Collective flows of protons and π^{−} mesons in ^{2}H + C,Ta and He + C, Ta collisions at 3.4 GeV/nucleon

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Collective flows of protons and π^--mesons in ^{2}H+C, Ta and He+C, Ta collisions at energy of 3.4 GeV/N

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Abstract. Collective flows of protons and negative pions have been studied in ^{2}H+C, Ta and He+C, Ta collisions at energy of 3.4 GeV/nucleon. The data has been obtained by 2m Propane Bubble Chamber (PBC-500) at JINR. It is found that the directed flow of protons and π^- -mesons characterized by d< P_x>/d(y) increases with increase of the mass numbers of colliding nucleus pairs; the elliptic proton flow points out of the reaction plane and also strengthens as system mass increases; the negative pion directed flow is in the reaction plane as proton one for the lighter (^{2}H+C, He+C) systems and in the opposite direction for the heavier (^{2}H+Ta, He+Ta) systems. In ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions, the linear dependence of directed and elliptic flow parameters from mass numbers of projectile and target nuclei ─ $(A_P \cdot A_T)^{1/2}$, is similar for protons while for π^--mesons the dependence of directed flow parameters is stronger. The Ultra-relativistic Quantum Molecular Dynamical Model (UrQMD) enlarged by the Statistical Multi-fragmentation Model (SMM) satisfactorily describes the obtained experimental results for all pairs of nuclei. The data for such asymmetric nuclear collisions are obtained for the first time.

1. Introduction

Study of collective flows in nucleus-nucleus interactions at high and intermediate energies, such as the bounce-off [1] of compressed mater in the reaction plane (called the directed flow) and the elliptic flow in the transverse direction (the squeeze-out [2] of the participant matter out of the reaction plane at the sufficiently low energies), is very important to learn more about the nuclear equation of state (see Refs. [3-7], and the beautiful review in [8]). The equation of state of nuclear matter (EoS – Equation-of-State) is the relationship specifying how the pressure, or alternatively the energy per particle, depends on density and temperature. Many different methods were proposed for experimental studies of the flows in relativistic nuclear collisions, of which the most commonly used is the transverse momentum analysis technique proposed by P. Danielewicz and G. Odyniec [9].

The collective flows are mainly studied with respect to the reaction plane, which is defined by a beam direction and the impact parameter **b** vector**.** In an experiment, the determination of the impact parameter **b** is not possible, and therefore instead of **b** a vector sum of transverse momenta of projectile and target nuclear fragments (first method), or participant protons (second method) are used. The fragmentation regions of projectile and target nuclei are not acceptable for experimental set-ups in some experiments, and therefore the reaction plane is defined by the second approach. The second approach is preferable also for the light nuclear systems, because the multiplicity of the participant protons is larger than the number of detected fragments.

Having determined the reaction plane, it is possible to find quantitative properties of the flows. At low and intermediate energies the average projection of a particle momentum on the reaction plane is used quite frequently, as well as a slope of its dependence on the particle rapidity. Coefficients of the Fourier decomposition of particle azimuthal distributions are very popular at high energies. For example, the elliptic flow has been explored by many collaborations AGS [10,11], GSI [12], NA49 [13],

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CERN/SPS [14, 15] by means of the second harmonic coefficient of the Fourier analysis of the azimuthal distributions ─ v_2.

The collective flows of nucleons, pions and nuclear fragments discovered in [16-19] are well established in collisions of heavy nuclei (see for a review Refs. [20,21], and the Part V of [8]). The information about them in interactions of light and medium projectile nuclei with various target nuclei is very restricted. Recently there has been renewed interesting in asymmetric systems since they offer more complete information than symmetric ones [22-24].

The flows of protons, pions and Λ hyperons have been investigated [25-28] in light nucleus interactions with nuclei at energies of 3.4 and 3.7 GeV/nucleon by the authors of this paper previously. It is worth to mention, that the values of the elliptic flow excitation function, v_2, obtained by us for protons correspond to the quite interesting energy region. According to the investigations in Au-Au collisions at AGS [29], an evolution from negative ($v_2<0$) to positive ($v_2>0$) elliptic flows has been observed in the energy interval of $2.0 \le E_{beam} \le 8.0$ GeV/nucleon, and an apparent transition energy E_{tr} ~4 GeV/nucleon has been pointed. Therefore, the results obtained by us at the energies seem to be interesting from the viewpoint of an enrichment of the existing results in the above mentioned energy region. We believe that the results obtained in the presented paper will bring a new light on the nature of the flows.

