Azimuthal distribution, azimuthal correlation, and reaction plane dispersion in the reaction 10.6 MeV/nucleon ^{84}Kr on ^{27}Al

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The azimuthal distribution and azimuthal correlation of the emitted light charge particles in coincidence with the forward-going heavy fragments in the reaction of 10.6 MeV/nucleon ^{84}Kr on ^{27}Al have been studied in detail. A novel way to extract the reaction plane dispersion by combining the azimuthal distribution constructed using the experimental measured reaction plane which contains a reaction plane dispersion and a two-particle azimuthal correlation which is free of reaction plane dispersion was described. This method was applied to the low-energy fission reaction ^{84}Kr+^{27}Al at 10.6 MeV/nucleon for light particles, p and α, with success. [S0556-2813(97)02308-X]

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I. INTRODUCTION

The collisions between heavy ions provide an excellent opportunity for scientists to study the properties of infinite nuclear matter at high and low densities [1–4]. At low incident energy ($<$100 MeV per nucleon), the mean field dominates. The emitted particles are deflected to a negative scattering angle; this is negative transverse flow. At high energy, the central collision zone is compressed to higher density than normal nuclear matter density. The repulsive pressure created at the compressed zone forces particles from the projectile and target spectators to ''bounce off'' from the beam axis resulting in positive transverse collective flow. The particles in the compressed region also escape in the directions both above and below the reaction plane (squeeze out) where they are not hindered by spectator matter. The evolution of collective motion with incident energy can be observed easily via azimuthal distributions and azimuthal correlations [5-7]. At low incident energies, the azimuthal distributions at middle rapidity show maxima at both $\phi=0°$ and $\phi=180°$ consistent with a rotationlike attractive deflection by the nuclear mean field [7-9]. With increasing incident energy this rotationlike deflection disappears in one incident energy [10]. Similar behavior exists also in the azimuthal correlations. Ideally, the complete description of the dynamics of heavy-ion reactions can be achieved through the measurement of invariant triple differential cross sections. Except for isotropic collective motion such as radial expansion, the understanding of the reaction dynamics and the measurements of triple differential cross sections require accurate knowledge of reaction planes. There are several methods to determine the reaction plane. Despite intense effort, few measurements free of reaction plane dispersions exist. In this article a novel way will be described to extract the reaction plane dispersion by combining azimuthal distributions constructed by using an experimentally measured reaction plane which contains reaction plane dispersion and two-particle azimuthal correlations which are free of reaction plane dispersions. The method was applied to the reaction ^{84}Kr+^{27}Al at 10.6 MeV/nucleon with success. For such a low-energy fission reaction (quasifission and fusion-fission), the reaction plane can be constructed from detected fission fragments, so it is convenient to study the azimuthal distribution and azimuthal correlation of particles in coincidence with fission fragments. Clearly, at this energy the particle multiplicity is much lower than that in intermediate energy, but the study of these aspects can still be performed. For the 10.6 MeV/nucleon ^{84}Kr+^{27}Al reaction system, some measured quantities and the related nuclear reaction mechanism have been studied already, such as fragment mass, charge distribution [11,12], and light particle multiplicity [13,14]. The analysis of the experimental data using the three source model indicates that most of the particles are emitted before scission and the fission delay time is extracted [15,16]. In this paper, we will discuss the reaction plane dispersion by studying azimuthal distributions and azimuthal correlations of light particles for this reaction.

II. EXPERIMENTAL SETUP

The experiment was performed by using the large scattering chamber (ASCHRA) in the RIKEN Accelerator Research Facility (3×4.8 m). A self-supporting ^{27}Al target (600 μg/cm^2 in thickness) was bombarded with an 890 MeV ^{84}Kr beam. The fragment was detected in a time of flight counter telescope which was placed at 10°. The telescope consists of two channel plate detectors (CPD) and a solid state detector (SSD). The flight path between the two channel plate detectors was 33.7 cm. Typical time resolution is 300 ps. The charged particles were measured by the 3π multidetector system which is composed of 120 phoswich detectors that cover the angular range between 10° and 160° in the laboratory system. A phoswich detector consists of a thin plastic scintillator and a thick BaF_2 crystal. The time resolution was about 1μs. The flight paths were varied from 60 cm at the forward angle to 15 cm at the backward. To determine the velocity of emitted light charged particles directly, especially for the detectors placed at the forward angles, we measured the flight time of light particles, which was derived from the time difference between a RF signal from the cyclotron and the timing signal of the detector. For experimental details see Refs. [15,16].

