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Azimuthal Distribution and Azimuthal Correlation of Light Particles Emitted in 10.6MeV/u $^{84}Kr + ^{27}Al$ Collision

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The emission of light particles in the 10.6 MeV/u $^{84}Kr + ^{27}Al$ collision in coincidence with fragments is studied. Emphasis is laid on characters of the anisotropic coefficient of the second order based on the fitting particle azimuthal distribution and particle-particle azimuthal correlation via Fourier expansion up to the second order. The derived results prove that particle emission is statistically independent with the same azimuthal distribution. It is found that the anisotropic coefficient of the second order depends weakly on fragment mass and increases with increasing emitted particle mass.

Key words: azimuthal distribution, azimuthal correlation, statistically independent emission.

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1. INTRODUCTION

Azimuthal distribution and azimuthal correlation of particles emission in intermediate- and high-energy heavy-ion reactions are considered as a probe in the extracting equation of the state of nuclear matter and in a medium nucleon-nucleon interaction cross section. So they were the focus of much attention. When E_{beam}/A is several hundreds of MeV, azimuthal distribution clearly indicates the enhancement of particle emission in out-of-plane, i.e., peaking at $\pm 90°$, which is a squeeze-out of nuclear matter. It is considered to be produced by the nuclear matter compression and/or nuclear shadowing effect [1-3]. At a few tens of MeV/nucleon, azimuthal distribution peaks are at 0° and $\pm 180°$ for midrapidity at the same time, i.e., light particles are preferentially emitted in the reaction plane. It indicates that the nucleus has the rotational collective motion [4-11]. With increasing entrance angular momentum, rotational angular velocity also increases; this effect becomes more evident, especially for heavy emitted particles [12]. Owing to the collective flow effect, azimuthal distribution evolves from peaking at 180° to 0° with rapidity changing from target rapidity to projectile rapidity. The first- and second-order anisotropic coefficients of azimuthal distribution and azimuthal correlation in this energy range usually decrease with increasing bombarding energy, but at a certain value, they become isotropic, and correspond to the disappearances of collective flow and collective rotation. Azimuthal distribution and azimuthal correlation of the emitted particles in this energy range reflect physical contents, but for bombarding energy down to 10 MeV/u heavy ion reactions, there is little research dedicated to these aspects.

Since the measurement of azimuthal distribution requires the knowledge of the reaction plane, before comparing theoretical values with experimental results, it is necessary to correct the experimental results via the correction of reaction plane determination. Meanwhile, azimuthal correlation avoids this complicated problem because it does not need any knowledge of the reaction plane [13,14]; furthermore, the systematic uncertainties associated with detector acceptance, efficiency, etc., can be minimized and the statistics are much improved.

For bombarding energy down to 10 MeV/u heavy-ion quasi-fission and fusion-fission reactions, the reaction plane can be constructed from detected fragments, so it is convenient to study azimuthal distribution and azimuthal correlation of particles in coincidence with fragments. Clearly, under such energy the particle multiplicity is much lower than that in intermediate energy, but the study of these aspects can still be performed. For 10.6 MeV/u ^{84}Ke + ^{27}Al reaction system, some measured quantities and related nuclear reaction mechanisms and properties have been studied, such as fragment mass, charge distribution [15,16], and light particle multiplicity [17,18]. The analysis of experimental data by the three-sources model indicates that most of particles are emitted before scission and, based on it, the fission delay time is extracted. In this paper, we obtain the information of reaction mechanism by studying azimuthal distributions and azimuthal correlations of light particles.

2. EXPERIMENTAL SETUP

The experiment was performed by using the large scattering chamber (ASCHRA) in the RIKEN Accelerator Research Facility (3m × 4.8m). A self-supporting ^{27}Al target (600 μg/cm^2 in thickness) was bombarded with an 890 MeV ^{84}Kr beam. Heavy fragments were detected during the time of a flight counter telescope which was placed at 10° respective to the beam direction. 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. The 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 and thick BaF_2 crystal. They have good time response. The flight paths from the target center to the phoswich detectors were varied from 60 cm at the forward angle to 15 cm at the backward. To determine the velocity of the emitted light-charged particles directly, especially for

