Study of collective matter flow in central C-Ne and C-Cu collisions at energy of 3.7 GeV per nucleon

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The transverse momentum technique is used to analyse charged-particle exclusive data in the central C-Ne and C-Cu interactions at energy of 3.7 GeV per nucleon. The clear evidence of in-plane and out-of-plane (squeeze-out) flow effects for protons and $\pi^-$ mesons have been obtained. In C-Ne interactions the $\pi^-$ mesons in-plane flow is in the same direction to the protons, while in C-Cu collisions pions show antiflow behaviour. From the transverse momentum and azimuthal distributions of protons and $\pi^-$ mesons with respect to the reaction plane the flow $F$ (the measure of the amount of collective transverse momentum transfer in the reaction plane) and the parameter $a_2$ (the measure of the strength of the anisotropic emission) have been extracted. The flow effects increase with the mass of the particle and atomic number of target $A_T$. The comparison of our in-plane flow results with flow data of various projectile/target configurations had been done by a scaled flow $F_S = F/(A_P^{1/3} + A_T^{1/3})$. $F_S$ demonstrates a common scaling behaviour among flow values from different systems.

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One of the main goals of relativistic heavy-ion collisions experiments is to study nuclear matter under extreme conditions of high density and temperatures, i.e. to learn more about the nuclear equation of state (EOS). An increasing number of observables which are accessible through heavy-ion collisions has been found to be sensitive to the EOS. In order to study the EOS, collective effects, such as the bounce-off of cold spectator matter in the reaction plane [1] — the directed transverse flow and the squeeze-out of hot and compressed participant matter perpendicular to the reaction plane [2] – the elliptic flow are frequently used. According to theoretical calculations the studies of flow can provide information on the collision dynamics as well as on a possible phase transition to soft quark matter.

Collective flow is the consequence of the pressure buildup in the high density zone through the short range repulsion between nucleons, i.e. through compressional energy. This effect leads to characteristic, azimuthally asymmetric sidewards emission of the reaction products. While the transverse flow in the reaction plane is influenced by the cold matter deflected by the overlap region of the colliding nuclei, the squeeze out is caused by the hot and compressed matter from the interaction region which preferentially escapes in the direction perpendicular to the reaction plane unhindered by the presence of the projectile and target spectators.

The efforts to determine the EOS and the more general aspect of producing high-energy densities over extended regions have led to a series of experiments to study relativistic nucleus-nucleus collisions at BEVALAC (Berkeley), GSI-SIS (Darmstadt), JINR (Dubna), AGS (Brookhaven National Laboratory) and SPS (CERN).

Using the transverse momentum technique developed by P. Danielewicz and G. Odyniec [3], nuclear collective flow has already been observed for protons, light nuclei, pions and Λ - hyperons emitted in nucleus-nucleus collisions at energies 0.4÷1.8 GeV/nucleon of BEVALAC, GSI-SIS [4-12], at 11÷14 GeV/nucleon of AGS [13,14] and at 158 GeV/nucleon of CERN [15]. The discovery of collective sidewards flow in Au+Au at the AGS was a major highlight at 1995 [14].

In this article we present experimental results obtained from the in and out-plane transverse momentum analysis for protons and π⁻ mesons in central C-Ne and C-Cu interactions at energy E=3.7 GeV per nucleon with the SKM-GIBS set-up of JINR. The signature for collective flow had been obtained. It shows the persistence of collective flow phenomena all the way up to AGS energies. The observed results obtained by streamer chamber technique allow to extend the experimental data available from BEVALAC, GSI-SIS and AGS. These results provide quantitative information on the transverse and out-of-plane (squeeze-out) elliptic flows and their dependence on beam energy and projectile/target mass.

SKM-GIBS 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 beam of C nuclei accelerated in
the synchrophasotron up to energy of 3.7 GeV/nucleon. The thickness of the solid target (of the form of thin disc) – Cu was 0.2 g/cm². Neon gas filling of the chamber also served as a nuclear target. The triggering system allowed the selection of ”inelastic” and ”central” collisions.

