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Bounce – off in ^{197}Au induced collisions with $Ag(Br)$ nuclei at 11.6 A GeV/c

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Abstract. Using emulsion detectors a transverse-momentum analysis of projectile fragments has been performed in Au induced nuclear interactions at 11.6 A GeV/c. Evidence for collective flow of the projectile fragments has been obtained. Angular distributions of the principal vectors of projectile and target fragments have shown strong azimuthal correlation.

PACS. 25.70.Mn Projectile and target fragmentation

1 Introduction

Experiments with relativistic heavy-ion beams give us a unique opportunity to study the properties of compressed and heated nuclear matter. This compression reveals itself by the flow of nuclear matter in the final stage of the reaction [1].

Flow was observed in heavy-ion experiments around 1 A GeV/c at the Berkeley Bevalac [2]. The strength of flow depends on the impact parameter of the nuclear collision. As an example the flow angle, calculated from the sphericity tensor which approximates the event shape by an ellipsoid, is strongly dependent upon the centrality of the collision and the incident energy.

Different aspects of flow phenomena have been observed: the bounce-off of the spectator fragments, the side-splash of participant matter which occurs in the reaction plane and the squeeze-out of nucleons perpendicular to the reaction plane.

At higher energies in collisions of ^{22}Ne [3] and ^{28}Si [4] beams with $Ag(Br)$ nuclei at 4.1 and 14.6 A GeV/c, respectively, the bounce-off of the spectator fragments was investigated. Particle yield ratios from 14.6 A GeV/c $^{28}Si + Au$ interactions were studied [5] and their correlation with the orientation of the transverse momenta of projectile fragments has been measured. Recently the presence of pronounced azimuthal event anisotropies indicating directed side-ward flow of the hot and excited matter formed in $^{197}Au + Au$ collisions at 11.4 A GeV/c has been reported [6]. This analysis was performed by Fourier expansion of the azimuthal distributions of the transverse energy on an event-by-event basis in different pseudorapidity windows as proposed in [7]. In this work the anisotropy of the transverse energy and the charged particle azimuthal spectra were studied for different centralities with respect to the reaction plane reconstructed on an event by event basis using the transverse energy distribution measured by calorimeters [8]. Finally, relativistic projectile fragments have been observed to exhibit collective flow in ^{197}Au induced interactions in emulsion at the BNL AGS [9].

In the present paper we report the results of a systematic study of collective flow in $Au + Ag(Br)$ interactions at 11.6 AGeV/c. For analysis we adopt the transverse momentum approach [10] and the unit vector method [11]. The aim is also to show that the emulsion technique is a sensitive tool to study flow phenomena.

2 Experiment

Emulsion chambers have been irradiated horizontally with ^{197}Au nuclei at 11.6 A GeV/c. The details of the experiment can be found in previous EMU01 papers (e.g. [12]). Tracks of secondary charged particles were classified according to the commonly accepted emulsion experiment terminology into following groups:

1. N_Z - multicharged projectile fragments, these are tracks due to relativistic nuclei with $Z \geq 2$, emitted at an angle $\Theta < 17$mrad ($\eta \geq 4.8$) with respect to the direction of the incident nucleus and of momentum about 11.6 A GeV/c. Typically we determine the number of alpha particles (N_α) and number of fragments (N_{fr}) with charge $Z > 2$, separately.
2. N_s - shower particles (fast particles with $\beta > 0.7$), these are tracks with ionization $I < 1.4I_0$, I_0 is the minimum ionization produced by singly charged particle. This group includes particles produced in the interactions as well as those singly charged particles knocked-out from the target nucleus. Relativistic single charged projectile fragments with emission angle $\theta < 1^\circ$ were excluded from the shower particles.
3. N_h - target fragments (h-particles), these are tracks formed by slow ($\beta < 0.7$) heavily ionizing ($I > 1.4I_0$) particles emitted from the struck target nucleus.
   Target fragments can be divided to two groups - grey (N_g) and black (N_b) particles. Their numbers obey the relation $N_b+N_g = N_h$. Grey particles have a range ≥ 3 mm in emulsion with ionization $I > 1.4I_0$ ($\beta < 0.7$) and consist mainly of recoil protons from the target. Black particles are singly and multi-charged fragments evaporated from the target spectator with a range < 3 mm.

