A NEW COMPONENT OF THE COLLECTIVE FLOW IN RELATIVISTIC HEAVY-ION COLLISIONS

H.H. GUTBROD[a,1], K.H. KAMPERT[b,1], B.W. KOLB[a,1], A.M. POSKANZER[c], H.G. RITTER[c] and H.R. SCHMIDT[a,1]

[a] *Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Fed. Rep. Germany.*
[b] *Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA*
[c] *University of Münster, D-4400 Münster, Fed. Rep. Germany*

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The reaction Au + Au at 400 MeV/nucleon is analyzed in the coordinate system given by the principal axes of the kinetic energy flow ellipsoid. In addition to the previously observed side-splash and bounce-off we find a pronounced component perpendicular to the reaction plane at mid-rapidity both in position- and momentum-space. The anisotropy is investigated as a function of multiplicity and is found to be most prominent for semi-central collisions.

1. Introduction

Theoretical predictions of collective effects [1–4] in relativistic heavy-ion collisions have been confirmed by experiments. A strong azimuthal correlation of particles emitted from the reaction zone has been found by means of sphericity analysis [5], the investigation of the average transverse momentum in the reaction plane [6–9] and the study of multi-particle correlation functions [10–13]. These methods have revealed two collective effects, both occurring *in* the reaction plane: (a) a sidewards deflection of spectator particles, the so-called "bounce-off", and (b) an azimuthally asymmetric emission of participant particles, to so-called "side-splash". Simulations within the framework of the intra-nuclear cascade model have not been able to describe these effects [5,14]. In this paper we shall investigate the occurrence of collective phenomena *perpendicular* to the reaction plane, using the full information which is available from 4π-spectrometers like the Plastic Ball [15], which measures the four-momentum of the charged particles. The sphericity analysis [14] reduces the available information to a few observables, like the flow angle and the azimuthal angle of the reaction plane. The transverse momentum method [6] shows that a reaction plane can be determined from the momenta of the emitted particles. It gives $\langle p_x \rangle$ and $\langle p_y \rangle$, the average in-plane and out-of-plane components of the transverse momenta, respectively, which are generally plotted as a function of rapidity. For symmetry reasons, $\langle p_y \rangle$ is zero at all rapidities, while $\langle p_x \rangle$ crosses zero at mid-rapidity. On the other hand, it is anticipated that pronounced collective effects take place at $y_{CM} \approx 0$ [3,14,16]. Furthermore, the emission perpendicular to the reaction plane is the only direction where matter might escape during the whole collision time without being hindered by either the target or projectile nucleus. As a consequence, this might lead to a jet-like emission pattern, also referred to as "out-of-plane squeeze-out" [3][#1]. Recently, an indication of an out-of-plane peak in the azimuthal particle distribution at mid-rapidity has been reported by the Diogene group [17] for Ne-induced reactions at 800 MeV/nucleon.

In this letter we shall analyze experimental event shapes, represented both in position and momentum

[1] Present address: CERN, EP-Division, CH-1211 Geneva 23, Switzerland.

[#1] The analysis of the event shape of relativistic heavy-ion collisions has been the subject of several theoretical investigations which can be found in refs. [3,4,15–17].

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space for the reaction Au+Au at 400 MeV/nucleon. We shall show that the appropriate coordinate system to represent the data is the flow ellipsoid coordinate system, i.e. the frame has to be determined event-by-event.

2. Experimental setup

The experiments were performed at the Berkeley Bevalac, using the Plastic Ball/Wall spectrometer [15]. This detector system has particle identification capability, in the angular range from 9° to 160° in the laboratory system, for singly and doubly charged particles as well as positively charged pions. The forward direction (0°–9° in the laboratory system) is covered by the Plastic Wall, measuring time-of-flight, ΔE, and the angle of the particles, thus identifying the nuclear charge and the velocity of the particles. The inner part of the Plastic Wall is also used to define the trigger of the whole spectrometer. The data discussed here were taken with a minimum bias trigger.