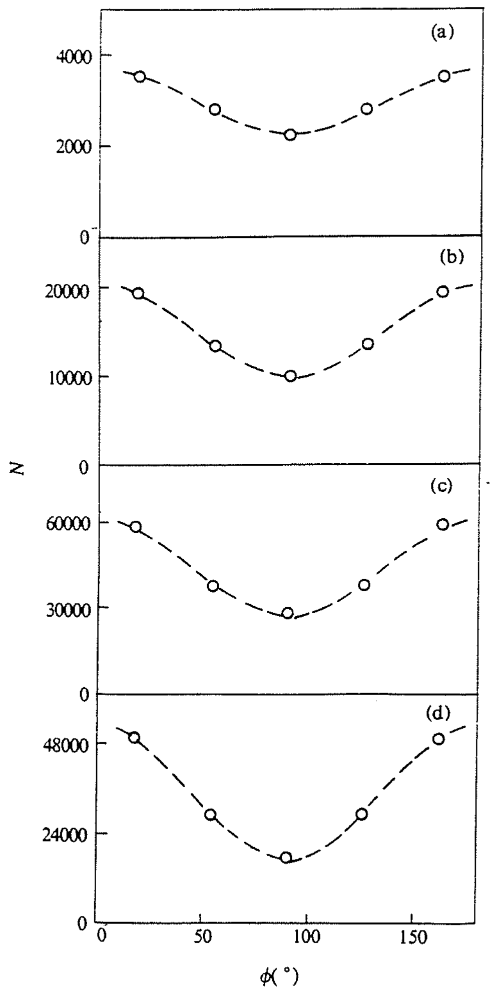

Fig. 1
Azimuthal distributions of protons after $\phi = 90°$ symmetrization under four mass windows for the $^{84}Kr + ^{27}Al$ reaction.
(a)-(d) correspond to fragment mass windows 20-40, 40-60, 60-80, 80-100, respectively.
○ experimental data, --- fit results of second-order Fourier series, N is the relative counts.

the detectors placed at the forward angles, we measured the flight time of light particles also, which was derived from the time difference between a RF signal from the cyclotron and a timing signal of a detector. For experimental details, see Refs. [15,16].

3. EXPERIMENTAL RESULTS

Owing to the effect of nucleus recoil caused by particles emission on azimuthal distribution and azimuthal correlation, there is the asymmetry of azimuthal distributions and azimuthal correlation at 0° and 180°. If we study the first-order anisotropic coefficient of azimuthal distribution and azimuthal correlation, the correction of the nuclear recoil effect must be taken into account, while this correction

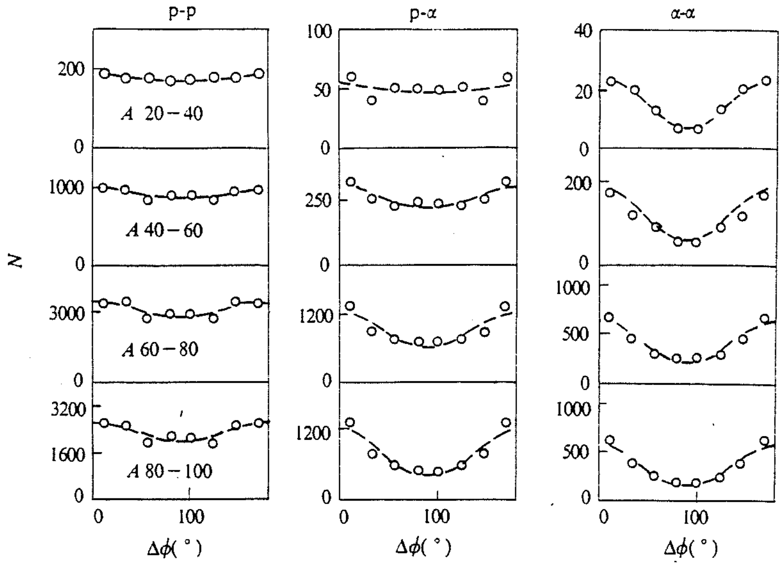

Fig. 2
Azimuthal correlations of light particles in coincidence with fragments after $\phi = 90°$ symmetrization for the $^{84}Kr + ^{27}Al$ reaction. Left, middle, and right panels correspond to p−p, p−α, α−α correlations, respectively. Figures from top to bottom correspond four mass windows, respectively.

depends on the correct selection of the recoil's nuclear mass. Because this paper studied mainly the rotational effect, we therefore make the symmetrization of $\phi = 90°$ for azimuthal distribution and azimuthal correlation. After such a treatment, the first-order anisotropic coefficient equals zero. It has no influence on extracting the second-order anisotropic coefficient, i.e., no influence on extracting the rotational effect, so we can study nuclear rotation directly, i.e., the ratio of purely out-of-plan emission to in-plane emission. This paper will study mostly the character of second-order anisotropic coefficient (which is called the anisotropic coefficient hereafter).

From the study of intermediate-energy heavy-ion reactions, we know that the azimuthal distribution of particles can be well described by the Fourier expansion up to the second order [7,8].

$$F(\phi) = a_0 + a_1 \cos(\phi) + a_2 \cos(2\phi), \tag{1}$$

Here, the first anisotropic coefficient a_1/a_0 reflects mainly the collective flow effect, and a_2/a_0 is the rotational behavior (for $+a_2/a_0$) or squeeze-out ($-a_2/a_0$).

