Collective-flow Correlations in ^{197}Au -emulsion Interactions at 10.6A GeV

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Abstract

We have studied the azimuthal angle correlations in pairs of alpha particles, in Intermediate Mass Fragments (IMFs), and in higher order multiplets observed in ^{197}Au -emulsion interactions at 10.6A GeV. The correlation functions for higher fragment multiplets (greater than three or more fragments) exhibit characteristic signatures which are enhanced compared to those of two-fragment correlation functions. The pure multiplet contribution is extracted from the observed higher-order correlation functions. The measurements of collective flow correlations in heavy-ion collisions are best obtained by studying several fragments with mixed charges including He fragments.

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During the last decade or so, the collective flow of nuclear matter has been extensively discussed in the literature. The magnitude of collective motion produced in relativistic heavy-ion collisions gives information about the effective pressure which is generated by compression and heating in the high density phase. Several signals of the collective motion have been observed, for example by studying the flow angle [1], sideward flow [2,3] and out of plane "squeeze-out" [4-6]. The sideward flow represents a small fraction of the transverse energy. The flow angle is expected to be maximum in central collisions [7], whereas sideward flow and out of plane "squeeze-out" [8] vanish in central col-

lisions for identical nuclei due to their symmetry; but in semicentral collisions, they have maximum values [5,9]. Recent investigations [5,9,10] have also revealed that the Intermediate Mass Fragments (IMFs) are more sensitive than the light charged particles (protons etc.) to the collective sideward flow and the expansion of the system in mid-central collisions. Heavier fragments exhibit stronger flow than light fragments because heavier fragments have relatively lower (undirected) thermal velocity than lighter particles [11]. The thermal energy components define the A-independent thermal energy per particle, whereas the flow energy (i.e. the original built-in compressional energy) is determined by the expansion velocity and therefore should increase with the mass (charge). The flow energy represents an increasingly larger fraction of the fragment energy and random undirected thermal motion becomes less important as the fragment mass (charge) increases. Most work on collective flow has been done at low energies $< 0.5A$ GeV [12]. Recently we have observed collective sideward flow of nuclear matter with the ^{197}Au beam at 10.6A GeV in nuclear emulsion which is a 4π detector and has the highest spatial resolution of any detector [10]. One can measure angles ≈ 0.1 mrad in emulsion. The presence of flow was deduced from transverse momentum analysis and from the azimuthal angle distributions of IMFs [10]. At present there is no information about the collectivity of the IMFs, which is the percentage of fragments that participate in the ordered motion at energies $> 1A$ GeV. In the present letter, we ex-

tract collectivity of IMFs of the ^{197}Au beam at 10.6A GeV for the first time.

Previous studies on the two-particle correlation of the IMFs have been quite important for the understanding of not only the collective dynamics in momentum space, but also for the space-time extent of the disassembling excited nuclear matter. IMFs experience significant repulsive final state Coulomb interactions which prevent the proximity of such particles in momentum space. This has important consequences for relative-angle correlation functions. Although the study of two-fragment correlation functions has been quite successful [13], their analysis cannot distinguish among fragment emission patterns dominated by one strongly correlated pair from those dominated by several correlated fragments. On the other hand, the study of correlations between three or more fragments (multiplicity > 3) can yield important information on the multifragment decay mechanism which is not obtainable from the two-particle correlation functions. Such studies can also provide important information on the predicted liquid-gas phase transition [14] in nuclear matter. Recent developments in the area of microscopic transport models [15] have helped to understand the flow data in terms of nuclear state variables. Most of this work has been done at low energies $\leq 1\text{A GeV}$ but here we present for the ^{197}Au beam at 10.6A GeV in nuclear emulsion (a 4π detector), a quantitative description of collectivity. Unlike other previous investigations of flow, we follow Ref. [12] and introduce an explicit correlation order N , which is a quantitative measure of collectivity, and also helps to demonstrate that the observed high-order effects are not dominated by low-order correlations. The latter point is crucial because multifragment correlation analysis necessarily includes the cumulative effect of correlations of all orders up to the highest to which the analysis is sensitive, unless explicit steps are taken to remove the low-order effects. The “pure multiplet” contribution is extracted in the present analysis from the higher-order correlation functions.

