Collective flow by the azimuthal correlation of projectile fragments in relativistic heavy-ion collisions

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An analysis that does not require the determination of reaction plane on an event-by-event basis, and involves only azimuthal correlation function of the projectile fragment pairs, has been employed to measure the collective flow of nuclear matter. Using this technique, we study the flow of projectile fragments of charge $Z \geq 2$ produced in ^{197}Au induced-emulsion reactions at 10.6A GeV. The collective flow is observed to be the most pronounced in semicentral collisions. The results are compared with those of ^{28}Si at 14.5A GeV, ^{238}U at 0.96A GeV, ^{84}Kr at 1.52A GeV, and ^{56}Fe at 1.7A GeV.

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According to the predictions of hydrodynamic models [1], a strong azimuthal correlation of particles produced in relativistic heavy-ion collisions is considered as a measure of the fluidlike behavior of nuclear matter [2]. This strong azimuthal correlation of particles is manifested into two collective effects [2] both occurring in the reaction zone: (i) an azimuthally asymmetric emission of participant particles, the so-called "side splash" of nuclear matter, and (ii) a sideward deflection of spectator fragments, the "bounce off" due to transverse communication with the reaction plane. The collective flow has been unambiguously established on an event-by-event basis in experiments involving 4π detectors such as the plastic ball [3] and streamer chamber [4].

The collective flow can be studied experimentally with the help of conventional transverse momentum analysis [5] in which the reaction plane $\mathbf{Q}$ is determined for each particle separately from the remaining particles in an event: $\mathbf{Q}_i = \sum_{j\neq i} w_j A_j \mathbf{P}_{t_j}$ and $p_i^x = \mathbf{P}_{t_i} \cdot \mathbf{Q}_i/|\mathbf{Q}_i|$, where $\mathbf{P}_{t_i}$ represents the transverse momentum of particle i, $w_j = 1$, A_j is the mass of particle j, and p_i^x/A is the transverse momentum vector of the particle i projected onto the reaction plane. Using this analysis of transverse flow [5], we observed the collective flow effects in emulsion at LBL energies [6]. In Ref. [7], a method of flow analysis that avoids the cumbersome procedure of determining the reaction plane on an event-by-event basis, and also circumvents the problem of finite dispersion in the estimation of the reaction zone, has been presented. This technique has been motivated by the prospect that such studies may provide new insights towards the solution of some ambiguities in low-density nuclear equation of state (EOS). In this paper, we use this method for the first time to investigate the collective flow of nuclear matter in ^{197}Au induced-emulsion collisions at 10.6A GeV from the Alternating Gradient Synchrotron at Brookhaven National Laboratory (BNL) and compare these results with those obtained from four additional data samples: (i) 14.5A GeV ^{28}Si ion from the BNL and (ii) ^{238}U at 0.96A GeV, ^{84}Kr at 1.52A GeV, and ^{56}Fe at 1.7A GeV from the Lawrence Berkeley Laboratory (LBL). An attempt has also been made to study the collective flow phenomenon on the basis of event centrality at BNL energy.

As discussed in Ref. [7], the collective flow can be parametrized in terms of azimuthal angle distributions of particle pairs provided the effects of the Coulomb interaction and quantum statistics of identical particles with small relative momentum are neglected. Under these assumptions, the probability of observing two particles having azimuthal angles ϕ_1 and ϕ_2 can be expressed as

$$\frac{d^2\sigma}{d\phi_1 d\phi_2} = A^2(1 + \lambda \cos\phi_1)(1 + \lambda \cos\phi_2), \qquad (1)$$

where λ is a constant as defined in Refs. [7,8]. The value of λ is a measure of the azimuthal anisotropy observed in a given data set and its magnitude may throw some light on the nuclear equation of state. The larger the value of λ is, the larger is the magnitude of the collective flow. The probability distribution $P(\psi)$ of the angle ψ between the transverse momenta of two correlated particles is, then, given by

