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STUDY OF AZIMUTHAL CORRELATIONS BETWEEN GROUPS OF PROTONS OR PIONS IN (d,He)C, CC, (d,He)Ta AND CTa COLLISIONS AT A MOMEMTUM OF 4.2 GeV/c PER NUCLEON

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abstract: *Azimuthal correlations between groups of particles (protons or pions) have been investigated in (d, He)C, CC, (d,He)Ta and CTa collisions at a momentum of 4.2 GeV/c/nucleon. For protons a "back-to back" ("negative") azimuthal correlations were observed in these interactions. "Back-to-back" correlations take place for pions for a light target ((d,He)C, CC) and "side-by-side" ("positive") correlations - for heavy one ((d,He)Ta and CTa). A correlation coefficient* $/\xi/$ *decreases for protons and increases for pions with increase of the projectile and target mass numbers. The dependence of W (the measure of the particles azimuthal alignment) on* $\Delta\varphi$ *(the angle between the vector sums of transverse momenta of the forward and backward emitted particles) shows similar behaviour for protons and pions in all observed interactions.*

The Ultra-relativistic Quantum Molecular Dynamics Models satisfactorily describe the experimental results both for protons and pions.

Key words: multiparticle azimuthal correlations, collision, nucleus, proton

INTRODUCTION

The primary goal of current relativistic heavy ion research is the creation and study of nuclear matter at high energy densities [1-3]. Open questions include the detailed properties of such excited matter, as well as the existence of a transition to the quark-gluon plasma (QGP) phase. Such a phase of deconfined quarks and gluons has been predicted to survive for ~3-10 fm/c in Au-Au collisions at the Relativistic Heavy Ion Collider (RHIC) [4] and several experimental probes have been proposed for its possible detection and study [1]. Collective flow constitutes in important observable [5-7] because it is thought to be driven by pressure built up early in the collision, and therefore can reflect conditions exciting in the first few fm/c. Collective flow leads to an anisotropy in the azimuthal distribution of emitted particles. Study of multiparticle correlations offers unique information about space-time evolution of the collective system [8-10].

During last years we have studied experimental data using the collective variables depending on the transverse momentum of all secondary charged particles in the azimuthal plane, to reveal a nontrivial effects in nucleus-nucleus collisions [11-15]. We have investigated multiparticle azimuthal correlations of protons and pions in central and inelastic collisions (4.2, 4.5 GeV/c/nucleon) within two experiments, 2 m streamer chamber placed in a magnetic field (SKM-200-GIBS) and 2 m Propane Bubble Chamber (PBC-500) of JINR. In order to investigate the mechanism of nucleus--nucleus interactions we have studied the correlations of these particles with respect to the relative reaction plane (directed and elliptic flows) [11-14], as well as with respect to the opening angle between particles emitted in the forward and backward hemispheres [15].

In this article we present results of the analysis of multiparticle correlations in (d, He)C, CC, (d,He)Ta and CTa collisions (4.2 GeV/c) between protons or pions. The dependence of these correlations on the projectile (A_P) and target (A_T) nucleus have been investigated.

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EXPERIMENTAL DATA

The data of dC, HeC, CC, dTa, HeTa and CTa interactions have been obtained using 2 m Propane Bubble Chamber (PBC-500) of JINR (beam energy E= 3.4 GeV/nucleon). The numbers of events for these collisions are listed in Table 1. The chamber was placed in a magnetic field of 1.5 T. Three Ta plates 140x70x1 mm in size mounted into the fiducial volume of the chamber at a distance of 93 mm from each other served as a nuclear target. The protons with momentum p<150 MeV/c have not been detected within this chamber (as far as their track lengths l<2 mm) and with p<200 MeV/c are absorbed in Ta target plate (the detector biases). The registration limit for pions - 50 MeV/c.

The method of separation of dC, HeC and CC collisions in propane, the processing of the data, identification of particles for all colliding pairs of nuclei and discussion of corrections are described in detail in [16]. Because protons was identified unambigiously only with momentum p<750 MeV/c it was necessary to remove π^+ -mesons admixture from proton yield. A separation of high momentum pions and protons was done statistically: the main assumption is based on the similarity of spectra of π^- and π^+ mesons (n_π, p_T, p_L) [14].