The inelastic trigger was selecting all inelastic interactions of incident nuclei on a target. The central trigger was selecting events with no charged projectile spectator fragments (with $P/Z > 3$ GeV/c) within a cone of half angle $\Theta_{ch} = 2.4°$ or $2.9°$ (the trigger efficiency was 99% for events with a single charged particle in the cone). The biases and correction procedures were discussed in detail in ref. [16,17]. The ratio $\sigma_{cent}/\sigma_{inel}$ (that characterizes the centrality of selected events) is - $(9\pm1)$% for C-Ne and $(21\pm3)$% - for C-Cu. In Table 1 the number of events are presented. Average measurement errors of the momentum and production angle determination for protons are $<\Delta P/P>=(8\div10)%$, $\Delta \Theta = 1°\div2°$ and for pions are $<\Delta P/P>=5\%$, $\Delta \Theta = 0.5°$.

The data have been analysed event by event using the transverse momentum technique of P.Danielewicz and G.Odyniec [3]. Using this method, nuclear collective flow for protons has been observed in central C-Ne and C-Cu interactions at a momentum of $P=4.5$ GeV/c/N (E=3.7 GeV/nucl) with the SKM-200 set-up of JINR and presented in our previous paper[18]. The results presented there for protons in C-Cu interactions are obtained on a statistics two times larger than in [18] and both results for C-Ne and C-Cu collisions are represented in terms of the normalized rapidity $y/y_p$ ($y_p$– projectile rapidity, $y_p=2.28$) in the laboratory system unlike of [18]. P.Danielewicz and G.Odyniec have proposed an exclusive way to analyse the momentum contained in directed sideards emission and present the data in terms of the mean transverse momentum per nucleon in the reaction plane $<P_x(Y)>$ as a function of the rapidity. The vector $\bar{Q}_j = \sum_{i \neq j} \omega_i \bar{P}_{i,j}$ was used for the reaction plane (the reaction plane is the plane containing $\bar{Q}_j$ and the beam axis) determination of each event, where $P_{i,j}$ is the transverse momentum of particle $i$, and $n$ is the number of particles in the event. Pions are not included. The weight $\omega_i$ is the function $\omega_i = y_i - <y>$ as in [9], where $<y>$ is the average rapidity, calculated for each event over all the participant protons, i.e. protons which are not fragments of the projectile ($P/Z > 3$ GeV/c, $\Theta < 4°$) and target ($P < 0.2$ GeV/c). The average multiplicities of analysed protons $<N_p>$ are listed in Table 1. The transverse momentum of each particle in the estimated reaction plane is calculated as $P_{xj}' = (\bar{Q}_j \cdot \bar{P}_{i,j}||\bar{Q}_j$.

The average transverse momentum $<P_x'(Y)>$ is obtained by averaging over all events in the corresponding intervals of rapidity.

For the event by event analysis it is necessary to perform an identification of $\pi^+$ mesons, the admixture of which amongst the charged positive particles is about $(25\div27)\%$. The identification has been carried out on the statistical basis using the two-dimentional ( $P_{||}$, $P_{\perp}$)
distribution. It had been assumed, that \( \pi^- \) and \( \pi^+ \) mesons hit a given cell of the plane \((P_\parallel, P_\perp)\) with equal probability. The difference in multiplicity of \( \pi^+ \) and \( \pi^- \) in each event was required to be no more than 2. After this procedure the admixture of \( \pi^+ \) is not exceeding \((5\div7)\%\). The temperature of the identified protons agrees with our previous result \([19]\), obtained by the subtraction method of spectra.

It is known \([4]\), 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 then the component \( P'_x \) in the estimated plane, hence \(<P_x> = <P'_x> / <\cos\varphi>\), where \( \varphi \) is the angle between the estimated and true planes. The correction factor \( K = 1 / <\cos\varphi> \) is subject to a large uncertainty, especially for low multiplicity. For the definition of \(<\cos\varphi>\) according to \([3]\), we divided randomly each event into two equal sub-events. The values of \( K \), averaged over all the multiplicities, are: \( K = 1.27 \pm 0.08 \) — for C-Ne, \( K = 1.31 \pm 0.04 \) — for C-Cu.