We have studied the directed flows of protons and negative pions in C+C, Ne, Cu, Ta interactions at the energies 3.4 and 3.7 GeV/nucleon [27]. In this paper, we present collective flow results of protons and negative pions in ^{2}H+C, Ta and He+C, Ta collisions at energy of 3.4 GeV/nucleon, registered in the 2m Propane Bubble Chamber (PBC-500) of JINR. The reaction plane have been defined by participant protons because the protons with momentum p<150 MeV/c have not been detected within the PBC-500 (as far as their track lengths l <2 mm) and protons with p<200 MeV/c are absorbed in Ta target plate (the detector biases). The experimental results will be compared to the predictions of the Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD) [30, 31] enlarged by the Statistical Multi-fragmentation Model [32].

The UrQMD model is now widely applied for simulations of particle production and flow effects in various nucleus-nucleus interactions [8,33,34], although its original design was directed towards high energies. It considers the nuclear mean field, the Coulomb interactions, and stochastic binary collisions. It allows one to use "soft" or "hard" EoS, the momentum dependent interactions and so on. An effective EoS of the model was determined in [35] (see also [36]). Below in the paper, we use the version 1.3 of the model with default values of the model parameters corresponding, especially, to "hard" EoS. The program was running in the so-called potential mode.

Recently, the model was successfully applied for a description of the HARDES Collaboration data on pion production in light nuclei collisions at 1 ─ 2 A GeV energy range [37,38].

2. Experimental Data

For the experiment, the 2 meter Propane Bubble Chamber (PBC-500) of JINR has been placed in the magnetic field of 1.5 T.

An investigation of the collective flow effects generally requires an analysing of collisions event-by-event, or exclusively. In this context, it has been important to put an effort into the identification of π^+ mesons, the admixture of which amongst positive charged particles was about 25÷27 %. The identification has been carried out on the statistical basis using two-dimensional ($P^{\perp}$, $P^{||}$) particle distributions [26]. It had been assumed, that π^- and π^+ mesons contribute to a given cell within the ($P^{\perp}$, $P^{||}$) plane with equal probability. The difference in multiplicity of π^+ and π^- in each event was required to be less than 3. After the performed identification, the admixture of π^+ mesons amongst the protons is estimated to be less than 5÷7 %. The remained positive particles were assumed as protons (^{2}H was excluded).

The procedures for separating out the ^{2}H+C and He+C collisions in propane (C_3H_8) and the processing of the data including particle identification and corrections have been described in detail in Ref. [39,40]. The analysis produced 4581 events of ^{2}H+C, 1424 of ^{2}H+Ta, 9737 of He+C and 1532 of He+Ta collision. In the experiment, the projectile fragmentation products have been identified as those characterized by the momentum p > 3.5 GeV/c and angle $\Theta < 3°$, and the target fragmentation products ─ protons with the momentum p < 0.25 GeV/c in the target rest frame. The participant protons used for a determination of the reaction plane were determined as protons with p > 0.25 GeV/c different from the single charged projectile fragments.

3. The directed flow of protons

We have investigated the directed flow of protons in ^{2}H+C, ^{2}H+Ta, He+C and He+Ta collisions at energy of 3.4 GeV/nucleon using the transverse momentum analysis technique developed by P. Danielewicz and G. Odyniec [9]. The participant protons have been used for the determination of the reaction plane.

The analysis has been carried out in the laboratory system. To eliminate the correlation of the particle with itself (autocorrelations) for each particle we estimated the reaction plane, with contribution of that particle removed from the definition of the reaction plane.

The reaction plane is spanned by the impact parameter vector **b** and the beam axis. Within the transverse momentum method, the direction of **b** is estimated event-by-event in terms of the vector constructed from particle transverse momenta:

$$\mathbf{Q_j} = \sum_{\substack{i=1 \\ i\neq j}}^{n} \omega_i \mathbf{P_i}^{\perp}, \qquad (1)$$

where i is a particle index and ω_i is the weight factor, $\omega_i = y_i - y_c$, y_i is rapidity of i-th particle, y_c is the average rapidity of the participant protons in each nuclear systems [41]. A projection of the transverse momentum, $\mathbf{P}^{\perp}_i$, of a particle onto the estimated reaction plane is:

$$P_{X\ j}' = \frac{\mathbf{P}_j^{\perp} \cdot \mathbf{Q}_j}{\left|\mathbf{Q}_j\right|} \qquad (2)$$