So, knowing inclusive π^- -meson distribution, one can estimate a yield of π^+ mesons in inclusive distribution of positive charged particles. (d, He)C and (d, He)Ta collisions has been combined for further analysis. For (d, He)Ta collisions the corrections for azimuthal angle distributions of protonsm and pions caused by azimuthal asymmetry of particles registration in the chamber were applied. Among positive charged particles we separated spectator fragments of projectile nuclei (p>3 GeV/c and ϑ<4° (C target), p>3.5 GeV/c and ϑ< 3° (Ta target)), and target evaporated fragments (p<0.3 GeV/c (C target), p<0.25 GeV/c (Ta target)). Other positive charged particles different from π^+ mesons were considered as “participating protons”. The sub-sample of ”semicentral” collisions with the number of particles N ≥3 were selected for the analysis from the whole ensemble of these inelastic collisions.

AZIMUTHAL CORRELATIONS BETWEEN PROTONS OR PIONS

In Refs. [9,10] a procedure to study of correlations between groups of particles has been developed. The azimuthal angle correlations were investigated using a relative opening angle between vector sums of transverse momenta of particles emitted in forward and backward hemispheres in the target fragmentation region (y_0=0.2). The data have been obtained at 4.9, 60 and 200 GeV (BEVALAC, CERN/SPS).

We have applied this method for our data, but our analysis has been carried out in the central rapidity region (laboratory system). The analysis has been performed event by event, in each event we denote the vectors:

$$\vec{Q}_B = \sum_{y_i < y_c} \vec{P}_{\perp_i} \qquad (1)$$

and

$$\vec{Q}_F = \sum_{y_i \geq y_c} \vec{P}_{\perp_i} \qquad (2)$$

where y_c is an average rapidity of participant protons for each colliding pears of nuclei. The admixture of deuterons between the participant protons is less than 0.5% It was checked out, that analysis results are coincide within statistical errors.

The correlation function C(Δφ) was determined as:

$$C(\Delta\varphi) = dN/d\Delta\varphi \qquad (3)$$

where Δφ is the angle between the vectors $\vec{Q}_B$ and $\vec{Q}_F$:

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$$\Delta\varphi = \arccos\frac{(\vec{Q}_B \cdot \vec{Q}_F)}{(|\vec{Q}_B| \cdot |\vec{Q}_F|)} \qquad (4)$$

Essentially, C(Δφ) measures whether the particles are preferentially emitted "back-to back" ("negative", Δφ=180° or "side-by-side" ("positive",Δφ=0°) [9].
The other multi-particle variable W was used also in [8]:

$$W = \frac{\left|\sum_{i=1}^{N}(\vec{p}_{\perp i}/m_i)\right|}{\sum_{i=1}^{N}(|\vec{p}_{\perp i}|/m_i)} \qquad (5)$$

W is defined as the measure of the particles azimuthal correlations.

Fig. 1,2 show the experimental correlation function C(Δφ) for protons from (d,He)C, CC, (d,He)Ta and CTa collisions.

