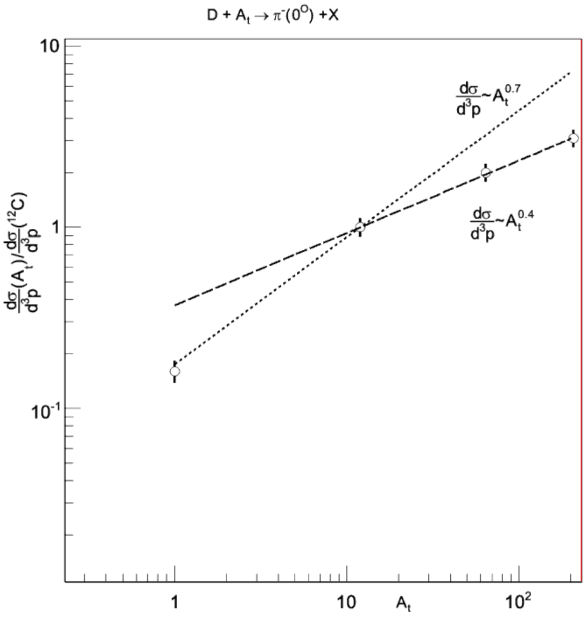

Fig.1

Dependence of the cross section from the atomic mass of the target nucleus for the reaction of a deuteron beam fragmentation into cumulative pion (from [5]). The cross section is normalized to the cross section of a carbon target. Line fit to the corresponding exponential dependencies.

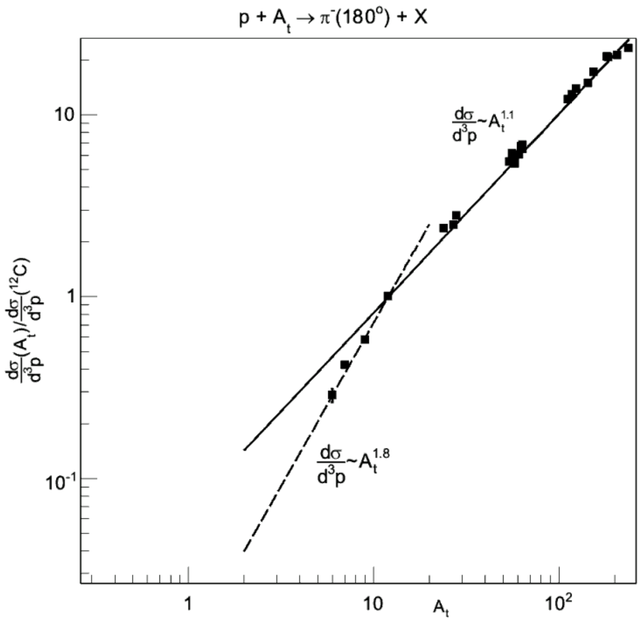

Fig.2

Cross section for the production of cumulative pions from the atomic mass of the target nucleus in the fragmentation of the target nucleus, from [6].]). The cross section is normalized to the cross section of a carbon target. Line fit to the corresponding exponential dependencies.

In the conventional to the present time models with cold flucton cumulative particles are prodused due to the high momentum components in fragmenting the nucleus [1-4]. The source of such high momentum components are configurations in which two or more nucleons are separated by distances smaller than the average distance between nucleons in the nucleus [1-4] . Such configuration, following [7], called fluctons. For the future it will not be important concrete structure of fluckton, i.e. no matter whether the nucleons that are part of fluckton, his "personality" (as proposed in [8]), or the nucleons in fluctine overlap (and then when describing the birth of cumulative particles must be taken into account nucleon degrees of freedom [1,2]). When describing the dependence of the cross section on the atomic mass of the target nucleus is taken into account not only the cumulative scattering particles on the nucleons of the target nucleus, but also the probability of formation and density distribution fluctine in the nucleus of the target. As shown in [9], the peripheral nature of the dependence of the cross section for the deuteron fragmentation into cumulative pions from the atomic mass of the target nucleus is due to scattering of the incident deuteron and produced of the pion-nucleon of the target nucleus. This paper discusses the reaction of the deuteron fragmentation into cumulative and double-cumulative pions produced at zero angle at the different targets. The connection with the structure of a target nucleus at small distances internucleonic was studied.

