Multifragment Azimuthal Correlation Functions: Probes for Reaction Dynamics in Collisions of Intermediate Energy Heavy Ions

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(Received 26 June 1992)

Multifragment azimuthal correlation functions have been measured as a function of beam energy and impact parameter for the Ar+Sc system ($E/A = 35$ to 115 MeV). The observed azimuthal correlation functions—which do not require corrections for dispersion of the reaction plane—exhibit strong asymmetries which are dependent on impact parameter and beam energy. Rotational collective motion and flow seem to dominate the correlation functions at low beam energies. It is proposed that multifragment azimuthal correlation functions can provide a useful probe for intermediate energy heavy ion reaction dynamics.

PACS numbers: 25.70.Pq

Collisions between nuclei at intermediate energies can lead to hot compressed nuclear matter. Over the last few years, many studies [1,2] have sought (a) to characterize the thermodynamic properties of this matter, and (b) to illuminate the dynamical processes that might be involved in its formation and subsequent decay. A strong focus for many of these efforts has been the study of azimuthal distributions with respect to an inferred reaction plane [3-6] (hereafter referred to as azimuthal distributions). In part, this focus has been motivated by the prospect that such studies may provide new insights toward the solution of well known ambiguities in the low density nuclear equation of state (EOS) [7,8]. The magnitude of parameters of the EOS can be related to the dominance of repulsive or attractive collective motions in heavy ion reactions. Such collective motions have been termed "flow." In fact, there is great value in the determination of the incident energy E_{bal} which corresponds to a balance between attractive and repulsive flow. Another type of collective motion often found in heavy ion reactions results from the rotation of an emitting source. An understanding of reaction dynamics requires distinction and characterization of the strength of these two types of collective motion.

Measured azimuthal distributions have been shown to be sensitive to each of these types of collective motion [4,5,9,10] and hence can play an important role in the study of reaction dynamics and the EOS. Despite the many experimental efforts and current theoretical progress on nuclear transport models [11], no consensus has been reached on even a coarse characterization of the EOS. Without doubt, an important contributor to this lack of consensus is the need for large corrections to experimental results that are due to the dispersion of the experimentally inferred reaction plane about the true reaction plane. Such corrections are a necessary prerequisite for any quantitative comparison of measured and calculated azimuthal distributions.

Multifragment azimuthal correlation functions provide a potentially powerful probe for intermediate energy heavy ion dynamics. Unlike azimuthal distributions, these correlation functions do not require any knowledge of the reaction plane [12]. A direct consequence of this fact is the circumvention of the need for any event-by-event estimation of the reaction plane and the associated corrections for dispersion of this plane about the true reaction plane. In addition, other systematic uncertainties associated with detector acceptance, efficiency, etc. can be minimized.

In this Letter we report multifragment azimuthal correlation functions for fragments emitted from Ar+Sc interactions ($E/A = 35$ to 115 MeV). We find strong anisotropies and asymmetries in the measured correlation functions at low beam energies which can be accounted for by the combined driving force of both rotational collective motion and transverse collective flow. The asymmetries in the correlation functions are not diminished with decreasing impact parameter but are found to decrease with increasing beam energy.

The ^{40}Ar beams ($E/A = 35$ to 115 MeV) used in these measurements were provided in 10 MeV steps by the K1200 cyclotron at the National Superconducting Cyclotron facility (NSCL). Charged reaction products were detected with the Michigan State University (MSU) 4π array [13]. The MSU 4π array consists of a main ball of 170 phoswich counters (arranged in 20 hexagonal and 10 pentagonal subarrays) covering angles from 23° to 157° and a forward array of 45 phoswich counters covering angles from 7° to 18°. Thirty Bragg curve counters were recently installed in front of the hexagonal and pentagonal subarrays; they were operated in ion chamber mode with a pressure of 500 torr of P5 gas (95% argon, 5% methane). The hexagonal anodes of the five most forward Bragg curve counters are segmented, giving a total of 55 separate ΔE gas counters for the measurements.

The Bragg curve counters served as ΔE detectors for charged particles that stopped in the fast plastic scintillator of the main ball. Consequently, the array was capable of detecting charged fragments from $Z=1$ to $Z=12$. Low energy thresholds were 17, 3, and 5 MeV/nucleon for fragments of $Z=1$, 3, and 12, respectively. The beam intensity was approximately 100 electrical pA of ^{40}Ar, and the thickness of the Sc target was 1.6 mg/cm^2. Data were taken with a minimum bias trigger [charged particle multiplicity $(m) \geq 2$] and a more central trigger $(m \geq 5)$.

