Eur. Phys. J. A **6**, 427–430 (1999)

THE EUROPEAN
PHYSICAL JOURNAL A

Flow effects in ^{84}Kr induced collisions in emulsion at 0.95 GeV per nucleon

M.I. Adamovich[5], E.S. Basova[6], M.M. Chernyavsky[5], A. Dirner[2], K.G. Gulamov[7], B. Jakobsson[4], L. Just[3], S.P. Kharlamov[5], S.A. Krasnov[1], A. Kravčáková[2], V.G. Larionova[5], S.Z. Nasyrov[6], V.S. Navotny[7], I.D. Ojha[8], G.I. Orlova[5], N.G. Peresadko[5], N.V. Petrov[6], V.V. Rusakova[1], N.A. Salmanova[5], B.K. Singh[8], V. Singh[8], K. Söderström[4], M. Tóthová[†2], M.I. Tretyakova[5], T.P. Trofimova[6], U.I. Tuleeva[6], S.K. Tuli[8], B.P. Tursunov[6], S. Vokál[2], J. Vrláková[2], B.S. Yuldashev[6]

[1] Joint Institute of Nuclear Research, 141980 Dubna, Russia
[2] Faculty of Science, P.J. Šafárik University, Jesenná 5, 041 54 Košice, Slovakia
[3] Institute of Experimental Physics, SAS, Watsonova 47, 043 53 Košice, Slovakia
[4] University of Lund, Sölvegatan 14, 22362 Lund, Sweden
[5] Lebedev Institute, Lenin pr. 53, 117924 Moscow, Russia
[6] Institute of Nuclear Physics, Tashkent, Uzbekistan
[7] Physical-Technical Institute, Timiryazeva 2, 700 084 Tashkent, Uzbekistan
[8] Banaras Hindu University, 221006 Varanasi, India

Received: 27 September 1999
Communicated by B. Povh

Abstract. Using emulsion detector the collective flow signals in inelastic interactions of ^{84}Kr nuclei with Ag(Br) at 950 MeV/nucleon are studied. A transverse momentum analysis is performed to determine the reaction plane. The bounce-off of spectator fragments is observed. In azimuthal distributions relative to the reaction plane squeeze-out and side-splash of participants are seen.

PACS. 25.70.Mn Projectile and target fragmentation

1 Introduction

Collective flow plays an important role in the expansion and decay of compressed and excited nuclear matter created in heavy ion collisions over a wide range of incident energies. Accurate measurements of collective flow provide the best possibility to learn about nuclear matter compressibility and, indirectly, the nuclear equation of state. The collective emission of nuclear matter was first predicted on the basis of the nuclear fluid dynamical model.

Evidence for a collective behaviour of charged fragments came for the first time from Plastic Ball detector experiment in Berkeley. Since this experiment the collective flow in heavy ion collisions was measured also at higher energies.

Several different signals of collective flow have been observed, occuring in the reaction plane - side splash of participants and bounce-off of spectators and out off the reaction plane - squeeze-out of participants.

In this paper we demonstrate the possibilities of emulsion experiments to measure collective flow.

2 Experiment

Stacks of NIKFI BR-2 nuclear photoemulsions with dimension of $10cm \times 20cm \times 600\mu m$ have been irradiated horizontally by a 950 MeV/nucleon ^{84}Kr beam at the SIS synchrotron at GSI, Darmstadt. The experimental detailes have been published in [1].

The total number of measured ^{84}Kr induced inelastic interactions in emulsion is 842. For all particles their polar (Θ) and azimuthal (Ψ) angles with respect to the direction of primary nucleus have been measured.

The secondary charged particles involved in the analysis are:

- Target fragments (TF) which consist of
  - g-particles (gray) – fast target fragments, mainly recoil protons, with kinetic energies of $26 \leq T < 400$ MeV/nucl.
  - b- particles (black) – slow spectator target fragments with kinetic energies $T < 26$ MeV/nucl..
- Projectile fragments (PF) – multiply charged ($Z \geq 2$) noninteracting (spectator) projectile fragments.
- s-particles (shower) – singly charged relativistic particles with velocities $\beta > 0.7$.

