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COLLECTIVE FLOW PHENOMENA OF PROTONS AND π^- MESONS IN NUCLEUS–NUCLEUS COLLISIONS AT A MOMENTUM OF $4.2 \div 4.5$ GeV/c PER NUCLEON

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Чхаидзе Л. В., Джобава Т. Д., Кладницкая Е. Н. E1-2005-100
Изучение коллективных потоков протонов и π^--мезонов
в ядро-ядерных соударениях при импульсе $4{,}2 \div 4{,}5$ ГэВ/c на нуклон

Исследованы коллективные свойства (направленный поток) протонов и π^--мезонов в HeC, CC, CNe, CCu и CTa-соударениях при импульсах $4{,}2 \div 4{,}5$ ГэВ/c на нуклон ($E = 3{,}4 \div 3{,}7$ ГэВ/нуклон). Экспериментальный материал получен на установке СКМ-200-ГИБС и 2-х метровой пропановой пузырьковой камере ЛВЭ ОИЯИ. Направленный поток пионов в HeC, CC и CNe-соударениях параллелен потоку протонов, а в CCu и CTa потоки антипараллельны. Величина потока протонов линейно возрастает с увеличением атомных масс сталкивающихся ядер от 95 до 178 МэВ, а абсолютная величина потока пионов увеличивается от 17 до 74 МэВ. Экспериментальные результаты для всех пар ядер сравнивались с предсказаниями кварк-глюонной струнной модели. Модель хорошо воспроизводит экспериментальные данные.

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Chkhaidze L. V., Djobava T. D., Kladnitskaya E. N. E1-2005-100
Collective Flow Phenomena of Protons and π^- Mesons
in Nucleus–Nucleus Collisions at a Momentum of $4.2 \div 4.5$ GeV/c per Nucleon

The collective properties of protons and π^- mesons in He–C, C–C, C–Ne, C–Cu and C–Ta collisions at a momentum of $4.2 \div 4.5$ GeV/c per nucleon ($E = 3.4 \div 3.7$ GeV/nucleon) have been investigated. The data is obtained by SKM-200-GIBS and 2-m Propane Bubble Chamber of JINR. The directed (in-plane) protons and π^- mesons have been observed in the above-mentioned interactions. In He–C, C–C and C–Ne interactions the directed flow of π^- mesons is in the same direction as for protons, while in C–Cu and C–Ta collisions pions show antiflow behaviour.
The absolute value of flow increases linearly with the increase of A_P, A_T, from 95 MeV for He–C up to 178 MeV for C–Ta for protons and from 17 MeV for He–C up to –74(module) MeV for C–Ta for π^- mesons. The Quark-Gluon String Model reproduces quite well the experimental results.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energies, JINR, and at the Institute of High Energy Physics and Informatization, TSU, Tbilisi.

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INTRODUCTION

One of the central goals of the experiments related with high-energy heavy-ion collisions is a study of nuclear matter under extreme conditions of high density and temperature vastly different from that in normal nuclei. The most impressive results of high-energy heavy-ion research so far are the new collective phenomena discovered in these reactions. Collective processes are well established both experimentally and theoretically, such as different collective flow patterns. A collective flow is a motion characterized by space–momentum correlations of dynamic origin. The collective effects lead to characteristic, azimuthally asymmetric sideward emission of the reaction products. The analysis of the main characteristics of the collective flow allows one to obtain the information about the fundamental properties of nuclear matter, connected particularly to the equation of state (EOS) [1].

Two different signatures of collective flow have been predicted:

a) the bounce-off of compressed matter in the reaction plane (a sidewards deflection of the spectator fragments) as well as the directed flow of nucleons from the overlap region between the colliding nuclei (participants) in the reaction plane.

b) the squeeze-out of the participant matter out of the reaction plane — the elliptic flow.

The method proposed by Danielewicz and Odyniec [2] turned out to be the most convenient and fruitful for the investigation of collective flow phenomena, which allows one to determine the reaction plane by using the transverse momenta of particles. The reaction plane is the plane defined by the impact parameter $\overrightarrow{b}$ and the beam direction. Lately the method of Fourier expansion of azimuthal particle distributions has been widely used [3].

At present the collective flow effects are investigated in a wide range of energies from several hundreds of MeV up to hundreds of GeV. The most part of the experiments are carried out using the electronic technique in the 4π geometry and only in the first experiments at Berkeley and lately at Dubna, the streamer chamber served as a detector.

A collective flow of charged particles has been observed experimentally for the first time at BEVALAC by the Plastic Ball [4–6] and Streamer Chamber [7] collaborations. It has been studied intensively at Berkeley and GSI [8–13], AGS [14–17] and CERN/SPS [18–21]. At RHIC (Relativistic Heavy Ion Collider) of BNL the STAR collaboration reported first results on the elliptic flow of charged particles at midrapidity in Au–Au collisions at the energy of $\sqrt{S}_{NN} = 130$ GeV [22].