Following the approach commonly exploited in interferometry studies [14,15], we define a multifragment azimuthal correlation function as follows [12]:

$$C(\Delta\phi) = \frac{N_{\rm cor}(\Delta\phi)}{N_{\rm uncor}(\Delta\phi)}, \qquad (1)$$

where $N_{\rm cor}(\Delta\phi)$ is the observed $\Delta\phi$ distribution for fragment pairs selected from the same event and $N_{\rm uncor}(\Delta\phi)$ is the $\Delta\phi$ distribution for fragment pairs selected from mixed events. The $\Delta\phi$ angles between all selected fragments in an event are used in the construction of the correlation function; that is, 3 $\Delta\phi$ angles are obtained for 3 fragments, 6 $\Delta\phi$ angles for 4 fragments, ..., $n(n-1)/2$ $\Delta\phi$ angles for n fragments. For the results presented here, mixed events were obtained by randomly selecting each member of a fragment pair from different events with the same impact parameter. Impact parameters were determined by way of cuts on the total transverse momentum [16].

In an earlier work, we have shown that both flow and rotational collective motion give rise to preferential emission of particles in the reaction plane with distinctly different rapidity (y) dependences [4,5]. In view of this, we have imposed rapidity selections on the azimuthal correlation functions in order to enhance possible signatures for these two modes of collective motion.

Figure 1 shows azimuthal correlation functions (E/A $=45$ MeV) for fragments with negative c.m. rapidities $(-0.5 < y < -0.05)$. The left panel shows results in which we demand the presence of a ^{4}He "trigger" fragment in each of the pairs used to determine $\Delta\phi$. The right panel shows similar results with the presence of a $Z=3$ trigger fragment in each pair.

The three frames in each panel present (from top to bottom) correlation functions for peripheral collisions $(0.66 < b/b_{\rm max} < 1.00)$, midcentral collisions $(0.33 < b/b_{\rm max} < 0.66)$, and central collisions $(0.00 < b/b_{\rm max} < 0.33)$, respectively. Here b is the estimated impact parameter and $b_{\rm max}$ is the maximum impact parameter [16]. The correlation functions (open circles) in Fig. 1 show large peaks at 0° which are a manifestation of azimuthal asymmetry in the emission pattern of the reaction products. These asymmetries, which are larger for the heavier trigger fragment, are attributed to strong collective effects in the reaction. It is noteworthy that the peaks in these correlation functions are not diminished for the more central collisions. Since a smaller rotational contribution to the correlation function is expected for more central collisions, this impact parameter dependence lends credence to the notion that nonrotational collective motion dominates these asymmetries in the correlation functions.

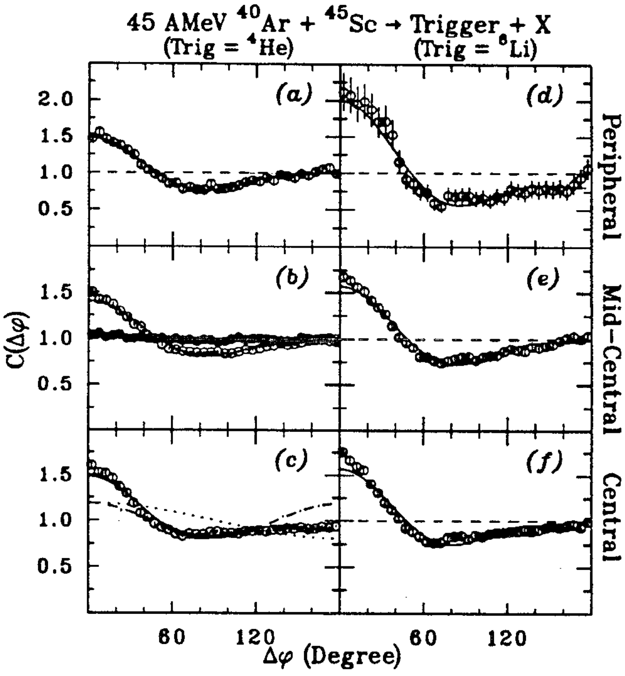

FIG. 1. Multifragment azimuthal correlation functions for negative rapidity fragments. Correlation functions are shown for a ^{4}He trigger fragment (left panel) and a $Z=3$ trigger fragment (right panel) for central [(c) and (f)], midcentral [(b) and (e)], and peripheral [(a) and (d)] reactions. The black solid lines represent fits to the correlation functions with a cosine function. The solid dots [in frame (b)] represent the correlation function from mixed events. The dot-dashed and dotted curves [in frame (c)] represent contributions from rotational collective motion and flow, respectively.