III. AZIMUTHAL DISTRIBUTION AND AZIMUTHAL CORRELATION

Due to the effect of the recoil caused by particle emission on the azimuthal distributions and azimuthal correlations, there is an asymmetry in the azimuthal distributions and azimuthal correlations at 0° and 180°. If we study the first-order anisotropic coefficient of azimuthal distributions and azimuthal correlations, the correction of the recoil effect must be taken into account, while this correction depends on the effective recoil nuclear mass which cannot be determined easily. Because this paper studies mainly the rotational effect, we symmetrize about $\phi=90°$ for the azimuthal distribution and azimuthal correlation. After such treatment, the first-order anisotropic coefficient equals zero. It has no influence on extracting the second-order anisotropic coefficient (below, called the anisotropic coefficient), i.e., no influence on extracting the rotational effect.

From the study of intermediate energy heavy-ion reactions, we know that azimuthal distributions of particles can be well described by a Fourier expansion up to second order [17,18]:

$$F(\phi)=a_0[1+a_1\cos(\phi)+a_2\cos(2\phi)]. \quad (1)$$

Here, the first anisotropic coefficient a_1 reflects the collective flow effect and a_2 reflects the rotational behavior (for positive a_2) or the squeeze-out (negative a_2). For the 10.6 MeV/nucleon ^{84}Kr+^{27}Al reaction, the reaction plane can be reconstructed via the direction of the heaviest fragment or two fission fragments and the beam. It is seen from Fig. 1 that azimuthal distributions of protons show anisotropy, peaking simultaneously at 0° and 180°, which implies that

