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Disappearance of rotational flow and reaction plane dispersions in Kr+Au collisions

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Two-particle azimuthal correlations have been used to extract reaction plane dispersion free triple-differential cross sections for d, t, and α particles for the midcentral collisions of ^{84}Kr+^{197}Au at $E/A=35$, 55, and 70 MeV. Both experimental measurements and extrapolations from lower incident energies suggest that rotational flow disappears at $E/A\approx 100$ MeV for light charged particles and that reaction plane dispersions introduce large uncertainties in extracting the disappearance of rotational flow. [S0556-2813(98)03703-0]

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Ideally, a complete description of the dynamics of heavy-ion reaction can be achieved through measurements of invariant triple-differential cross sections [1–9]. In reality, the experimentally extracted reaction planes suffer from significant uncertainties due to the dispersion of the particles used in the reaction plane reconstruction. Despite intense effort, few measurements of triple-differential cross sections free of reaction plane dispersions exist [8]. Recently, a method has been proposed to extract single-particle triple-differential azimuthal distributions from two-particle azimuthal correlation functions [10]. In this Brief Report, this method is applied to the ^{84}Kr+^{197}Au reactions.

Measurements with ^{84}Kr ions at beam energies of $E/A=35$, 55, and 70 MeV were performed with beams from the K1200 cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University (MSU). Measurements at $E/A=100$ MeV were performed at the Laboratoire National SATURN at Saclay. The emitted charged particles were detected with the combined MSU Miniball/Washington University Miniwall 4π phoswich detector array. Unit charge resolution up to $Z=10$ was routinely achieved for particles that tranversed the fast plastic scintillator. Details of the experiments can be found in Ref. [11].

The triple-differential distributions [6,8] depend strongly on impact parameters. Following Refs. [11], we assumed that the charged-particle multiplicity N_c detected in the Miniball array depends monotonically upon the impact parameter

$$\hat{b}=\frac{b}{b_{\max}}=\left[\int_{N_c(b)}^{\infty} dN_c P(N_c)\right]^{1/2}. \tag{1}$$

Here $P(N_c)$ is the probability distribution for the charged particle, which exhibits a rather structureless plateau and a near-exponential falloff at the highest multiplicities. The reduced impact parameter $b/b_{\max}$ assumes values of 1 ($N_c=4$) for the most peripheral collisions and 0 for the most central collisions. In the present work, a middle central gate of $0.3<b/b_{\max}<0.7$ is applied. This gate was chosen as a compromise to keep enough statistics to construct two-particle correlation functions and to have reasonable anisotropy to study rotational flow that vanishes at $b=0$. To minimize the effect of transverse flow, a rapidity gate of $-0.5<y/y_{\text{c.m.}}<0.5$ is also applied to the data, where y is the rapidity of the emitted particle and $y_{\text{c.m.}}$ is the center-of-mass rapidity of the system.

To avoid the complexities in determining the reaction planes, two-particle correlations have been used to extract the energy where sideward flow disappears [12]. In principle, they can also be used to extract the energy where rotational flow disappears [13]. The azimuthal correlation function is defined as

$$C(\Delta\phi)=\frac{N_{\text{corr}}(\Delta\phi)}{N_{\text{uncorr}}(\Delta\phi)}, \tag{2}$$

where $\Delta\phi$ is the relative azimuthal angle between the two particles and $N_{\text{corr}}(\Delta\phi)$ and $N_{\text{uncorr}}(\Delta\phi)$ are the distribution of the coincident fragment pairs and uncorrelated fragment pairs from different events, respectively. Figure 1 shows the α-α correlation functions for ^{84}Kr+^{197}Au at $E/A=35$, 55, 70, and 100 MeV. At low energy where the mean-field interaction dominates, charged particles are emitted mainly in the reaction plane [5–8] and the correlations exhibit the typical V shape that flattens with increasing incident energies. The slight asymmetries occurring between $\Delta\phi=0°$ and $\Delta\phi=180°$ may come from collective flow, Coulomb repul-

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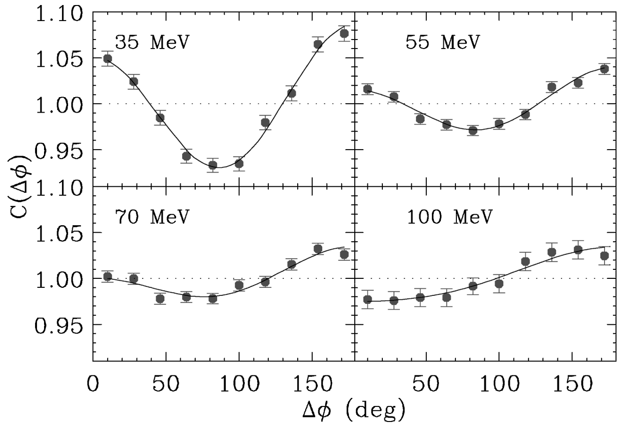

FIG. 1. α-α azimuthal correlations for $^{84}Kr+^{197}Au$ reactions at $E/A=35$, 55, 70, and 100 MeV. See the text for detailed gating conditions.