We have checked for spurious azimuthal correlations by using "test events" in which the correlations have been removed. To create such events, we randomly select fragments from different events with the same impact parameter. The test events so obtained were analyzed with the same procedure employed for real events. Correlation functions obtained from these test events are shown as dark circles in Fig. 1(b). They clearly indicate the absence of any spurious azimuthal correlations in the results obtained from the real data. It is also important to point out here that contributions to the correlation functions (shown in Fig. 1) due to particle unstable resonances are not significant. Such contributions arise from fragment pairs with relative momenta ≤ 50 MeV/c. They constitute an insignificant fraction ($<1\%$) of the total number of fragment pairs employed to determine the correlation functions. In fact, the removal of fragment pairs with relative momenta ≤ 50 MeV/c gives no noticeable effect on the azimuthal correlation functions shown in Fig. 1.

Multifragment azimuthal correlation functions, as defined in Eq. (1), have not been commmonly exploited in the study of reaction dynamics. In view of this, we show—by way of reaction simulations—some of the expected patterns for flow and collective rotational motion in Fig. 2. Our simulations—which are made for several characteristic event shapes—employ Gaussian fragment momentum distributions to simulate collective motion. For rotational collective motion we used an oblate momentum distribution ($\sigma_x = \sigma_z > \sigma_y$) where z is the beam axis, x is in the reaction plane, and y is normal to the reaction plane. For flow we used a prolate momentum distribution rotated (20°) about the y axis. Figure 2 shows simulated azimuthal correlation functions for fragments with negative c.m. rapidities ($-0.5 < y < -0.05$). Figure 2(c) shows the correlation function which results if only collective flow is assumed while Fig. 2(a) shows the expected result if only rotational collective motion is present. Figure 2(b) shows the resultant correlation function if both forms of collective motion are assumed. For the latter figure, equal contributions from flow and rotational collective motion were assumed. Figure 2 shows distinctly different correlation patterns which are characteristic of these types of collective motion. Namely, collective flow shows up as $C(\Delta\phi) > 1$ at small $\Delta\phi$ and as $C(\Delta\phi) < 1$ at large $\Delta\phi$ [see Fig. 2(c)], while rotational motion gives a minimum near $\Delta\phi = 90°$ and $C(\Delta\phi) > 1$ at both large and small $\Delta\phi$.

The simulated correlation function, which assumes both rotation and flow [Fig. 2(b)], and those obtained from experimental data (Fig. 1) are strikingly similar in their qualitative forms. This similarity suggests contributions from both flow and rotation to the experimental correlation functions.

Figure 3 shows azimuthal correlation functions for fragments detected at midrapidity ($-0.05 < y < 0.05$). Frames (a), (b), and (c) show results for central, midcentral, and peripheral collisions, respectively. As in Fig. 1, we have demanded the presence of a ^{4}He fragment in each of the fragment pairs used to determine the correlation functions. The pronounced peak at 0° in the azimuthal correlation functions for fragments detected at negative rapidities (see Fig. 1) are clearly absent in those for fragments detected at midrapidity (Fig. 3). This result is consistent with the correlation function one expects from predominantly rotational collective motion [see Fig. 2(a)]. However, it should be stressed here that midrapidity fragments cannot give a unique signature for collective flow. Consequently, a clear signature for the flow

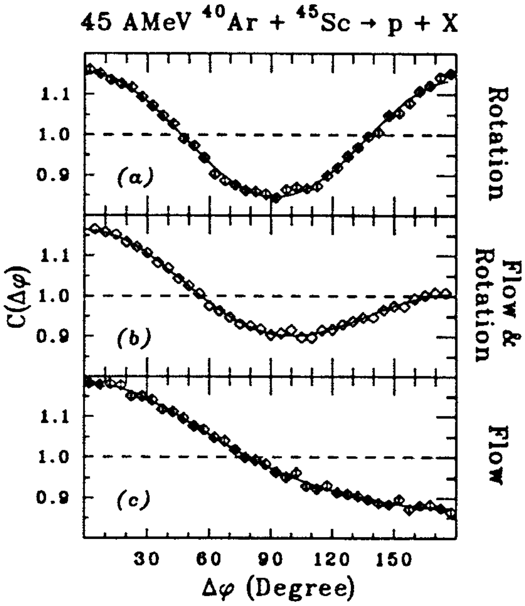

FIG. 2. Multifragment azimuthal correlation functions for simulated reactions of Ar+Sc (45A MeV). Correlation functions are shown for negative rapidity fragments with pure rotational collective motion (a), pure flow (c), and a mixture of both forms of collective motion (b). The solid lines are drawn to guide the eye.