We employ the approach of interferometry analysis [12] and define the azimuthal correlation function $C(\psi_2)$ as

$$C(\psi_2) = \frac{P_{\text{corr}}(\psi_2)}{P_{\text{uncorr}}(\psi_2)}, \quad (1)$$

where $P_{\text{corr}}(\psi_2)$ represents the distribution of ψ_2 for the correlated particle pairs occurring in the same event, and $P_{\text{uncorr}}(\psi_2)$ 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. Thus, the ψ_2 angles between all selected fragments in an event are used in the construction of the correlation function (i.e. 3ψ angles are obtained for 3 fragments, 6ψ angles for 4 fragments etc..... $n(n-1)/2$ ψ angles for n fragments). If $C(\psi_2) > 1$ at small values of ψ_2 and $C(\psi_2) < 1$ at large values of ψ_2 , this is an indication of the collective flow phenomenon. Previously we have proved that collective flow is observed to be most pronounced in semicentral collisions [16]. One of the important advantages of the present method is the absence of any requirement that fragments heavier than He-particle ($Z = 2$) be identified.

The details of the present experiment on the ^{197}Au beam at 10.6A GeV from BNL Experiment No. 875 in emulsion target are given in Ref. [17]. Out of 1500 nuclear interactions, we selected 1097 peripheral events having at least one projectile fragment (PF) of charge $Z \geq 2$. In our previous work on collective flow [10], Fig. 1(b) showed that due to the bounce-off effect experienced by He-particles, their transverse momentum per nucleon P_t/A distribution had a long tail and for all He-particles it was very large as compared with other heavy fragments with $Z \geq 3$. In the flow measurements as shown in Fig. 2 of Ref. [10], He-particles were included. We now exclude all heavier PFs of $Z \geq 3$ and follow the procedure laid out in that paper for He-particles only. In Fig. 1(a) we show the distribution of average transverse momentum of He-particles against transverse momentum P_t/A for all He-events with $N_h \geq 0$, where N_h is the sum of grey and black low energy particles produced from the target. Here, $P_{t,i} = \tan \theta_i P_i$, where θ_i is the emission angle of i th projectile fragment and P_i is the longitudinal momentum per nucleon [10]. The transverse momentum is projected into the approximate reaction plane by evaluating the scalar product $P_t^x/A = P_{t,i} \cdot \mathbf{Q}_i / |\mathbf{Q}_i|$, where $\mathbf{Q}_i = \sum_{j \neq i} w_j A_j \mathbf{P}_{ij}$ and $w_i = 1$ for the fragments in the forward direction; the sum runs over all the particles of the event except for the particle i . This distribution is identical in shape to Fig. 2 of Ref. [10] except that the $\langle P_t^x/A \rangle$ peak values here for He-particles are slightly lower. The accuracy in the determination of the event planes was determined as before [10] by subdividing each event randomly into two subevents. The difference ($\Delta\psi$) between the azimuthal angles of two estimated planes is shown in Fig. 1(b). They all peak near zero as before [10]

and $\sigma_0 \approx 24^\circ$. In Fig. 1(c) we show the correlation in position space of the PFs with $Z = 2$. Here the fraction of PFs transverse momentum that lies in the reaction plane $\langle P_t^x/P_t \rangle$ is plotted against pseudorapidity (η_{lab}) in the laboratory frame. The maximum in the collective momentum transfer occurs near the projectile rapidity, and the section of the curve with $2 \leq \eta_{lab} \leq 4$ was used to measure the slope for the flow determination. The magnitude of the slope which determines the flow for He-particles is shown in Fig. 1(c) with the best fit value of 0.321 ± 0.041 and it is less than the slope value of 0.539 ± 0.107 for the best fit for PFs of $Z \geq 3$ as shown in Fig. 4 of Ref. [10]. In the following section, we shall show that the information that we obtained by analyzing the $\langle P_t^x \rangle$ correlation complements the results obtained from the collective flow. The normalized azimuthal angle distribution of the fragments with $Z \geq 2$ for events with number of PFs, $N_{PF} \geq 3$ is shown in Fig. 1(d). The distribution is almost isotropic.