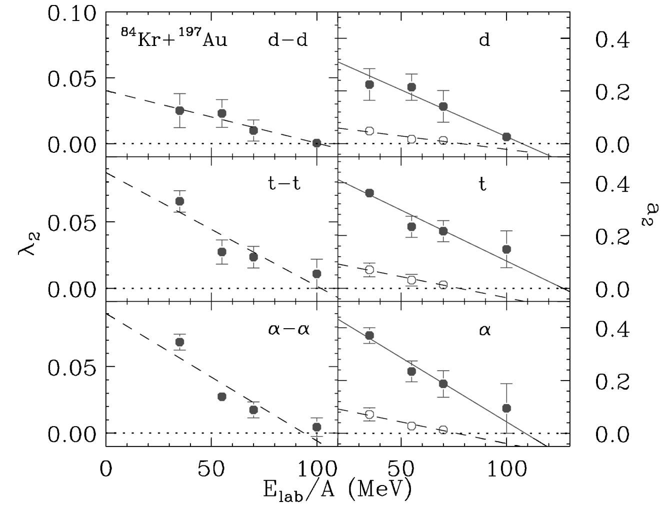

FIG. 2. Left panels, coefficients λ_2 of Eq. (3) plotted as a function of incident energies, right panels: a_2^{expt} (open points) and a_2^{true} (solid circles) as functions of incident energy for d, t, and α particles.

sion as well as recoil. These effects become more dominant with increasing incident energies. At $E/A=100$ MeV the correlation function no longer exhibits a minimum at $\Delta\phi=90°$, but rather shows an enhancement at $\Delta\phi=180°$.

In the past, the correlations have been fit with a Fourier series with the expression [10,13,14]

$$C(\Delta\phi)\propto 1+\lambda_1\cos(\Delta\phi)+\lambda_2\cos(2\Delta\phi), \qquad (3)$$

where λ_1 and λ_2 can be treated as fit parameters to the data. The solid lines in Fig. 1 show the quality of the fit. In this expression, λ_2 represents the rotational flow in the reaction plane. Table I lists all the fit values of λ_1 and λ_2 for the d-d, t-t, and α-α correlations. The magnitudes of λ_1 are very small (similar values of λ_1 were obtained by applying the gates $y/y_{\mathrm{c.m.}}<0$ or $y/y_{\mathrm{c.m.}}>0$) due to the absence of measurable transverse flow for Kr+Au reactions below $E/A=100$ MeV [15]. Thus the effect of λ_1 will be neglected in the present study.

The left-hand panels of Fig. 2 show the incident energy dependence of λ_2 for d-d, t-t, and α-α azimuthal correlation functions. The uncertainties shown mainly come from fitting the in-plane to out-of-plane asymmetry. λ_2 decreases with incident energy and vanishes around $E/A=100$ MeV. Since the Coulomb interactions between two charged particles force λ_2 to be slightly positive even if the distribution is isotropic, it is difficult to determine the exact energy where rotational flow vanishes. In Ref. [13], where λ_2 values have been extracted from central $^{40}Ar+^{45}Sc$ collisions from $E/A=15$ to 135 MeV, λ_2 flattens out around $E/A=100$ MeV and remains positive even at the higher incident energies. Due to lack of guidance from theoretical models, there is no *a priori* reason to adopt any particular function to describe the energy dependence of λ_2. For simplicity, a simple linear function is chosen to fit the data on the left-hand panels of Fig. 2 (dashed lines). The energies where rotational flow disappears $E(\lambda_2=0)$ are 100 MeV, 100 MeV, and 93 MeV for d, t, and α particles, respectively.

If the two particles used in the azimuthal correlations are emitted independently of each other in the same event, the correlation function $C(\Delta\phi)$ can be described by the convolution of single-particle azimuthal distributions $P(\phi)$ [7,8],

$$C(\Delta\phi)=\int_0^{2\pi}P(\phi)P(\phi+\Delta\phi)d\phi. \qquad (4)$$

TABLE I. λ_1 and λ_2 from the particle-particle correlation in the Kr + Au system.