It is seen from Fig. 1 that azimuthal distributions of protons show evident anisotropy, peaking simultaneously at 0° and 180°, which implies that nuclei exist in rotational behavior, the light particles are preferentially emitted in the reaction plane.

For the correlation between light particles and fragments, we may make a fit of the Fourier series with the expression

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

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 isotropicly, then $\lambda_1 = \lambda_2 = 0$.

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

If particles are statistically independently emitted with the same azimuthal distribution $F(\phi)$ in an event, then the azimuthal correlation function is related to $F(\phi)$ via the convolution [20]

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

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

$$C(\Delta\phi) = a_0^2 + 0.5 a_1^2 \cos(\Delta\phi) + 0.5 a_2^2 \cos(2\Delta\phi) \, , \tag{4}$$

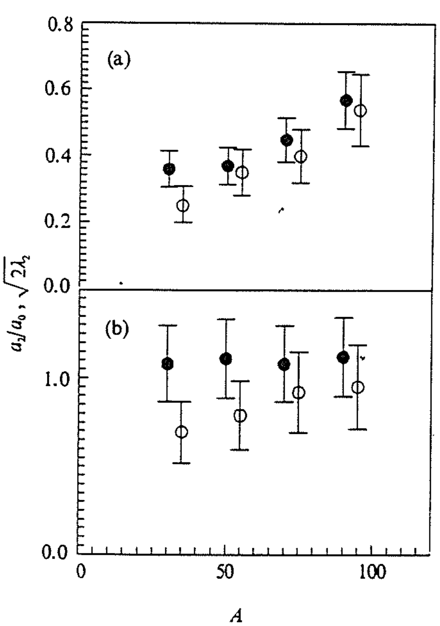

Fig. 3

The anisotropic coefficient of azimuthal distribution a_2/a_0 (○) and that of azimuthal correlation $\sqrt{2\lambda_2}$ (●) as a function of fragment mass for the $^{84}Kr+^{27}Al$ reaction.
(a) proton, (b) α-particle.

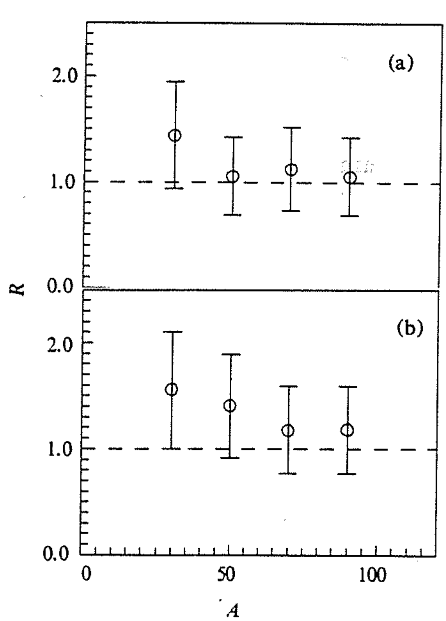

Fig. 4

The ratio of anisotropic coefficient of azimuthal correlation to that of azimuthal distribution for the $^{84}Kr + ^{27}Al$ reaction distribution.
(a) proton, (b) α-particle, $R = \sqrt{2\lambda_2} / (a_2 / a_0)$.

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

$$a_2 / a_0 = \sqrt{2\lambda_2}\,, \tag{5}$$

Equation (5) gives the relation between the anisotropic coefficient of azimuthal distribution and that of azimuthal correlation.

Figure 3 shows the anisotropic coefficient of azimuthal distribution and azimuthal correlation extracted in $^{84}Kr + ^{27}Al$ reaction as function of fragment mass. Figure 4 gives the ratio between these two coefficients. It is seen that, within error bars, the equality $a_2 / a_0 = \sqrt{2\lambda_2}$ is approximately valid for protons and α-particles. This result implies that particles are indeed statistically independently emitted with the same azimuthal distribution in an event.

Below we quantitatively study the relation between anisotropy and particle mass. In Ref. [21], the anisotropy is defined as:

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

where I and T are angular momentum and temperature of the mother nucleus, respectively; μ is the reduced mass between particle and daughter nucleus; R is the barrier radius [22]; J is the momentum of the inertial system, calculated by the RFRM model [23]. In terms of Eq.(6), the ratio of anisotropy for α-particle to that of protons approximately equals to 3.6 for 10.6 MeV/u $^{84}Kr + ^{27}Al$ reaction. From Fig. 5, it is seen that, within error bars, $\lambda_{2\alpha} \approx 4\lambda_{2p}$. This is consistent with the conclusion from Fig. 2 and Eq.(6). It indicates that for this reaction system, the anisotropy of light particle increases with increasing the light particle mass.