$$P(\psi) = A^2(1 + 0.5\lambda^2 \cos\psi). \qquad (2)$$

By employing the approach of interferometry analysis [9], the azimuthal correlation function $C(\psi)$ is defined as

$$C(\psi) = \frac{P_{\rm corr}(\psi)}{P_{\rm uncorr}(\psi)}, \qquad (3)$$

where $P_{\rm corr}(\psi)$ represents the distribution of ψ for the correlated particle pairs occurring in the same event and $P_{\rm uncorr}(\psi)$ is obtained from the distribution of uncorrelated particle pairs generated by the mixing of events such that each member of a pair is randomly chosen from a different event with the same multiplicity. If $C(\psi) > 1$ at small values of ψ and $C(\psi) < 1$ at large values of ψ, then it is an indication of the collective flow phenomenon. The magnitude of an observed flow can be determined from the best-fit value of λ in Eq. (2) for a particular data set. For a flat distribution of $C(\psi)$, $\lambda = 0$ and consequently there is no collective flow effect.

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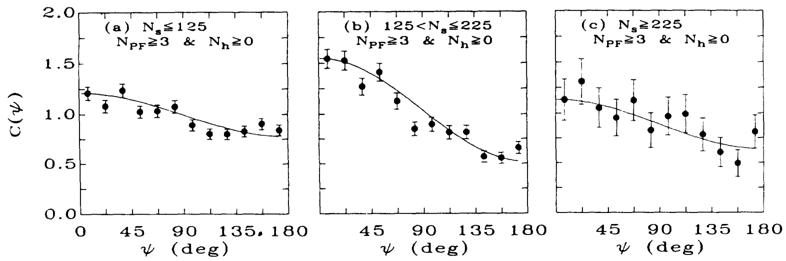

FIG. 1. Azimuthal correlation function $C(\psi)$ vs ψ for three subgroups of shower particles: (a) peripheral events ($N_s \leq 125$), (b) midcentral events ($125 < N_s \leq 225$), and (c) central events ($N_s > 225$) in ^{197}Au induced-emulsion reactions. Solid circles show the experimental data and solid curves are the best fittings to data according to Eq. (2) with $A = 1$.

In experiment 875, conducted at the Brookhaven AGS, we exposed three stacks of Fuji nuclear emulsion to a beam of ^{197}Au ions at 10.6A GeV. The stacks were exposed to these nuclei in a horizontal orientation so that a great majority of the individual ^{197}Au ions was confined in a single-emulsion pellicle. The primary tracks of ^{197}Au ions were followed by along-the-track scanning technique and about 1500 inelastic nuclear interactions were recorded within the first few cm. In each event, charges (Z) of the projectile fragments (PF's) were determined by exploiting several conventional methods as discussed elsewhere [10]. For the present analysis, a unique kind of data sample was selected such that each event had at least three PF's of charge $2 \leq Z \leq 17$ and also the number of singly charged shower particles (N_s) was > 50. These stringent selection criteria reduced our sample to 166 events. In some of the events, more than 300 shower particles were observed. The polar angles of all the particles produced in an event were determined very accurately from the vector directions of the emitted tracks with respect to a noninteracting beam track selected in the vicinity of the interaction vertex (the relative primary method) [11]. The xyz coordinates of all the tracks, including the vertex and the relative primary track, were subjected to three-dimensional track reconstruction programs to compute the polar angles. In emulsion, it is customary to categorize events on the basis of target size: light targets with $N_h \leq 7$ and heavy targets having $N_h \geq 8$, where N_h stands for the number of black and grey tracks produced from the target nucleus of emulsion. In order to facilitate the comparison, three additional data sets consisting of 108 events of ^{238}U at 0.96A GeV, 275 interactions of ^{84}Kr at 1.52A GeV, and 158 events of ^{56}Fe at 1.7A GeV from the experiments carried out at LBL [10] and one data sample composed of 142 events of ^{28}Si at 14.5A GeV from BNL [11] were also used.