The dependence of the projection on the rapidity, y, was constructed for each interacting nuclear pair. For the further analysis, the average transverse momentum in the reaction plane, $\langle P_{x\,j}'(y)\rangle$, is obtained by averaging over all events in the corresponding intervals of rapidity (Fig. 1). The transverse flow parameter $F=d\langle P_x\rangle/d(y)$ ─ slope of the average momentum at the intersection point $y=y_c$ [19], has been extracted (Table 1). Since the component Px of a particle momentum in the true reaction plane is systematically larger than the component Px' in the estimated plane, we have to correct our data for the resolution of the reaction plane. To determine the correction factor, an angle Φ between the true and estimated reaction planes has to be defined. The correction factor $k=1/\langle\cos\Phi\rangle$, where $\langle\cos\Phi\rangle$ is given by the ratio [9, 42]:

$$\langle\cos\Phi\rangle = \frac{\langle \omega P_X' \rangle}{\langle \omega P_X \rangle} = \langle \frac{\omega \mathbf{P}_j^{\perp} \cdot \mathbf{Q}_j}{\left|\mathbf{Q}_j\right|} \rangle \sqrt{\frac{\langle Q^2 - \sum_{i=1}^{n} (\omega P_i^j)^2 \rangle}{\langle n^2 - n \rangle}} \qquad (3)$$

where n is proton multiplicity in an event. The $\langle\cos\Phi\rangle$ values obtained for different systems are listed in Table 1. The values of $\langle P_x\rangle$ corrected for $\langle\cos\Phi\rangle$ from eq. (3) are shown in Figs. 1, 2.

Table 1. The numbers of experimental and UrQMD simulated events and multiplicities of protons (prior to the multiplicity cut), values of $\langle\cos\Phi\rangle$ (Φ is the angle between the true and the estimated reaction plane) and the flow parameter ─ F**.**

$A_P + A_T$	^{2}H+C	He+C	^{2}H+Ta	He+Ta
N_{exper}/N_{prot}	4581 / 9630	9737 / 33008	1424 / 6632	1532 / 8354
N_{UrQMD} / N_{prot}	27502 / 66510	31716 / 108871	8710 / 37200	8919 /55518
$\langle\cos\Phi\rangle$	0.850	0.860	0.680	0.690
$F_{exper.}$ (MeV/c)	87.3 ± 6.3	94.9 ± 5.2	131.3 ± 6.6	138.7 ± 5.4
F_{UrQMD} (MeV/c)	83.5 ± 2.6	89.9 ± 1.3	130.3 ± 3.9	137.2 ± 2.1

For the analysis, minimum three participant protons, $N_{part}\geq 3$, are required for the reliable determination of the reaction plane. Figs. 1, 2 present the directed flow effects of protons and negative pions in ^{2}H+C, He+C, ^{2}H+Ta and He+Ta collisions. As seen, the flow parameter **F** increases with the increase of the mass numbers of projectile, A_P, and target, A_T, nuclei (Table 1). The dependences of F on $(A_P \cdot A_T)^{1/2}$ for protons in ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions are shown on Fig. 3 together with our earlier results [28]. They are in the line with data for more heavy colliding systems at lower energies (see Fig. 4 of [20]).

The obtained experimental results from ^{2}H+C, Ta and He+C, Ta collisions were compared with the predictions of the Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD) and our earlier experimental results from C+C, C+Ne, C+Cu and C+Ta systems which were compared with the predictions of the Quark-Gluon String Model (QGSM). Detailed description of the UrQMD can be found in [30,31]. The UrQMD is a microscopic transport model based on the covariant propagation of all hadrons on classical trajectories in a combination with stochastic binary scatterings, a colour string formation and resonance decays. The UrQMD model is designed as multi-purpose tool for studying a wide variety of heavy ion related effects ranging from multi-fragmentation and collective flow to particle productions and correlations in the energy range from SIS to RHIC. At high densities (ρ > 2-3 ρ_0) and/or temperatures, one expects a phase transition or even a smooth crossover to Quark Gluon Plasma (QGP). An existence of a coexistence region of plasma (strongly interacting quarks and gluons not confined to well separated hadrons) and hadron gas might lead to observable effects in the flow excitation function and other observables. The correspondently extended UrQMD model can be used to study such phase transitions and effects. In the present version of the model (1.3) we consider the potential interactions between nucleons and excitations of the residual nuclei. The last one is needed for a determination of the reaction plane by the participant protons in the model, because some evaporated protons can be registered as participant ones.

