Azimuthal correlation of multifragments of ^{208}Pb nuclei at 160A GeV

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Abstract

The azimuthal angle correlations in pairs of projectile fragments (PFs) of charge $Z = 2$ and $Z > 2$ are studied in the ^{208}Pb -emulsion interactions at 160A GeV, as a function of their transverse momentum (P_t). The correlation strength increases with the centrality of the collision (except at $b=0$), and is much larger than the ^{197}Au data at 10.6A GeV.

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Heavy-ion collisions offer the possibility to study extremely heated and compressed nuclear matter, which breaks up into fragments of different charges. At present, a full theoretical understanding of multi-fragment production in finite nuclear systems is not available. Alternative models for the emission of projectile fragments (PFs) have been proposed, ranging from static thermodynamical treatments [1-4] to rate-equation approaches based on the generalization of compound-nucleus decay models [5-7]. Most of the models in Refs. [1-6] do not account for the collective flow in heavy-ion collisions which was first predicted by Stoecker et al. [8] and later confirmed experimentally Gustafson et al. [9] at low energy $\approx 1\text{A GeV}$. The collective flow has been observed, for the first time, with PFs of charge $Z \geq 2$, at the highest to date available energies of ^{197}Au beam at 10.6A GeV from AGS [10] and of ^{208}Pb beam at 160A GeV from the CERN SPS [11]. There are also measurements of azimuthal anisotropic distributions of singly charged particles produced from the ^{197}Au beam at BNL [12] and the ^{208}Pb beam at CERN [13]. The prediction of multifragmentation and collective flow in heavy-ion collisions are studied with

molecular dynamics [14] and microscopic quantum molecular dynamics [15] theories. The flow-parameter determination require the knowledge of the reaction plane [16] and their results should be corrected for the uncertainties related to the reconstruction of the reaction plane from the detected reaction products [17]. In a 4π detector these uncertainties could be quite large. In spite of considerable efforts, the study of the extracted physical observables however fails to provide an unambiguous delineation of the reaction processes to date. One way to circumvent this difficulty is revealed by studying the particle-particle azimuthal correlation function. This type of analysis does not require the knowledge of reaction plane. Additional experimental information based on the dependence of the correlation functions on the impact parameter is necessarily required to discriminate among various theories. Two-particle correlations at small relative momentum offer the opportunity to probe the space-time evolution of excited nuclear systems which may help to understand the multifragmentation mechanism.

The azimuthal angular correlation function $1 + R_2(\Delta\phi_{12})$ defined by the ratio [18,19]

$$1 + R_2(\Delta\phi_{12}) = \frac{\sum P_{\text{corr}}(\Delta\phi_{12})}{\sum P_{\text{uncorr}}(\Delta\phi_{12})}. \quad (1)$$

The ordered motion of the emitted particles can be detected from Eq. (1), where $\Delta\phi_{12} = \phi_1 - \phi_2$ is the relative azimuthal angle between the two PFs in the plane perpendicular to the beam axis (i.e. the angle between their transverse momenta) [10,15]. $P_{\text{corr}}(\Delta\phi_{12})$ is the coincidence yield for the correlated particle pairs occurring in the same event with relative azimuthal angle $\Delta\phi_{12}$, and $P_{\text{uncorr}}(\Delta\phi_{12})$

is the background (uncorrelated) yield generated by the mixing of events i.e. by randomly selecting each of the fragment pairs from different events with the same multiplicity. In most of the studies of the two-particle correlation function, an a priori arbitrary normalization of the correlation function is used so that $R_2(\Delta\phi_{12})$ tends to zero at large $\Delta\phi_{12}$. This may be true for proton-proton correlation functions, but for the PFs, the correlation functions are sensitive to energy-momentum conservation, and therefore in general, the correlation function $R_2(\Delta\phi_{12})$ may not converge asymptotically to zero [17] and hence we have not introduced any normalization of the correlation functions in discussing the results of the present experiment in Figs. (1-3). This explains why in most cases the Figs. (1-3) indicate a correlation always above unity at large $\Delta\phi_{12}$ values.

In the current article, we present *for the first time*, the azimuthal correlation for the PFs of identical charges ($Z = 2$) and non-identical charges ($Z \geq 2$) produced from the ^{208}Pb beam to date at the highest beam energy of 160A GeV in emulsion and compare these results with data from the ^{197}Au beam at 10.6A GeV. We concentrate on two-particle correlations [as given by Eq. (1)] as a function of the azimuthal angle difference of two PFs selected by their collective charges Z_{bound} , the transverse momentum P_T of individual PFs and the number of shower particles N_s produced in a given interaction. The effect of impact parameter which relates to the violence of the collision is observed indirectly through the variables P_T and N_s .