E_{lab}/A		35 MeV	55 MeV	70 MeV	100 MeV
d-d	λ_1	-0.012±0.005	-0.017±0.003	-0.017±0.004	-0.011±0.005
	λ_2	0.025±0.013	0.023±0.01	0.0099±0.008	0.0003±0.0003
t-t	λ_1	-0.016±0.005	-0.0034±0.005	-0.013±0.004	-0.014±0.007
	λ_2	0.065±0.008	0.027±0.009	0.023±0.008	0.011±0.011
α-α	λ_1	-0.018±0.003	-0.012±0.002	-0.017±0.003	-0.030±0.003
	λ_2	0.069±0.006	0.028±0.004	0.018±0.006	0.0045±0.007

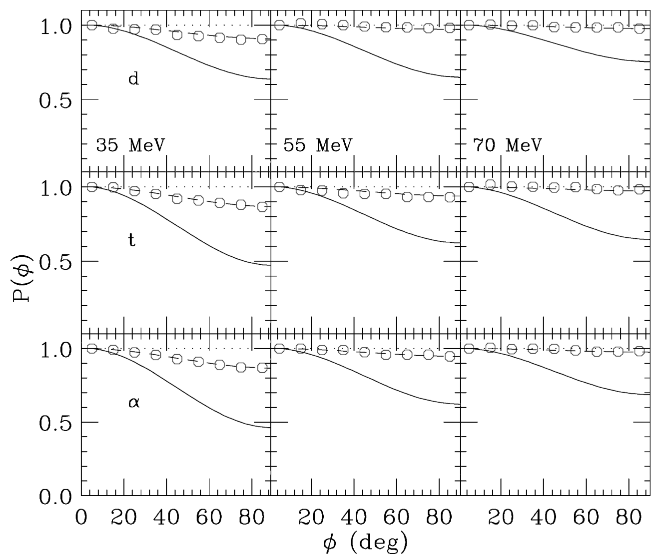

FIG. 3. Single-particle azimuthal distributions: open points are the data, dashed lines are fits to the data according to Eq. (5), and solid lines are true azimuthal distributions from Eqs. (4) and (6).

Empirically, the single-particle distribution $P(\phi)$ can be described by a function similar to Eq. (3) [9,10],

$$P(\phi)\propto 1+a_1\cos(\phi)+a_2\cos(2\phi). \tag{5}$$

Combining Eqs. (3)–(5), one obtains a relationship between a_i and λ_i,

$$a_i=\sqrt{2\lambda_i}. \tag{6}$$

In the right-hand panels of Fig. 2, $a_2^{\rm true}$ from Eq. (6) are plotted as solid points. If linear fits are applied to the extracted values of $a_2^{\rm true}$ (solid lines) for incident energies of $E/A=35$, 55, 70, and 100 MeV, the $E(a_2^{\rm true}=0)$ are 110 MeV, 122 MeV, and 113 MeV for d, t, and α particles, respectively, about 20 MeV higher than those obtained from the linear fit of λ_2. An uncertainty of 20 MeV is assigned to the $E(a_2^{\rm true}=0)$ and $E(\lambda_2=0)$ values based on the differences obtained from the fits. Even larger uncertainty exists between $E(a_2^{\rm true}=0)$ and $E(\lambda_2=0)$ values if the azimuthal correlation data of Ref. [13] are analyzed in the same way. Thus, even though particle azimuthal correlations do not suffer from complications arising from reaction plane dispersions, currently they cannot provide very precise determination of the energy where rotational flow disappear [13] unless the exact energy dependence of λ_2 or $a_2^{\rm true}$ can be determined.

From Eqs. (5) and (6) one can construct the triple-differential cross sections from the experimentally measured two-particle azimuthal correlation functions. The solid lines in Fig. 3 shows the ''true'' single-particle azimuthal distributions $P(\phi)\propto 1+\sqrt{2\lambda_2}\cos(2\phi)$ for d, t, and α particles at $E/A=35$, 55, and 70 MeV. The distributions are normalized to 1 at $\phi=0°$. For comparison, the experimental azimuthal distributions (open points) were obtained using the reaction planes constructed by the momentum tensor method described in Refs. [5,8]. The same impact parameter and rapidity gates used in the two-particle correlation functions have been applied to these data. Data at $E/A=100$ MeV are not shown here due to problems associated with extracting the reaction planes at this energy. Study of Au+Au reactions suggests that squeeze out effects from repulsive nucleon-nucleon interactions start to dominate around $E/A=100$ MeV and the reaction planes determined from the momentum tensor method are not correct [16]. A detailed description of squeeze out effects at high incident energy is beyond the scope of this short report.