Various flow phenomena have been observed by unique emulsion method in collisions of 1–160 GeV/c different nuclei with Ag(Br) targets [23]. The flow of protons and π^- mesons has been observed at Dubna by the SKM-200-GIBS collaboration [24] in central C–Ne and C–Cu collisions at a momentum of 4.5 GeV/c per nucleon and in semicentral C–C [25, 26] and C–Ta [27] collisions at a momentum of 4.2 GeV/c per nucleon registered in the 2-m Propane Bubble Chamber using the method of Danielewicz and Odyniec [2] where the reaction plane was determined by summation of the transverse momenta of protons [24, 26] and the method of Fourier expansion of azimithal distributions of particles [25, 27]. The most complete experimental data of collective flow effects are presented in the review article [28].

In this paper, we present the experimental results of collective behaviour of protons and π^- mesons in He–C, C–C, C–Ne, C–Cu and C–Ta collisions at a momentum of $4.2 \div 4.5$ GeV/c per nucleon registered in the SKM-200-GIBS set-up and 2-m Propane Bubble Chamber of JINR. We have measured directed flow of protons and π^- mesons.

1. EXPERIMENTAL DATA

In this paper, the collective properties of protons and π^- mesons in He–C, C–C, C–Ne, C–Cu and C–Ta collisions at a momentum of $4.2 \div 4.5$ GeV/c per nucleon registered in the SKM-200-GIBS set-up and 2-m Propane Bubble Chamber of JINR are studied.

The SKM-200-GIBS set-up consists of a 2-m streamer chamber, placed in a magnetic field of 0.8 T, and a triggering system. The streamer chamber was exposed to a beam of C nuclei accelerated in the synchrophasotron up to a momentum of 4.5 (GeV/c)/nucleon. The thickness of the solid target Cu (in the form of a thin disc) was 0.2 g/cm^2. Neon gas filling of the chamber also served as a nuclear target. A central trigger was used to select events with no charged projectile spectator fragments (with $P_Z > 3$ GeV/c) within a cone of half angle $\theta_{\rm ch} = 2.4$ or 2.9° (the trigger efficiency was 99% for events with a single charged particle in the cone). The ratio $\sigma_{\rm cent}/\sigma_{\rm inel}$ (that characterizes the centrality of selected events) is $(9 \pm 1)\%$ for C–Ne and $(21 \pm 3)\%$ for C–Cu. Details of data-acquisition techniques of C–Ne (723) and C–Cu (663) interactions and the experimental procedures, such as biases involved and correction procedures utilized in our data analysis, have been presented in previous publications [29, 30]. The study of collective flow phenomenon needs «event-by-event» analysis, which requires the exclusive analysis of each individual collision. In this connection there has been a necessity to perform an identification of π^+ mesons, the admixture of which amongst the charged positive particles is about $(25 \div 27)\%$. The identification has been carried out on the statistical basis using the two-dimensional (P_T, P_L)

distribution [31]. It had been assumed that π^- and π^+ mesons hit a given cell of the plane (P_T, P_L) with equal probability. The difference in multiplicity of π^+ and π^- in each event was required to be no more than 2. After performed identification, the admixture of π^+ mesons amongst the protons does not exceed $(5 \div 7)\%$.

The data on He–C, C–C and C–Ta interactions have been obtained using 2-m Propane Bubble Chamber of JINR. The chamber was placed in a magnetic field of 1.5 T. Three Ta plates $(140 \times 70 \times 1)$ mm^3 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 method of separation of He–C and C–C collisions in propane, the processing of the data, identification of particles and discussion of corrections is described in detail in [32].

The experimental data contained 9737 He–C, 15962 C–C and 2469 unambiguously identified C–Ta inelastic collisions.

The subsample of «semicentral» events with the number of participant protons $N_{\text{part}} \geqslant 3$, $N_{\text{part}} \geqslant 4$ and $N_{\text{part}} \geqslant 6$ respectively were selected for the analysis from the whole ensemble of He–C, C–C and C–Ta collisions. With this aim, the target fragments ($P < 0.3$ GeV/c) and projectile stripping ($P > 3$ GeV/c and angle $\theta < 4°$) fragments were excluded from the ensemble of protons-participants. In consequence, the groups of semicentral 5800 He–C, 9500 C–C and 1620 C–Ta collisions were separated.

2. TRANSVERSE FLOW OF PROTONS

The method of Danielewicz and Odyniec [2] has been used for study of collective flow protons. This method is based on the summation of the transverse momenta of selected particles. The most of experimental data at energies below 4 GeV/nucleon has been analyzed by this method. It gives satisfactory results even at a small available statistics obtained by the film detectors.