1.1 Basic definitions and motivation

To clarify the concept of "twice-cumulative pions" let us consider the following inclusive reactions:

$$p + p = \pi(0^o) + X. \tag{3}$$

$$D + p = \pi(0^o) + X. \tag{4}$$

It is assumed that both reactions have the same energy per nucleon. The maximum energy of the pion, which it may have in the appropriate reaction, we will denote by $E_\pi^{max}(A_b + A_t \to \pi)$.

Pions with small energy, so that their production is allowed by the conservation laws in the collision of two protons (reaction (3)) will be called non-cumulative. I.e. non-cumulative pions have an energy less than the limiting energy for reaction (3):

$$E_\pi \le E_\pi^{max}(D + p \to \pi). \tag{5}$$

Pions with energies greater than it is permitted in the collision of protons with protons, but less than the maximum energy achievable by the collision of deuteron with protons will called cumulative pions. In this case, since the pions appear at the zero angle, it is the fragment of the incident deuteron. The energy of the cumulative pions lies in the interval:

$$E_\pi^{max}(p + p \to \pi) < E_\pi \le E_\pi^{max}(D + p \to \pi) . \tag{6}$$

Pions with energy greater than permitted in the collision of the incident deuterons with protons will be called "twice cumulative". This means that for the energy of the twice cumulative pions the following inequality holds:

$$E_\pi^{max}(D + p \to \pi) < E_\pi . \tag{7}$$

Thus, the production of twice cumulative pions only possible in the reaction of collision incident deuteron with target nucleus heavier than hydrogen nucleus, i.e. in the reaction:

$$D + A_t = \pi(0^o) + X;\ A_t > 1. \tag{8}$$

Dependence on the initial energy of maximum values of energy pions produced at zero angle, for various combinations of target nuclei and the beam is shown in Fig. 3.

As noted above, in models with cold fluctons cumulative pions (reaction (4)) is born in a collision of deuteron with a nucleon of target nucleus due to high-momentum components in the deuteron. I.e. when passing through the target nucleus of the incident deuteron should not experience inelastic interactions until production of the cumulative pions.

Because of the rapid decrease of the cross section of cumulative pions with increasing momentum and emission angle is necessary that the produced pion leaves the nucleus of the target without collision (for details see Ref. [9]). This means that the cross section is defined by the following expression:

$$d\sigma/d^3p \propto \iint dzdbb(\sigma(NN \to \pi)n_N(z,b))\overline{W}_D([-\infty,z],b)\overline{W}_\pi([z,\infty],b)\,, \qquad (9)$$

where b and z are the impact parameter and the value of the coordinate along the trajectory of the deuteron, $\overline{W}_D([-\infty,z],b)$ denotes the probability for the deuteron reach the point of production of cumulative pion without interaction, $\overline{W}_\pi([z,\infty],b)$ is the probably for the produced pion leave target nucleus without scattering, and $n_N(z.b)$ is the nucleon density at the point of the cumulative pion production.