For the present analysis 183 semicentral collisions of ^{84}Kr+Ag(Br) were chosen. The selected events are characterized by the number of target fragments $N_{TF} \geq 8$ (representing an Ag or Br target) and the number of multiply charged projectile spectators $N_{PF} \geq 4$.

3 Experimental results

There are few possible methods of observing collective flow. We used the conventional transverse momentum analysis [2], proposed by Danielewicz and Odyniec in which the reaction plane is determined.

If there is any collective flow observable among the spectators this allows to determine experimentally a reaction plane as a plane defined by a beam direction and the plane vector $\boldsymbol{Q}_i$:

$$\boldsymbol{Q}_i = \sum_{j=1, j\neq i}^{N_{PF}} \omega_j A_j \boldsymbol{P}_{t,j}, \qquad i = 1, 2, ..., N_{PF} \qquad (1)$$

where A_j is the mass number of projectile fragment, and $\boldsymbol{P}_{t,j}$ is the transverse momentum of fragment j.

In order to remove autocorrelations $\boldsymbol{Q}_i$ is calculated from the transverse momenta $\boldsymbol{P}_{t,j}$ of all fragments in the event except the i one.

The coefficients ω_j are normally introduced to exclude particles from the midrapidity region. In our case, $\omega_j = 1$ because only relativistic projectile fragments emitted in the forward region were used.

Assuming that each projectile fragment i has the same longitudinal momentum per nucleon, P_l, as the incident projectile nucleus, the transverse momentum per nucleon of the ith fragment is given by $P_{t,i} = P_l \cdot tan\Theta_i$.

To study the bounce-off of the projectile fragments the transverse momenta of the projectile fragments $\boldsymbol{P}_{t,i}$ were projected onto their reaction plane by

$$P'_{Q,i} = \boldsymbol{P}_{t,i} \cdot \frac{\boldsymbol{Q}_i}{\mid \boldsymbol{Q}_i \mid}, \qquad i = 1, ..., N_{PF}. \qquad (2)$$

Since momentum vectors are not projected on the true reaction plane, but on an estimated one, we put a prime on $P_{Q,i}$.

Similarly as in reference [3], the accuracy of the reaction plane determination method has been tested by the following procedure. The projectile fragments in each event were randomly divided into two parts with equal number of fragments and the reaction planes have been estimated for these subevents.

The distribution of the differences between the azimuthal angles $\delta\psi$ of the two constructed reaction planes is shown in Fig. 1. The fact that the experimental distribution shows a forward peak indicates that the constructed reaction planes are not accidental but reflect the physical correlations among projectile fragments. The width of this distribution serves as a measure for the resolution of the reaction plane after division by factor 2, see [3]. Using this method, a reaction plane resolution of 23.1° was achieved

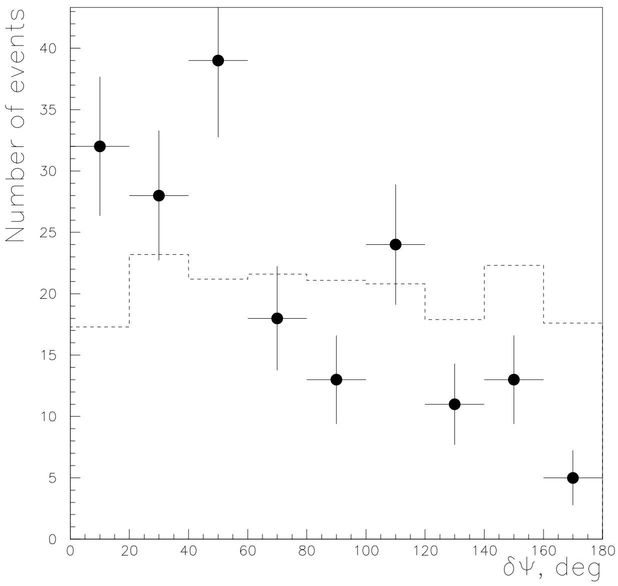

Fig. 1. The distribution of the differences between the azimuthal angles of the two constructed reaction planes in one event

which is comparable to the accuracy reported for other experiments [4].