The number of singly charged shower particles N_s produced in an interaction can be conveniently considered as a measure of event centrality [12]. Consequently, we divide 166 events of ^{197}Au into three subgroups: peripheral events with $N_s \leq 125$, semicentral events having $125 < N_s \leq 225$, and central interactions with $N_s > 225$. In Figs. 1(a)–1(c), we depict variation of azimuthal correlation function $C(\psi)$ as a function of ψ for PF's of charge $Z \geq 2$ for these three subsamples of events in ^{197}Au beam. The errors shown are of statistical origin in each case. Clearly, magnitude of the correlation function $C(\psi)$ is more than unity at small values of ψ, and is always less than one for large values of ψ. This indicates the presence of the collective flow of nuclear matter at BNL energy. The solid curve in these figures represents a minimized χ^2 fittings to each of the data set used in the present analysis. The best fitted value of λ along with its error for each of three subgroups is given in Table I. The values of $C(\psi)$ for midcentral events as shown in Fig. 1(b) are the highest at lower ψ values and the magnitude of the flow is characterized by the value of λ which is higher for Fig. 1(b) than for Fig. 1(a) or Fig. 1(c). Therefore, the collective flow effect at BNL energy is observed to be the maximum for the midcentral subsample.

Now, we investigate the collective flow effect on the basis of identical and nonidentical PF pairs. This is achieved by taking the whole data set of ^{197}Au interactions involving all emulsion targets, $N_h \geq 0$: (i) by considering events with at least three PF's ($N_{\rm PF}$) of charge $Z \geq 2$ (nonidentical PF pairs) and (ii) by selecting those interactions in which at least three α-particle tracks (N_α) with $Z = 2$ were seen (identical PF pairs). The outcome of such an analysis is diagrammatically shown in Figs. 2(a) and 2(b) for events with $N_{\rm PF} \geq 3$ and $N_\alpha \geq 3$, respectively. Once again, the collective flow has been observed in both the data sets by using the

TABLE I. The best fitted value of λ in Eq. (2) and the minimized χ^2 value for the data on 10.6A GeV ^{197}Au and 14.5A GeV ^{28}Si events with $N_h \geq 0$. Here, $N_{\rm ev}$ stands for the number of events used.

Ion	$N_{\rm ev}$	Event type	λ	χ^2
^{197}Au	67	$N_s \leq 125$	0.662 ± 0.081	0.49
^{197}Au	68	$125 < N_s \leq 225$	0.990 ± 0.120	1.09
^{197}Au	31	$N_s > 225$	0.748 ± 0.134	0.69
^{197}Au	166	$N_{\rm PF} \geq 3$	0.770 ± 0.059	0.43
^{197}Au	156	$N_\alpha \geq 3$	0.690 ± 0.055	1.10
^{28}Si	142	$N_{\rm PF} \geq 3$	0.988 ± 0.083	1.05

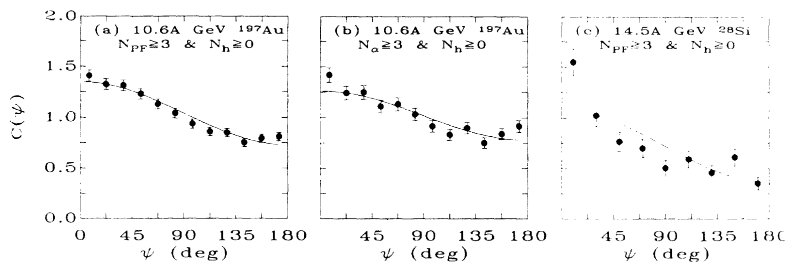

FIG. 2. Azimuthal correlation function $C(\psi)$ vs ψ for the ^{197}Au data with (a) $N_{\rm PF} \geq 3$ of charge $Z \geq 2$ and (b) $N_\alpha \geq 3$ with $Z = 2$. (c) The same as in (a), but for the ^{28}Si ion at 14.5A GeV from BNL. Solid circles represent the experimental data and solid curves are the best fittings to data in accordance with Eq. (2) having $A = 1$.