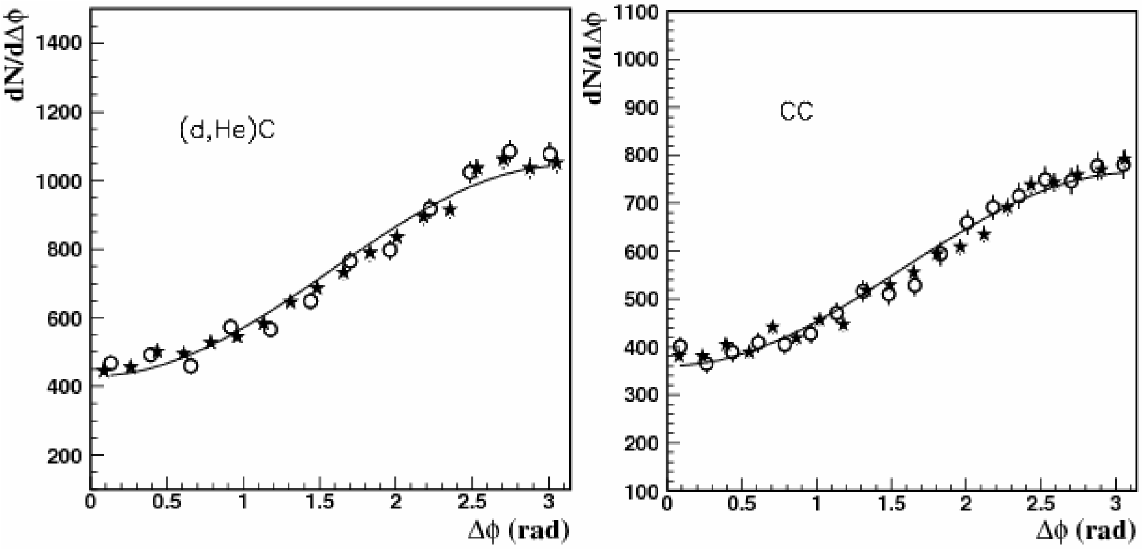

Fig.1. The dependence of the correlation function C(Δφ) on the Δφ for protons from (d,He)C and CC collisions: (o) -- experimental and (★) -- generated (see text) data, correspondingly. The curves are the results of the approximation of the data (see text).

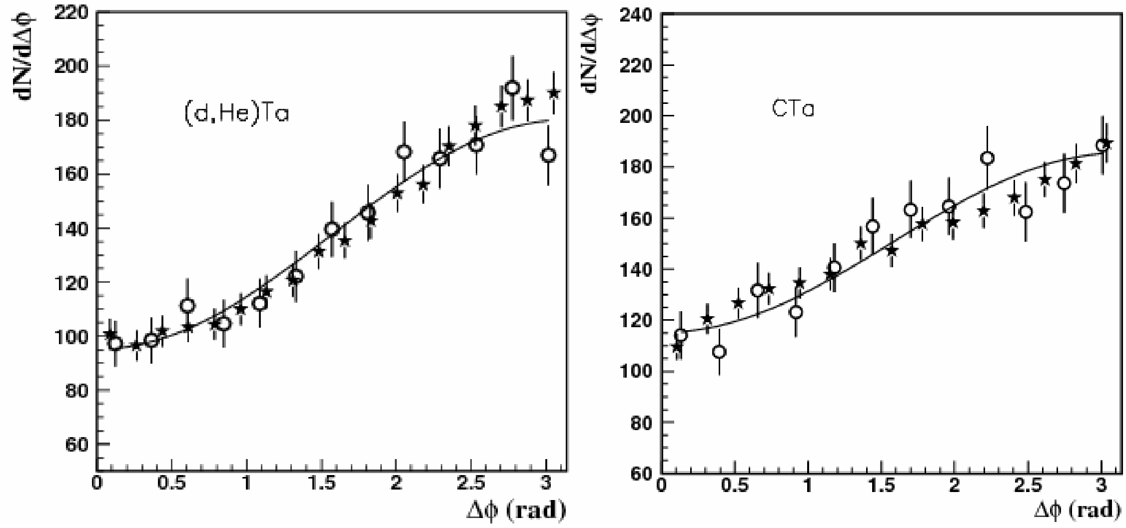

Fig.2. The dependence of the correlation function C(Δφ) on the Δφ for protons from (d,He)Ta and CTa collisions: (o) -- experimental and (★) -- generated (see text) data, correspondingly. The curves are the results of the approximation of the data (see text).

One can observe from Figures a clear correlation for protons (correlation increases with $\Delta\varphi$, and reaches a maximum at $\Delta\varphi = 180°$). To quantify these experimental results, the data were fitted by the function:

$$C(\Delta\varphi) = 1 + \xi\cos(\Delta\varphi) \quad (6)$$

Results of the fitting are listed in Table 1. The strength of the correlation is defined as:

$$\varsigma = C(0^0) / C(180^0) = (1 + \xi)/(1 - \xi) \quad (7)$$

As it can be seen from the Table 1, the correlation coefficient $\xi<0$ and thus the strength of correlation $\varsigma< 1$ for protons in all interactions, meaning that protons are preferentially emitted back-to-back.

Table 1. The number of experimental and generated events ($N_{ev.prior}/N_{ev.cut}$ - prior and after cut), the correlation coefficient (ξ) and the strength of the correlation (ς) for protons in (d,He)C, CC, (d,He)Ta and CTa collisions.