3. Choice of the coordinate system

The choice of the coordinate system is motivated by the experimentally well-established existence of non-zero flow angles [5,9,18] and thus the ability to determine the reaction plane. We wish to analyze the event in a coordinate system which coincides with the principal axes of the flow ellipsoid.

The flow ellipsoid is calculated from the sphericity tensor [14], given by $S_{ij}=\sum p_i(\nu)p_j(\nu)/2m_\nu$, where $\bar{p}(\nu)$ and m_ν are the momentum and the mass, respectively, of the νth fragment. The three eigenvectors $\bar{e}_k$ of the tensor lie along the principal axes of the corresponding tensor ellipsoid and the eigenvalues λ_k are the squares of the half axes. The eigenvector corresponding to the largest eigenvalue lies, per definition, in the reaction plane and points in the flow direction. It is usually denoted with $\bar{e}_1$.

However, the transverse momentum analysis is a better method to approximate the "true" reaction plane than the sphericity method [6,19]. In the transverse momentum method the reaction plane is defined by the vector $\bar{Q}=\sum w_\nu \bar{p}_T(\nu)$ and the beam axis, where the $\bar{p}_T(\nu)$ are the transverse momenta of the particles. The weights w_ν for forward and backward going particles are +1 and −1, respectively. The accuracy of $\bar{Q}$ pointing into the true reaction plane is improved by excluding mid-rapidity particles.

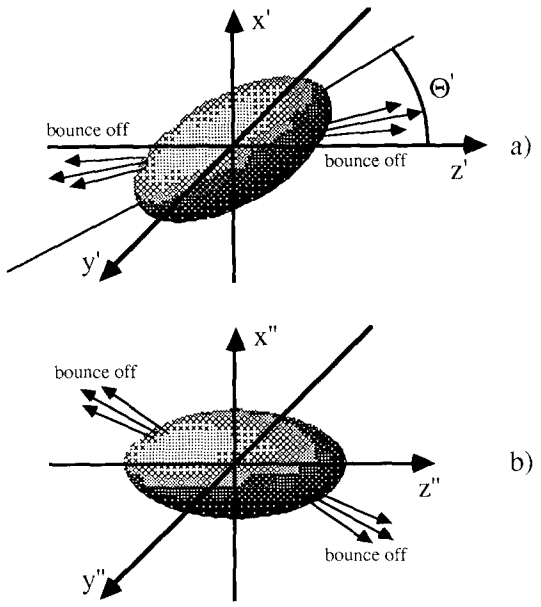

Fig. 1. Presentation of the coordinate transformations applied to the data. (a) The coordinate system K′ after rotation of the event into the reaction plane. The distribution of participants and the spectator bounce-off are indicated by the ellipsoid and by the arrows, respectively. (b) The coordinate system K″ after rotation of the event by the flow angle Θ'. It coincides with the principal axes of the ellipsoid of the sphericity tensor.

Therefore, in a first step, we rotate the event around the beam axis so that $\bar{Q}$ lies along the positive x'-axis. Fig. 1a shows an artist's view of the event after this rotation to the reaction plane coordinate system K′. The distribution of participants and the spectator bounce-off is indicated by the ellipsoid and by the arrows, respectively. The reaction plane is denoted $x'z'$. As a next step we evaluate the flow angle Θ' in the reaction plane by means of a modified sphericity analysis, i.e. we want to impose the reaction plane determined by the transverse momentum analysis as a symmetry plane for the flow ellipsoid. Thus the sphericity tensor S'_{ij} is modified for so that its eigenvector $\bar{e}'_1$ will lie in the reaction plane $x'y'$ as given by the transverse momentum analysis. This means that the elements S'_{xy} and S'_{zy}, for which reflection symmetry requires $\langle S'_{xy}\rangle = \langle S'_{zy}\rangle = 0$, are set to zero

for each event, and the flow angle Θ' is calculated from the modified tensor. The events are then rotated by $-\Theta'$ around the y'-axis. The resulting flow ellipsoid coordinate system K″ (fig. 1b) is denoted by $x''y''z''$, where $y''=y'$.