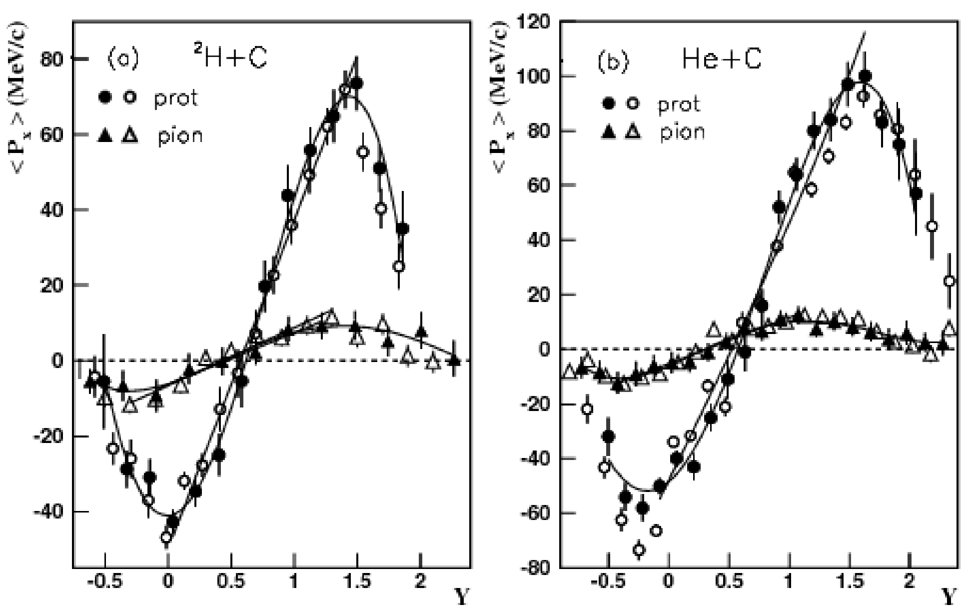

Fig. 1. The dependence of $<P_X(Y)>$ on the laboratory rapidity, Y, for protons and π^--mesons in ^{2}H+C and He+C collisions (figures a and b, correspondently). The closed symbols are the experimental data, and the open ones ─ the model calculations. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the intervals of the rapidity 0.25<y<1.70 and 0.10<y<1.85, respectively. The curved lines guide the eye over data.

50000 events have been generated for ^{2}H+C and He+C collisions, and 10000 events for ^{2}H+Ta and He+Ta collisions at energy of 3.4 GeV/nucleon by using the UrQMD model. The experimental selection criteria have been applied to the generated events. Then for further analysis, 27502, 31716, 8710 and 8919 events respectively have been selected. For UrQMD events the projection of the transverse momentum onto true reaction plane was determined. The values of the flow parameter F have been extracted for protons from the dependences of $<P_x(y)>$ on rapidity for each nuclear pair (Table 1.). As seen, there is quite good agreement in the experimental and theoretical distributions (Figs. 1÷3).

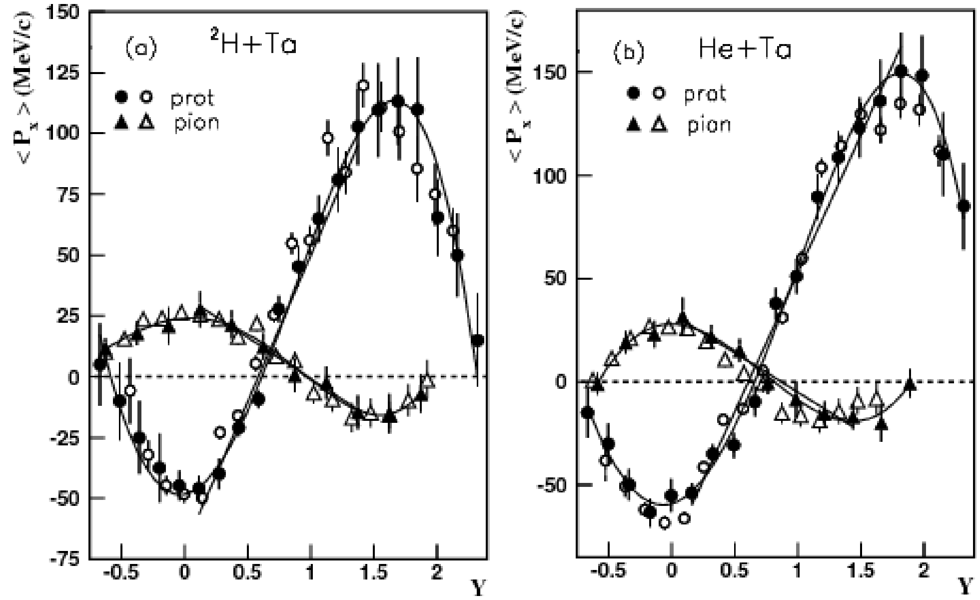

Fig. 2. The dependence of <$P_X(Y)$> on the laboratory rapidity, Y, for protons and π^--mesons in ^{2}H+Ta (a) and He+Ta (b) collisions. Closed symbols correspond to experimental data and open ones to model. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the narrow intervals of the rapidity $-0.07<y<1.35$ and $-0.10<y<1.65$, respectively. The curved lines guide the eye over data.