For higher-order collective flow analysis a different kind of data sample was selected with 378 events such that each event had a number of PFs ≥ 3 , each fragment having charge $Z \geq 2$. Fig. 2(a) depicts azimuthal correlation function $C(\psi_2)$ as a function of ψ_2 for PFs of charge $Z \geq 2$. It shows a slight enhancement at low ψ_2 as suggested by the fit, when compared to Fig. 2(b). If we consider only the He-particles ($Z = 2$) with $N_\alpha \geq 3$ in each event, then the sample size is 329 events, and the distribution $C(\psi_2)$ is shown in Fig. 2(b). Fig. 2(c) represents the correlation in 237 events with $N_{PF} \geq 3$ of fragments with $Z \geq 3$ (i.e. with no He-particles). Here, almost all the points are below $C(\psi_2) = 1$. They show anticorrelations which are dominated by the long range Coulomb interactions between the higher charged fragments. We observe that the correlation function $C(\psi_2)$ of heavier fragments mixed with He-particles exhibits slightly stronger correlation statistically as well as by best fitting than with either He-particles or heavier fragments ($Z \geq 3$) alone. The magnitude of $C(\psi_2)$ reflects the strength of the correlation, and this increases with a decrease in ψ_2 values. It appears that for two-particle correlation, the presence of heavier fragments makes a small change in the $C(\psi_2)$ distribution [Fig. 2(a) and 2(b)]. But when we go to higher order correlation functions like $C(\psi_3)$, $C(\psi_4)$ and $C(\psi_5)$, the presence of heavier fragments make a big difference and they increase with the order N , as discussed in below.

We can generalize the observable ψ_2 to quan-

tify the collective flow of groups of N fragments in an event which are more closely spaced in azimuth than in a random distribution. We define the triplet observable as a geometric mean of the three azimuthal separations within the triplet $C(\psi_3) = (\psi_{ij}\psi_{jk}\psi_{ik})^{1/3}$, where ψ_{ij} is the smaller angle between the vectors $\mathbf{p}_i$ and $\mathbf{p}_j$. We plot the corresponding correlation function $C(\psi_3)$ evaluated for all possible triplets in a multiplet of N fragments, where we define

$$\psi_N = (\prod^K \psi)^{1/K}, \text{ and } K = \frac{1}{2}N(N-1). \quad (2)$$

Here the product runs over all K azimuthal separations $\Delta\psi$ in the multiplet, and we use events with a wide range of multiplicities M : the number of entries an event contributes to a $P(\psi_N)$ histogram scales like $h = M!/[(M-N)!N!]$, with the consequence that at large N , events with higher M completely swamp those with lower M when all entries have equal weight. To compensate for this, all $P(\psi_N)$ entries are weighted by M/h , thus ensuring that each event makes a contribution to the final result that is proportional to the number of tracks in that event.

We use Eq. (2) and the definition of h to calculate the function $C(\psi_3)$ and present the results in Fig. 2(d), 2(e) and 2(f) for 155 events having PFs of $Z \geq 2$ with $3 \leq N_{PF} \leq 5$, for 146 events with only He-particles with $3 \leq N_\alpha \leq 5$ and for 135 events having PFs of $Z \geq 3$ with $3 \leq N_{PF} \leq 5$, respectively. The strength of the correlation is reflected in the value of $C - 1$ which is higher for the fragments mixed with He-particles [Fig. 2(d)] than either with He-particles [Fig. 2(e)] or with heavier fragments of $Z > 2$ [Fig. 2(f)] alone. But the spread in the correlation angle ψ_3 is slightly larger with light fragments ($Z = 2$). Also the value of $C(\psi_3)$ with mixed events in Fig. 2(d) is about three times the value of $C(\psi_2)$ as shown in Fig. 2(a) and about two times the value as shown in Fig. 2(f) at small values of ψ_N . Similarly, the correlation strength of four fragments $C(\psi_4)$ is shown in Fig. 2(g), 2(h) and 2(i) which represent 90 events with fragments of charges $Z \geq 2$ with $4 \leq N_{PF} \leq 5$, 102 events with fragments of charges $Z = 2$ and $4 \leq N_\alpha \leq 5$, and 80 events with fragments of charges $Z \geq 3$ and $4 \leq N_{PF} \leq 5$, respectively. When there are four or more PFs, the correlation strength for small values of ψ_4 , among the heavier fragments with $Z \geq 3$ [Fig. 2(i)] increases much faster than among lighter PFs of $Z = 2$ [Fig. 2(h)]. The values of $C(\psi_4)$ in Fig. 2(g) are almost a factor of two greater than

$C(\psi_3)$ in Fig. 2(d), for small values of ψ_N . Just like the previous case of three fragments, the correlation strength is larger with mixed fragments of $Z \geq 2$, and in Fig. 2(g) it is one and a half times larger than in Fig. 2(i), and it is almost four times larger compared with Figs. 2(h) at small ψ_4 values. For five fragments, the correlation strength is shown in Fig. 3(a), 3(b) and 3(c), respectively, with 90 events for all fragments, 102 events for He-particles, and 80 events for heavier fragments alone. The strength is once again highest for mixed fragments; the values of $C(\psi_5)$ shown in Fig. 3(a) are higher than the values of $C(\psi_4)$ in Fig. 2(g). But the relative increase in the correlation strength is not as large here as found in Fig. 2(g) when compared with Fig. 2(d).