To verify this result, we performed a similar test using mixed events. The mixed events have been generated from the original total sample of fragments randomly distributed in the new events [5]. Thus mixed events should possess no correlations in the reaction plane. The resulting distribution is shown in Fig. 1 as a dashed histogram. It is constant and does not show any correlation.

The experimental P'_Q distribution is presented in Fig. 2a (solid histogram). The average transverse momentum per nucleon in the reaction plane $< P'_Q >$ would be equal to zero if $P_{t,i}$ is randomly distributed in the azimuthal plane and it will differ from zero if a directed flow deviates from the zero-angle direction. The measured value is $< P'_Q >_{exp}= 23.6 \pm 2.3$ MeV/c/nucleon. As the particle momenta are not projected onto the true reaction plane, the average momenta get reduced $< P'_Q >=< P_Q > \cdot < cos\phi >$, where ϕ is the azimuthal angle deviation of the estimated plane from the true one.

The mixed events P'_Q distribution is shown in Fig. 2a as the dashed histogram. The mean value is $< P'_Q >_{ME}=$ 0.6 ± 0.8 MeV/c/nucleon. One observes that our data significantly differ from the null-hypothesis and display the bounce-off of the projectile fragments as predicted by Stöcker [6]. The randomized events do not manifest this bounce-off effect.

The azimuthal distributions of projectile fragments and target fragments relative to the reaction plane constructed from projectile fragments are shown in Figs. 2b and 2c.

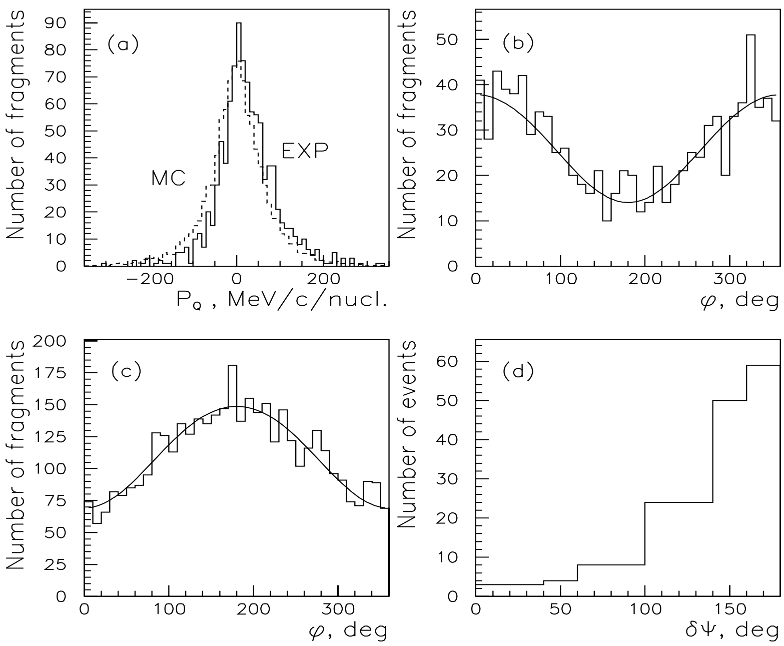

Fig. 2. (**a**) The transverse momenta of the projectile fragments projected onto the reaction plane, where EXP=this experiment and ME=mixed events, (**b**) azimuthal angle distribution of projectile fragments and (**c**) target fragments relative to the reaction plane, (for projectile fragments the autocorrelation are removed, (**d**) distribution of the difference of the azimuthal angles of the plane vectors constructed separately for projectile and target fragments

Table 1. Fit parameters according to (3)

	S_1	S_2
Projectile fragments	0.453±0.043	−0.012±0.045
Target fragments	−0.360±0.022	−0.013±0.022
s-particles ($-0.6 < \eta_{rel} < 0.6$)	−0.044±0.047	−0.187±0.050
s-particles ($0.6 \leq \eta_{rel} < 2.13$)	0.295±0.034	0.009±0.033
g-particles	−0.338±0.028	−0.050±0.028

The curves which overlay the histograms in the figure are fits with the standard formula

$$F(\varphi) = \frac{N}{2\pi}(1 + S_1 cos\varphi + S_2 cos2\varphi) \quad (3)$$

which is often used to describe collective flow [7].