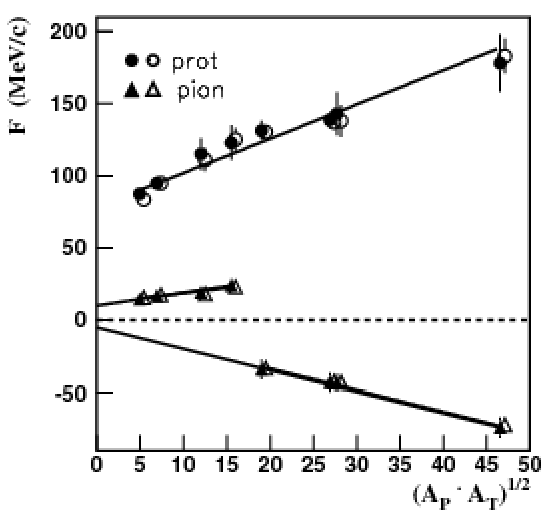

Fig. 3. The dependences of F — directed flow parameter on $(A_P \cdot A_T)^{1/2}$ for protons (upper) and π^--mesons (down) in ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions. Closed symbols correspond to experimental data and open ones to the QGSM and UrQMD calculations.

4. Proton elliptic flow

We have investigated the proton elliptic flow in ^{2}H+C, ^{2}H+Ta, He+C and He+Ta collisions at energy of 3.4 GeV/nucleon. The azimuthal ϕ distributions of the protons have been obtained and presented in Figs. 4, 5 where ϕ is the angle of the transverse momentum of each particle in the event with respect to the reaction plane ($\cos\phi = P_x/P^{\perp}$). Due to low multiplicities of the participant protons in ^{2}H+C and ^{2}H+Ta interactions, we plotted in the Fig. 4 the distributions on $|\phi|$ in the interval 0÷3.14 rad. The azimuthal angular distributions show maxima at ϕ=90° and 270° with respect to the event plane. The maxima are associated with preferential particle emission perpendicular to the reaction plane (squeeze-out). To treat the data in a quantitative way, the azimuthal distributions have been fitted with the Fourier cosine-expansion (given the system invariance under reflections with respect to the reaction plane) dN/dϕ=a_o(1+a'_1cosϕ+a'_2cos2ϕ). The squeeze-out signature is the negative value of the coefficient a'_2, and this coefficient is the measure of the strength of the anisotropic emission. Compared to the coefficient a_2 associated with a distribution relative to the true reaction plane, the coefficient a'_2 is reduced, $a'_2 = a_2 \langle\cos 2\Phi\rangle$ [28, 43-45], where

$$\langle \cos 2\Phi \rangle = \frac{\left|\langle (P_X')^2 - (P_Y')^2 \rangle\right|}{\left|\langle (P_X)^2 - (P_Y)^2 \rangle\right|} \qquad (4)$$

the numerator and denominator on the r.h.s. are, respectively, obtained from

$$\langle (P_X')^2 - (P_Y')^2 \rangle = \langle 2(\frac{\mathbf{P}_j^{\perp} \cdot \mathbf{Q}_j}{Q_j})^2 - (P_j^{\perp})^2 \rangle \qquad (5)$$

and

$$\left|\langle (P_X)^2 - (P_y)^2 \rangle\right| = \sqrt{\frac{\langle 2\overline{\overline{T}} : \overline{\overline{T}} - \sum_{i=1}^{n} (P^{\perp}{}_i)^4 \rangle}{\langle n^2 - n \rangle}} \qquad (6)$$

In the above, the transverse tensor $\overline{\overline{T}}$ is

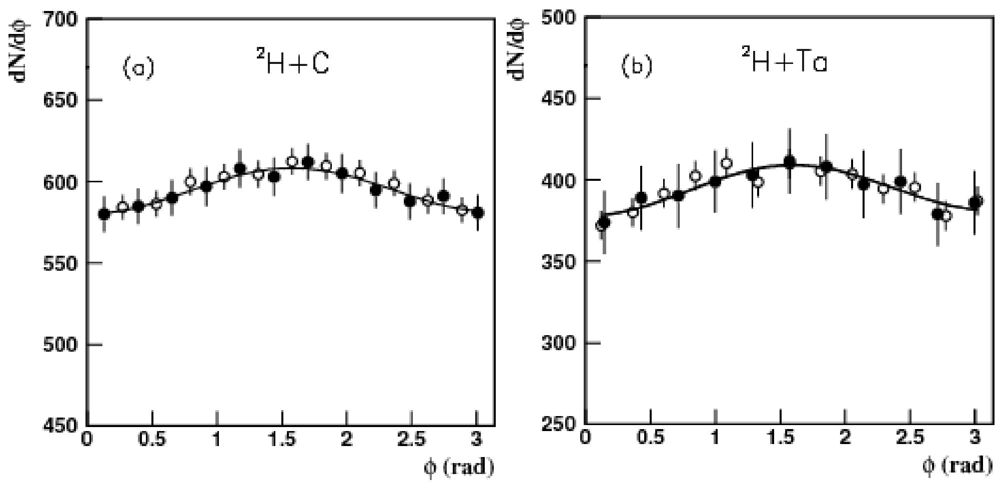

Fig. 4. The azimuthal distributions of the participant protons with respect to the estimated reaction plane in ^{2}H+C (a) and ^{2}H+Ta (b) collisions. Closed symbols correspond to experimental data and open ones to model. The lines represent fits to the equation dN/dϕ=a_o(1+a'_1cosϕ+a'_2cos2ϕ).