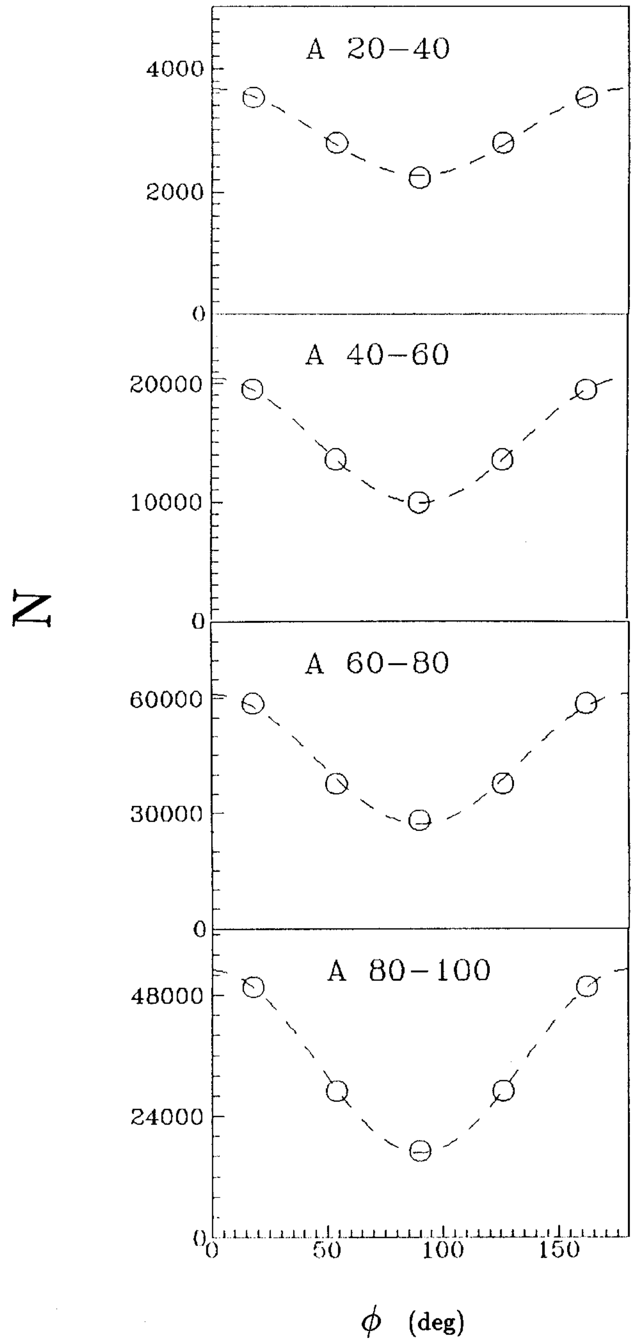

FIG. 1. Azimuthal distributions of protons after $\phi=90°$ symmetrization under four fragment mass windows for the 10.6 MeV/nucleon ^{84}Kr+^{27}Al reaction. (a)–(d) correspond to fragment mass windows 20–40,40–60,60–80,80–100, respectively. ○: experimental data, – – –: fitted results by Eq. (1), N is the relative count.

there is rotational behavior and the light particles are preferentially emitted in the reaction plane.

For the particle-particle correlation between light particles and fragments, we may make a fit via the Fourier series too:

$$C(\Delta\phi)=A[1+\lambda_1\cos(\Delta\phi)+\lambda_2\cos(2\Delta\phi)], \quad (2)$$

where λ_1 and λ_2 are treated as parameters and $\Delta\phi$ is the azimuthal difference of two emitted particles in an event. If they are emitted isotropically, then $\lambda_1=\lambda_2=0$.

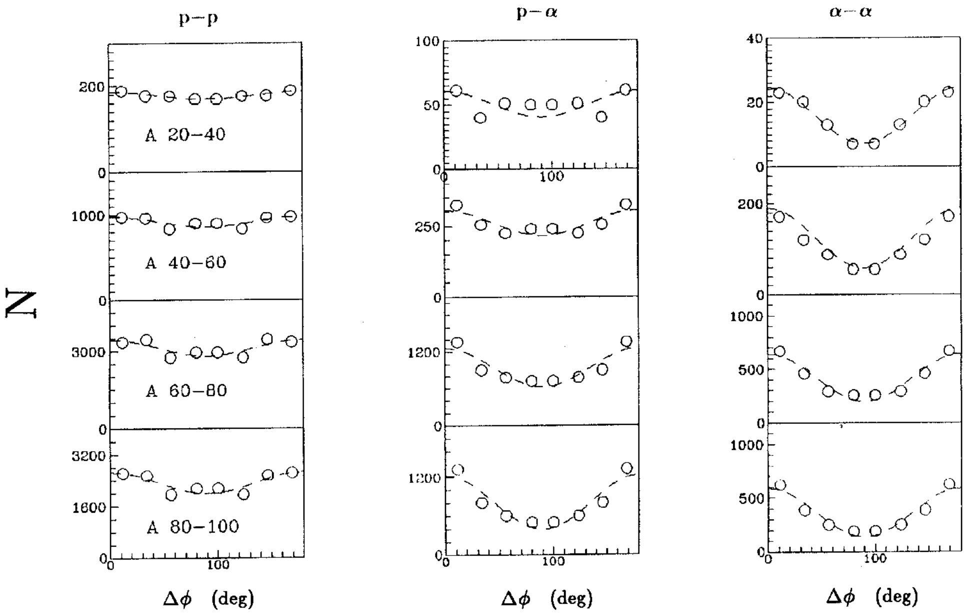

FIG. 2. Azimuthal correlations of light particles in coincidence with fragments after $\phi=90°$ symmetrization for the 10.6 MeV/nucleon ^{84}Kr+^{27}Al reaction. Left, middle, and right panels correspond to the p-p, p-α, and α-α correlations, respectively. The top to bottom panels correspond to four mass windows, as in Fig. 1.