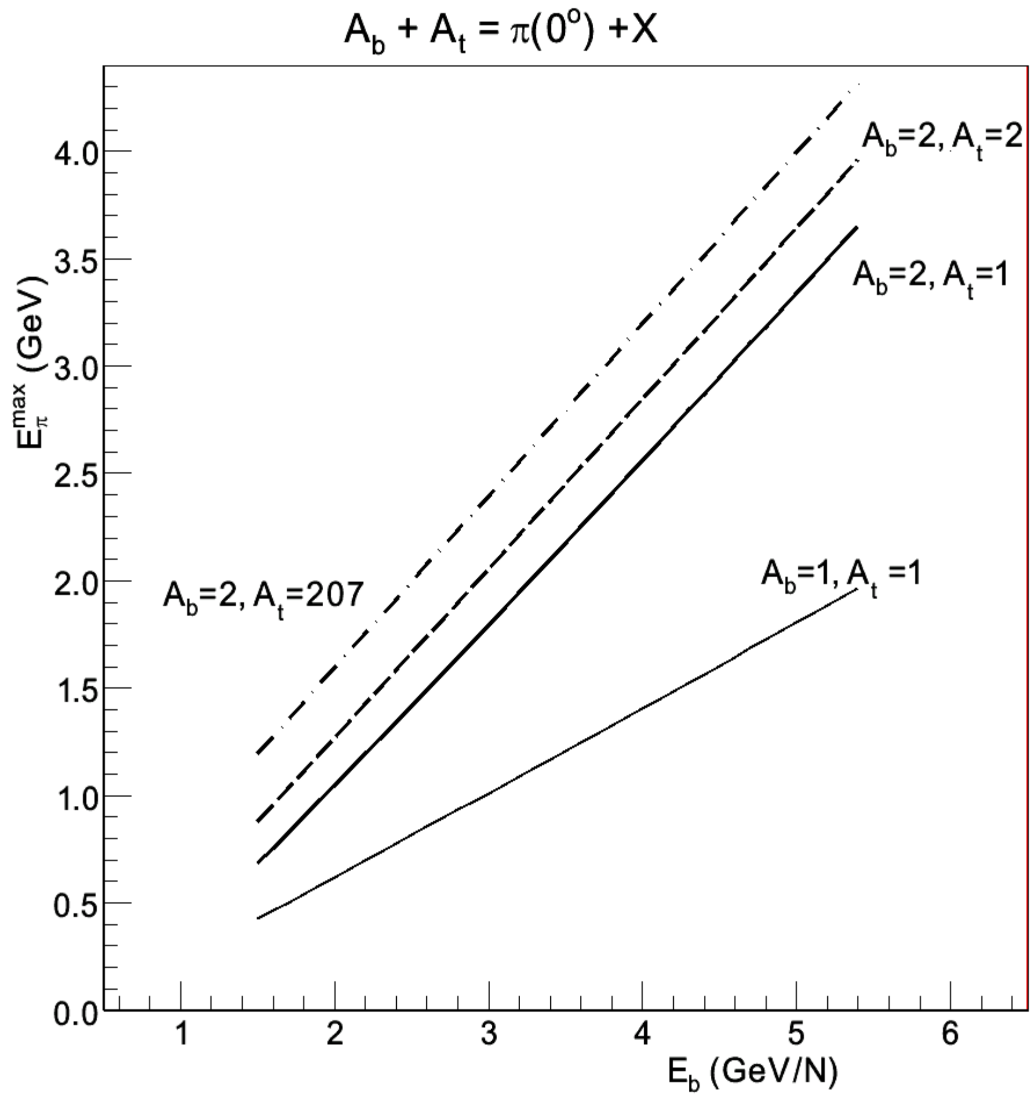

Fig.3

Maximum energy of the pion $E_\pi^{max}(A_b + A_t \to \pi)$ available for different colliding nuclei vs energy per nucleon of the beam particle .

According to such a space-time picture, the main contribution to the cross section is come from the trajectories, the total length of which are close to the sum of the mean free path of the deuteron and pion. The mean free path of the deuteron $\lambda_D \cong 1$ fm and the pion $\lambda_\pi \cong 2.4$ fm for the middle and heavy nucleus. This means that for medium and heavy nuclei the main contribution to the cross section come from large impact parameters (see [9]). This dependence is confirmed by experimental data on the dependence of the cross section of deuteron fragmentation into cumulative pions [5,11-12]. Obtained in these articles the cross section for the production of cumulative pions can be approximate by the following dependence:

$$d\sigma/d^3p(D + A_t \to \pi + X) \propto A_t^\alpha; (A_t \geq 12, \alpha \cong 0.4) \quad . \qquad (10)$$

It is noteworthy that the similar dependence in the non-cumulative region is close to the surface dependence $\alpha \cong 0.6$ [11]. In the framework of this mechanism such kind of dependence is distinct due to the fact that for pion production in the field of non-cumulative is not necessary to require that the pion was produced by deuteron as a whole, and that the pion has to leave the target nucleus without interaction.