The reaction plane is the plane containing the impact parameter $\overrightarrow{b}$ and beam axis. Taking into account that the definition of $\overrightarrow{b}$ experimentally is not possible, in the transverse momentum analysis method of Danielewicz and Odyniec the vector $\overrightarrow{b}$ is replaced by $\overrightarrow{Q}$. The reaction plane vector $\overrightarrow{Q}$ in each individual event is defined by the transverse vector:

$$\overrightarrow{Q_j} = \sum_{i=1}^{n} \omega_i \overrightarrow{P_{Ti}}, \tag{1}$$

where i is a detected particle index and ω_i is a weight. In Eq. (1) the vector $\overrightarrow{Q_j}$ is summing over all protons; $\omega_i = 1$ for $y_i > y_c + \delta$, $\omega_i = -1$ for $y_i < y_c - \delta$, and $\omega_i = 0$ for $y_c - \delta < y_i < y_c + \delta$; y_i is the rapidity of particle i. For He–C and C–C interactions we take $\delta = 0.2$, for C–Ne, C–Cu and C–Ta interactions we take $\delta = 0.4$. These values of δ remove particles from midrapidity. For the analysis of C–Ne, C–Cu and C–Ta interactions we chose the events with the number of participant protons $N_{\rm part} \geqslant 6$ and for He–C and C–C collisions respectiveley $N_{\rm part} \geqslant 3$ and $N_{\rm part} \geqslant 4$. The analysis of He–C and C–C interactions has been performed in the c.m.s., while C–Ne, C–Cu and C–Ta have been analyzed in laboratory system. To remove the autocorrelations, Danielewicz and Odyniec [2] supposed to estimate the reaction plane for each particle j, i.e., to project P_{Ti} onto the summary vector of all other particles in the same event:

$$\overrightarrow{Q_j}' = \sum_{i \neq j}^{n} \omega_i \overrightarrow{P_{Ti}}. \tag{2}$$

The transverse momentum of each particle, (namely, of protons) in the estimated reaction plane is calculated as

$$P'_{xj} = \{\overrightarrow{Q_j}' \cdot \overrightarrow{P_{Tj}} / |\overrightarrow{Q_j}'|\}. \tag{3}$$

The dependence of the mean transverse momentum of each particle in the reaction plane $\langle P_x \rangle$ on the rapidity y is constructed. The average transverse momentum $\langle P_x(y) \rangle$ is obtained by averaging over all events in the corresponding intervals of rapidity.

It is known [2] that the estimated reaction plane differs from the true one, due to the finite number of particles in each event. The component P_x in the true reaction plane is systematically larger than the component P'_x in the estimated plane, hence:

$$\langle P_x \rangle = \langle P'_x \rangle / \langle \cos\phi \rangle, \tag{4}$$

where ϕ is the angle between the estimated and true planes. The correction factor $k = 1/\langle \cos\phi \rangle$ is the subject of a large uncertainty, especially for low multiplicity. In [2] the method for the definition of the correction factor has been proposed. The correction factor $k = 1/\langle \cos\phi \rangle$ has been estimated according to [2, 33]:

$$\langle \cos\phi \rangle = \frac{\langle \omega P'_x \rangle}{\langle \omega P_x \rangle} = \frac{\langle w \overrightarrow{P}_T \overrightarrow{Q}' / |\overrightarrow{Q}'| \rangle}{[\langle Q^2 - \sum (\omega_i P_{Ti})^2 \rangle / \langle N^2 - N \rangle]^{1/2}}, \tag{5}$$

N — number of events, the values of $\langle \cos\phi \rangle$ and the correction factor k for all pairs of nuclei are presented in table.

Figures 1 and 2 show the dependence of the corrected $\langle P_x(y) \rangle$ on y for protons in He–C, C–C, C–Ne (Fig. 1) and C–Cu and C–Ta (Fig. 2) at a momentum of $4.2 \div 4.5$ GeV/c per nucleon ($E = 3.4 \div 3.7$ GeV/nucleon). The data exhibit S-shape behaviour which demonstrates the collective transverse momentum transfer between the backward and forward hemispheres.

From the mean transverse momentum distributions, one can extract the transverse flow F, i.e., the slope of the momentum distribution at midrapidity (in the intersection point $y = 0$):

$$F = \frac{\partial [P_x]}{\partial y}|_{y_{\rm c.m.s.}=0}. \tag{6}$$

F is a measure of the amount of collective transverse momentum transfer in the reaction plane, i.e., intensity of nuclear interactions.