From the total number of 1185 completely measured ^{197}Au induced inelastic interactions in emulsion 347 events of $^{197}Au + Ag(Br)$ collisions at medium impact parameters have been chosen for the present analysis. The relative number of such events to the total (Ag, Br) interactions is 68%. Selected events are characterized by the number of target fragments $N_h \geq 8$ (representing interactions with Ag or Br targets) and $N_\alpha \geq 3$, where N_α is the number of projectile alpha fragments. Hence these two selection criteria correspond approximately to an impact parameter cut at about 0.8 $(R_{Au}+R_{Ag,Br})$. The longitudinal momentum of the incident nucleus is 11.6 A GeV/c (P_l). The polar (Θ) and azimuthal (Ψ) angles of both projectile (PF) and target (TF) fragments with respect to the direction of the primary nucleus have been measured. The spatial resolution is better than 0.02 rapidity ($\eta = -ln \tan \Theta/2$) units over a large range in phase space. The charge of PFs was determined by δ-ray counting with an accuracy about 3 charge units for intermediate fragment charges [12]. The mass of a fragment of charge Z is assumed to be $A = 2Z$.

3 Results

The azimuthal angular distribution of projectile fragments is essentially uniform, showing that the technique with nuclear emulsions can be used for the analysis performed here. Assuming that each projectile fragment i has the same longitudinal momentum per nucleon P_l as the projectile nucleus, the transverse momentum per nucleon of the ith fragment is given by $P_{t,i} = P_l.tan\Theta_i$, where Θ_i is the emission angle of the ith fragment. The vector $\vec{P_{t,i}}$ points in the azimuthal direction of the emitted fragment. In our experiment the average value of transverse momenta for helium fragments is 125 MeV/c per nucleon

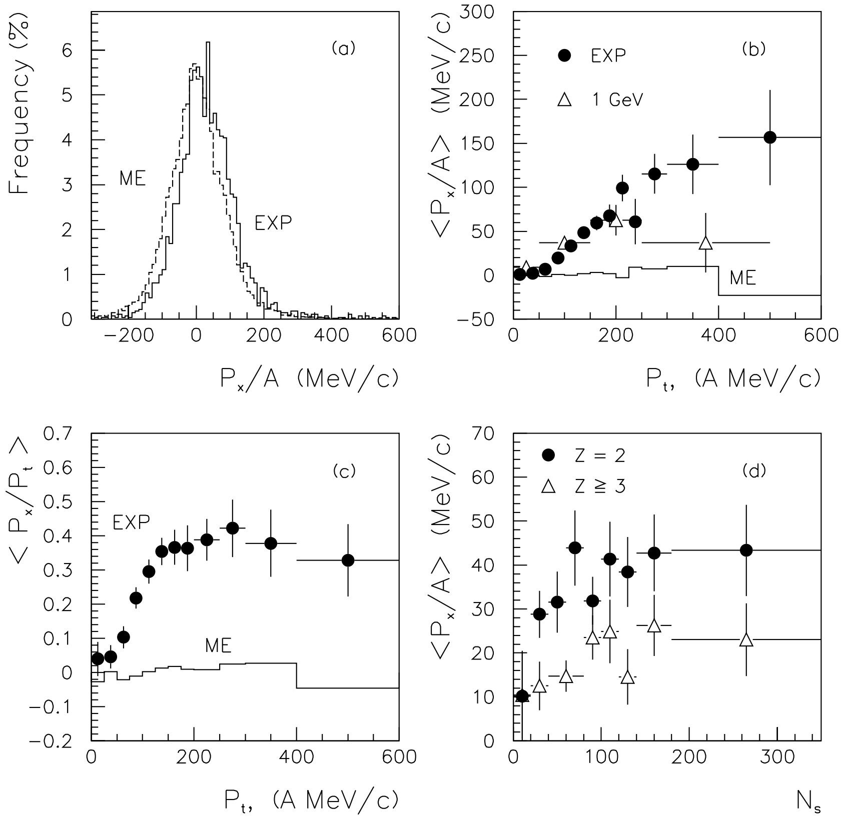

Fig. 1. a The pseudo-transverse momenta of the PFs projected onto the reaction plane, where EXP = this experiment and ME = mixed events; **b** The $< P_x/A >$ dependence on P_t; **c** The $< P_x/P_t >$ dependence on P_t; **d** The $< P_x/A >$ dependence on N_s

while for heavier fragments the value is 68 MeV/c per nucleon. These values decrease by a factor of 0.6 for lower energy Au data [13] measured at ~ 1.0 A GeV/c.

