RESULTS FROM SKM-200-GIBS ON MULTIPARTICLE AZIMUTHAL CORRELATIONS IN C-Ne AND C-Cu COLLISIONS AT ENERGY OF 3.7 GeV PER NUCLEON

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ABSTRACT

• 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. 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 in-plane flow of $\pi^-$ mesons is in the same direction as for 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 collective transverse momentum transfer in the reaction plane) and the parameter $a_2$ (the measure of the anisotropic emission strength) have been extracted. The flow effects increase with the mass of the particle and the mass number of target $A_T$.

• The comparison of our in-plane flow results with flow data for various projectile/target configurations was made using the scaled flow $F_S = F / (A_p^{1/3} + A_T^{1/3})$. $F_S$ demonstrates a common scaling behaviour for flow values from different systems.

• The Quark Gluon String Model (QGSM) was used for the comparison with the experimental data. The QGSM yields a signature of in-plane and out-of-plane flow effects in C-Ne and C-Cu collisions for protons.
One of the main goals of relativistic heavy-ion collision experiments is to study nuclear matter under extreme conditions of high densities 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 directed transverse flow (the bounce-off of cold spectator matter in the reaction plane) [1] and the elliptic flow (the squeeze-out of hot and compressed participant matter perpendicular to the reaction plane) [2], are frequently used. According to theoretical calculations, flow studies 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 build-up in the high density zone through the short range repulsion between nucleons, i.e. through compressional energy. This effect leads to characteristic, azimuthally asymmetric sideward 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 densities over extended regions have led to a series of experiments studying 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 the energies of 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 sideward flow in Au+Au at the AGS was a major highlight of 1995 [14].

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 E=3.7 GeV per nucleon. Data were obtained on the SKM-GIBS set-up at JINR. The obtained signature shows the persistence of collective flow phenomena all the way up to AGS energies. Our results, obtained by streamer chamber technique, provide quantitative information on the transverse and out-of-plane (squeeze-out) elliptic flows and their dependence on beam energy and projectile/target mass complementing the experimental data available from BEVALAC, GSI-SIS and AGS.

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 the beam of C nuclei accelerated in the synchrophasotron up to the energy of 3.7 GeV/nucleon. The thickness of the solid target in the shape of a thin Cu disc was 0.2 g/cm². Neon gas filling the chamber also served as a nuclear target. The experimental set-up and the logic of the triggering system are presented in Fig.1 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 Θ_{ch} = 2.4° or 2.9°. The trigger efficiency for events with a single charged particle in the cone was 99% The biases and
correction procedures were discussed in detail in Refs. [16,17]. The ratio $\sigma_{\text{cent}}/\sigma_{\text{inel}}$ that characterizes the centrality of selected events is - (9±1)% for C-Ne and (21±3)% - for C-Cu. In Table 1 the number of events is presented. Average measurement errors of the momentum and production angles are: for protons $\langle \Delta P/P \rangle = (8\div 10)\%$, $\Delta \Theta = 1^0 \div 2^0$; for pions $\langle \Delta P/P \rangle = 5\%$, $\Delta \Theta = 0.5^0$.

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 at JINR and described in detail elsewhere [18]. The results for protons in C-Cu interactions presented here are obtained on a statistics twice as large as in [18]. Results for both C-Ne and C-Cu collisions are presented in terms of the normalized rapidity in the laboratory system $y/y_p$ where $y_p=2.28$ is the projectile rapidity. P.Danielewicz and G.Odyniec have proposed to present the data in terms of the mean transverse momentum per nucleon in the reaction plane $< P_x(Y) >$ as a function of rapidity. The vector

$$\vec{Q}_j = \sum_{i\neq j}^n \omega_i \vec{P}_{\perp i}$$

was used for the reaction plan for each event. The reaction plane is the plane containing $\vec{Q}_j$ and the beam axis, where $P_{\perp i}$ is the transverse momentum of particle $i$, and $n$ is the number of particles in the event. Pions were not included. The weight $\omega_i = y_i - < y >$ [9], where $< y >$ is the average rapidity of the participant protons, calculated for each event. The participant protons are those which are neither projectile nor target fragments. 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