From Fig. 2 we see that the anisotropic coefficient for α-α (i.e., $[W(0°)+W(180°)]/W(90°)$) is larger than that of p-α, while the latter is larger than that of p-p. This indicates that anisotropy increases with increasing the mass of emitted particles. Figure 2 also shows that anisotropy depends weakly on fragment mass. This increase is related to the change of reaction mechanism. Since the fragment detector was placed at 10° with respect to the beam direction, which is larger than grazing angle of 5.62° in this reaction, most of the quasielastic scatters and evaporation residues have not been detected. The fragments with mass around 90 mainly comes from fully deep inelastic scattering (DIC). The products with mass around $A=70$ include the contribution from DIC and quasifission. $A=50$–30 mainly corresponds to the products of symmetric fission and asymmetric fission (fusion-fission). Quasifission corresponds to larger entrance angular momentum than fusion-fission, while DIC corresponds to even larger entrance angular momentum. This character is reflected on a_2 and λ_2, i.e., it increases slightly with increasing the fragment mass. From the study of azimuthal distributions of protons (see Fig. 1), the same conclusion can be obtained.

If particles are statistically independently emitted with the same azimuthal distribution $F(\phi)$ in an event, then azimuthal correlation function is related to $F(\phi)$ via the convolution [19]

$$C(\Delta\phi)=\int_0^{2\pi}F(\phi)F(\phi+\Delta\phi)d\phi. \tag{3}$$

Substituting Eq. (1) into Eq. (3), we derive the form of $C(\Delta\phi)$ as [17]

$$C(\Delta\phi)=2\pi a_0^2[1+0.5a_1^2\cos(\Delta\phi)+0.5a_2^2\cos(2\Delta\phi)]. \tag{4}$$

Comparing Eq. (2) and Eq. (4), one obtains

$$a_1=\sqrt{2\lambda_1}$$

and

$$a_2=\sqrt{2\lambda_2}. \tag{5}$$

Equation (5) gives the relation between the anisotropic coefficients of the azimuthal distributions and those of azimuthal correlations.

Figure 3 shows the anisotropic coefficient of azimuthal distribution and azimuthal correlation extracted from the 10.6 MeV/nucleon ^{84}Kr+^{27}Al reaction as a function of fragment mass. This experimental a_2 is slightly larger than

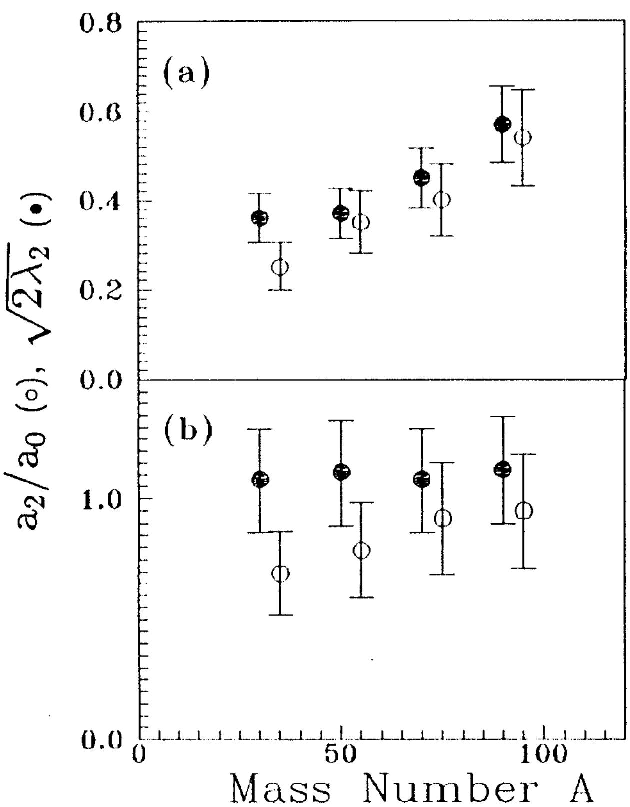

FIG. 3. The anisotropic coefficient of azimuthal distribution a_2 (○) and azimuthal correlation $\sqrt{2\lambda_2}$(●) as a function of fragment mass: (a) proton, (b) α particle.