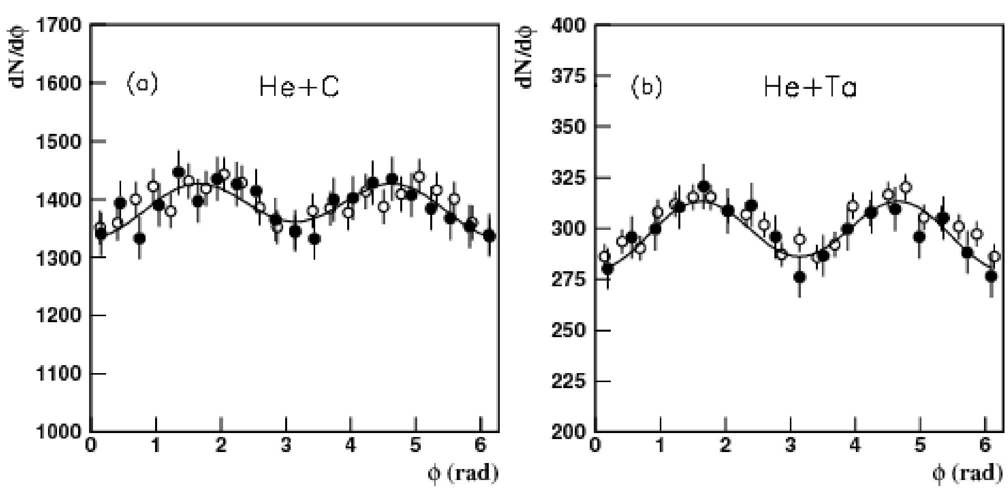

Fig. 5. The azimuthal distributions of the participant protons with respect to the estimated reaction plane in He+C (a) and He+Ta (b) collisions. Closed symbols correspond to experimental data and open ones to model. The lines represent fits to the equation dN/dϕ=a_o(1+a'_1cosϕ+a'_2cos2ϕ).

$$T^{\alpha\beta} = \sum_{i=1}^{n}(P_i^{\alpha}P_i^{\beta} - \frac{1}{2}(P_i^{\perp})^2\delta^{\alpha\beta}), \alpha = x, y \qquad (7)$$

and

$$\overline{\overline{T}} : \overline{\overline{T}} = \sum_{\alpha,\beta=x}^{y} T^{\alpha\beta}T^{\alpha\beta} = (T^{xx})^2 + (T^{yy})^2 + (T^{xy})^2 \qquad (8)$$

With Eq. (5), we find that <cos2Φ> ≈ 0.67 for the protons of the given nuclear systems, and the elliptical modulation parameters, corrected according to <cos2Φ>, from the fits made under different cuts to analyzed particles, are provided in Table 2. The elliptic anisotropy, quantified in terms of the a_2 coefficient (a_2=2v_2), was extracted from the azimuthal distributions of the protons with respect of the reaction plane at midrapidity. One can see that there is some indication that a2 increases with transverse momentum and projectile and target nuclei mass numbers for the above mentioned nuclear pairs (Table 2,). In the Fig. 6, the results obtained in this paper are presented together with our earlier results for C+C, C+Ne, C+Cu and C+Ta collisions [28]. They are comparable.

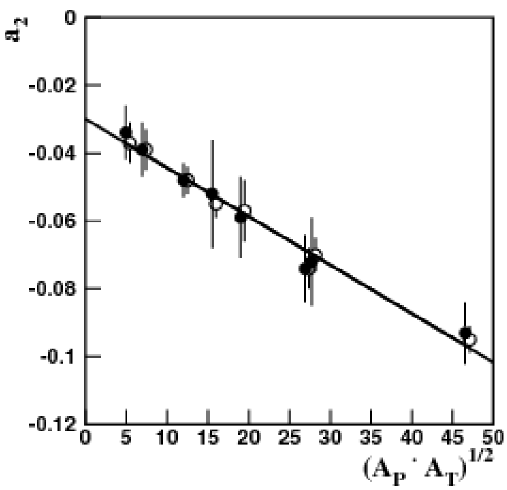

Fig. 6. The dependences of a_2-elliptic flow parameter on $(A_P \cdot A_T)^{1/2}$ for protons in ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions. Closed symbols correspond to experimental data and open ones to the QGSM and UrQMD calculations.

Table 2. Characteristics of proton elliptic flow for experimental and UrQMD-simulated collision events.