TABLE II. Reaction plane dispersion in the Kr + Au system.

E_{lab}/A		35 MeV	55 MeV	70 MeV
d-d	$\langle\cos(2\Delta\phi)\rangle$	0.21 ± 0.10	0.12 ± 0.12	$0.083\ ^{+0.130}_{-0.083}$
	$2\Delta\phi$(deg)	78 ± 5	83 ± 7	85^{+5}_{-7}
t-t	$\langle\cos(2\Delta\phi)\rangle$	0.19 ± 0.07	0.13 ± 0.09	$0.061^{+0.090}_{-0.061}$
	$2\Delta\phi$(deg)	79 ± 5	82 ± 5	86^{+4}_{-5}
α-α	$\langle\cos(2\Delta\phi)\rangle$	0.19 ± 0.06	0.11 ± 0.08	$0.065^{+0.087}_{-0.065}$
	$2\Delta\phi$(deg)	79 ± 4	83 ± 5	86^{+4}_{-5}

In general, the experimental azimuthal distributions show a fairly small anisotropy while the true azimuthal distributions are relatively sharp. The difference between experimental (open circles) and true azimuthal distributions (solid lines) shown in Fig. 3 are so large that the reaction plane dispersions cannot be neglected. To quantify the reaction plane dispersions, the dashed lines are the fits of Eq. (5) to the data. The fit values of $a_2^{\rm expt}$ for d, t, and α particles are plotted as open points in the right-hand panels of Fig. 2. The uncertainties in $a_2^{\rm expt}$ are obtained by varying $a_2^{\rm expt}$ in Eq. (5) until the resulted anisotropy $P(0°)/P(90°)$ is 5% above and below the best-fit values.

If the experimentally determined reaction planes are close to the true reaction planes as in the case of low-energy fission reactions [17], then $a_2^{\rm expt}\approx a_2^{\rm true}$. However, for the present study, the $a_2^{\rm true}$ (solid circles) are much larger than the $a_2^{\rm expt}$. If linear fits are applied to the extracted values of $a_2^{\rm expt}$ (dashed lines), the $E(a_2^{\rm expt}=0)$ are 78 MeV, 77 MeV, and 76 MeV for d, t, and α particles, respectively, almost 40 MeV lower than $E(a_2^{\rm true}=0)$ for light charged particles. Since $E(a_2^{\rm expt}=0)$ and $E(a_2^{\rm true}=0)$ should be the same, the discrepancies indicate large errors associated with the extraction of the energy where rotational flow disappears. One major contribution to the uncertainties could be that the simple linear functional form used to extract $E(a_2^{\rm expt}=0)$ is wrong [4]. Experimentally, the exact incident energy dependence of these parameters may be determined with more data points below $E/A=100$ MeV or via theoretical model simulations. Above $E/A=100$ MeV, the squeeze out effects are expected to dominate [16] and the current algorithm to determine $a_2^{\rm true}$ [Eqs. (2)–(6)] may not be valid. Independent of the exact incident energy dependence of $a_2^{\rm true}$ and $a_2^{\rm expt}$, it is clear from Fig. 2 that large reaction plane dispersions are associated with extracting $a_2^{\rm expt}$ and that the dispersions will affect the extracted energies where the rotational flow disappear. Until now, such effect have not been taken into account [4].

To quantify the reaction plane dispersions, $\langle \cos(2\Delta\phi)\rangle$ can be defined as

$$\langle \cos(2\Delta\phi)\rangle = \frac{a_2^{\mathrm{expt}}}{a_2^{\mathrm{true}}}. \tag{7}$$

These values are listed in Table II. The uncertainties mainly come from the errors associated with a_2^{expt} since the errors associated with a_2^{true} is much smaller in most cases. In general, $2\Delta\phi$ is large, close to 90°, suggesting that reaction planes are poorly determined from the detected particles. As expected, the dispersion $2\Delta\phi$ increases with increasing incident energies.

In summary, we have extracted triple-differential cross sections for d, t, and α particles using two-particle correlation functions. As these cross sections are free from reaction plane dispersions, they can be compared directly with transport model calculations such as Boltzmann-Uehling-Uhlenbeck theory and quantum molecular dynamic model. We have also examined the reaction plane dispersion and its effects on extracting the energy where rotational flow disappears. The results suggest that correction for reaction plane dispersions are very important to extract such values from single-particle azimuthal distributions.

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