This quantity was the subject of less experimental bias and it enabled one to compare different reactions and results of different experimental set-ups to each other. The straight lines in Figs. 1 and 2 are the result of the fit of experimental data in the rapidity y interval ($-0.7 \div 0.7$ for He–C; $-0.6 \div 0.6$ for C–C; $0.3 \div 1.8$ for C–Ne; $0.2 \div 1.6$ for C–Cu; $0.1 \div 1.4$ for C–Ta;) The values of F for protons, corrected by the factor $k = 1/\langle\cos\phi\rangle$, in He–C, C–C, C–Ne, C–Cu and C–Ta interactions are presented in table.

The number of experimental ($N_{\rm exp}$) and Quark-Gluon String Model ($N_{\rm QGSM}$) events, $\langle\cos\phi\rangle$, the correction factor k and the flow F for protons

	He–C	C–C	C–Ne	C–Cu	C–Ta
$N_{\rm exp}$	9737	15962	723	663	2469
$N_{\rm QGSM}$	25000	50000	16337	5137	10000
$\langle\cos\phi\rangle$	0.866	0.893	0.848	0.784	0.720
$k = 1/\langle\cos\phi\rangle$	1.155	1.119	1.179	1.279	1.389
$F_{\rm exp}$ (MeV/c) (for protons, corrected by k)	95±8	115±11	123±12	143±15	178±20
$F_{\rm QGSM}$ (MeV/c)	93±6	111±8	125±8	138±11	183±12
$F_{\rm exp}$ (MeV/c) (for pions, corrected by k)	17±3	19±3	24±5	–43±6	–74±7
$F^{\pi^-}_{\rm QGSM}$ (MeV/c)	18±3	18±3	23±3	–43±4	–72±4

In Fig. 3 the dependence of F on mass numbers of projectile A_P and target A_T is presented. One can see from table and Fig. 3 that with the increase of A_P, A_T, the value of F increases linearly from $F = 95 \pm 8$ MeV for He–C up to $F = 178 \pm 20$ MeV for C–Ta.

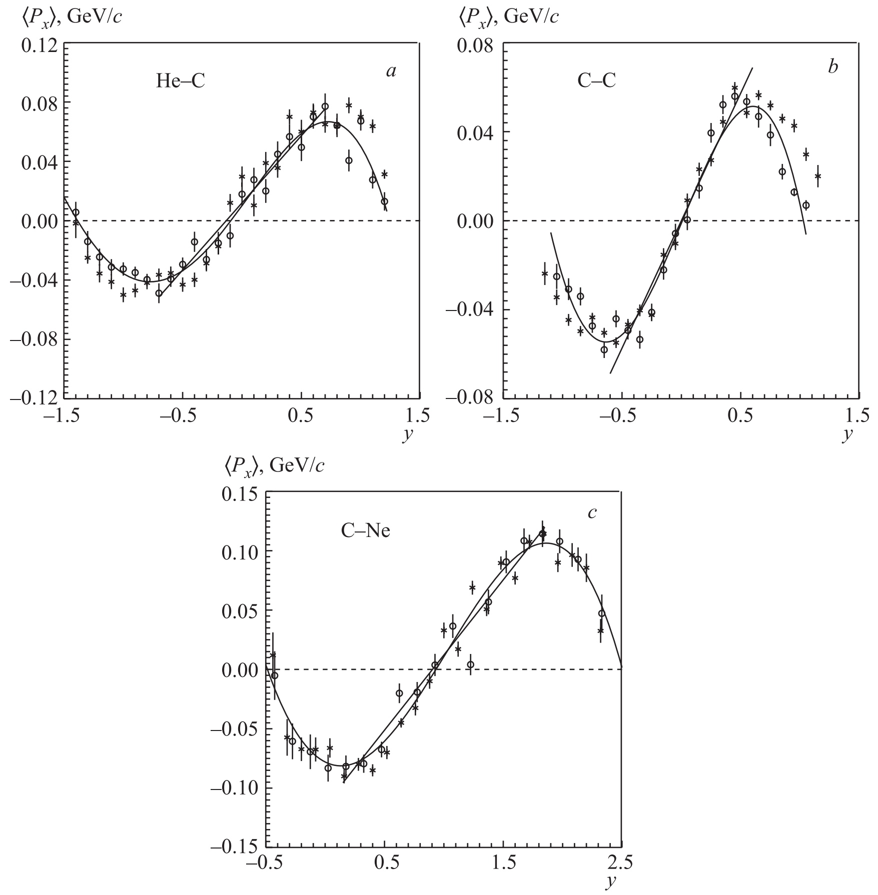

Fig. 1. The dependence of $\langle P_x(y) \rangle$ on y for protons in He–C (a), C–C (b) and C–Ne (c) collisions in c.m.s. (He–C, C–C) and laboratory (C–Ne) systems. $\circ$ — the experimental data, $*$ — QGSM generated data. The solid lines are the result of the linear approximation of experimental data in the intervals $-0.7 \div 0.7$ for He–C, $-0.6 \div 0.6$ for C–C, $0.3 \div 1.8$ for C–Ne. The solid curves for visual presentation of experimental events are results of approxomation by 4th-order polynomial

In our previous papers [24, 26] the directed (in-plane) and elliptiic flow of protons in C–C, C–Ne and C–Ta collisions at a momentum of $4.2 \div 4.5$ GeV/c per nucleon have been observed. We would like to emphasize that in [24, 26]:

1. The reaction plane has been defined for the participant protons, i.e., protons which are not fragments of the projectile ($P/Z > 3$ GeV/c, $\theta < 4°$) and target ($P/Z < 0.3$ GeV/c). They represent the protons participating in the collision.