The $cos\varphi$ terms is sensitive to the yield within the reaction plane. The parameter S_1 is a measure of the strength of the flow. The parameter S_2 reflects the particle emission perpendicular to the reaction plane and is a measure of the strength of the so called "squeeze-out" effect. The values of these fit parameters are shown in Table 1. We observe the preferential emission of projectile fragments in the direction of the reaction plane and target fragments opposite to this direction.

The difference $\Delta\varphi$ of the azimuthal angles of the plane vectors constructed separately for projectile and target fragments in the same event is shown in Fig. 2d. The plane vector $\boldsymbol{Q}$ of the target fragments has been constructed for each event according to formula (1), where coefficients $\omega_j = 1$, $A_j = 1$ and instead of $\boldsymbol{P}_j$ a unit vector of the azimuthal direction of Ψ_j has been considered. The sum runs over all target fragments in the given event. A strong correlation is present here, favoring the opposite directions of the projectile and target plane vectors. These results confirm our previous conclusion about bounce-off detection.

As the squeeze-out is caused by hot matter which has been stopped it should be centered around midrapidity. A useful approximation to the rapidity of a particle is the pseudorapidity, η, which is defined as $\eta = -ln(tan(\Theta/2))$, where Θ is a polar angle. For our analysis we define relative pseudorapidity η_{rel}, where

$$\eta_{rel} = \frac{\eta - \eta_{CM}}{\eta_{CM}}. \quad (4)$$

Here η_{CM} and η are the pseudorapidity of the CM system and of the detected particle in the laboratory frame, respectively.

We now turn our attention to the azimuthal distribution of the relativistic shower particles.

Figure 3a shows the azimuthal distribution of s-particles around the central pseudorapidity, satisfying $|\eta_{rel}| < 0.6$, relative to the reaction plane. Calculations made within the frame of the cascade code [8] showed that the ratio of shower pions to protons is about 2:1 in this pseudorapidity window.

A similar result can be obtained from our data, Fig. 3b, where the η_{rel} distributions of pions and protons of s-particles are shown. Here $\eta^f_{rel} = 2.13$ is the relative pseudorapidity corresponding to the fragmentation cone $\vartheta_f = 7°$, see [1]. Pions have been separated from protons in the way presented in [9] where the number of pions is defined as $N_\pi = N_s - N_p$. Here $N_p = Z_{Proj} - Q$ is the number of protons in the event, Z_{Proj} is the charge of projectile nucleus and $Q = \sum Z_{PF}(Z_{PF} \geq 2)$ is the charge sum of the projectile spectator fragments in a given event. Using this formula N_p protons with smallest polar angles have been excluded from the total sample of s-particles.

Again a fit according to (3) is shown in Fig. 3a with parameter values listed in Table 1. A clear visible double humped structure indicates the prefered emission per-