A_P, A_T	$N_{ev.\,prior}$ /$N_{ev.\,cut}$	ξ	ς
(d,He)C exp.	14318/7793	-0.417±0.015	0.411±0.015
UrQMDM	**59218/23901**	**-0.418± 0.009**	**0.410±0.009**
CC exp.	15962/9669	-0.369±0.013	0.461±0.014
QGSM	**35754/23817**	**-0.365±0.009**	**0.474±0.011**
(d,He)Ta exp.	2956/1728	**-0.309 ±0.028**	**0.528±0.033**
UrQMDM	**17629/12298**	**-0.321±0.022**	**0.514±0.025**
CTa exp.	2469/1779	**-0.214±0.033**	**0.647±0.040**
QGSM	**9130/7930**	**-0.199±0.015**	**0.637±0.012**

We have studied a dependence of the correlation coefficient (ξ) on mass numbers of projectile A_P and target A_T for protons. The absolute values of ξ for protons decreases linearly with the increase of A_P, A_T, from -0.417±0.015 for (d,He)C up to -0.214±0.030 for CTa (see Table 1, Fig. 3) .

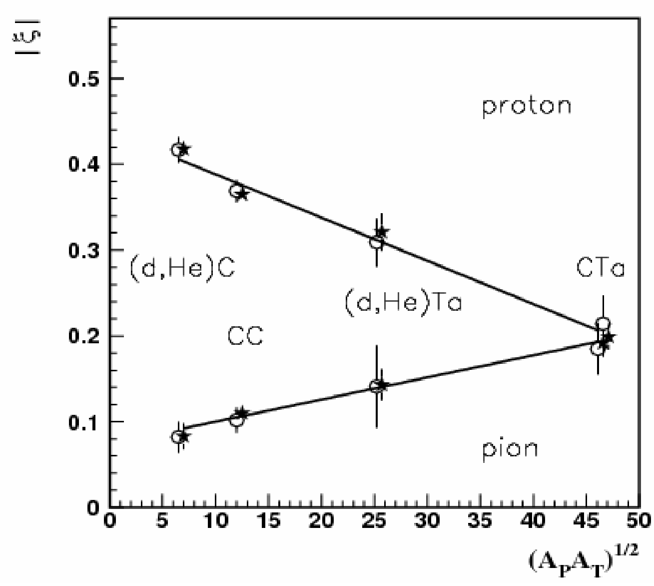

Fig.3. The dependence of the correlation coefficient (ξ) on $(A_P \cdot A_T)^{1/2}$ for protons and pions in (d,He)C, CC, (d,He)Ta and CTa collisions: (o) experimental and (★) generated (see text) data.

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Back-to-back correlations have been observed between protons or pions with the Plastic-Ball detector in p + Au collisions at energy of 4.9, 60 and 200 GeV/nucleon [9, 10, 17]. Because, the azimuthal correlation function was defined in the target fragmentation region, the correlation parameters in the wide range of energy increases inappreciable. In CC (2500 event) inelastic interactions at a momentum of 4.2 GeV/c per
nucleon [8] had been obtained the back-to-back azimuthal correlations between protons or pions, emitted in the forward and backward hemispheres in the c.m.s. of the collisions
(-0.5 < y< 0.5). The absolute values of the asymmetry coefficient ξ= 0.26±0.01 -- for protons [8]. There are for protons in CC collisions (15962 events) ξ= 0.369±0.013, the selection criterion N ≥ 3, in this work. Also, we determined the absolute values of ξ=0.24 ±0.01 for protons (N ≥ 2 and -0.5 < y < 0.5), which is agreement of their result on the restricted statistics.

The back-to back emission of protons can be understood as results of (local) total momentum conservation [10]. This behavior is in a good agreement with collective nuclear matter flow concept [18].

In view of the strong coupling between the nucleons and pions, it is interesting to know the correlations between pions. Thus, we have studied also correlations between pions. Correlation functions for pions in (d,He)C, CC, (d,He)Ta and CTa interactions are presented in Figs. 4, 5. One can observe from Fig. 4, a clear back-to-back (ξ< 0, ς< 1) correlations for pions for light systems of (d,He)C and CC.

For heavy, asymmetric pairs of nuclei (d,He)Ta and CTa the side-by-side (ξ> 0 and ς> 1) correlations of pions can be seen from Fig. 5 (Table 2). Similar, side-by-side correlations of pions have been observed in p+Au collisions at Bevalac (4.9 GeV/nucleon) and CERN-SPS (60 and 200 GeV/nucleon) energies [9, 10].