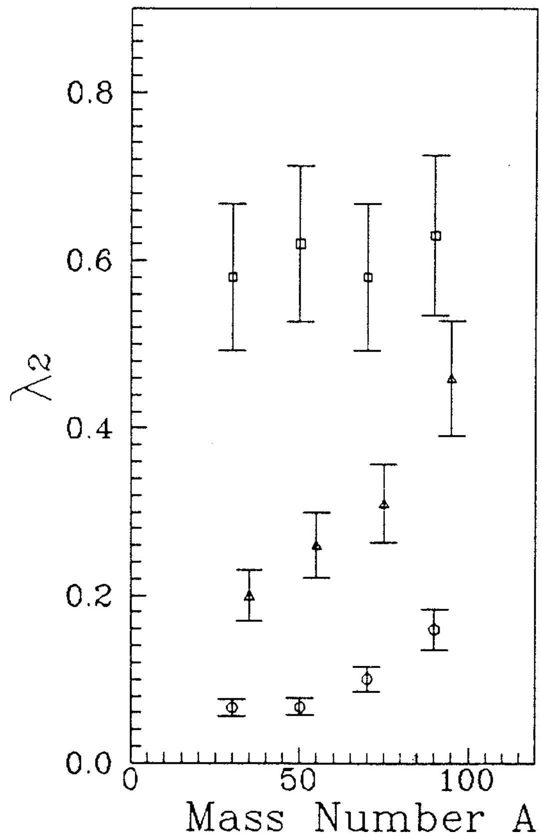

FIG. 4. The anisotropic coefficient of azimuthal correlation for like particles and unlike particles (○: p-p, △: p-α, □: α-α) as functions of the fragment mass.

$\sqrt{2\lambda_2}$ for all fragment windows, because a_2 is reduced by the dispersion of the reaction plane. But the value of a_2 is actually close to the value of $\sqrt{2\lambda_2}$, this indicates that the reaction plane was reconstructed well via the direction of one fragment and the beam. In Ref. [20], the anisotropy is defined as

$$\beta = \frac{I^2}{2TJ}\,\frac{\mu R^2}{\mu R^2 + J}. \tag{6}$$

Here, I and T are the angular momentum and the temperature of the mother nucleus, respectively, μ is the reduced mass between the emitted particle and the daughter nucleus, R is the barrier radius [21], and J is the moment of inertia of the system, which can be calculated by the RFRM model [22]. In terms of Eq. (6), the anisotropy of light particles increases with increasing light particle mass for the 10.6 MeV/nucleon ^{84}Kr+^{27}Al reaction. From Fig. 4, it is also seen that the anisotropic coefficients λ_2 of α-α azimuthal correlations are larger than those of the α-p azimuthal correlations, and the latter are larger than those for p-p azimuthal correlations. This is consistent qualitatively with the conclusion deduced from Eq. (6).

IV. REACTION PLANE DISPERSION

Our novel way to extract the reaction plane dispersions is based on combining azimuthal distributions constructed using the experimentally measured reaction plane, which contains the reaction plane dispersion, and two particle azimuthal correlations, which are free of the reaction plane dispersion. Here we will not discuss any method to determine the reaction plane in detail, but will give the way to extract the reaction plane dispersion. When a certain way to determine the reaction plane was used in the experimental data analysis, our way will give its dispersion which can be used in the correction of the analyzed data. The experimental coefficients a^{exp} can be corrected for reaction plane dispersion through the deconvolution relation [10]

$$a_2^{\text{true}} = \frac{a_2^{\text{exp}}}{-1+2\langle\cos^2(\delta\phi)\rangle} = \frac{a_2^{\text{exp}}}{\langle\cos(2\delta\phi)\rangle},$$

$$a_1^{\text{true}} = \frac{a_1^{\text{exp}}}{\langle\cos(\delta\phi)\rangle}, \tag{7}$$

where a^{true} are the Fourier series parameters in a reference frame bound to the true reaction plane, i.e., the coefficients a in Eqs. (1) and (4). $\langle\delta\phi\rangle$ is the azimuthal reaction plane dispersion of the constructed reaction plane with respect to the true reaction plane. If both the experimental azimuthal distributions which contain reaction plane dispersions and azimuthal correlation functions which are free of reaction plane dispersions have been analyzed, we may estimate the reaction plane dispersion via [17]

$$\langle\cos(2\delta\phi)\rangle = \frac{a_2^{\text{exp}}}{\sqrt{2\lambda_2}}, \quad \langle\cos(\delta\phi)\rangle = \frac{a_1^{\text{exp}}}{\sqrt{2\lambda_1}}. \tag{8}$$