Fig.1 show the dependence of \(<P_x>\) on the normalized rapidity \(y/y_p\) in the laboratory system for protons and pions in C-Ne (Fig.1.a) and C-Cu (Fig.1.b) collisions. For protons the data points are already corrected (multiplied by \( K \)) for the deviation from the true reaction plane. The data exhibit the typical \( S \)-shape behaviour which demonstrates the collective transverse momentum transfer between the forward and backward hemispheres.

From the mean transverse momentum distributions we can extract an observable – the transverse flow \( F = <P_x>/d(y/y_p) \), i.e. the slope of the momentum distribution at midrapidity. It is a measure of the amount of collective transverse momentum transfer in the reaction. Technically \( F \) is obtained by fitting the central part of the dependence of \(<P_x>\) on \(y/y_p\) by the first order polynomial function, this coefficient is the flow \( F \). The fit was done for \(y/y_p\) between 0.01 \(\div\) 0.90. The straight lines in Fig.1 show the results of this fit. The values of \( F \) are listed in Table 1. We have analysed the influence of the admixture of ambiguously identified \( \pi^+ \) mesons on the results. The error in flow \( F \) includes the statistical and systematical errors. One can see from the Table 1, that with the increase of the atomic number of the target \( A_T \), the value of \( F \) increases. A similar tendency had been observed at lower energies \([4\text{-}7,10]\).

It is of great interest to compare the flow values for a wide range of data. A way of comparing the energy dependence of flow values for different projectile/target mass combinations was suggested by A.Lang et al \([20]\) and first used by J.Chance in \([10]\). To allow for different projectile/target \((A_P,A_T)\) mass systems, they divided the flow values by \( (A_{1/3}^P + A_{1/3}^T) \) and called \( F_S = F/(A_{1/3}^P + A_{1/3}^T) \) the scaled flow.

Fig.2 shows a plot of \( F_S \) versus energy per nucleon of the projectile. We have included our data, the data from the EOS \([10,21]\), E-895, E-877 \([21]\), FOPI \([12]\) experiments along with the values derived from the Plastic Ball \([7,11]\) and the Streamer Chamber \([4,9]\) experiments for a variety of energies and mass combinations. The values of flow \( F \) for E-895, E-877 are
taken from Fig.5 of [21]. Then these values are recalculated in terms of $F_S$. For the EOS and the Plastic Ball data all the isotopes of $Z=1$ and 2 are included, except for [11] where the data is for $Z=1$. The Streamer Chamber data [4,9] normally include all protons, whether free or bound in clusters as in our case. In Fig.2 the scaled flow values $F_S$ follow, within the uncertainties, a common trend with an initial steep rise and then an indication of a gradual decrease. It is worth to mention, that the data obtained by streamer chamber technique (including our results) are somewhat (slightly) larger than ones obtained by the electronic experiments. This is caused may be by the small mixture of bounded protons (deutons, $^3H$, $^4He$).

In our previous paper [18] the collective flow for the protons in C-Ne and C-Cu interactions have been compared with the predictions of the Quark Gluon String Model (QGSM). The QGSM reproduced the experimental results, but underestimated the values of flow $F$.

In view of the large number of pions created at our energies and reactions and the strong coupling between the nucleon and pion, it is interesting to know if pions also have a collective flow behaviour and if yes, how the pion flow is related to the nucleon flow.