$$P_{xj}' = \{ \vec{Q}_j \cdot \vec{P}_{\perp j} / |\vec{Q}_j| \}$$

The average transverse momentum $< P_{xj}'(Y) >$ 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±27)%. The identification has been carried out on the statistical basis using the two-dimensional ($P_{\parallel}$, $P_{\perp}$) distribution. It was assumed, that $\pi^-$ and $\pi^+$ mesons hit a given cell in the plane ($P_{\parallel}$, $P_{\perp}$) with equal probability. The difference in multiplicities of $\pi^+$ and $\pi^-$ in each event was required to be no more than 2. After this procedure the admixture of $\pi^+$ did not exceed (5±7)%. The temperature of the identified protons agrees with our previous result [19], obtained by the method of spectra subtraction.

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 than 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. In order to determine $< \cos \varphi >$ according to [3], we divided each event randomly into two equal sub-events and calculated vectors $\vec{Q}$ for each of these sub-events. Then $\varphi$ was estimated as the angle between these two vectors. The values of $K$ averaged over all multiplicities are: $K = 1.27 \pm 0.08$ for C-Ne, $K = 1.31 \pm 0.04$ for C-Cu.
Figs. 2, 3 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. 2) and C-Cu (Fig. 3) collisions. For protons the data points are multiplied by the factor $K$ described above to correct 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.

Based on the mean transverse momentum distributions we can extract an observable – the transverse flow $F = < P_x > / d(y/y_p)$, 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 $y/y_p$ with a linear function, with the slope equal to the flow $F$. The fit was done for $y/y_p$ between 0.01 ÷ 0.90. The straight lines in Figs. 2, 3 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, and the quoted error in the flow $F$ includes both the statistical and systematical uncertainties. One can see from the Table 1, that with the increase of the mass number of the target $A_T$ the value of $F$ increases. A similar tendency was observed at lower energies [4-7,10].

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 $(A_P^{1/3} + A_T^{1/3})$ and called $F_S = F / (A_P^{1/3} + A_T^{1/3})$ the scaled flow.

Fig. 4 shows a plot of $F_S$ versus the projectile energy per nucleon. Fig. 4 presents our results and 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] and 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 are given only for $Z=1$. The Streamer Chamber data [4,9] normally include all protons, whether free or bound in clusters as in our case. The scaled flow $F_S$ follows, within the uncertainties, a common trend with an initial steep rise and then a gradual decrease. It is worth noting that the data obtained by streamer chamber technique (including our results) are slightly higher than those obtained by the electronic experiments. This may be caused by a small mixture of bound protons (deutons, $^3H$, $^4He$).

Several theoretical models of nucleus-nucleus collisions at high energy have been proposed [22]. The Quark Gluon String Model (QGSM) [23] was used for a comparison with experimental data. The QGSM is based on the Regge and string phenomenology of particle production in inelastic binary hadron collisions [24]. The QGSM simplifies the nuclear effects (neglects the potential interactions between hadrons, coalescence of nucleons and etc.). A detailed description and comparison of the QGSM with experimental data in a wide energy range can be found in paper [25]. The model yields a generally good overall fit to most experimental data [25].

We have generated C-Ne and C-Cu interactions using Monte-Carlo generator COLLI, based on the QGSM and then traced through the detector and trigger filter.