One can see from Table 2 that the absolute values of the correlation coefficient (|ξ|) for pions increase and the strength of correlations (ς) decrease with target mass (Fig. 3) due to the increasing amount of matter in the pion path.

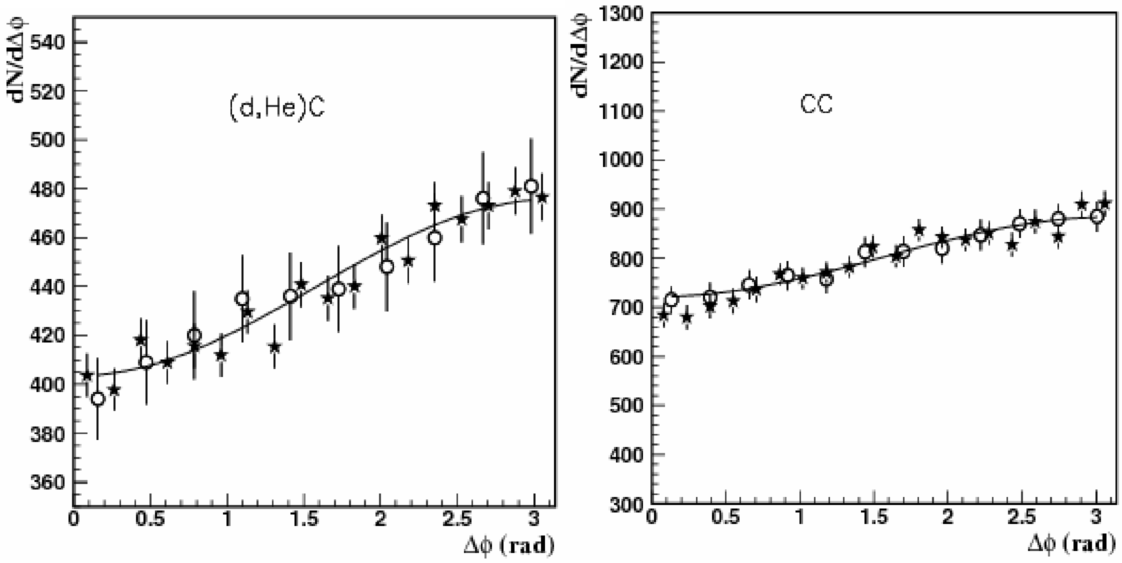

Fig.4. The dependence of the correlation function C(Δφ) on the Δφ for pions from (d,He)C and CC collisions: (o) -- experimental and (★) -- generated (see text) data, correspondingly. The curves are the results of the approximation of the data (see text).

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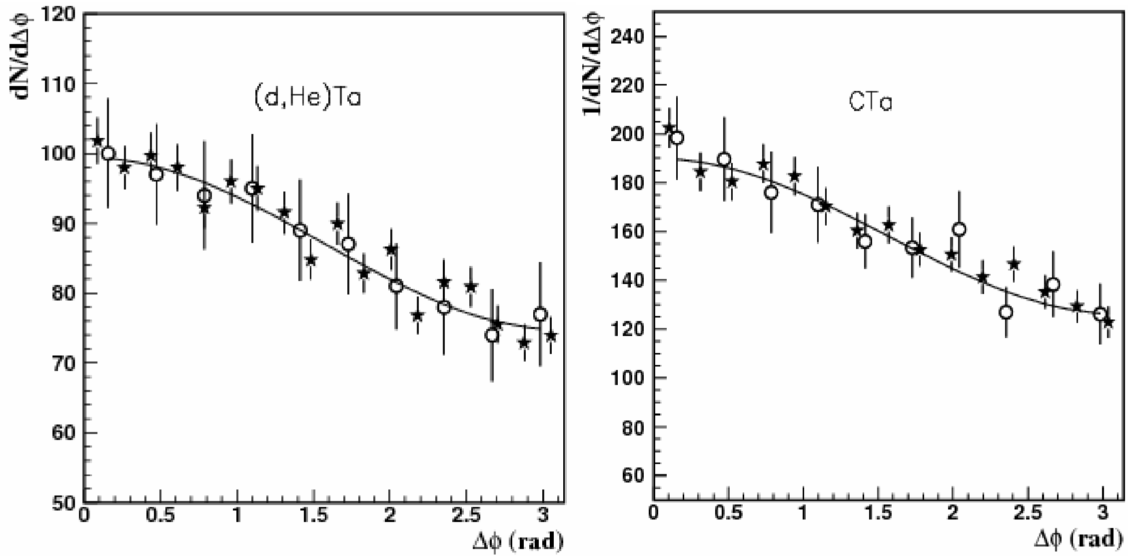