In turn, in the considered space-time picture is necessary to take into account that twice cumulative pions can be produced only in the scattering of the deuteron on fluctons in the target nucleus. This means that unlike in the case of cumulative pions in the expression for the cross section should stand the density of the fluctons $n_F(z.b)$:

$$d\sigma/d^3p \propto \iint dzdbb(\sigma(NN \to \pi)n_F(z,b))\overline{W}_D([-\infty,z],b)\overline{W}_\pi([z,\infty],b)\,. \qquad (11)$$

Note that this expression differs from the expression for the cross section of cumulative pions (8) by replacing in the integral the density of the nucleons by the density of the fluctons in the target nucleus $n_N(z,b) \to n_F(z,b)$.

In this paper, it is shown that the dependence of the cross section of twice cumulative pions from the atomic mass of the target nucleus is sensitive to the distribution of fluctons, and therefore experimental data on the cross section of twice-cumulative pions allow critically evaluate different models proposed to describe the distribution fluctons by volume of the nucleus. The results of the simulation of the cross section birth twice cumulative pions (reaction (7) under the condition (6)) for the model volume flucton and tube flucton model is discused.

1.2 Simulation

In the simulation of one event in the first stage of the collision the position of the nucleons in the colliding nuclei is determined. For medium and heavy nuclei the Wood-Saxon distribution [13] was used:

$$P_A(r) = \frac{N}{1 + \exp((r - R_A)/d)}\,, \qquad (12)$$

where r is the distance to the center of the nucleus, and d is the diffuseness parameter. Nuclear radius was chosen to be equal to the:

$$R_A = r_0 \cdot A^{1/3}\,, \qquad (13)$$

with $r_0 = 1.2$ fm. Normalization constant N chosen from the condition:

$$\int_0^\infty P_A(r) r^2 dr = 1. \qquad (14)$$

The distribution of distances between the proton and the neutron in deuteron was chosen in accordance with the Hulthen wave function [14]:

$$P_D(r_{pn}) = \frac{2ab(a+b)}{(a-b)^2} \cdot \frac{(\exp(-2ar_{np}) + \exp(-2ar_{np}) - 2\exp(-(a+b)r_{np})}{r_{np}^2}\,, \qquad (15)$$

where r_{np} is the distance between the protons and neutrons and $a = 0.228$ (1/fm), and $b = 1.7$ (1 / fm). The position of the nucleons in ^4He was described by the normal distribution [15]:

$$P_{^4He}(r) = \frac{4}{\sqrt{\pi}\,d^3} \cdot \exp(-r^2/d^2), \quad (16)$$

with $d = 1.7$ фм.

Center of the target nucleus was chosen at the origin. After that independently played out the coordinates of all the nucleons of the target nucleus and beam nucleus. When this state is in accordance with one of the distribution (12), (13) or (14). The Z axis is directed along the beam. Impact parameter was played inside the circle of radius R_b:

$$R_b = \sqrt{x^2 + y^2} = 1.2 \cdot (R_{A_b} + R_{A_t} + 1.2)\ , \quad (17)$$

where R_{A_t} and R_{A_b} are the radii of the target nucleus and the nucleus of the beam, respectively. For nuclei with $A \geq 12$ nuclear radius was calculated in accordance with (12), for the deuteron taken $R_D = 5$ fm and for ^4He $R_{^4He} = 3$ fm considered. After fixing the coordinates of the nucleons in colliding nuclei considered the scattering of nucleons by the following scheme. Along the path of the hadron was chosen the cylinder with radius $r_{hN} = \sqrt{\sigma_{hN}/\pi}$. If this cylinder got the nucleon from target nucleus, it was believed that the selected hadron experienced collision. If into the cylinder there are several nucleons the first in the time is taken into account . Likewise, the interaction of a secondary hadrons was described, only the speed of the secondary hadrons is not directed along the axis of the collision. In further calculations, the following values of the total cross sections were utilize:

1. nucleon – nucleon scattering

$$\sigma_{NN} = 45\,\text{мб} \Rightarrow r_{NN} = 1.197\,\text{фм}\ , \quad (18)$$

2. pion – nucleon scattering

$$\sigma_{\pi N} = 30\,\text{мб} \Rightarrow r_{\pi N} = 0.977\,\text{фм}\ . \quad (19)$$

Coordinates of the cumulative particles are selected equal to the coordinates of the nucleon deuteron, who first collide with the nucleon of the target nucleus.