A_P+A_T	^{2}H+C (-0.3 ≤ y ≤ 2.1)	He+C (-0.3 ≤ y ≤ 2.3)	^{2}H+Ta (-0.2 ≤ y ≤ 1.8)	He+Ta (-0.2 ≤ y ≤ 1.8)
$a_{2exper.}$	-0.034 ± 0.006	-0.040 ± 0.006	-0.059 ± 0.009	-0.074 ± 0.012
P_T> 200 MeV/c	-0.041 ± 0.008	-0.049 ± 0.008	-0.076 ± 0.010	-0.089 ± 0.013
P_T> 300 MeV/c	-0.048 ± 0.009	-0.058 ± 0.009	-0.093 ± 0.011	-0.109 ± 0.014
$a_{2mod.}$	-0.037 ± 0.006	-0.039 ± 0.006	-0.057 ± 0.007	-0.071 ± 0.006
P_T> 200 MeV/c	-0.043 ± 0.007	-0.050 ± 0.007	-0.075 ± 0.008	-0.088 ± 0.007
P_T> 300 MeV/c	-0.051 ± 0.008	-0.060 ± 0.008	-0.091 ± 0.009	-0.107 ± 0.008

The obtained experimental results have been compared to the predictions of the UrQMD model. The experimental selection criteria have been applied to the generated events. The elliptic flow parameters with respect of the true reaction plane have been calculated (Table 2) for UrQMD events also. Quite good agreement between experimental and theoretical distributions has been obtained for proton elliptic flow in the above mentioned collisions (Figs. 5,6).

The elliptic flow has been investigated by various experimental groups for different systems. The elliptic flow measurements of charged hadrons in Cu+Cu and Au+Au collisions at $\sqrt{S_{NN}}$= 62.4 and 200

GeV (the PHOBOS Collaboration) do not show any dependence on $(A_P \cdot A_T)^{1/2}$ (see Ref. [46], fig. 2 a, c). The ALICE group has found about a 30% increase in the magnitude of v_2 at going from $\sqrt{S_{NN}}$=200 Gev (Au+Au) to 2.76 TeV (Pb+Pb) (see Ref. [47], fig. 4).

5. Directed flow of π^--mesons

We have investigated the directed flow of the π^--mesons for our nuclear systems. Negative pions with momentum p>50 MeV/c have been detected within the chamber. There are no auto-correlations for pions, because the reaction plane is determined by protons. The average component of a pion transverse momentum in the reaction plane evaluated using Eq. (3) are presented in Figs. 1, 2, and the values of flow parameter F at crossover from the fits to data are given in the Table 3.

The dependences of F ─ directed flow parameter (absolute values), on $(A_P \cdot A_T)^{1/2}$ for π^--mesons in ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions are plotted in Fig. 3. The results obtained in this paper are presented together with our earlier results [28] as for pions as for protons. As seen, the flow parameter F increases with the increase of the mass numbers of A_P and A_T nuclei (Table 3.)

Table 3. The number of experimental and UrQMD simulated π^- mesons and the values of the flow parameter F**.**

$A_P + A_T$	^{2}H+C	He+ C	^{2}H+Ta	He+Ta
N_{π^-} EXP	3452	8776	1137	2200
N_{π^-} MOD	23210	37786	11781	9770
$F_{EXP.}$ (MeV/c)	14.4 ± 3.6	16.9 ± 2.3	-34.0 ± 6.5	-42.9 ± 6.3
$F_{MOD.}$ (MeV/c)	15.4 ± 1.5	17.3 ± 1.5	-33.2 ± 3.1	-42.5 ± 3.3

One can see from the Tabl. 3, that in ^{2}H+C and He+C collisions the direction of pion flow is the same as the proton flow, while in ^{2}H+Ta and He+Ta interactions the direction of the pion flow is opposite to the proton flow (anti-flow). The FOPI Collaboration (see [48], Fig. 29) observed that positive charged pion flow shows anti-flow only in the peripheral Au+Au interactions at 1.5 A GeV. The direction of negative charged pion flow coincides with the proton one in the same interactions at all centralities. At higher energy (40, 158 A GeV), the NA49 Collaboration found only anti-flow of pions at all centralities [49]. According to our data, there is a possibility to study a transition from the flow to the anti-flow in asymmetric nuclear collisions.

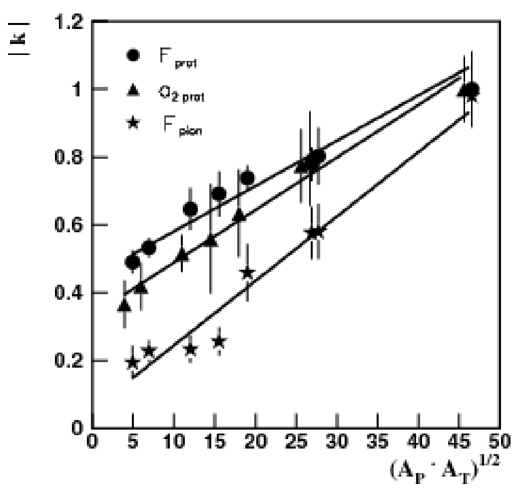

Fig. 7. The dependences of the normalized (divided on the maxima of those values) directed and elliptic flow parameters on $(A_P \cdot A_T)^{1/2}$ for protons and π^--mesons in experimental ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions. The lines represent linear fits to the data.