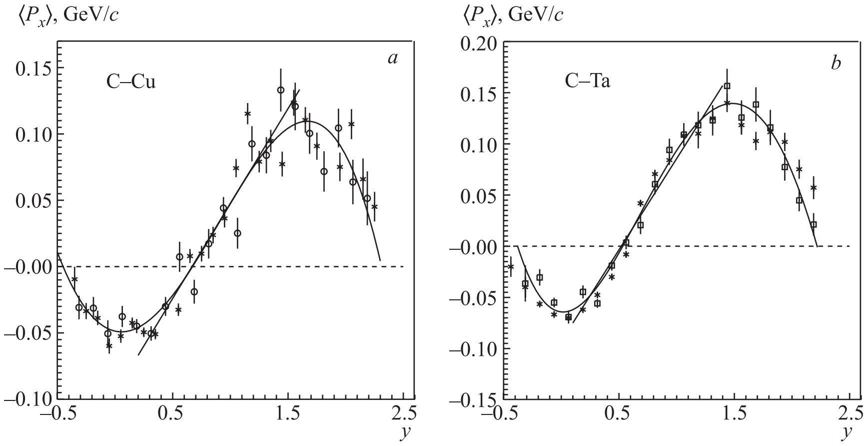

Fig. 2. The dependence of $\langle P_x(y) \rangle$ on y for protons in C–Cu and C–Ta collisions in laboratory system. $\circ$ — the experimental data, $*$ — QGSM generated data. The solid lines are the result of the linear approximation of experimental data in the intervals $0.2 \div 1.6$ for C–Cu, $0.1 \div 1.4$ for C–Ta. The solid curves for visual presentation of experimental events are results of approxomation by 4th-order polynomial

2. The original weight ω_i has been replaced by the continuous function $\omega_i = y_i - \langle y \rangle$ as in [34], where $\langle y \rangle$ is the average rapidity, calculated for each event over all the participant protons.

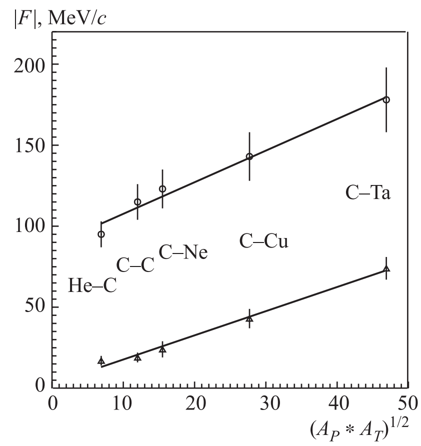

Fig. 3. The dependence of absolute value of F on $(A_P * A_T)^{1/2}$ for protons ($\circ$) and π^- mesons ($\triangle$) in He–C, C–C, C–Ne, C–Cu and C–Ta collisions

According to the above-mentioned approach (definition of reaction plane by participant protons) we have obtained in [26] for protons in C–C collisions at a momentum of 4.2 GeV/c per nucleon flow $F = 136 \pm 11$ MeV/c, in C–Ne collisions at a momentum of 4.5 GeV/c per nucleon [24] flow $F = 134 \pm 12$ MeV/c and in C–Cu collisions [24] $F = 198 \pm 13$ MeV/c. We would like to note that the values of F obtained in this paper are smaller by $\sim 10 \div 15\%$ for C–C and C–Ne interactions and by $\sim 28\%$ for C–Cu interactions in comparison with the values obtained in our previous articles [24, 26]. It seems that the definition of $\overrightarrow{Q}$ by Eq. (1) is more reliable than that by the participant protons [24, 26].

It is worth emphasizing that He–C is the lightest system of colliding nuclei in which the transverse (directed) flow of protons has been observed.