Such a method can be easily generalized to the correlations between unlike particles called particle X and particle Y:

$$C(\delta\phi) = A[1+\lambda_1^{X-Y}\cos(\delta\phi)+\lambda_2^{X-Y}\cos(2\delta\phi)]$$

$$= \int_0^{2\pi} F_X(\phi)F_Y(\phi)\,d\phi, \tag{9}$$

where the azimuthal distributions for particle X and particle Y are

$$F_X(\phi) = a_{0X}[1+a_{1X}\cos(\phi)+a_{2X}\cos(2\phi)], \tag{10}$$

$$F_Y(\phi) = a_{0Y}[1+a_{1Y}\cos(\phi)+a_{2Y}\cos(2\phi)]. \tag{11}$$

Inserting Eqs. (10) and (11) into Eq. (9), we can get the relations between coefficients a and λ easily:

$$C(\delta\phi) = 2\pi a_{0X}a_{0Y}[1+0.5a_{1X}a_{1Y}\cos(\delta\phi)$$

$$+0.5a_{2X}a_{2Y}\cos(2\delta\phi)], \tag{12}$$

$$\lambda_1^{X-Y} = 0.5a_{1X}a_{1Y},$$

and

$$\lambda_2^{X-Y} = 0.5a_{2X}a_{2Y}. \tag{13}$$

Considering that the azimuthal distributions contain reaction plane dispersions and azimuthal correlations are free of re-

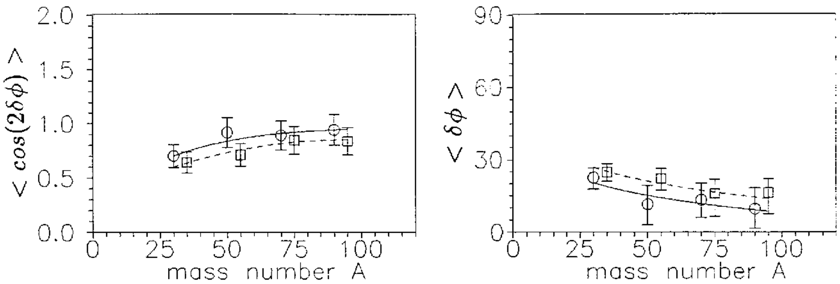

FIG. 5. The reaction plane dispersions $\langle\cos(2\delta\phi)\rangle$ which equal $a_2/\sqrt{2\lambda_2}$ (left panel) and $\langle\delta\phi\rangle$ (right panel) as a function of the fragment mass in the reaction of the 10.6 MeV/nucleon ^{84}Kr on ^{27}Al. The open circles (solid line) are for the proton and the squares (dashed line) are for the α particle. These latter symbols are shifted by five mass units for ease of comparison. The lines are to guide the eyes.

action plane dispersions, we can obtain reaction plane dispersions again for particle X and particle Y:

$$a_{2X}^{\mathrm{true}}=a_{2X}^{\mathrm{exp}}/\langle\cos(2\,\delta\phi)\rangle_X,\quad a_{1X}^{\mathrm{true}}=a_{1X}^{\mathrm{exp}}/\langle\cos(\,\delta\phi)\rangle_X,\tag{14}$$

$$a_{2Y}^{\mathrm{true}}=a_{2Y}^{\mathrm{exp}}/\langle\cos(2\,\delta\phi)\rangle_Y,\quad a_{1Y}^{\mathrm{true}}=a_{1Y}^{\mathrm{exp}}/\langle\cos(\,\delta\phi)\rangle_Y,\tag{15}$$

$$\langle\cos(2\,\delta\phi)\rangle_X\langle\cos(2\,\delta\phi)\rangle_Y=a_{2X}^{\mathrm{exp}}a_{2Y}^{\mathrm{exp}}/(2\lambda_2^{X-Y}),\tag{16}$$

$$\langle\cos(\,\delta\phi)\rangle_X\langle\cos(\,\delta\phi)\rangle_Y=a_{1X}^{\mathrm{exp}}a_{1Y}^{\mathrm{exp}}/(2\lambda_1^{X-Y}).\tag{17}$$