In the generator COLLI there are two possibility to generate events: 1) at not fixed impact parameter $b$ and 2) at fixed $b$. From the $b$ distributions we obtained the mean values $< b > = 2.20$ fm for C-Ne collisions and $< b > = 2.75$ fm for C-Cu and total samples
of events for these \(< b >\) had been generated (Table.1). The QGSM overestimates the production of low momentum protons with \( P < 0.2 \text{ GeV/c} \), which are mainly the target fragments and were excluded from the analysis. From the analysis of generated events the protons with deep angles greater \( 60^\circ \) had been excluded, because such vertical tracks are registered with less efficiency on the experiment. The QGSM yields a significant flow signature for protons, which follows trends similar to the experimental data Figs 2,3. The values of \( F \), obtained from the QGSM for protons are listed in Table 1. One can see, that the QGSM slightly overestimates the flow for C-Ne and underestimates for C-Cu. This model underestimates also the transverse flow at BEVALAC energies (1.8 GeV/n) [3,4]. As shown by H.Stocker and Greiner [26], the reason that the QGSM fails to reproduce the flow data in the energy region of 1÷5 GeV/n, is the negligence of mean-field effects.

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.

For this purpose the reaction plane was defined for the participant protons, and the transverse momentum of each \( \pi^- \) meson have been projected onto this reaction plane. Figs. 2,3 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 \( F = 29 \pm 5 \text{ MeV} \); for C-Cu — \( F = -47 \pm 6 \text{ MeV} \). The straight lines in Fig. 2,3 show the results of this fit. The fit was done in the following intervals of \( y/y_p \): 0.04 ÷ 0.7 for C-Ne ; -0.06 ÷ 0.6 for C-Cu . The absolute value of \( F \) increases with the mass number of target \( A_T \), indicating the rise of the collective flow effect. The similar tendency was observed 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 Fig.2,3, that for C-Ne collisions the \( \vec{P}_x \) for pions is directed in the same direction as for protons i.e. flows of protons and pions are correlated, while for C-Cu interactions the \( \vec{P}_x \) of \( \pi^- \) mesons is directed oppositely to that of the protons (antiflow). As obtained in Ref. [27], at AGS energy of 11 GeV/nucleon the flow of \( \pi^+ \) mesons is in the direction opposite to the protons, similarly to the 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 that observed at AGS energies. Thus, it seems that the flow effects for pions decrease with increased energy. Theoretical calculations in the framework of the Isospin Quantum Molecular Dynamics (IQMD) model have predicted [28] 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) [29] 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 was studied in [28-31]. The investigation revealed that the origin of the in-plane transverse momentum of pions is the pion scattering process (multiple \( \pi N \) scattering) [28] and the pion absorption [30,31]. However, in [29] it was found that 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 was explained in [28] as due to multiple \( \pi N \) scattering. However, in [29,31] 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. 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 the only way the 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], was clearly identified in the experiments [32] by observation of an enhanced out-of-plane emission of protons, mesons and charged fragments.

In order to extend these investigations, we have studied the azimuthal angular distributions ($\phi$) of the pions and protons. The angle $\phi$ is the angle of the transverse momentum of each particle in an event with respect to the reaction plane ($\cos\phi = P_x/P_t$). The analysis was restricted only to the mid-rapidity region by applying a cut around the center of mass rapidity. Figs. 5,6 show distributions for protons and $\pi^-$ mesons in C-Ne Fig.5 and C-Cu collisions Fig.6. For visual presentation the data on C-Cu were shifted upwards. For $\pi^-$ mesons the analysis was performed from 0 to $180^0$ due to lower statistics than for protons. The azimuthal angular distributions for the protons and pions show a maxima at $\phi=90^0$ and $270^0$ with respect to the event plane. This maxima are 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 were fitted by polynomial:

$$dN/d\phi = a_0 (1 + a_1 \cos\phi + a_2 \cos^2\phi)$$

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 coefficient $a_2$ extracted from the azimuthal distributions of protons and $\pi^-$ mesons are presented in Table 2. The fitted curves are superimposed on the experimental distributions (Figs.5,6). The QGSM data for protons in C-Ne and C-Cu collisions are also superimposed in Fig.5 and the values of $a_2$ are listed in Table 2. One can see, that the model describes the experimental azimuthal distributions.