For this purpose the reaction plane have been obtained by (over) the protons and the transverse momentum of each $\pi^-$ meson have been projected onto this reaction plane. Fig.1 show the dependence of $<P_x>$ on the normalized rapidity $y/y_p$ in the laboratory system for $\pi^-$ mesons in C-Ne and C-Cu collisions. The data exhibit the typical S-shape behaviour as for the protons. The values of flow $F$ for $\pi^-$ mesons are: for C-Ne collisions $F = 29 \pm 5$ MeV; for C-Cu $F = -47 \pm 6$ MeV. The straight lines in Fig.1 show the results of this fit. The fit was done in the following intervals of $y/y_p$: 0.04 $\div$ 0.7 for C-Ne; -0.06 $\div$ 0.6 for C-Cu. The absolute value of $F$ increases with the atomic number of target $A_T$, which indicates on the rise of collective flow effect. The similar tendency have been obtained in [8] for $\pi^-$ and $\pi^+$ mesons in Ne-Naf, Ne-Nb and Ne-Pb interactions at 800 MeV/nucleon energy.

One can see from the Fig.1, that for C-Ne collisions the $\vec{P}_x$ of the pions is directed in the same direction as protons i.e. flow of protons and pions are correlated, while for C-Cu interactions the $\vec{P}_x$ of $\pi^-$ mesons is directed oppositely to that of the protons (antiflow).

At AGS energy of 11 GeV/nucleon [22] have been obtained that the flow of $\pi^+$ mesons is in the direction opposite to the protons, similar to observations in semi-central Pb-Pb collisions at energy 158 GeV/nucleon in WA98 collaboration at SPS CERN [15]. The magnitude of the directed flow in [15] is found to be significantly smaller than observed at AGS energies. Thus it seems that the flow effects for the pions decreases with the increasing the energy. Theoretical calculations using the Isospin Quantum Molecular Dynamics (IQMD) model have predicted [23] the existence of pion antiflow at projectile- and target rapidities for Au-Au collisions at GSI-SIS energies – 1 GeV/nucleon. On the other hand within the framework of the relativistic transport model (ART 1.0) [24] for heavy-ion collisions (Au-Au) at AGS
energies, pions are found to have a weak flow behaviour.

The origin of the particular shape of the $\vec{P}_x$ spectra for pions had been studied in [23-26]. The investigation revealed, that the origin of the in-plane transverse momentum of pions is the pion scattering process (multiple $\pi N$ scattering) [23] and the pion absorption [25,26]. However in [24] had been found, that the pions show a weak flow behaviour in central collisions due to the flow of baryon resonances from which they are produced.

The anticorrelation of nucleons and pions in [23] was explained as due to multiple $\pi N$ scattering. However in [24,26] it had been shown, that the anticorrelation is a manifestation of the nuclear shadowing effect of the target- and projectile-spectator through both pion rescattering and reabsorptions. In our opinion, our results indicate, that the flow behaviour of $\pi^-$ mesons in light system – C-Ne is due to the flow of $\Delta$ resonances, whereas the antiflow behaviour in C-Cu collisions is the result of the nuclear shadowing effect.

The preferential emission of particles in the direction perpendicular to the reaction plane (i.e. "squeeze-out") is particularly interesting since it is only way where nuclear matter might escape without being rescattered by spectator remnants of the projectile and target and is expected to provide direct information on the hot and dense participant region formed in high energy nucleus-nucleus interactions. This phenomenon, predicted by hydrodynamical calculations [2], has been clearly identified in the experiments [27] by the observation of an enhanced out-of-plane emission of protons, mesons and charged fragments. For beam energies of $1 \div 11$ GeV/nucleon the elliptic flow results from a strong competition between the early "squeeze-out" and the late stage "in-plane flow" [28]. The magnitude and the sign of elliptic flow depend on two factors: a) the pressure built up in the compression stage compared to the energy density and b) the passage time of the projectile and target spectators.

In order to extend these investigations, the azimuthal $\phi$ ( $cos\phi = P_x/P_t$) distributions of the pions and protons with respect to the reaction plane have been studied. The angle $\phi$ is the relative azimuthal angle between the true reaction plane and the emitted particle. To select particles emitted from the participant zone, the analysis was restricted only to the mid-rapidity region by applying a cut around the center of mass rapidity. Fig.3 show respective distributions for protons and $\pi^-$ mesons in C-Ne (Fig.3.a) and C-Cu (Fig.3.b) collisions. For visual representation the data of C-Cu are shifted up. For $\pi^-$ mesons the analysis was performed from 0 to 180° due to the lower (smaller) statistics then for the protons. The azimuthal angular distributions for the protons and pions show a maxima at $\phi=90^\circ$ and $270^\circ$ with respect to the event plane. This maxima is associated with preferential particle emission perpendicular to the reaction plane (squeeze-out, or elliptic flow). Thus a clear signature of an out-of plane signal is evidenced.