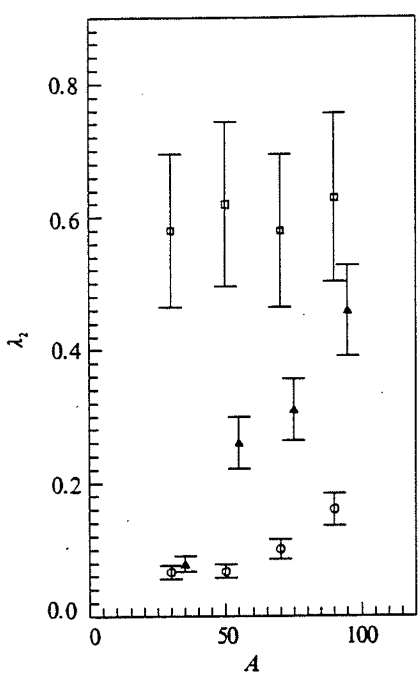

Fig. 5

The anisotropic coefficient of azimuthal correlation for different light particles (○ p-p, Δ p-α, □ α-α) as a function of fragment mass for the $^{84}Kr + ^{27}Al$ reaction.

4. DISCUSSION

By studying azimuthal distribution and azimuthal correlation of light particles in coincidence with fragments in 10.6 MeV/u ^{84}Kr + ^{27}Al reaction, the following conclusions can be obtained: the particles are emitted statistically independent with the same azimuthal distribution; the second-order anisotropic coefficient of azimuthal distribution and azimuthal correlation slightly increases with increasing fragment mass, and also increases with increasing the emitted particle mass nearly proportionally. The anisotropy β of the emitted light particles from the composite system formed in reaction can be extracted. We obtained $\beta = 1.2 \pm 0.3$ from azimuthal correlation of light particles in coincidence with the fragment mass window between 80 and 100, which is consistent with $\beta \sim 1.5$ used to fit the same experimental data via the three-sources model by T. Nakagawa, *et al.*. This value is smaller than of a spherical nuclei $\beta \sim 3$ which is calculated using a mean angular momentum $J = 72\hbar$ for 10.6 MeV/u ^{84}Kr + ^{27}Al reaction under binary decay. The 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. Azimuthal distribution and azimuthal correlation of light particles in coincidence with fragments can provide the information of reaction mechanism, collective behavior, and the deformation of the composite system. Further research is in progress.

REFERENCES

[1] H.H. Gutbord, *et al.*, *Phys. Lett.*, **B46** (1989): p. 267.
[2] KAOS Collaboration, D. Brill, *et al.*, *Phys. Rev. Lett.*, **71** (1993): p. 336.
[3] TAPS Collaboration, L.B. Venema, *et al.*, *Phys. Rev. Lett.*, **71** (1993): p. 835.
[4] M.B. Tsang, *et al.*, *Phys. Rev. Lett.*, **60** (1988): p. 1479.
[5] W.K. Wilson, *et al.*, *Phys. Rev.*, **C41** (1990): R1881.
[6] G.D. Westfall, *et al.*, *Nucl. Phys.*, **A519** (1990): 141c.
[7] W.Q. Shen, *et al.*, *Nucl. Phys.*, **A551** (1993): p. 333.
[8] Y.G. Ma, *et al.*, *Phys. Rev.*, **C48** (1993): R1492.
[9] Y.G. Ma, *et al.*, *Z. Phys.*, **A346** (1993): p. 285.
[10] R. Popescu, *et al.*, *Phys. Lett.*, **B331** (1994): p. 285.
[11] G. Pantis and S. Das Gupta, *Phys. Rev.*, **C49** (1994): p. 338.
[12] C.B. Chitwood, *et al.*, *Phys. Rev.*, **C34** (1986): p. 858.
[13] S. Wang, *et al.*, *Phys. Rev.*, **C44** (1991): p. 1091.
[14] R.A. Lacey, *et al.*, *Phys. Rev. Lett.*, **70** (1993): p. 1224.
[15] T. Nakagawa, *et al.*, *Nucl. Phys.*, **A583** (1995): p. 149.
[16] K. Yuasa-Nakagawa, *et al.*, *Phys. Lett.*, **B351** (1995): p. 77.
[17] S.M. Lee, *et al.*, *Nucl. Phys.*, **A519** (1990): p. 221.
[18] K. Yuasa-Nakagawa, *et al.*, *Phys. Lett.*, **B283** (1992): p. 185.
[19] R. Wada, *et al.*, *Nucl. Phys.*, **A539** (1992): p. 326.
[20] M.B. Tsang, *et al.*, *Phys. Lett.*, **B297** (1992): p. 243.
[21] L. Schad, *et al.*, *Z. Phys.*, **A318** (1984): p. 179.
[22] J.M. Alexander, *et al.*, *Z. Phys.*, **A313** (1984): p. 311.
[23] A.J. Sierk, *et al.*, *Phys. Rev.*, **C33** (1986): p. 2039.