The values of $a_2$ are used to quantify the ratio $R$ of the number of particles emitted in the perpendicular direction 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. One can see that $a_2$ and $R$ are increasing, both for protons and $\pi^-$ mesons, with increasing the transverse momentum and the mass number of target $A_T$ and also with narrowing of the cut applied around the center of mass rapidity. The squeeze-out effect is more pronounced for protons than for $\pi^-$ mesons. Our results on rapidity, mass and transverse momentum dependence of the azimuthal anisotropy are consistent with analyses from Plastic Ball, FOPI, Kaos, TAPS [32,33] collaborations and are confirmed by IQMD calculations [34]. In experiments (E-895, E-877, EOS) [36] at AGS and SPS (CERN) (NA49) energies the elliptic flow is typically studied at midrapidity and quantified in terms of the second Fourier coefficient $v_2 = <\cos 2\phi>$. The Fourier coefficient $v_2$ is related to $a_2$ via $v_2 \approx a_2/2$. We have estimated $v_2$ both for C-Ne and C-Cu. The dependence of the elliptic flow excitation function (for protons) on energy $E_{lab}$ is displayed in Fig.7. Recent calculations have made specific predictions for the beam energy dependence of elliptic flow for Au-Au collisions at $1 \div 11$ GeV/nucleon [33]. 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.7, that the excitation function $v_2$ clearly shows an evolution from negative to positive elliptic flow within the region $2 \leq E_{\text{beam}} \leq 8 \text{ GeV/nucleon}$ and point to an apparent transition energy $E_{tr} \sim 4 \text{ GeV/nucleon}$.
SUMMARY

- We have reported experimental results, presented in terms of the mean transverse momentum per nucleon projected onto the reaction plane, 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. $F$ increases with the mass of the particle and mass number of target $A_T$.
- In C-Ne interactions flow of $\pi^-$ mesons is in the same direction as that of the protons, while in C-Cu collisions pions show the antiflow behaviour. The comparison of our in-plane flow results with flow data for various projectile/target configurations was made using the scaled flow $F_S = F/(A_{P}^{1/3} + A_{T}^{1/3})$. $F_S$ demonstrates a common scaling behaviour for flow values from different systems.
- A clear signature of an out-of-plane flow (squeeze-out) have been obtained from the azimuthal distributions of protons and $\pi^-$ mesons with respect to the reaction plane at mid-rapidity region.
- Azimuthal distributions have been parametrized by a second order polynomial function, and the parameter $a_2$ of the anisotropy term $a_2 \cos 2\phi$ have been extracted. The ratio $R = (1 - a_2)/(1 + a_2)$ was also calculated. The squeeze-out effect was shown to increase with the transverse momentum, mass number of target $A_T$ and also with narrowing of the rapidity range. It is more pronounced for protons than for $\pi^-$ mesons.
- The Quark Gluon String Model (QGSM) was used for the comparison with the experimental data. The QGSM yields a signature of in-plane and out-of-plane flow effects in C-Ne and C-Cu collisions for protons.

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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    |
| Number of generated events| 8400   | 9327   |
| \(< N_p >\)               | 12.4 ± 0.5       | 19.5± 0.6     |
| \(K=1/<\cos\phi>\)        | 1.27 ± 0.08      | 1.31 ± 0.04   |
| \(F_{exp}\) for protons (MeV/c) | 134 ±12 | 198±13 |
| \(F_{mod}\) for protons (MeV/c) | 160 ±10 | 190±9 |
| \(F_{exp}\) 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 $dN/d\phi = a_0(1 + a_1\cos\phi + a_2\cos2\phi)$.