4. Results

Figs. 2a–2c show the azimuthal distribution of particles relative to the reaction plane[#2] (φ'-distribution in the K′ coordinate system) for three rapidity bins (around target-, mid-, and projectile rapidity), respectively. The data are selected for semi-central collisions, corresponding to the third of five multiplicity bins, as defined in ref. [7]. A strong alignment of the particles in regions of projectile and target rapidity at $\varphi'=0°$ and $\varphi'=180°$ can be seen. This alignment corresponds to the two branches of the S-shaped curve of conventional $\langle p_x \rangle$ analysis [5]. However, in a narrow bin at mid-rapidity the particles are aligned *perpendicularly* to the reaction plane. This can be clearly seen in fig. 2b, where the two peaks in the φ'-distribution reflect a preferential out-of-plane emission.

In this representation of the data the bounce-off cannot be clearly separated from the side-splash because these particles are emitted at the same φ'-angles. The resulting φ'-distribution at target and projectile rapidity will therefore always have contributions from both participants and spectators, if the latter ones are not excluded by additional momentum cuts. Furthermore, inefficiencies for the detection of low energy particles will distort the φ'-distributions predominantly at backward rapidities.

The emission pattern becomes much clearer, if we represent the events in the flow ellipsoid coordinate system K″. The events are rotated around the y'-axis by the flow angle Θ' so that the new z-axis z'' is determined by the main axis of the flow ellipsoid. Fig. 3a shows now the φ''-distribution as a function of the normalized momentum per nucleon along the major axis of the ellipsoid: $p_z'' := P_z''^{\mathrm{CM}}/P_{\mathrm{proj}}''^{\mathrm{CM}}$. The φ''-anisotropy at $p_z'' \approx 0$, as can be seen from fig. 3b, is more pronounced as compared to fig. 2b, which results from the fact that now the principal axes of the flow ellipsoid are used as a coordinate system. Furthermore, it can be seen that the preferential emission of particles into the out-of-plane direction ($\varphi'' = \pm 90°, 270°$) as opposed to an emission into the x''-direction extends now over the whole p_z''-axis. There are large distortions at target and projectile momentum. However,

[#2] Autocorrelations have been removed by excluding the particle of interest from the evaluation of both the reaction plane [6] and the flow angle.

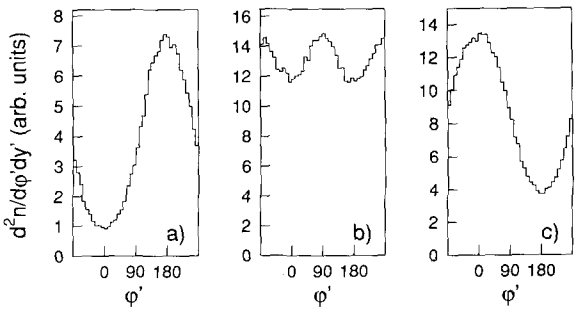

Fig. 2. φ'-distributions of the number of particles in different rapidity bins: (a) $-1.2<y'/y'^{\mathrm{CM}}<-0.8$; (b) $-0.1<y'/y'^{\mathrm{CM}}<0.1$; (c) $0.8<y'/y'^{\mathrm{CM}}<1.2$.

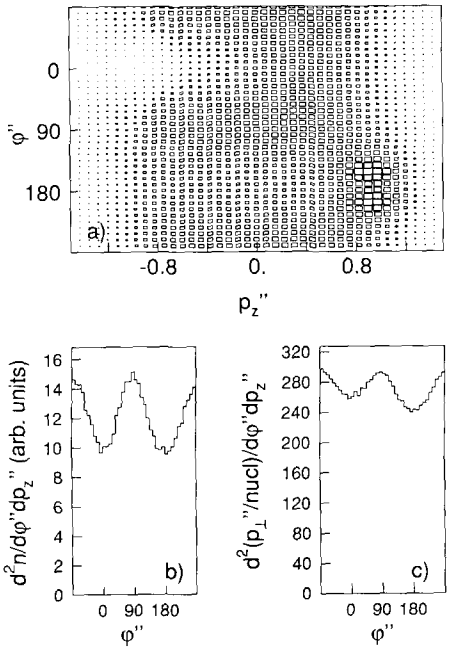

Fig. 3. (a) Distribution of the number of particles in the plane φ'' versus p_z''. The size of the squares is proportional to the number of particles. (b) φ''-distribution of the number of particles for $-0.1<p_z''<0.1$. (c) φ''-distribution of the average transverse momentum per nucleon for $-0.1<p_z''<0.1$.