Experimental results of directed flow of protons have been compared with the Quark-Gluon String Model (QGSM) predictions. A detailed description of the QGSM can be found in [35, 36]. The QGSM is based on the Regge and string phenomenology of particle production in inelastic binary hadron collisions. The QGSM simplifies the nuclear effects (neglects the potential interactions between hadrons, coalescence of nucleons, etc.) The procedure of generation consists of 3 steps: the definition of colliding nuclei, production of quark-gluon strings and fragmentation of strings (breakup) into observed hadrons. After hadronization the newly formed secondary hadrons are allowed to rescatter. In the QGSM the sidewards flow is a sole result of the rescattering of secondaries, which produces the amount of collective energy. The model yields a generally good overall fit to most experimental data [35, 36]. We have generated He–C, C–C, C–Ne, C–Cu and C–Ta interactions using the Monte-Carlo generator COLLI [37], based on the QGSM and then traced the generated data through the detector and trigger filter (C–Ne and C–Cu).

In the generator COLLI, there are two possibilities to generate events: 1) at unfixed impact parameter $\tilde{b}$ and 2) at fixed b. From the impact parameter distributions, the mean values of b have been obtained: $\langle b \rangle = 2.80$ fm for He–C semicentral collisions, $\langle b \rangle = 2.65$ fm for C–C semicentral collisions, [26] $\langle b \rangle = 2.20$ fm for C–Ne central collisions [24], $\langle b \rangle = 2.75$ fm for C–Cu central collisions [24] and $\langle b \rangle = 6.54$ fm for C–Ta semicentral collisions. For the obtained values of $\langle b \rangle$, total samples of events have been generated. The numbers of generated events are presented in table. From the analysis of generated events, the protons with deep angles greater than $60°$ have been excluded additionally, because such vertical tracks are registered with less efficiency in the experiment. Similarly as for the experimental data, the selection criteria of events have been applied to QGSM events, namely, for the analysis of C–Ne, C–Cu and C–Ta interactions the events with the number of participant protons $N_{\mathrm{part}} \geqslant 6$ and for He–C and C–C collisions respectively $N_{\mathrm{part}} \geqslant 3$ and $N_{\mathrm{part}} \geqslant 4$ have been chosen.

One can see from Figs. 1 and 2 that the QGSM yields flow signature for protons similar to the experimental data and describes quite well the experimental data. The values of F, obtained from the QGSM, are presented in table and superimposed on Fig. 3.

3. TRANSVERSE FLOW OF π^- MESONS

Pions are copiously produced in relativistic heavy-ion collisions. Interesting information about the hot and dense hadronic matter formed transiently during the reaction can be obtained by studying the pions.

In view of the strong coupling between the nucleon and pion, it is interesting to know if pions also have a collective flow behaviour and how the pion flow is related to the nucleon flow.

The emission pattern of pions in the reaction was also studied first at BEVALAC by Streamer Chamber group [38, 39] and later at SATURNE by DIOGENE group in 0.8 GeV/nucleon Ne–nucleus collisions [40] by analyzing the average transverse momentum of pions in the reaction plane as a function of rapidity.

We have studied the flow effects of π^- mesons. The transverse momentum of each π^- meson was projected onto the reaction plane, defined in Sec. 2. The analysis have been performed in c.m.s. in He–C and C–C collisions and in laboratory system in C–Ne, C–Cu and C–Ta collisions, respectively. Figures 4 and 5 show the dependence of $\langle P_x \rangle$ on the rapidity y for π^- mesons in He–C, C–C C–Ne, C–Cu and C–Ta collisions. The straight lines in Figs. 4 and 5 show the results of this fit. The fit was done in the following intervals of y: $-0.9 \div 0.9$ for He–C; $-0.75 \div 0.75$ for C–C; $-0.15 \div 1.2$ for C–Ne; $0.15 \div 1.6$ for C–Cu; $0.0 \div 1.2$ for C–Ta. The values of flow F for π^- mesons for all pairs of nuclei are listed in table. One can see from table and Fig. 3, that the absolute value of F for π^- mesons increases linearly with the increase of mass numbers of projectile (A_P) and target (A_T), similarly as in case of protons and the proton flow is larger, then pion flow. The similar tendency was observed in [40] for π^- and π^+ mesons in Ne–NaF, Ne–Nb and Ne–Pb interactions at 0.8 GeV/nucleon. It is worth mentioning that in our previous papers [24, 26, 28] we have studied the flow effects of π^- mesons in C–C, C–Ne and C–Cu interactions where the reaction plane was defined for the participant protons. The values of flow F for π^- mesons in [24, 28] were: for C–C collisions $F = 22 \pm 6$ MeV; for C–Ne collisions $F = 29 \pm 5$ MeV; C–Cu – $F = -47 \pm 6$ MeV. One can see (table) that the results obtained in [24, 26, 28] are slightly larger than the ones obtained in this work.

One can see from Figs. 4 and 5 that in He–C, C–C and C–Ne collisions $\overrightarrow{P_x}$ for pions is directed in the same direction as for protons, i.e., flows of protons and pions are correlated, while for C–Cu and C–Ta interactions the $\overrightarrow{P_x}$ of π^- mesons is directed oppositely to that of the protons (antiflow).