| $A_p - A_T$ | Particle       | Applied Cut                      | $a_2$       | $R$       |
|-------------|----------------|----------------------------------|-------------|-----------|
| C-Ne        | Protons        | $-1 \leq y_{cm} \leq 1$          | -0.049±0.014| 1.10±0.03 |
|             | $-1 \leq y_{cm} \leq 1; P_T \geq 0.3 \text{ GeV/c}$ | -0.074±0.014 | 1.16±0.04 |
|             | $\pi^-$ mesons | $-1 \leq y_{cm} \leq 1$          | -0.035±0.013| 1.07±0.04 |
|             | $-1 \leq y_{cm} \leq 1; P_T \geq 0.1 \text{ GeV/c}$ | -0.050±0.014 | 1.09±0.03 |
| C-Cu        | Protons (mod.) | $-1 \leq y_{cm} \leq 1$          | -0.058±0.004| 1.12±0.01 |
|             | Protons (exp.) | $-1 \leq y_{cm} \leq 1$          | -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 |
|             | $-1 \leq y_{cm} \leq 1; P_T \geq 0.1 \text{ GeV/c}$ | -0.056±0.015 | 1.12±0.04 |
"inelastic" trigger $= S_1 \land S_2 \land S_3 \land S_4 \land \bar{S}_5 \land \bar{S}_6$

"central" trigger $= S_1 \land S_2 \land S_3 \land S_4 \land \bar{S}_n \land \bar{S}_{ch}$

Figure 1: Experimental set-up. The trigger and trigger distances are not to scale
Figure 2: The dependence of $<P_x>$ on the normalized rapidity $y/y_p$ in the laboratory system in C-Ne collisions. $\bigcirc$ – for protons, $\bigtriangleup$ – for $\pi^−$ mesons, $\ast$ – the QGSM data for protons. The lines represent linear fits of experimental data in the intervals $0.01 \leq y/y_p \leq 0.90$ for protons and $0.04 \leq y/y_p \leq 0.70$ for $\pi^−$ mesons. The curves show the 4th order polynomial fits.
Figure 3: The dependence of $< P_x >$ on the normalized rapidity $y/y_p$ in the laboratory system in C-Cu collisions. $\bigcirc$ – for protons, $\bigtriangleup$ – for $\pi^-$ mesons, $\bigstar$ – the QGSM data for protons. The lines represent linear fits of experimental data in the intervals $0.01 \leq y/y_p \leq 0.90$ for protons and $-0.06 \leq y/y_p \leq 0.6$ for $\pi^-$ mesons. The curves show the 4th order polynomial fits.
Figure 4: Scaled flow values versus beam energy per nucleon, for different projectile/target systems: ⋆ – Nb-Nb Plastic Ball, ● – Ni-Au EOS, △ – Au-Au Plastic Ball, ○ – Ni-Ni FOPI, ● – Ni-Cu EOS, ‡ – Au-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 5: The azimuthal distributions with respect to the reaction plane of midrapidity protons $dN/d\phi$. ○ for C-Ne ($-1 \leq y_{cm} \leq 1$), △ for C-Cu ($-1 \leq y_{cm} \leq 1$) interactions, * the QGSM data. Also shown are the fits using the function $dN/d\phi = a_0(1 + a_1 \cos \phi + a_2 \cos 2\phi)$. 
Figure 6: The azimuthal distributions with respect to the reaction plane of midrapidity $\pi^-$ mesons. $\circ$ – for C-Ne ($-1 \leq y_{cm} \leq 1$), $\triangle$ – for C-Cu ($-1 \leq y_{cm} \leq 1$) interactions, $\ast$ – the QGSM data. Also shown are the fits using the function $dN/d\phi = a_0(1+a_1\cos\phi+a_2\cos2\phi)$. 

$\text{C-Cu}(\pi^-,X)$

$\text{C-Ne}(\pi^-,X)$
Figure 7: The dependence of the Elliptic flow excitation function $v_2$ on energy $E_{lab}/A$ (GeV): ⭐ – FOPI, ⬤ – MINIBALL, ⬤ – EOS, ⬤ – E-895, ⭐ – E-877, ⬤ – NA49, △ – C-Ne, C-Cu (our results).