The anti-correlation of nucleons and pions was explained in Ref. [50] as due to an effect of multiple πN scattering. However, in Ref. [51-53] it was shown that the anti-correlation is a manifestation of the nuclear shadowing of the target and projectile-spectators through both pion re-scattering and re-absorptions. Quantitatively, the shadowing can produce in-plane transverse momentum components comparable to the momenta itself and, thus, much larger than components due to collective motion for pions [54]. In our opinion, our results indicate that the flow behaviour of π^--mesons in the light systems is due to the flow of Δ resonances, whereas the anti-flow behaviour in the heavier systems (^{2}H+Ta and He+ Ta) is the result of the nuclear shadowing effect. There the flow parameter F - the measure of the amount of collective transverse momentum transfer in the reaction plane, increases with the increase of projectile and target nuclei mass numbers (Table 3). Our results agree with the results for different projectile and target nuclei configurations obtained at different energies and accelerators (GSI-SIS, AGS).

As shown in Refs. [55,56], the ratios of multiplicities of π^+- and π^--meson coming from the decay of the Δ^{++} and Δ^0 resonances to the multiplicities of the directly produced are about 62% and 48%, respectively, in the considered energy range and colliding nuclei, at least for He+C and C+C interactions at 4.2 A GeV/c. It means that Δ decay is dominant mechanism of pion production on the light targets. The shadowing can have influence on the directly produced mesons and Δ's, especially, in the collisions with heavy targets. The shadowing must be small in the interactions with light targets, which explain our observed flow of pions on the carbon target.

The obtained experimental results have been compared with the predictions of the UrQMD model. The dependence of the projection of π^--mesons transverse momentum onto the reaction plane (determined by the participant protons) on the rapidity, *y*, was calculated. There is quite good agreement in the experimental and theoretical distributions (Figs. 1÷3).

In Fig.7, the dependences of F-directed flow parameter (for protons and π^--mesons) and of a_2-elliptic flow parameter (for protons) on the $(A_P \cdot A_T)^{1/2}$ in the above mentioned collisions are presented. In order to show the both dependences at the same figure, we have normalized the parameters on their maximum values, $k= F/F_{max}$, $k= a_2/a_{2max}$. The values of F_{max} and a_{2max} for C+Ta interactions were taken from [26]. Because k=1 for C+Ta collisions, the results were shifted slightly on the figure to guide the eye. One can see from Fig. 7, that in ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions the linear dependences of the directed and elliptic flow parameters from system mass are similar for protons while for π^--mesons the dependence of the directed flow parameters is a little bit stronger.

7. Conclusions

The directed transverse collective flows of protons and π^--mesons and elliptic flow of protons emitted from ^{2}H+C, He+C, ^{2}H+Ta and He+Ta reactions at energy 3.4 GeV/nucleon have been studied. We can summarize our results as:

1) The ^{2}H C system is the lightest studied one, and the ^{2}H Ta and He Ta ones are fully (extremely) asymmetrical systems in which collective flow effects (directed and elliptic) have been ever detected (for protons and π^--mesons). As shown, the negative pions exhibit the directed flow consistent with that for protons in the ^{2}H+C and He+C collisions. On the other hand, for the ^{2}H+Ta and He+Ta interactions, the pion flows turn into anti-flow with the pion average in-plane momenta becoming opposite to those for protons. The directed flow parameter F increases with the increase of the mass of projectile and target nuclei for both protons and negative pions. For protons, the increase is from 87.3±6.3 (^{2}H+C) to 138.7±5.4 (He+Ta) (MeV/c) (whereas for negative pions the increase is from 14.4±3.6 MeV/c for ^{2}H+C-interactions to 48.7±7.2 MeV/c for He+Ta ones);

.

2) The proton elliptic flow parameter a_2 increases with the increase of the mass numbers of projectile, A_P, and target, A_T, nuclei from 0.034 ± 0.006 for ^{2}H+C-interactions to 0.074±0.012 for He+Ta ones.

3) The flow measurements have been described by the Ultra Relativistic Quantum Molecular Dynamics model (UrQMD). There is quite good agreement between the experimental and the theoretical distributions.

4) In ^{2}H+C, He+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu and C+Ta collisions, the linear dependence of directed and elliptic flow parameters from mass numbers of projectile and target nuclei – $(A_P \cdot A_T)^{1/2}$, is similar for protons while for π^--mesons the dependence of directed flow parameters is stronger.

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