The experimental results for pions for all pairs of nuclei have been compared with the QGSM. The values of F obtained from QGSM data are listed in table and corresponding distributions are superimposed in Figs. 4 and 5 on experimental ones. The QGSM shows the similar tendency as experimental data and reproduces the experimental results quite well.

The correlation of nucleon and pion flows had been observed experimentally by the DIOGENE group for central Ne–NaF, Ne–Nb and Ne–Pb collisions ($b \leqslant 3$ fm) at an energy of $E = 0.8$ GeV/nucleon [39]. At BEVALAC by Streamer

Chamber group the flow behaviour for pions have been obtained also in Ar–KCl, Ar–Pb and La–La interactions [38]. These results are in agreement with our findings for He–C, C–C and C–Ne. At BEVALAC energy of 1.15 GeV/nucleon the antiflow of π^- and π^+ has been observed by the EOS collaboration [41] in Au–Au collisions, similarly to the observations at AGS energy of 11 GeV/nucleon by the E877 collaboration [15] in Au–Au collisions and at CERN-SPS energy of 158 GeV/nucleon by the WA98 collaboration [20] in semicentral Pb–Pb collisions.

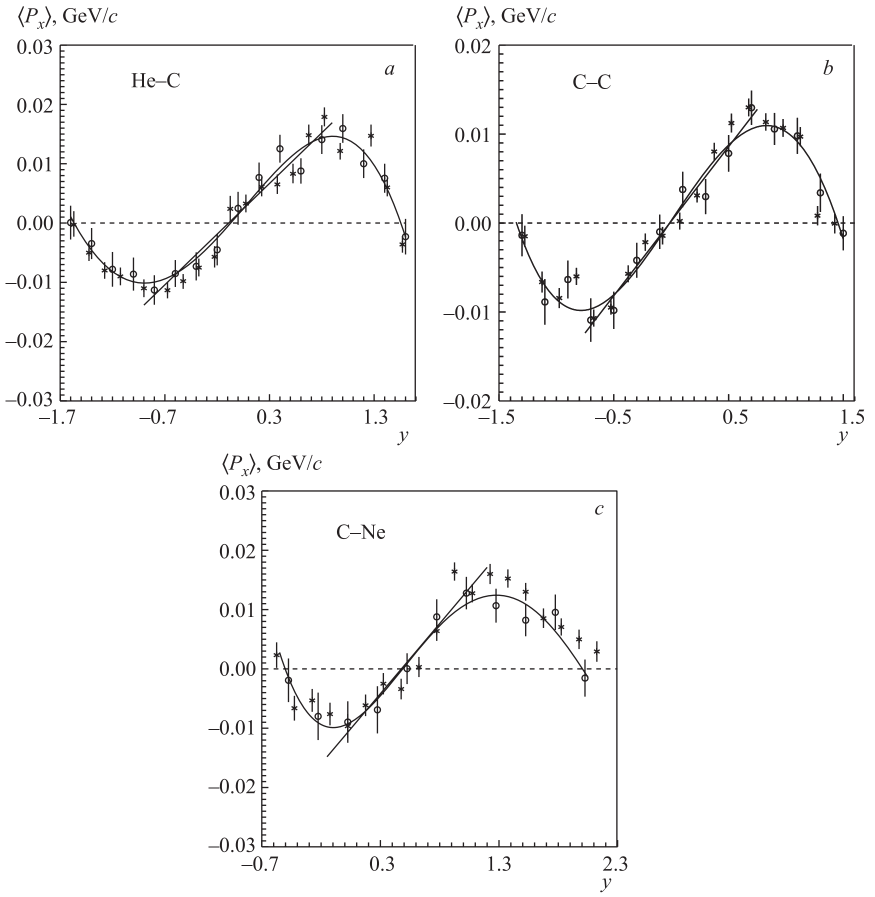

Fig. 4. The dependence of $\langle P_x(y)\rangle$ on y for π^- mesons in He–C (*a*), C–C (*b*) and C–Ne (*c*) collisions in c.m.s. (He–C, C–C) and laboratory (C–Ne) systems. $\circ$ — the experimental data, $*$ — QGSM generated data. The solid lines are the result of the linear approximation of experimental data in the intervals $-0.9 \div 0.9$ for He–C, $-0.75 \div 0.75$ for C–C, $-0.15 \div 1.20$ for C–Ne. The solid curves for visual presentation of experimental events are results of approxomation by 4th-order polynomial

The magnitude of the directed flow in Ref. [20] is found to be significantly smaller than that observed at AGS energies. Thus, it seems that the flow effects for pions decrease with an increase of the energy.