In order to condense the information contained in the correlation function $C(\psi_N)$, we define an azimuthal flow magnitude, $F(N)$, which characterizes the additional correlation effect for each step in N :

$$F(N) = L_N - L_{N-1},$$

$$L_{N-1} = \sum_{0 < \psi \leq 90} C(\psi_N) - 1. \quad (3)$$

Here, L_N is evaluated using the same set of ψ bins for N fragments, where $3 \leq N \leq 5$. Fig. 3(d) shows the experimental results for fragments with $N = 3$ to 5, for fragments of charge $Z = 2$, $Z \geq 3$, and with mixed fragments $Z \geq 2$. The slope for fragments with $Z \geq 2$ is definitely larger than for light fragments of charge $Z = 2$, and this result provides information independent of the measure of collectivity.

We conclude that in the interactions of the ^{197}Au beam with emulsion nuclei at 10.6A GeV, the transverse momentum flow of He-particles is slightly smaller than for PFs of $Z \geq 2$. There is a quantitative difference between two-fragment correlation functions and those for fragment multiplets $N \geq 3$. Lighter and heavier PFs do not participate equally in the collective expansion after the collision. Lighter fragments exhibit lower values of collectivity compared with heavier fragments (when $\psi_N > \psi_2$). In either case, the flow magnitude increases with the number of participating PFs, and in particular with mixed fragments including He fragments it is always greater than for either of the separate species of PFs for any order of N . The slope of the flow magnitude $F(N)$ increases by a factor of 2.5 when He-fragments and mixed fragments are compared. This is a new result which is being reported here for the first time with the ^{197}Au beam at 10.6A GeV with the hope that it would help the model builders to

improve their calculations for the degree of collectively and also to generate PFs which have not been done, as far as we know, at such high energies. The results from the transverse momentum flow complement the results of the collectivity of PFs and the latter will require large statistics of PFs to calculate a quantitative value of the correlation strength.

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Figure Captions

Fig. 1 (a) Average transverse momentum per nucleon $\langle P_t^x/A \rangle$ against P_t/A for the PFs of $Z = 2$. (b) Distribution of difference of azimuthal angles $\Delta\psi$ for vectors $\mathbf{Q}_1$ and $\mathbf{Q}_2$ constructed from two halves of each event for the whole sample. (c) $\langle P_t^x/P_t \rangle$ as function of η_{lab} for the PFs with $Z = 2$. Solid curve is a best fit polynomial through the data points. (d) $(dN/d\psi)/N_{ev}$ as a function of azimuthal angle ψ of the PFs ($Z \geq 2$) in events with $N_{PF} \geq 3$, where N_{ev} stands for the number of events.

Fig. 2 Azimuthal correlation function $C(\psi_2)$ vs. ψ_2 for the ^{197}Au events with: (a) $N_{PF} \geq 3$ of $Z \geq 2$, (b) $N_\alpha \geq 3$ of $Z = 2$ and (c) $N_{PF} \geq 3$ of $Z \geq 3$. Filled circles show the experimental data and solid curves in Figs. 2(a) and 2(b) are the best fits to data according to Eq. (2) in Ref. [17]. $C(\psi_3)$ vs. ψ_3 for the events with: (d) $3 \leq N_{PF} \leq 5$ of charge $Z \geq 2$, (e) $3 \leq N_\alpha \leq 5$ with $Z = 2$ and (f) $3 \leq N_{PF} \leq 5$ of $Z \geq 3$. $C(\psi_4)$ vs. ψ_4 for the events with: (g) $4 \leq N_{PF} \leq 5$ of charge $Z \geq 2$, (h) $4 \leq N_\alpha \leq 5$ with $Z = 2$ and (i) $4 \leq N_{PF} \leq 5$ of $Z \geq 3$. The dotted line is the reference level from which the correlation strength is measured.

Fig. 3 $C(\psi_5)$ vs. ψ_5 for the events with: (a) $4 \leq N_{PF} \leq 5$ of charge $Z \geq 2$, (b) $4 \leq N_\alpha \leq 5$ with $Z = 2$ and (c) $4 \leq N_{PF} \leq 5$ of $Z \geq 3$. The dotted line is the reference level from which we measure the correlation strength. (d) $F(N)$ as a function of N for events with fragments of charge: (i) $Z \geq 2$ (filled circles), (ii) $Z = 2$ (filled triangles) and (iii) $Z \geq 3$ (filled squares). Dashed lines represent the best fits.

Jain and Singh Fig.1

Jain and Singh Fig.2