The reaction plane is defined by the direction of the incident nucleus and the plane vector $\vec{Q}$, which is constructed individually for each single particle i from the transverse momenta $\vec{P_{t,j}}$ of all remaining particles in the same event by $\vec{Q}= \sum_{j=1}^{N_{fr}} \omega_j A_j \ \vec{P_{t,j}}$, where $j \neq i$ ($i = 1, 2, ..., N_{fr}$), N_{fr} is the number of PFs and A_j is the mass of the fragment. The vector $\vec{Q}$ is only an estimation for the true reaction plane. The definition of $\vec{Q}$ ensures that the autocorrelations [10] are removed by calculating $\vec{Q}$ for each particle separately from the transverse momenta of all remaining particles, without including the particle itself. The coefficients ω_j are introduced to exclude particles from the mid-rapidity region. Because only the forward going relativistic projectile fragments have been included to determine the reaction plane, $\omega_j = 1$.

The momentum component $\vec{P_t}$ of i-th projectile fragment ($i = 1, ..., N_{fr}$) is projected on the reaction plane by $P_x/A = (\vec{P_t} \ . \ \vec{Q})/ \ |\vec{Q}|$. The experimental P_x/A distribution is presented in Fig. 1a (solid histogram). The average transverse momentum per nucleon in the reaction plane $< P_x/A >$ would be equal to zero if P_t is randomly distributed in the azimuthal plane and it will differ from zero if the directed flow of the particles deviates from the zero-angle direction. The measured value is $< P_x/A >_{exp}= 32.0 \pm 1.8$ MeV/c. This value is not corrected for the difference in the direction of the estimated reaction plane ($\vec{Q}$) and the true reaction plane. Such a correction would reduce the obtained value by a factor $< \cos \Phi >$ [10]. The angle Φ is here the azimuthal deviation of the vector $\vec{Q}$ from the true reaction plane.

To investigate if the obtained value represents a significant flow of transverse momentum, the same procedure has been applied to mixed events (ME) which lack a dynamic effect in the reaction plane. The mixed events have been generated from the original sample of events by randomly distributing the projectile fragments amongst the generated events. The result is $< P_x/A >_{ME}= -0.2 \pm 0.7$ MeV/c.

The mixed events P_x/A distribution is shown in Fig. 1a as a dashed histogram. One observes that our data significantly differ from zero and display this bounce-off of the projectile fragments as predicted by Stöcker [14]. The randomized events do not manifest this bounce-off effect. Figure 1b presents the $< P_x/A >$ dependence on P_t from this experiment compared to results from Au data measured at a projectile momentum around 1 A GeV/c [13]. The behaviour of the measured dependence $< P_x/A >$ versus P_t in our case is consistent with the previous low-energy data up to transverse momenta ~ 200 MeV/c per nucleon. Our data significantly differ from zero and display the bounce-off of the projectile fragments. The analysis shows that the randomized events do not give collec-