Fig.5. The dependence of the correlation function C(Δφ) on the Δφ for pions from (d,He)Ta and CTa collisions: (o) -- experimental and (★) -- generated (see text), correspondingly. The curves are the results of the approximation of the data (see text).

The reason for the observed difference between protons and pions is that the pions are absorbed in the excited target matter ($\pi + N \rightarrow \Delta$ and $\Delta + N \rightarrow N + N$) [9, 10]. While the back-to-back emission of protons can be understood as a result of the transverse momentum conservation. The pion correlations show, in the data, an opposite behavior. The side-by-side correlation of pions can be naturally explained on the base that pions, which are created in collision suffer at $b \neq 0$ fm (b is the impact parameter) either rescattering or even complete absorption in the target spectator matter. Both processes will result in a relative depletion of pions in the geometrical direction of the target spectator matter and hence will cause an azimuthal side-by-side correlation as observed in the experimental data. This picture is further supported by calculations

Table 2. The number of experimental and generated events ($N_{ev.\ prior}/N_{ev.\ cut}$ - prior and after cut), the correlation coefficient (ξ) and the strength of the correlation (ς) for pions in (d,He)C, CC, (d,He)Ta and CTa collisions.

A_P, A_T		$N_{ev.\ prior}/N_{ev.\ cut}$	ξ	ς
(d,He)C	**exp.**	14318/4405	-0.082±0.018	0.848 ± 0.031
	UrQMDM	**59218/16371**	**-0.083± 0.015**	**0.847±0.026**
CC	**exp.**	15962/8463	-0.102±0.015	0.815 ± 0.012
	QGSM	**35754/21598**	**-0.110±0.009**	**0.821±0.020**
(d,He)Ta	**exp.**	2956/1076	**0.141 ±0.048**	**1.328±0.037**
	UrQMDM	**17629/8696**	**0.143±0.018**	**1.334±0.030**
CTa	**exp.**	2469/1596	**0.185±0.030**	**1.506±0.126**
	QGSM	**9130/7472**	**0.192±0.016**	**1.519±0.092**

within the framework of the RQMD model [10], which includes pion absorption by the excited nuclear matter based on experimentally measured cross sections.

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It is worth to mention, that in paper [8] the multiparticle correlations of protons or pions in the azimuthal plane were studied in CC collisions by using only the part of experimental data as compared to the data used in our study. The definite peak in the range of the W ~ 1 has been observed. However we have ascertained, that the peak in the range of W ~ 1 is conditioned by double particle (two particle) correlations at large angles. On Fig. 6 the distributions of W for the events with number of particles N ≥ 2 and N ≥ 3 for protons and pions in CC collisions are presented. The same distributions are observed for all pairs of colliding nuclei. These distributions, for protons and pions in CC and CTa interactions at, N ≥ 3 are shown in on Fig. 7. In paper [8] the selection criterion was that N ≥ 2.