The data sample used in this paper consists of nuclear interactions in emulsion exposed to the ^{208}Pb beam at 160A GeV from the CERN SPS (Expt. No. EMU11) and to the ^{197}Au beam at 10.6A GeV from the Brookhaven National Laboratory AGS (Expt. No. 875). By following along the primary tracks, we observed 1034 and 1500 nuclear events in emulsion with the ^{208}Pb and ^{197}Au [19] beams, respectively. Nuclear emulsion has the best spatial resolution among all the detectors. The angles of all the PFs were measured with an error less than 0.1 mrad by relative primary method [10]. Spectator protons from the projectile nucleus are produced mostly within a very narrow forward cone with semi-vertex angle, θ_c , given by the Fermi momentum. The values of θ_c are ≈ 1.3 and 20 mrad for the ^{208}Pb and ^{197}Au ions, respectively. The charges of all the PFs were determined by the combination of several methods: grain, gap and δ -ray densities and the track widths, as discussed in Refs. [10] for ^{197}Au

and ^{208}Pb beams, respectively. For α -particles, grain density ($4g_0$) was used, where g_0 is the minimum ionization in emulsion. For δ -ray densities more than 200 δ -rays were counted for each track.

For the present analysis, we selected events which have at least four PFs of charge $2 \leq Z \leq 20$ in the ^{208}Pb as well as ^{197}Au beams. These restrictions reduced the number of events to 334 for the ^{208}Pb beam and to 363 for the ^{197}Au beam. Fig. 1(a) exhibits the distribution of azimuthal correlation function of PFs of identical charges $Z = 2$ for the ^{208}Pb and ^{197}Au beams. The slopes of an azimuthal correlation function are not sensitive to the direction of the collective flow but they are sensitive to its magnitude. The magnitude of the correlation function for the ^{208}Pb beam is more enhanced than for the ^{197}Au beam at small relative angles ($\Delta\phi \leq 45^\circ$), but at large $\Delta\phi > 60^\circ$, the functional values are ≈ 1.5 . The positive correlation is due to collective sideward motion of bouncing nuclear matter [10]. With the increase in the projectile energy, the influence of the collective motion increases as is exhibited in Fig. 1(a) for the ^{208}Pb beam at 160A GeV when compared with the ^{197}Au beam at 10.6A GeV. The errors shown throughout the paper are statistical in nature for the number of PFs used. The shape of the correlation functions, in general, reflects an interplay between the long-range Coulomb interaction between the projectile fragments, their mutual interaction as well as the interaction with the neighboring fragments. When we include heavier fragments of charge $Z \geq 3$ with $Z = 2$ particles, then the distributions of the correlation function are shown in Fig. 1(b). The relative intensity of the correlation functions for both the beams are unchanged from Fig. 1(a) showing that fragments of $Z = 2$ play a very dominant part in the correlation function distributions. If we use only heavier fragments of charge $Z \geq 3$ as exhibited in Fig. 1(c), then the relative intensity of the correlations is further reduced for both the beams as compared to the results of Figs. 1(a) and 1(b). This indicates that heavier fragments may not participate as fully as the lighter fragments in collective expansion. We observed this effect before and was explained in Fig. 2 of Ref. [10] in connection with the collective flow. But when we use higher ordered correlation functions ($N > 2$), the presence of heavier fragments of charge $Z \geq 3$ enhances the correlation intensity as compared to PFs of $Z = 2$ and it was previously shown in Ref. [10].

We further calculate the transverse momentum of the PFs produced in the ^{208}Pb beam as explained

in Ref. [10]. For each fragment we calculate $P_{ti} = \tan \theta_i P_i$, where θ_i is the emission angle of the i th PF with respect to the primary beam and P_i is the longitudinal momentum per nucleon of the PFs. For the determination of P_i values, we have assumed that the longitudinal momentum P_i per nucleon of the PFs at such high energy 160A GeV is the same as that of the incident projectile [10].

In order to obtain information about the distribution of the azimuthal correlation function on the basis of different impact parameters, we divided the Helium producing interactions of the ^{208}Pb beam into two categories of transverse momentum distributions. Fig. 2(a) depicts the distribution of the correlation function of fragments $Z = 2$ with two transverse momentum (P_t) cuts: (i) $P_t \leq 150$ MeV/c and (ii) $P_t > 150$ MeV/c. The strength of the correlation function for more central events (with $P_t > 150$ MeV/c) at low $\Delta\phi_{12}$ values, is much higher than for events with low $P_t \leq 150$ MeV/c values.