Let us consider three possible mechanisms of the production of the twice cumulative pion in the deuteron fragmentation

1. The direct mechanism in which pions are produced in the collision of one of the nucleons of the incident deuteron on flucton in the nucleus of the target, and this pions leave the nucleus of the target without interaction:

$$D(pn) + A_t = \pi(0^o) + X. \quad (20)$$

2. Cascade mechanism with intermediate pion. In this mechanism, the pion is produced in a collision with one of the nucleons N_1 of the target nucleus, but not necessarily at zero angle and after scattering on other nucleon of the target N_1 still moving at a zero angle without interaction, leaves the target nucleus.

$$\begin{array}{c} D(pn) + N_1 = \pi_{cs} + X_1 \\ \downarrow \\ \pi_{cs} + N_2 = \pi(0^o) + X_2 \end{array} . \quad (21)$$

3. Cascade mechanism with intermediate nucleon passes in the same way, only the intermediate particle is a nucleon N_{cs} , which in the second collision produced pion emitted from the nucleus at a zero angle without interaction.

$$\begin{array}{c} D(pn) + N_1 = N_{cs} + X_1 \\ \downarrow \\ N_{cs} + N_2 = \pi(0^o) + X_2 \end{array} . \qquad (22)$$

In [9] it is shown that the cross section of the cumulative pion in the cascade process with intermediate pion (21) does not exceed 0.6% of the cross section of the direct process in the fragmentation of the deuterium on the nucleus of lead and drops sharply with decreasing mass of the target nucleus. In the same article it is shown that the cross section of the cumulative pion in the cascade process with intermediate nucleon is not greater than 0.1%. of the cross section of the direct process. Without dwelling on the details of the simulation, we note that for twice cumulative region maximum contribution of cascade process - as with intermediate pion and with intermediate nucleon did not exceed 0.1%. Evaluation of cross sections of twice-cumulative pions were taken from [16]. In further calculations, the contribution of cascade processes are not taken into account.

1.3 The simulation results

We give the results of the calculation of the cross section in the deuteron fragmentation twice cumulative pions for the next two models of the fluctons.

1. Model of the volume flucton. In this model flucton considered as configuration, when two or more nucleons of the target is situated into a spherical volume of radius R_f [1,4]. In a future, R_f will be called the radius of the flucton. In the interval of a flucton radii $0.4\text{ фм} \le R_f \le 0.8\text{ фм}$ the cross section dependence from the atomic mass of the target nucleus is the same. But in this case, the absolute values of the cross sections increase with increasing of flucton radius, changing the value of 8 times (in proportion to the cube of the radius of the fluctons).

2. Another model, for which the simulation was carried out, was the model of the tube [18]. In this model flucton is a cylinder with a radius R_f and a length L along the direction of the beam particle.

The simulation results of the cross section of twice cumulative pions production from the atomic mass of the target nucleus for the some parameters fluctons shown in Figure 4. The same figure shows the experimental data [5] for the cross section of cumulative pions production from the atomic mass of the target nucleus in the fragmentation of the incident deuterons.