the target cuts are clearly visible in fig. 3a as a depletion at $\varphi'' = 0°$ and $p_z'' < 0$, while the bounce-off particles can now be seen as structure at projectile momentum and $\varphi'' = 180°$. The two-peak structure of the bounce is the result of the strong Coulomb repulsion from a heavy projectile remnant, generating a "hole" in the emission pattern.

In fig. 3c we show the azimuthal dependence of the transverse momentum per nucleon ($p_\perp''$/nucleon). Again we find an anisotropy in φ'' at $p_z'' \approx 0$. This means that not only the density of particles is enhanced in the out-of-plane direction but these particles are also emitted with a higher average transverse momentum per nucleon!

The anisotropy in φ'' discussed above corresponds to an elliptical distribution of the particles both in position and in momentum in the $x''y''$-plane. The distributions in figs. 3b, 3c have been fitted with $f(\varphi'') \propto 1 + \alpha \cos(2\varphi'')$ yielding the half axes $R_{x''}$ and $R_{y''}$ as extrema of f, where α is a fit parameter. Fig. 4 shows the multiplicity dependence of the aspect ratio $R_{y''}/R_{x''}$ for the position density (filled circles) and the momentum per nucleon (open circles). Both ratios exhibit the same tendency: they first rise with multiplicity, reach a maximum and then decrease with multiplicity[#3]. In the limit of an impact parameter $b = 0$ symmetry requires that the ratios become equal to one. This limit, however, cannot be reached experimentally: even triggering on very high multiplicity will always select a range of impact parameters. Furthermore, the probability that the impact parameter lies between b and $b+db$ is proportional to b and therefore the contributions of very central collisions have only very small weight.

[#3] It should be noted that the aspect ratios $\sqrt{\lambda_2'/\lambda_3'}$ obtained from sphericity analysis are about 30% smaller than the ratios $R_{y''}/R_{x''}$ quoted above. This reflects the fact that $R_{y''}/R_{x''}$ is taken at $p_z'' \approx 0$, while $\sqrt{\lambda_2'/\lambda_3'}$ is evaluated for the whole event.

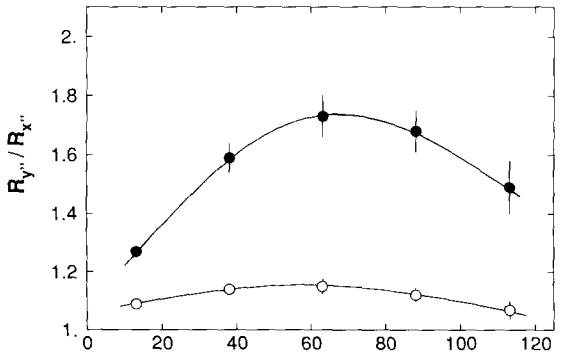

Fig. 4. Aspect ratio of the half axes of an ellipsis at $p_z'' \approx 0$ describing the distribution of particles (filled circles) and the momentum per nucleon (open circles) in the $x''y''$ plane as a function of multiplicity. The solid curves are to guide the eye.

5. Conclusions

In conclusion, we have found that events in relativistic heavy-ion collisions have a considerable azimuthal anisotropy at mid-rapidity, in accordance with predictions from fluid dynamical calculations [3]. The anisotropy occurs both in position and momentum space. This squeeze-out effect is most pronounced if the events are analyzed in the coordinate system given by the principal axes of the sphericity tensor. Squeeze-out particles escape from the hot and dense reaction zone unhindered by surrounding cold target- or projectile-matter. This opens the possibility of a "window" through which one can look directly at the compressed and hot fireball. Detailed studies of energy spectra, pion yields, composite particle ratios, etc. in this window might give further useful information for a precise determination of the equation of state of nuclear matter.

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