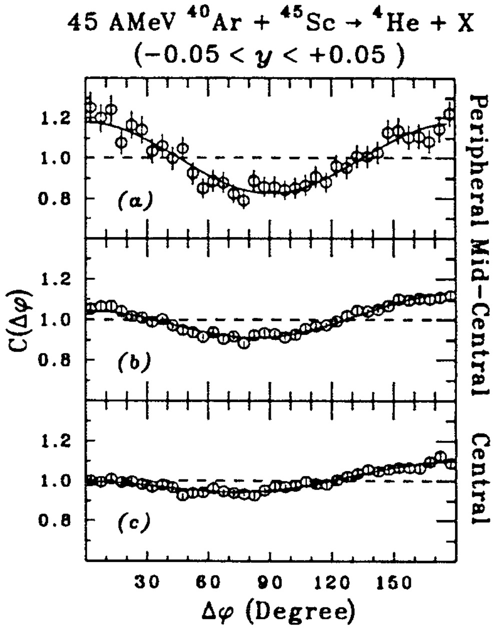

FIG. 3. Multifragment azimuthal correlation functions for midrapidity fragments. Results are shown for central (c), midcentral (b), and peripheral (a) reactions. The solid lines are drawn to guide the eye.

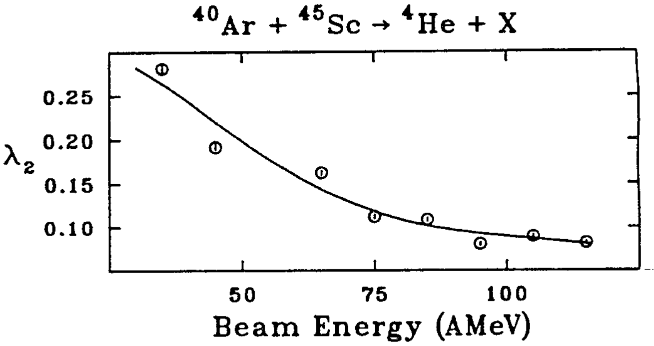

FIG. 4. The rotational coefficients λ_2 vs beam energy. These values illustrate the decreasing contribution of rotational collective motion to multifragment azimuthal correlation functions. The solid line is drawn to guide the eye.

contributions to these midrapidity correlation functions is not expected. Nevertheless, it is noteworthy that the expected increase in the anisotropy with increasing impact parameter is evident in Fig. 3. An apparent deficit in the correlation functions at small $\Delta\phi$ for central and midcentral collisions could very well be due to final state interactions [17] and/or momentum conservation.

We have parametrized the experimental azimuthal correlation functions and carried out fits in order to study their energy dependence. From our fits, we find that we can account for the correlation functions if our parametrization assumes major contributions from both rotational collective motion as well as collective flow.

We have performed the fits with cosine function $[\lambda_0 + \lambda_1\cos(\Delta\phi) + \lambda_2\cos(2\Delta\phi) + \cdots]$. We note here that from elementary geometrical considerations the terms in $\cos(\Delta\phi)$ and $\cos(2\Delta\phi)$ can be associated with collective flow and rotational collective motion, respectively. In general, three terms from the cosine function were sufficient for good fits. Slightly better fits were obtained with four terms. In all cases the first term (λ_0) was found to be equal to 1. The solid lines in Fig. 1 illustrate results for such fits. For illustrative purposes we have also shown the respective contributions attributed to flow (dotted curve) and rotational collective motion (dot-dashed curve) for central collisions in Fig. 1(c). The dotted and dot-dashed curves indicate that the flow and rotational contributions to collective motion at 45 MeV/nucleon are of approximately equal strength.

Figure 4 shows the λ_2 coefficients extracted from these fits as a function of beam energy. In this figure it can be seen that λ_2 decreases with increasing beam energy, indicating the demise of rotational collective motion with increasing beam energy. At the higher beam energies, the onset of instantaneous multifragmentation might be inhibiting the establishment of a rotating source. Qualitatively similar results have been observed for the Ar+V system by Wilson *et al.* [4,5]. The consistency between the present results and those of Ref. [5] lends support to the utility of the multifragment azimuthal correlation function as a simple and powerful probe of heavy ion dynamics. The main point of interest here is that these correlation functions provide a way to eliminate systematic errors arising from reaction plane estimates. It is this step which often creates ambiguities in comparisons between data and results from model calculations.

In summary, multifragment azimuthal correlation functions for the Ar+Sc system have been measured as a function of impact parameter and beam energy. The correlation functions show asymmetries which are enhanced for central collisions, but decrease with increasing beam energy. The correlation functions can be well accounted for if two types of collective motion—rotation and flow—are assumed to be dominant. The directness and precision of these multifragment azimuthal correlation functions can be argued to provide one of the premier quantitative probes for heavy ion reaction dynamics. To this end, additional work is currently in progress.

This work was supported in part by the National Science Foundation under Grants No. PHY-89-13815 (NSCL) and No. PHY-92-11611 (Stony Brook).

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