Within the framework of the relativistic transport model (ART 1.0) [42] for heavy-ion collisions at AGS energies, pions are found to have a weak flow behaviour in central collisions. This enhancement in the direction of the baryonic matter for the most central events was attributed to the rescattered pions retaining some momentum from the Δ's from which they decayed. The Δ's exhibited the same flow signature as the final-state nucleons [43].

The origin of the particular shape of the $\overrightarrow{P_x}$ spectra for pions was studied in Refs. [42, 43]. The investigation revealed that the origin of the in-plane transverse momentum of pions is the pion scattering process (multiple πN scattering) [43] and the pion absorption [44]. The $\langle P_x \rangle$ distribution of pions is not a collective effect in the sense of the nucleonic bounce-off: the observable is the same, but the cause is different. The final-pion P_x distribution reflects the complicated reaction dynamics of pion production, reabsorption, rescattering as well as the collective flow of baryon resonances.

The anticorrelation of nucleons and pions was explained in Ref. [43] as due to multiple πN scattering. However, in [42, 44] it was shown that anticorrelation is a manifestation of the nuclear shadowing effect of the target and projectile spectators through both pion rescattering and reabsorptions. Our results indicate that the flow behaviour of π^- mesons in light systems He–C, C–C and C–Ne is

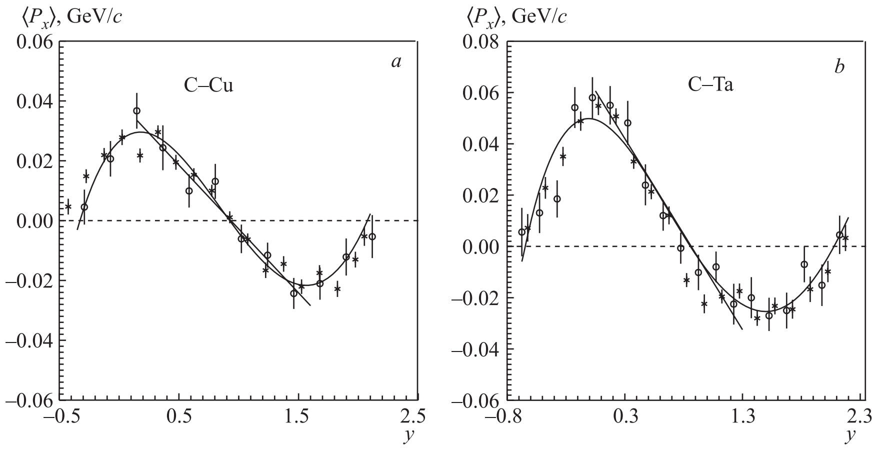

Fig. 5. The dependence of $\langle P_x(y) \rangle$ on y for π^- mesons in C–Cu and C–Ta collisions in laboratory system. $\circ$ — the experimental data, $*$ — QGSM generated data. The solid lines are the result of the linear approximation of experimental data in the intervals $0.15 \div 1.60$ for C–Cu, $0.0 \div 1.25$ for C–Ta. The solid curves for visual presentation of experimental events are results of approxomation by 4th-order polynomial

due to the flow of Δ resonances, whereas the antiflow behaviour in heavier C–Cu and C–Ta systems is the result of the nuclear shadowing effect.

CONCLUSIONS

The collective properties of protons and π^- mesons in He–C, C–C, C–Ne, C–Cu and C–Ta collisions at a momentum of $4.2 \div 4.5$ GeV/c per nucleon ($E = 3.4 \div 3.7$ GeV/nucleon) have been investigated.

1. The directed (in-plane) flow effects of protons and π^- mesons have been investigated. The transverse momentum technique of Danielewicz and Odyniec was used for data analysis. Clear evidence of directed (in-plane) flow effects for protons and π^- mesons has been obtained. From the transverse momentum distributions of protons and π^- mesons with respect to the reaction plane, the flow F (the measure of the collective transverse momentum transfer in the reaction plane) has been extracted. The dependence of F on mass numbers of projectile A_P and target A_T was studied. The absolute value of F increases linearly with the increase of A_P, A_T, from $F = 95\pm8$ MeV for He–C up to $F = 178\pm20$ MeV for C–Ta for protons and from $F = 17 \pm 3$ MeV for He–C up to $F = -74 \pm 6$ MeV for C–Ta for π^- mesons respectively.

In He–C, C–C and C–Ne collisions flows of protons and pions are correlated, while for C–Cu and C–Ta interactions π^- mesons is directed oppositely to that of the protons (antiflow).

Our results indicate that the flow behaviour of π^- mesons in light systems He–C, C–C and C–Ne is due to the flow of Δ resonances, whereas the antiflow behaviour in heavier C–Cu and C–Ta systems is the result of the nuclear shadowing effect.

2. All experimental results have been compared with the predictions of the Quark-Gluon String Model. The model reproduces experimental data quite well.

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