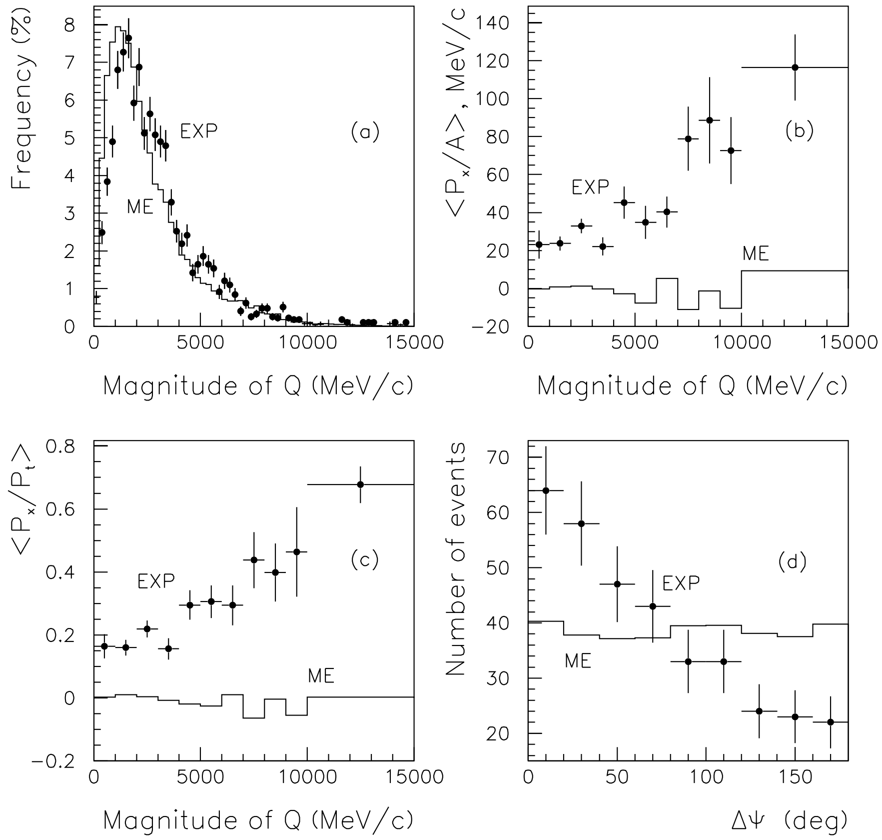

Fig. 2. a The distribution of the absolute values of the plane vector $\vec{Q}$; **b** The dependence of $< P_x/A >$ on the magnitude of the plane vector $\vec{Q}$; **c** The dependence of $< P_x/P_t >$ on the magnitude of the plane vector $\vec{Q}$; **d** The relative azimuthal angles between the two constructed planes

tive flow in any of the present P_t bins. The fraction of the transverse momentum of PFs that lies in the reaction plane $< P_x/P_t >$ is given in Fig. 1c as a function of P_t. The distribution shows that at higher P_t a large fraction (about 40 %) of the PFs P_t is in the reaction plane.

To study the dependence of the mean transverse momentum per nucleon $< P_x/A >$ in the reaction plane on the impact parameter b we classified the events according to the number of relativistic s-particles. It is well known that the value of N_s is a good measure of the impact parameter (see for example [15]).

The dependences of the mean values $< P_x/A >$ on the number of shower tracks N_s are presented in Fig. 1d for alpha particles and heavier projectile fragments. The strong dependence of $< P_x/A >$ on the number of s-particles (and so on the impact parameter) is seen in our data. The dependence is linear for quasiperipheral collisions ($N_s < 100$) with a plateau for the medium N_s and increases in the case of semi-central events $N_s \approx 300$. The value of $< P_x/A >$ doubles when going from $N_s < 100$ to $N_s > 200$. The same centrality dependence was observed by E877 Collaboration [6]. Note that due to our selection criteria ($N_h \geq 8, N_\alpha \geq 3$) really central events are excluded from the studied sample. Our data show a decreasing transverse momenta of the PFs projected onto the reaction plane with increasing fragment charge.

Up to now we have used the calculated direction of the plane vector $\vec{Q}$ only. Let us now try to use our knowledge about its magnitude. The distribution of the measured values $|\vec{Q}|$ (Fig. 2a) is shifted to the right in comparison with the one obtained for the ME (Fig. 2a, dashed histogram). The average values of $\vec{Q}$ are 2962±43 MeV/c and 2705±16 MeV/c for our experiment and ME, respectively. The dependences of $< P_x/A >$ (Fig. 2b) and $< P_x/P_t >$ (Fig. 2c) on $|\vec{Q}|$ from this experiment are compared with the ME. Strong correlation of these variables on the magnitude of $\vec{Q}$ is evident for $|\vec{Q}|>$ 7000 MeV/c. The magnitude of $|\vec{Q}|$ could be caused either by a large of number of PFs with small charges or by a few PFs with large charge values when the plane vector $\vec{Q}$ is constructed. Without regard to these two possibilities the values of $< P_x/A >$ are very large (> 60 MeV/c) for $|\vec{Q}|>$ 7000 MeV/c and $< P_x/P_t >$ even reaches up to about 0.7 in this case. It clearly indicates bounce-off since the ME do not show the observed behaviour not even at high $|\vec{Q}|$ values where $< P_x/P_t > \simeq < P_x/A > \simeq 0$.