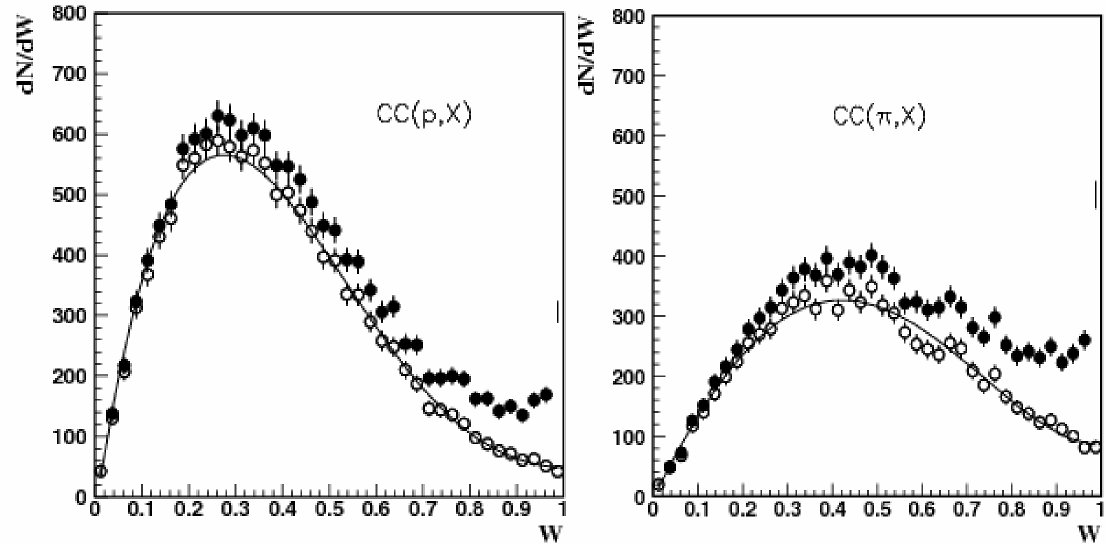

Fig.6. The distributions of W for the events with number of particles N ≥ 2 (•) and N ≥ 3 (o) for protons and pions in CC collisions. Solid curves are the results of the approximation of the data by 4th order polynoms.

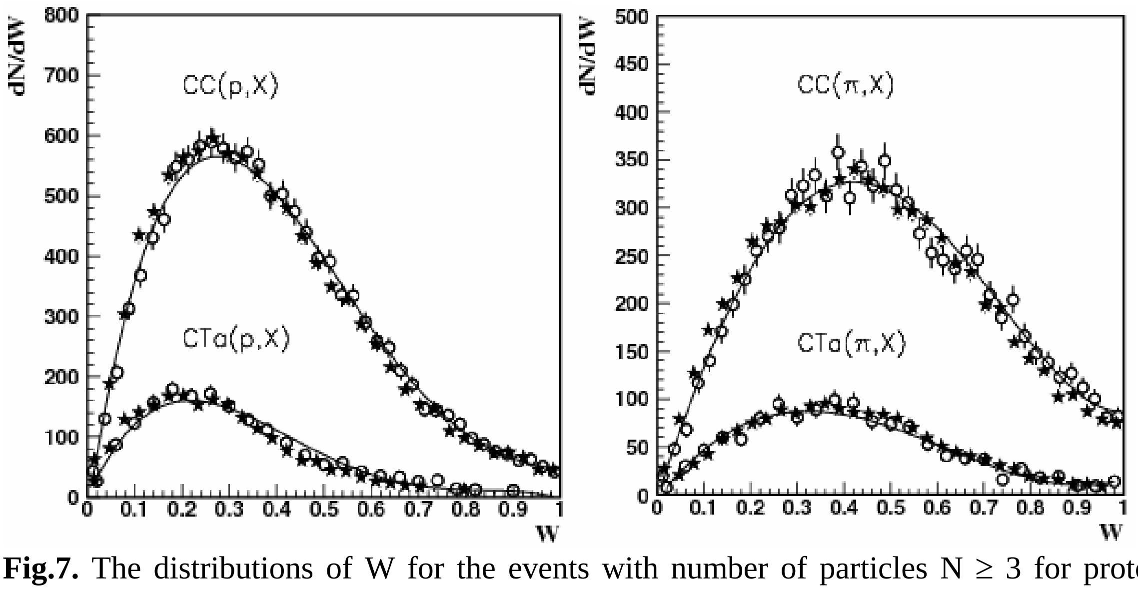

Fig.7. The distributions of W for the events with number of particles N ≥ 3 for protons and for pions in CC and CTa collisions: (o) -- experimental and (★) -- generated (see text) data, correspondingly. Solid curves are the results of the approximation of the data by 4th order polynoms.

We have studied also the dependence of W (the measure of the particles azimuthal alignment) on Δφ (the angle between the vector sums of transverse momenta of the forward and backward emitted particles). These distributions are normalized on the corresponding sum of

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weights ∑W. One can see from Fig. 8 that these distributions have similar behavior for protons in all observed interactions and as well as for pions.