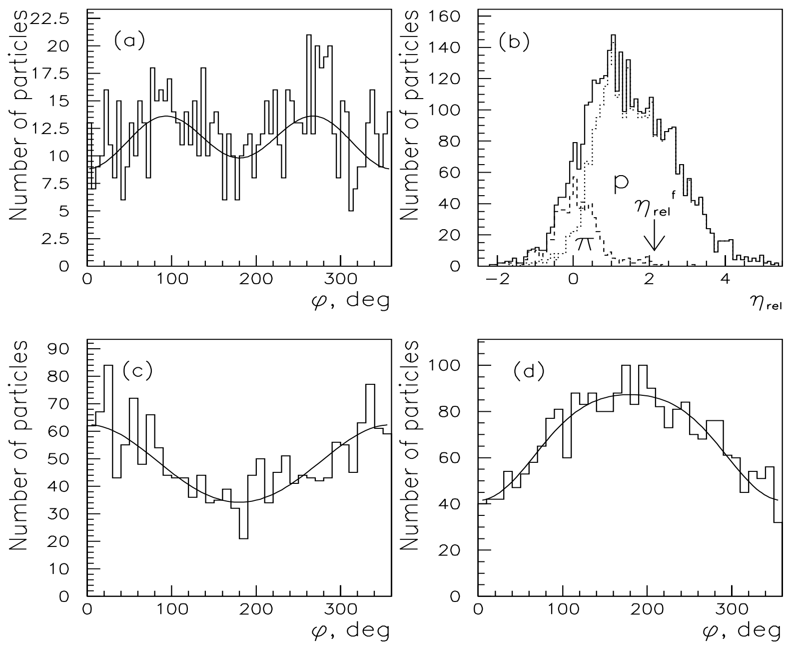

Fig. 3. (**a**) Azimuthal angle distribution of s-particles with $-0.6 < \eta_{rel} < 0.6$, relative to the reaction plane, (**b**) relative pseudorapidity distribution of s-particles, (**c**) azimuthal distribution of s-particles ($0.6 \leq \eta_{rel} < 2.13$) relative to the reaction plane, (**d**) azimuthal distribution of g-particles relative to the reaction plane

pendicular to the reaction plane. Hence the relativistic s-particles near central pseudorapidity exhibit the effect of squeeze-out. This effect is associated with final state interaction of relativistic particles produced in hot zone with spectator matter located in the reaction plane [10].

The azimuthal distribution of relativistic s-particles with $0.6 \leq \eta_{rel} < 2.13$, i.e. with projectile like pseudorapidities relative to the reaction plane is shown in Fig. 3c. Normally we use all shower particles, but, in order to minimize the contribution from the projectile spectator protons, only shower particles produced outside of the fragmentation cone (at angles larger than 7°, i.e. $\eta_{rel} < 2.13$) have been included in this case.

As can be seen, these particles are preferentialy emitted into the reaction plane.

Figure 3d shows the azimuthal distribution of fast target fragments (g-particles) relative to the reaction plane. This group consists mainly of knocked-out protons. A clear emission of particles opposite to the direction of the reaction plane can be seen. The curves are the results of the fit to these distributions by the previously used formula. These two results demonstrate the side-splash of the participants at the projectile-like pseudorapidity region ($\eta_{rel} \geq 0.6$) and for target knocked out protons.

4 Conclusion

The investigation of ^{84}Kr induced interactions has been made using emulsion detector.

The presence of general signatures of collective flow effects in $^{84}Kr + Ag(Br)$ collisions at 0.95 AGeV were found.

The bounce-off effect of projectile spectator fragments was observed, which allowed us to determine the reaction plane with accuracy $\sigma \approx 23.1°$. Significant squeeze-out was observed for relativistic particles with $\eta \approx \eta_{CM}$. Side-splash was observed in azimuthal distributions of both relativistic particles at $\eta > \eta_{CM}$ and fast target fragments.

This work was partly supported by the Grant Agency for Science at the Ministry of Education of the Slovak Republic (grant No. 1/6022/99).

References

1. Krasnov S.A. et al., Czech. J. Phys. *46*, 531 (1996)
2. Danielewicz P. and Odyniec G., Phys. Lett. *157B*, 146 (1985)
3. Wilson W.K. et al., Phys. Rev. C *45*, 738 (1992)
4. Venema L.B. et al., Phys. Rev. Lett. *71*, 835 (1993)
5. Adamovich M.I. et al., Physics of Atomic Nuclei *60*, 1435 (1997)
6. Stöcker H. et al., Phys. Rev. Lett. *44*, 725 (1980)
7. Kugler A. et al., Phys. Lett. B *335*, 319 (1994)
8. Musulmanbekov G.J., *in* Proc. 11th EMU01 Coll. Meeting, Dubna, May 11-13, 1992 (Ed. V. Bradnova), JINR, Dubna, 1992, p.288
9. Adamovich M.I. et al., Phys. Lett. B *352*, 472 (1995)
10. Kugler A., Czech. J. Phys. *45*, 545 (1995)