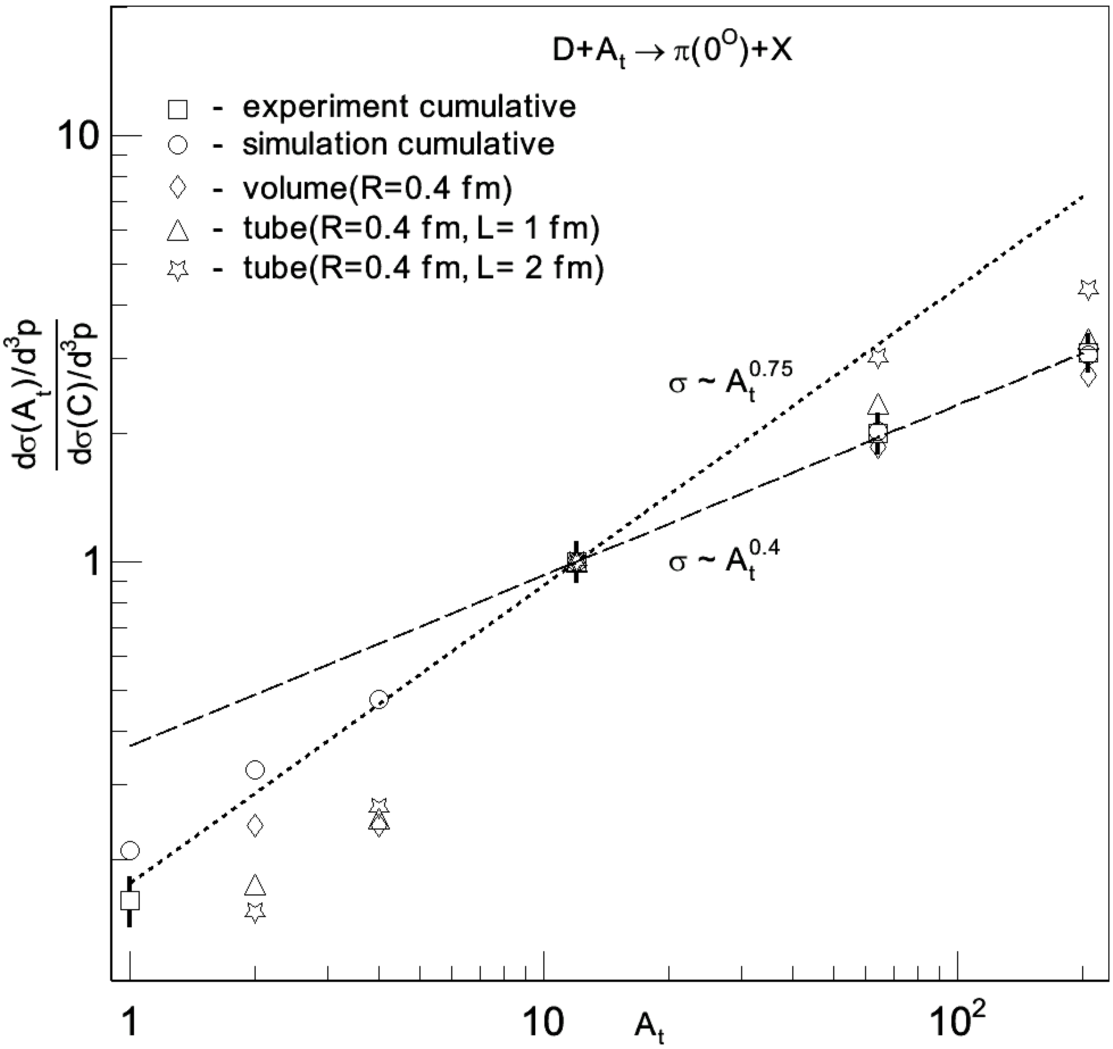

Fig. 4.

Simulation results of the cross section of deuteron fragmentation into twice cumulative pions (7) from the atomic mass of the target nucleus for various parameters and kind of fluctons. Open squares - experimental data for cumulative pions from [5]. Open circles - the result of simulation for cumulative pions in the approach used in this paper (see. [9]). Lines are drawn to illustrate the nature of atomoc mass dependance.

1.4 Conclusions

On the basis of simulation it was shown that the dependence on the atomic mass of the target nucleus cross sections for reaction of a deuteron fragmentation into twice cumulative pions at zero angle depends on the fluctons model. Therefore the experimental data for this dependence will allow to get additional information about the structure of flucton**.**

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