To treat the data in a quantitative way the azimuthal distributions had been fitted by Fourier series: $dN/d\phi = a_0(1 + a_1cos\phi + a_2cos2\phi)$
The anisotropy factor $a_2$ is negative for out-of-plane enhancement (squeeze-out) and is the measure of the strength of the anisotropic emission. The values of the coefficients $a_2$ extracted from the azimuthal distributions of protons and $\pi^-$ mesons are presented in Table 2. The fitted curves are superimposed on the experimental distributions (Fig.3).

The values $a_2$ are used to quantify the ratio $R$ of the number of particles emitted perpendicular to the number of particles emitted in the reaction plane, which represents the magnitude of the out-of-plane emission signal: $R = (1 - a_2)/(1 + a_2)$. A ratio $R$ larger than unity implies a preferred out-of-plane emission. The values of $R$ are listed in Table 2 respectively. One can see from Table 2, that the $a_2$ and $R$ increases both for protons and $\pi^-$ mesons with: narrowing the cut applied around the center of mass rapidity (protons in C-Cu interactions); increasing the transverse momentum and the atomic number of target $A_T$. The squeeze-out effect is more pronounced for protons than for $\pi^-$ mesons. Our results concerning rapidity, mass and transverse momentum dependence of the azimuthal anisotropy are consistent with analysis from the Plastic Ball, FOPI, Kaos, TAPS [27,29] collaborations and are confirmed by IQMD calculations [30].

In the experiments (E-895, E-877, EOS) [31] at AGS and SPS (CERN) (NA49) energies the elliptic flow is typically studied at midrapidity and quantified in terms of the second Fourier coefficient $v_2 \approx <\cos 2\phi >$. The Fourier coefficient $v_2$ is related to $a_2$ via the equation $v_2 = a_2/2$. We have estimated $v_2$ for C-Ne and C-Cu. The dependence of the elliptic flow excitation function (for protons) on energy $E_{lab}$ is displayed in Fig.4. Recent calculations have made specific predictions for the beam energy dependence of elliptic flow for Au-Au collisions at $1 \div 11$ GeV/nucleon [28]. They indicate a transition from negative to positive elliptic flow at a beam energy $E_{tr}$, which has a marked sensitivity to the stiffness of the EOS. In addition, they suggest that a phase transition to the Quark-Gluon Plasma (QGP) should give a characteristic signature in the elliptic flow excitation function due to the significant softening of the EOS. One can see from Fig.4, that the excitation function $v_2$ clearly shows an evolution from negative to positive elliptic flow within the region $2 \leq E_{beam} \leq 8$ GeV/nucleon and point to an apparent transition energy $E_{tr} \sim 4$ GeV/nucleon.

In summary, in this paper we have reported experimental results, presented in terms of the mean transverse momentum per nucleon projected onto the reaction plane $< P_x >$ as a function of the normalized rapidity $y/y_p$ in laboratory system. We have determined the flow $F$, defined as the slope at midrapidity. The $F$ increases with the mass of the particle and atomic number of target $A_T$. In C-Ne interactions the $\pi^-$ mesons flow is in the same direction to the protons, while in C-Cu collisions pions show antiflow behaviour. The comparison of our in-plane flow results with flow data of various projectile/target configurations have been done by a scaled flow $F_S = F/(A_p^{1/3} + A_T^{1/3})$. $F_S$ demonstrates a common scaling behaviour among flow values from different systems. From the azimuthal distributions of protons and $\pi^-$ mesons with respect to the reaction plane at mid-rapidity region a clear signature of an
out-of-plane flow (squeeze-out) have been obtained. The azimuthal distributions have been parametrized by second order Fourier series and the parameter $a_2$ of the anisotropy term $a_2 \cos 2\phi$ have been extracted. The $R = (1 - a_2)/(1 + a_2)$ ratio have been calculated. The squeeze-out effect increases with the transverse momentum, atomic number of target $A_T$ and also by narrowing the applied cut around the center mass rapidity. It is more pronounced for protons than for $\pi^-$ mesons.