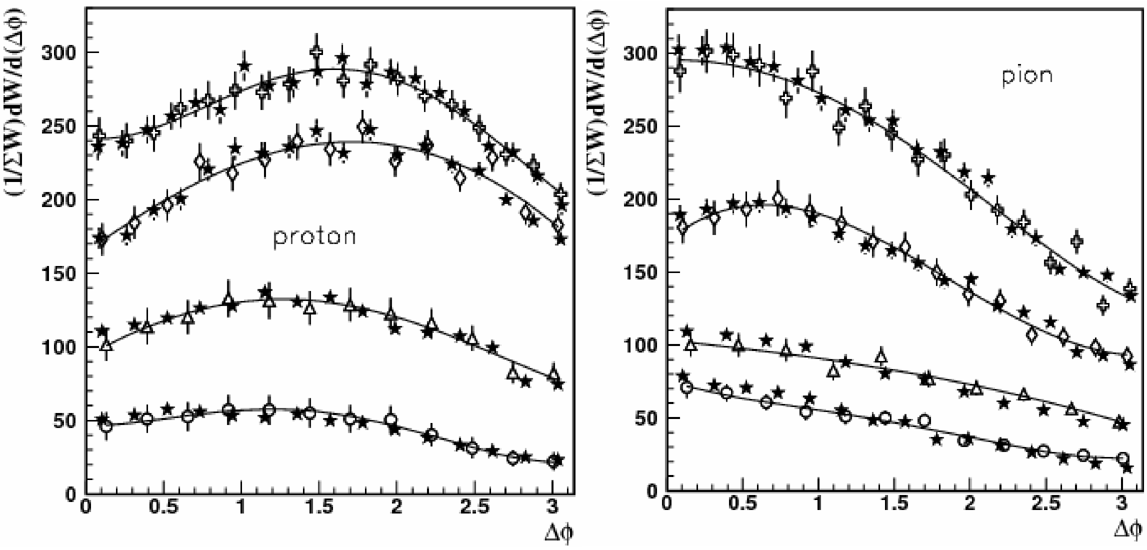

Fig.8. The dependence of W on Δφ (as described in the text) for protons and for pions in experimental (◊) -- (d,He)C, (+) -- CC, (Δ) -- (d,He)Ta, (o) -- CTa and generated (★) data, correspondingly. Solid curves are the results of the approximation of the data by 4th order polynoms.

Several theoretical models [19, 20] have been proposed for nucleus-nucleus collisions at high energy. We have used the Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD) [21-23] for comparison of the model results with experimental data. The UrQMD model is now widely applied for simulations of particle production and flow effects in various nucleus-nucleus interactions [24, 25]. We have generated dC (2.79 fm), HeC (2.79 fm), CC (2.65 fm), dTa (5.31 fm), HeTa (5.46 fm) and CTa (6.53 fm) interactions by UrQMD. We have 50000 events for each dC, HeC, CC interactions and 10000 events for dTa, HeTa and CTa collisions.

The experimental selection criteria have been applied to the generated events and additionally, the protons with deep angles greater than 60^0 had been excluded, because in the experiment the registration efficiency of such vertical tracks was low.

From the generated events it was selected events with two protons with p>150 MeV/c for C-target and with p>200 MeV/c for Ta-target (Table 1). As seen, there is a quite well agreement between the experimental and the theoretical distributions (Figs. 1÷7).

CONCLUSION

The study of azimuthal correlations have been carried out between protons as well as between pions in (d,He)C, CC, (d,He)Ta and CTa collisions:

1. For protons a "back-to back" correlations were observed in these interactions. The absolute values of correlation coefficient ξ decrease and the strength of correlation ς increase with increase of the projectile (A_P) and target (A_T) mass numbers.

2. A "back-to-back" pion correlations had been obtained for a light target (d,He)C and CC) and "side-by-side" correlation - for heavy one ((d,He)Ta and CTa). The correlation coefficient (|ξ|) increase with increase of (A_P) and (A_T).

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3. The peak in the range of the measure of the particles azimuthal alignment W ~ 1 is caused by double particle (two particle) correlations at large angles for events with the number of particles N ≥ 2 and disappears for events with N ≥ 3.
4. The dependence of W on Δφ (the angle between the vector sums of the forward and backward emitted particles) shows similar behavior for protons in all observed interactions as well as for pions.
5. The UrQMD satisfactorily describes azimuthal correlations of protons and pions for all pairs of nuclei.

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