In order to test the reaction plane determination the method proposed in [10] has been used. Each event was randomly divided into two parts and the reaction planes have been estimated separately for these sub-events. The distribution of the differences between the azimuthal angles of the two constructed reaction planes is shown in Fig. 2d. This distribution is peaked at 0° with a width $\sigma \approx 49.8°$. The fact that the distribution is not flat and peaks at zero indicates that the obtained reaction planes

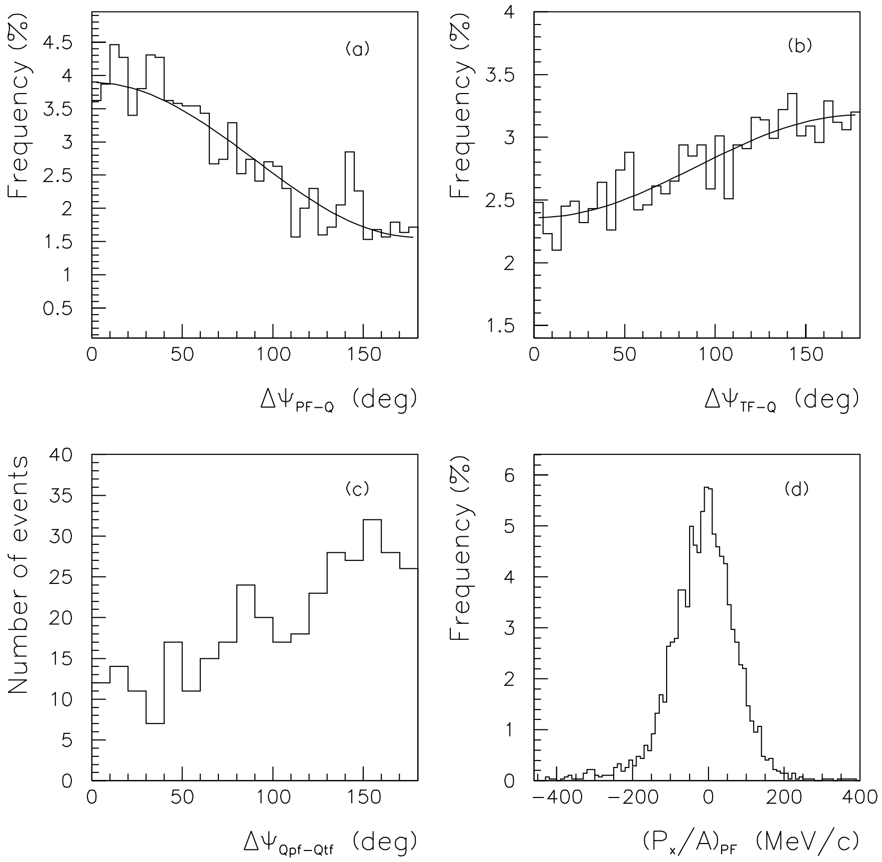

Fig. 3. a The azimuthal angles of the PFs with respect to the reaction plane; **b** The azimuthal angles of the TFs with respect to the reaction plane; **c** The relative azimuthal angle between two reaction planes made from PFs and TFs; **d** The PFs transverse momenta projected on the reaction plane constructed from TFs

are not accidental, but reflects physical correlations among the emitted fragments. To verify this we have performed the same test using mixed events. The resulting distribution, shown as a dashed histogram in Fig. 2d, is constant and does not show any correlations. The width σ was found to be related to the width σ_0 of the distribution of found reaction planes around the true reaction plane by $\sigma_0 = \sigma/2$ [16]. This value serves as a measure for the resolution of the plane vector $\vec{Q}$. The obtained value $\sigma_0 \approx 24.9°$ is comparable to the values reported in [9].

The distributions of azimuthal angles of the PFs ($\Delta\Psi_{PF-Q}$) and TFs ($\Delta\Psi_{TF-Q}$) with respect to the reaction plane are presented in Fig. 3a and 3b, respectively. In both cases the plane vector $\vec{Q}$ is constructed from PFs and autocorrelations in Fig. 3a are excluded. The preferential emission of the fragments with respect to the reaction plane is evident, peaking at 0° for PFs and 180° for TFs. Both distributions are well described by trigonometric dependences $(1 + b.\cos\Delta\Psi)$ [17] with $\chi^2 = 1.4$ and 0.7 for PFs and TFs, respectively. So PFs (TFs) are emitted in the direction near to $\vec{Q}$ ($-\vec{Q}$).