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FIGURE CAPTIONS

Fig.1 The dependence of $< P_x >$ on the normalized rapidity $y/y_p$ in the laboratory system in C-Ne (a) and C-Cu (b) collisions. $\circ$ – for protons, $\triangle$ – for $\pi^-$ mesons. The lines are the result of the approximation of experimental data of protons and $\pi^-$ mesons by first order polynom in the interval of $0.01 \leq y/y_p \leq 0.90$ for protons (C-Ne, C-Cu) and $0.04 \leq y/y_p \leq 0.70$ (C-Ne), $-0.06 \leq y/y_p \leq 0.60$ (C-Cu) for $\pi^-$ mesons. The curves for visual presentation - result of approximation data by 4-th order polynoms.

Fig.2 Scaled flow values versus beam energy per nucleon for different projectile/target systems. $\blacksquare$ – Nb-Nb Plastic Ball $\triangle$ – Au-Au Plastic Ball, $\circ$ – Ni-Ni FOPI, $\bullet$ – Ni-Cu EOS, $+$ – Au-Au EOS, $\oplus$ – Ni-Au EOS, $\star$ – Ar-Pb Streamer Chamber, the value at $E=1.08$ AGeV represents Ar-KCl Streamer Chamber, $\circ$ – C-Ne, C-Cu our result, $\star$ – Au-Au E-895, the value at $E=10$ AGeV represents Au-Au from E-877. To improve the distinction between data points at the same beam energy, some of the beam energy values have been shifted.

Fig.3 The azimuthal distributions with respect to the reaction plane of mid rapidity protons $dN/d\phi$ (a) and $\pi^-$ mesons (b). $\circ$ – for C-Ne ($-1 \leq y_{cm} \leq 1$), $\triangle$ – for C-Cu ($-1 \leq y_{cm} \leq 1$) interactions. The curves — result of approximation by $dN/d\phi = a_0(1 + a_1\cos\phi + a_2\cos^2\phi)$.

Fig.4 The dependence of the elliptic flow excitation function $v_2$ on energy $E_{lab}/A$ (GeV). $\star$ – FOPI, $\circ$ – MINIBALL, $\bullet$ – EOS, $\blacksquare$ – E-895, $\times$ – E-877, $\oplus$ – NA49, $\triangle$ – C-Ne, C-Cu our results.
Table 1. The number of experimental events, the average multiplicity of participant protons $< N_p >$, the correction factor $K$ and the flow $F$ for protons and $\pi^-$ mesons.

Table 2. The values of the parameter $a_2$ and the ratio $R$ for protons and $\pi^-$ mesons extracted from the azimuthal distributions fitted by $dN/d\phi = a_0(1 + a_1 \cos \phi + a_2 \cos 2\phi)$. 
Table 1. The number of experimental events, the average multiplicity of participant protons $< N_p >$, the correction factor $K$ and the flow $F$ for protons and $\pi^-$ mesons.

|                         | C-Ne   | C-Cu   |
|-------------------------|--------|--------|
| Number of exper. events | 723    | 667    |
| $< N_p >$               | 12.4 ± 0.5 | 19.5 ± 0.6 |
| $K = 1/ < \cos \varphi >$ | 1.27 ± 0.08 | 1.31 ± 0.04 |
| $F$ for protons (MeV/c) | 134 ± 12 | 198 ± 13 |
| $F$ for $\pi^-$ mesons (MeV/c) | 29 ± 5   | -47 ± 6  |
Table 2. The values of the parameter $a_2$ and the ratio $R$ for protons and $\pi^-$ mesons extracted from the azimuthal distributions fitted by $dN/d\phi = a_0(1 + a_1 \cos \phi + a_2 \cos 2\phi)$.