We should have the following relations:

$$\lambda_2^{X-X}\lambda_2^{Y-Y}=(\lambda_2^{X-Y})^2,\quad \lambda_1^{X-X}\lambda_1^{Y-Y}=(\lambda_1^{X-Y})^2,\tag{18}$$

where X and Y represent particles like p, d, t, α, Li, etc.

Actually we can obtain reaction plane dispersions from like particle correlations and unlike particle correlations according to the relation between coefficients a_2 and λ_2 and the relation between a_1 and λ_1. They should be the same within experimental error bars. Here we present the results from like particle and unlike particle correlations from the reaction of the 10.6 MeV/nucleon ^{84}Kr on ^{27}Al.

Taking these data and applying them to our novel way for determining the reaction plane dispersion, we obtained the reaction plane dispersion as function of fragment mass which is show in Fig. 5. The left panel shows the reaction plane dispersion $\langle\cos(2\delta\phi)\rangle$ while the right panel shows $\langle\delta\phi\rangle$. Here for 10.6 MeV/nucleon ^{84}Kr on ^{27}Al we used the beam axis and the direction of the detected fragment as the reaction plane. The dispersions extracted from different particles (protons and α particles here) should be the same according to our method. Figure 5 shows that they are truly the same within error bars, which include the statistical error and the error of the fitting procedure. $\langle\cos(2\delta\phi)\rangle$ and $\langle\delta\phi\rangle$ have slight fragment mass dependence, as pointed out above and with increasing mass of the fragment the angular momentum will be larger, therefore the anisotropy of azimuthal distribution and azimuthal correlation will be larger, while the dispersion of the reaction plane determination will be smaller; this is similar to the conclusion in Ref. [17]. These results indicate that our way to extract the dispersion is successful for the reaction 10.6 MeV/nucleon ^{84}Kr on ^{27}Al. In an intermediate energy reaction such as (36–100) MeV/nucleon ^{40}Ar on ^{27}Al [17], the dispersion of the reaction plane determination via Danielewicz's method [23] depends on the collective flow; it increases rapidly when the flow goes to zero [24]. When the incident energy approaches the energy of the disappearance of rotation, the reaction plane dispersion $\langle 2\,\delta\phi\rangle$ approaches 90°. The error bars for reaction plane dispersion and corrected coefficients a_2 increase strongly when the incident energy approaches this energy. This means actually that for totally isotropic emission of particles no reaction plane can be determined in Danielewicz's method (see Fig. 6 in Ref. [17]). The corrected a_2 for this point has a huge error bar. By using these corrected a_2 values the experimental corrected triple differential cross sections for various particles can be obtained. The experimental corrected triple differential cross sections for various particles and the disappearance energy of the rotational flow and transverse flow can be compared directly with transport model calculations such as BUU and QMD. Because of the rapid increase of the dispersion of reaction plane near the disappearance energy, special caution should be taken here. A better method for reaction plane determination for small collective flow should be found. For reactions such as 10.6 MeV/nucleon ^{84}Kr on ^{27}Al, the direction of the fission fragment can be used to reconstruct the reaction plane. The dispersion of such reaction plane determination is small (see Fig. 5). Unlike light particle correlations (here p-α) were analyzed from the experimental data of the reaction of 10.6 MeV/nucleon ^{84}Kr on ^{27}Al. Together with the azimuthal distribution of protons and α particles, the dispersion product $\langle\cos(2\delta\phi)\rangle_p^{p\alpha}\langle\cos(2\delta\phi)\rangle_\alpha^{p\alpha}$ was obtained according Eq. (16). For comparison the dispersion product $\langle\cos(2\delta\phi)\rangle_p^{pp}\langle\cos(2\delta\phi)\rangle_\alpha^{\alpha\alpha}$ extracted from like particle correlation is made also. These dispersion products as a function of the fragment mass are shown in Fig. 6. In this figure $\langle\cos(2\delta\phi)\rangle_p^{pp}\langle\cos(2\delta\phi)\rangle_\alpha^{\alpha\alpha}$ was shifted by five mass units for ease of comparison. They are the same within error bars.