Also the plane vector $\vec{Q}$ of the TFs has been constructed for each event according to previously used formula, where the coefficients $\omega_j = 1, A_j = 1$ and instead of $\vec{P}_j$ a unit vector of the azimuthal direction of Ψ_j has been considered. The sum runs over all TFs in the given event. The distribution of the relative azimuthal angle ($\Delta\Psi_{Q_{pf}-Q_{tf}}$) between "projectile" and "target" plane vectors (Fig. 3c) shows strong correlation between them with the average azimuthal angle equal $106.5° \pm 2.7°$. The E877 Collaboration has previously reported [6] a corresponding pronounced event anisotropy. The transverse momenta of the PFs have been projected into the reaction plane constructed from the TFs (Fig. 3d). The mean value of $< P_x/A >_{PF}$ is equal to (-15 ± 2 MeV/c). These results confirm our previous conclusion about collective flow detection.

Supplementary results can be obtained by the method proposed in [11]. The unit vectors in the direction of emission of the projectile and target fragments are summed to give their principal vectors. Here the beam direction is along the z-axis and the x-axis is directed perpendicular to the emulsion plane. Thus the polar angle Θ of the principal vector $\vec{V}$ is given by $\arccos(V_z/V)$, where $V = \sqrt{V_x^2 + V_y^2 + V_z^2}$ and V_x, V_y, V_z are the components of $\vec{V}$ along the axes, and the azimuthal angle is given by $\Psi_F = \arctan(V_x/V_y)$. The principal vectors of PFs ($\vec{V_{PF}}$) and TFs ($\vec{V_{TF}}$) are assumed to be in the direction of their sources with respect to the beam direction.

The distribution of the flow angle Θ_F^{PF} (the polar angle Θ_F for $\vec{V_{PF}}$) shown in Fig. 4a is compared with a ME sample consisting of events with mixed tracks from different events (histogram in Fig. 4a).

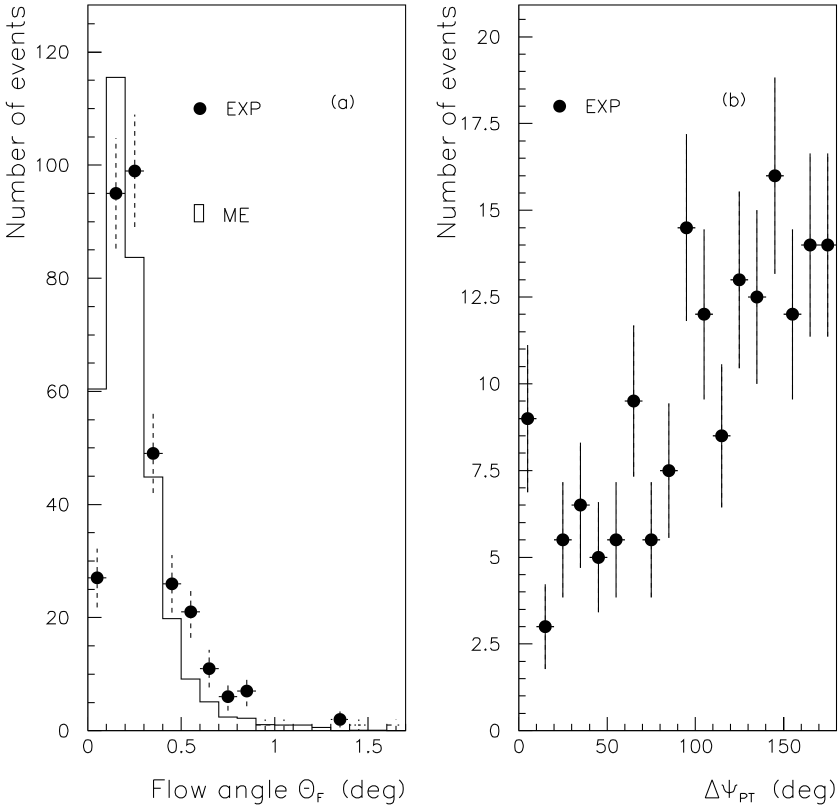

Fig. 4. a The distribution of the flow angle of the PFs; **b** The azimuthal angle between the projectile and target principal vectors

Table 1. The dependences of flow angles of PFs and azimuthal angular correlations between PFs and TFs on centrality (∗ target spectator fragments excluded)

N_s	$< \Theta_F >$	$< \Delta\Psi_{PT} >$	$< \Delta\Psi^{*}_{PT} >$
< 100	0.26 ± 0.02	107.4 ± 3.8	96.1 ± 3.9
	(0.23)	(89.8)	(90.6)
$100 - 200$	0.32 ± 0.02	107.8 ± 4.4	104.1 ± 4.6
	(0.23)	(91.4)	(90.7)
> 200	0.47 ± 0.06	102.8 ± 7.0	110.2 ± 7.0
	(0.30)	(89.7)	(90.6)

The average angle $< \Theta_F >$ for PFs equals $0.31° \pm 0.02°$ and differs from the MEs average (0.24°). The experimental Θ_F spectrum is shifted to the right compared with the ME sample. This shift can be considered as an indication of sideward flow, i.e. the bounce-off of PFs.