| $A_p - A_T$ | Particle | Applied Cut | $a_2$       | $R$        |
|------------|----------|-------------|-------------|------------|
| C-Ne       | Protons  | $-1 \leq y_{cm} \leq 1$ | -0.049±0.014 | 1.10±0.03  |
|            |          | $-1 \leq y_{cm} \leq 1$; $P_T \geq 0.3$ GeV/c | -0.074±0.014 | 1.16±0.04  |
|            | $\pi^-$ mesons | $-1 \leq y_{cm} \leq 1$ | -0.035±0.013 | 1.07±0.04  |
|            |          | $-1 \leq y_{cm} \leq 1$; $P_T \geq 0.1$ GeV/c | -0.050±0.014 | 1.09±0.03  |
| C-Cu       | Protons  | $-1 \leq y_{cm} \leq 1$ | -0.065±0.014 | 1.14±0.04  |
|            |          | $-1 \leq y_{cm} \leq 1$; $P_T \geq 0.3$ | -0.081±0.014 | 1.18±0.05  |
|            |          | $-0.6 \leq y_{cm} \leq 0.6$ | -0.077±0.017 | 1.17±0.04  |
|            |          | $-0.6 \leq y_{cm} \leq 0.6$; $P_T \geq 0.3$ | -0.088±0.020 | 1.19±0.06  |
|            | $\pi^-$ mesons | $-1 \leq y_{cm} \leq 1$ | -0.041±0.013 | 1.08±0.03  |
|            |          | $-1 \leq y_{cm} \leq 1$; $P_T \geq 0.1$ GeV/c | -0.056±0.015 | 1.12±0.04  |
Figure 1: The dependence of $< P_x >$ on the normalized rapidity $y/y_p$ in the laboratory system in C-Ne (a) and C-Cu (b) collisions. $\circ$ – for protons, $\triangle$ – for $\pi^-$ mesons. The lines are the result of the approximation of experimental data of protons and $\pi^-$ mesons by first order polynomials in the interval of $0.01 \leq y/y_p \leq 0.90$ for protons (C-Ne, C-Cu) and $0.04 \leq y/y_p \leq 0.70$ (C-Ne), $-0.06 \leq y/y_p \leq 0.6$ (C-Cu) for $\pi^-$ mesons. The curves for visual presentation - result of approximation data by 4-th order polynomials.
Figure 2: Scaled flow values versus beam energy per nucleon for different projectile/target systems. × – Nb-Nb Plastic Ball, △ – Au-Au Plastic Ball, ○ – Ni-Ni FOPI, • – Ni-Cu EOS, + – Au-Au EOS, ⊕ – Ni-Au EOS, ⋆ – Ar-Pb Streamer Chamber, the value at E=1.08 AGeV represents Ar-KCl Streamer Chamber, ⋉ – C-Ne, C-Cu our result, ∗ – Au-Au E-895, the value at E=10 AGeV represents Au-Au from E-877. To improve the distinction between data points at the same beam energy, some of the beam energy values have been shifted.
Figure 3: The azimuthal distributions with respect to the reaction plane of midrapidity protons $dN/d\phi$ (a) and $\pi^-$ mesons (b). $\circ$ — for C-Ne ($-1 \leq y_{cm} \leq 1$), $\triangle$ — for C-Cu ($-1 \leq y_{cm} \leq 1$) interactions. The curves — result of approximation $dN/d\phi = a_0(1 + a_1\cos\phi + a_2\cos2\phi)$. 

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Figure 4: The dependence of the Elliptic flow excitation function $v_2$ on energy $E_{\text{lab}}/A$ (GeV). $\star$ – FOPI, $\circ$ – MINIBALL, $\bullet$ – EOS, $\diamond$ – E-895, $\times$ – E-877, $\oplus$ – NA49, $\triangle$ – C-Ne, C-Cu our results.