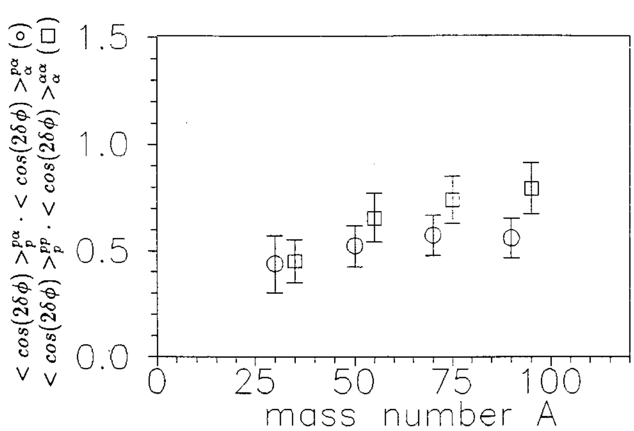

FIG. 6. The dispersion products extracted from unlike particle correlation, p-α (○), and like particle correlations, p-p and α-α (□), as a function of the fragment mass. The squares extracted from like particle correlations are shifted by five mass units.

Obviously, they show slight fragment mass dependence as the dispersion $\langle\cos(2\delta\phi)\rangle$ extracted from like particle correlation. This indicates again that our way to extract the dispersion is successful in the reaction of 10.6 MeV/nucleon ^{84}Kr on ^{27}Al.

V. SUMMARY

By studying the azimuthal distribution and the azimuthal correlation of light particles in coincidence with fragments in 10.6 MeV/nucleon $^{84}\mathrm{Kr}+{}^{27}\mathrm{Al}$ reaction, we found that the second-order anisotropic coefficient of azimuthal distribution and azimuthal correlation slightly increases with increasing fragment mass, but nearly proportionally increases with increasing the emitted particle mass. The anisotropy coefficient β of the emitted light particles from the composite system formed in the reaction can be extracted. We obtained $\beta=1.2\pm0.3$ from the azimuthal distribution of α particles in coincidence with fragments in the mass window between 80 and 100, which is consistent within error bars to $\beta\sim1.5$ which was used to fit the same experimental data via three sources model by Nakagawa *et al.* [13]. This value is smaller than the value $\beta\sim3$ of the α particle azimuthal distribution which is calculated using a mean angular momentum $J=72\hbar$ for the 10.6 MeV/nucleon $^{84}\mathrm{Kr}+{}^{27}\mathrm{Al}$ reaction under binary decay and assuming the spherical configuration. A possible reason is that most light particles are emitted between the saddle and scission points, i.e., the emission is related to the larger deformation of the composite system.

We have presented a novel way to extract the reaction plane dispersion by combining the azimuthal distributions constructed using the experimental measured reaction plane which contains a reaction plane dispersion and two particle azimuthal correlations which are free of the reaction plane dispersion. The new method was applied to the 10.6 MeV/nucleon $^{84}\mathrm{Kr}+{}^{27}\mathrm{Al}$ reaction for light particles, p and α.

When the direction of the fission fragment and the beam axis was used as the reaction plane, the extracted dispersions from different like particle correlations were the same within error bars and they have a slight fragment mass dependence. The extracted dispersion product from unlike particle correlations is the same within error bars as the dispersion product from like particle correlations. This indicates that our way to extract the dispersion is successful for the reaction of 10.6 MeV/nucleon ^{84}Kr on ^{27}Al.

For intermediate energy heavy-ion reactions the normal way to determine the reaction plane [23] has big dispersion when the incident energy approaches the disappearance energy. A better way should be found for this case. For the low-energy fission reactions such as 10.6 MeV/nucleon ^{84}Kr on ^{27}Al by using the direction of the fission fragment the dispersion of reaction plane determination is quite small.

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