above-mentioned criteria of $C(\psi)$ and λ values. The best fitted value of λ is also given in Table I. Within statistical errors, the values of λ obtained for nonidentical and identical PF pairs are nearly equal. This proves that the current analysis, within statistical errors, is insensitive to the PF identity and corroborates the findings of Ref. [7]. To compare the above results with another heavy-ion beam from BNL, we present the data of the ^{28}Si beam at 14.5A GeV in Fig. 2(c) for events with $N_{\rm PF} \geq 3$ and $N_h \geq 0$. This data set also indicates the presence of flow effect. The value of λ is given in Table I. In comparison to ^{197}Au data with $N_{\rm PF} \geq 3$ and $N_h \geq 0$, ^{28}Si data show a larger value of λ. Using the conventional transverse momentum technique [5], the collective flow has been observed to be larger for the PF's of charge $Z \geq 3$ and such like asymmetry is attributed to strong flow effects in the reactions involving heavier fragments [12]. The present technique of analysis, within experimental errors, is not sensitive enough to detect this effect.

By keeping the target size fixed, we now study the flow effects as a function of the projectile mass and its energy. For this purpose, the above analysis is repeated by imposing a cut on the target size in such a way that all the data samples chosen involve events with $N_h \geq 8$ and $N_{\rm PF} \geq 3$ of charge $Z \geq 2$. The highest-energy 10.6A GeV ^{197}Au data are presented in Fig. 3(a). To investigate the mass dependence under exactly similar experimental circumstances, we present the results of three different heavy ions accelerated at LBL with energy in the range from 0.96A to 1.7A GeV, viz., ^{238}U at 0.96A GeV, ^{84}Kr at 1.52A GeV, and ^{56}Fe at 1.7A GeV, in Figs. 3(b), 3(c), and 3(d), respectively. In all the cases, the collective flow effect is also evident as reported in Ref. [6]. The value of λ for each case is given in Table II. Within error bars, the λ value seems to be independent of the projectile mass at LBL energies, and, consequently, the magnitude of the collective flow appears to be the same for these three projectiles. To support our findings on ^{56}Fe at 1.7A GeV, we may cite a recent work of Wang *et al.* [6] in which the collective flow has been observed for ^{40}Ar+KCl and ^{40}Ar+BaI$_2$ reactions at 1.2A GeV from LBL. This is further supported by our former study with ^{56}Fe ion at 1.7A GeV and ^{40}Ar beam at 1.8A GeV from LBL, using the transverse momentum technique [5]. When we compare our results of the ^{197}Au beam from BNL and ^{238}U ion from LBL, an apparent difference in value of λ can be noticed. This may be an energy effect: ^{197}Au ion has energy more than ^{238}U ion by a factor of 10, although

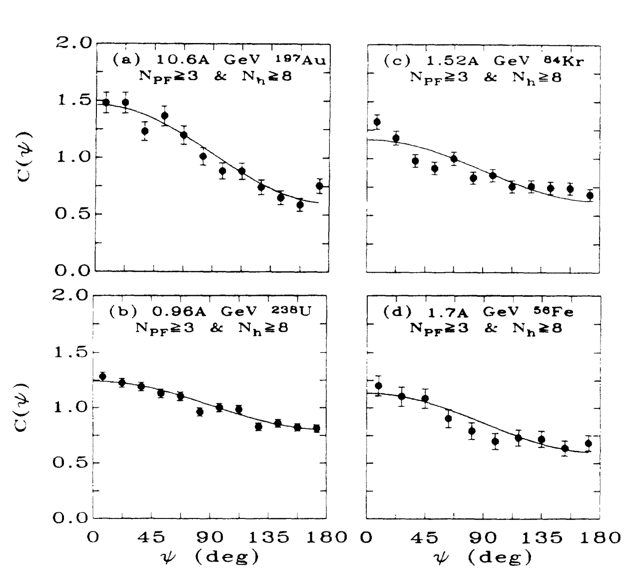

FIG. 3. Same as in Fig. 2, but for the events with $N_h \geq 8$ and $N_{\rm PF} \geq 3$ of charge $Z \geq 2$ for (a) ^{197}Au at 10.6A GeV, (b) ^{238}U at 0.96A GeV, (c) ^{84}Kr at 1.52A GeV, and (d) ^{56}Fe at 1.7A GeV.