The dependence of the flow angles of PFs on centrality (measured by the number of shower particles) is given in Table 1. Increasing Θ_F with decreasing impact parameter (increasing N_s) is clearly seen. This tendency is not described by ME calculations (the ME values are given within brackets). The correlation of Θ_F present in our experiment is stronger in comparison with ^{28}Si induced collisions with $Ag(Br)$ nuclei at 14.6 A GeV/c [4], where the values $< \Theta_F >= 0.15° \pm 0.02°, 0.15° \pm 0.02°$ and $0.23° \pm 0.05°$ have been measured for events with number of TFs equal $8-13$, $14-19$ and ≥ 20, respectively. In our experiment the average flow angle of the TFs is equal $36.3° \pm 1.5°$.

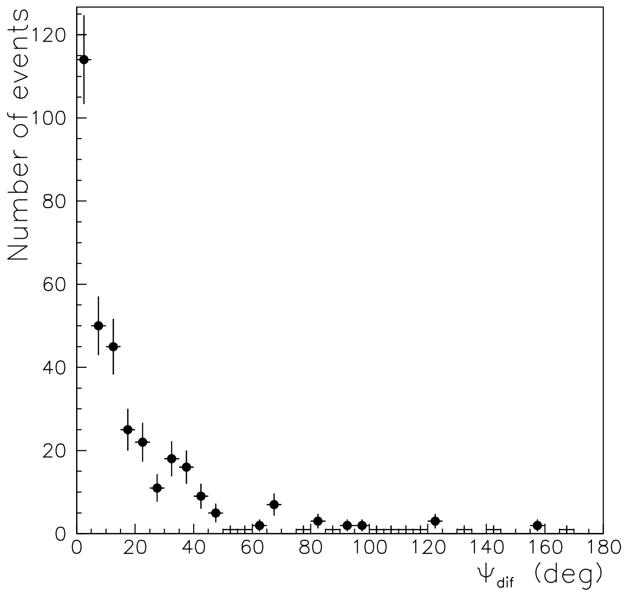

Fig. 5. The angle between the PFs principal vector and the reaction plane

The azimuthal angular correlations between PFs and TFs (Fig. 4b), where $\Delta\Psi_{PT} = \mid \Psi_F^{PF} - \Psi_F^{TF} \mid$, show a tendency to emit nuclear fragments from the two colliding nuclei into opposite directions in the azimuthal plane. The average angle is $< \Delta\Psi_{PT} >= 107.0° \pm 2.7°$. Such a behaviour is not reproduced by ME where the mean value is 90.3°. As one can see (Tab. 1) there is no dependence of $\Delta\Psi^{PT}$ on N_s in contrast to the previous case (Θ_F). However if the target spectators (b-particles in emulsion terminology) are excluded from the principal vector $\vec{V_{TF}}$ then a weak dependence of $\Delta\Psi_{PT}$ on N_s is seen. So our data clearly show that $\vec{V_{PF}}$ and $\vec{V_{TF}}$ prefer to be emitted back-to-back. The presence of finite flow angles in our data indicates that in those events a reaction plane defined by the flow and the beam axes exists. Of course this reaction plane should be identical to the one determined by the former transverse momentum analysis. That this is the case is shown in Fig. 5 which presents the difference in azimuthal angle Ψ_{dif} between the reaction planes determined by the two methods. The value of $< \Psi_{dif} >= 20.9° \pm 1.5°$.

Two different approaches have given compatible reaction planes and our previous observation of the bounce-off of the PFs has been confirmed.

4 Conclusions

Investigations of ^{197}Au induced nuclear interactions at 11.6 A GeV/c have been made using emulsion detector. Transverse momentum and flow analyses have been performed. The bounce-off of the fragments of the ^{197}Au nuclei in the collisions with $Ag(Br)$ target nuclei at middle range impact parameters has been observed. The back-to-back correlation of the projectile and target fragments in the azimuthal plane has been obtained. The mixed events sample cannot reproduce the observed effects.

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