In order to compare the ^{208}Pb beam with the ^{197}Au beam against the different values of relative azimuthal angle $\Delta\phi_{12}$, Fig. 2(b) displays for the ^{197}Au beam the correlation distributions of $Z = 2$ fragments for $P_t \leq 150$ MeV/c and $P_t > 150$ MeV/c, respectively. The correlation strength at small $\Delta\phi_{12}$ is higher for the ^{208}Pb beam with much higher energy [Fig. 2(a)] than in the ^{197}Au beam as shown in Fig. 2(b). In ^{197}Au beam, the cuts in the data for P_t do not separate them from one and other within the statistical errors and this is different from the observations in the ^{208}Pb beam [Fig. 2(a)].

We may give some possible explanation of the "backgrounds" for uncorrelated pairs. In the present analysis of the data we have assumed that the PFs have the same energy per nucleon as that of the primary beam, and this assumption is more relevant at higher energy like ^{208}Pb beam at 160A GeV as compared to lower energy beam of ^{197}Au at 10.6A GeV. Moreover, we have used selected events which have at least four or more PFs of charge $2 \leq Z \leq 20$. If one of the PFs may happened to have slightly lower energy than the primary beam, its P_t value will effect the distribution of the correlation function between all the fragments belonging to that event.

As we have measured the multiplicity (N_s) of the shower particles produced in both the beams interacting with emulsion nuclei, we use this parameter to indicate the effect of impact parameter. The events with the emission of $Z = 2$ particles in the ^{208}Pb and ^{197}Au data samples were divided into two sub-

samples having $N_s \leq 125$ and $N_s > 125$. Figs. 3(a) and 3(b) display the azimuthal correlation function for different relative azimuthal angle $\Delta\phi$ for the sub-samples of the ^{208}Pb and ^{197}Au beams, respectively. There is a considerable scattering among the data points in the ^{197}Au beam. Fig. 3(b) does not show the impact parameter dependent effect in the ^{197}Au beam at 10.6A GeV as clearly as is observed in the 160A GeV ^{208}Pb beam of higher energy in Fig. 2(a). Higher charged multiplicities represent relatively more violent collisions.

We conclude that there is strong two-particle azimuthal correlations of nuclear fragments (for $Z = 2$ and $Z > 2$) in ^{208}Pb beam. The relative intensity of the azimuthal angle correlation function of the PFs of $Z = 2$ from the ^{208}Pb beam at 160A GeV, increases much more rapidly with the decrease toward small relative azimuthal angle separation $\Delta\phi_{12}$ when compared with the ^{197}Au beam at 10.6A GeV. The strength of the correlation function for the ^{208}Pb beam is much higher when compared with the corresponding small $\Delta\phi_{12}$ values of the ^{197}Au data. The correlation intensity is further reduced for the PFs of heavier charges $Z > 2$. The azimuthal correlation strength of the PFs produced from the ^{208}Pb beam increases with the centrality of the collision and it is much larger than the values we get from the ^{197}Au beam at low energy. The azimuthal distribution of multifragments is quite sensitive to the magnitude of the collective flow and the present results support our previous findings of collective flow observed in ^{197}Au [10] and ^{208}Pb [11] beams which are energy dependent. We hope that the above information would be useful for the model builders.

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Figure Captions

Fig. 1 (a) Azimuthal correlation function $1 + R_2(\Delta\phi_{12})$ as a function of $\Delta\phi_{12}$ for the PFs of charge $Z = 2$ emitted in the events of: (i) the ^{208}Pb ion at 160A GeV (closed circles) and (ii) the ^{197}Au projectile at 10.6A GeV (open circles). (b) The same as in Fig. 1(a), but for PFs of charge $Z \geq 2$ in: (i) the ^{208}Pb data (closed circles) and (ii) the ^{197}Au data (open circles). (c) The same as in Fig. 1(a), but for PFs of charge $Z \geq 3$ in: (i) the ^{208}Pb data (closed circles) and (ii) the ^{197}Au data (open circles).

Fig. 2 Azimuthal correlation function $1 + R_2(\Delta\phi_{12})$ as a function of $\Delta\phi_{12}$ PFs with $Z = 2$ and $P_t \leq 150$ MeV/c (closed circles) and $P_t > 150$ MeV/c (open circles) for (a) the ^{208}Pb and (b) ^{197}Au beams.

Fig. 3 Azimuthal correlation function $1 + R_2(\Delta\phi_{12})$ as a function of $\Delta\phi_{12}$ of PFs with $Z = 2$ and $N_s \leq 125$ (closed circles) and $N_s > 125$ (open circles) for (a) the ^{208}Pb and (b) ^{197}Au beams.

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Singh and Jain Fig. 2

Singh and Jain Fig. 3