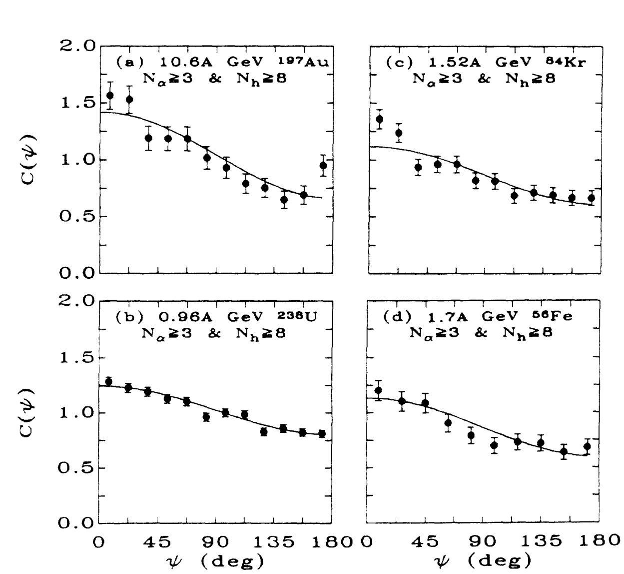

FIG. 4. Same as in Fig. 2, but for the events with $N_h \geq 8$ and $N_\alpha \geq 3$ of charge $Z = 2$ for (a) ^{197}Au at 10.6A GeV, (b) ^{238}U at 0.96A GeV, (c) ^{84}Kr at 1.52A GeV, and (d) ^{56}Fe at 1.7A GeV.

TABLE II. The same as in Table I for the data of ^{197}Au, ^{238}U, ^{84}Kr, and ^{56}Fe induced-emulsion events with $N_h \geq 8$.

Ion	Events with $N_{PF} \geq 3$	λ	χ^2	Events with $N_\alpha \geq 3$	λ	χ^2
^{197}Au	70	0.911±0.109	0.52	67	0.853±0.104	1.18
^{238}U	108	0.655±0.063	0.19	108	0.655±0.063	0.57
^{84}Kr	275	0.778±0.047	2.66	207	0.766±0.053	2.19
^{56}Fe	158	0.787±0.063	1.27	105	0.675±0.066	0.49

both ions have almost the same mass. As a consequence, ^{197}Au ion exhibits a stronger collective flow of nuclear matter. To perform this analysis for the target and PF sizes fixed, we select the events with $N_h \geq 8$ (heavy targets) and $N_\alpha \geq 3$ ($Z = 2$) for these four projectiles. The collective flow just like before is again observed at BNL as well as at LBL energies and this is shown in Figs. 4(a)–4(d) for ^{197}Au, ^{238}U, ^{84}Kr, and ^{56}Fe, respectively. The value of λ, as obtained from these figures, is listed in Table II. Again, the collective flow effect is observed to be the maximum with a ^{197}Au ion at BNL energy. ^{238}U, ^{84}Kr, and ^{56}Fe beams accelerated at LBL have the same magnitude of λ showing a behavior that does not depend upon the PF mass.

By using an azimuthal correlation function analysis, we find an evidence of the collective flow effects at BNL and LBL energies. The magnitude of the collective flow is observed to be the maximum in midcentral collisions of ^{197}Au ion at 10.6A GeV and is comparable with that of ^{28}Si data with $N_{PF} \geq 3$ and $N_h \geq 0$ from BNL (Table I). With the present technique, the flow effect appears to be the same, within the statistical errors, for the projectile fragments at the low energy [$\approx$ (1–2)A GeV] (Table II).

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