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In-plane and Out-of-plane Emission of Light Charged Particle from $^{40}Ar+^{197}Au$ Collisions at 25 MeV/u

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The in-plane and out-of-plane emission of light particles from $^{40}Ar+^{197}Au$ collisions at 25 MeV/u was studied by means of coincidence measurement of light particles with two fission fragments. An in-plane emission enhancement was observed for mid-rapidity p, d, t, α particles, indicating that a rotational effect exists in this reaction system. This enhancement becomes more obvious with the increase of mass of the particles, or with the increase of the impact parameters. It was also found that for projectile-like particles the in-plane emission is dominant.

Key words: reaction plane, in-plane emission, out-of-plane emission, rotation effect, impact parameter.

1. INTRODUCTION

In the past decade, the collective flow of nuclear matter has widely been studied in high-energy and intermediate-energy heavy ion collisions [1–3] to extract important information about the nuclear equation of state (EOS) and the in-medium nucleon-nucleon cross section [4,5]. At high energies of a few hundred MeV/nucleon to 1 GeV/nucleon, the interaction is dominated by the repulsive nucleon-nucleon scattering, causing the particles emitted at forward c.m. angles to be deflected to the side of the incident projectile, i.e., the collective flow in the reaction plane (the in-plane flow) is

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positive. At intermediate energies of a few tens of MeV/nucleon, the interaction is dominated by the attractive part of the nuclear mean field and the in-plane flow is negative. At a certain incident energy, the attractive part and the repulsive part of the interaction balance each other and the in-plane flow disappears. On the other hand, the out-of-plane flow of nuclear matter reflects the emission mechanism of particles. At high energies, particles are preferentially emitted in the direction perpendicular to the reaction plane (the so-called out-of-plane emission), this is named the squeeze-out effect [6]. Conversely, at intermediate energies, such as $^{40}Ar+^{51}V$ reactions at 35 MeV/u, the in-plane emissions of particles are observed to be dominant, indicating that a rotational effect exists in the participants [7]. Recently, the evolution from in-plane enhancement to out-of-plane enhancement with the increasing incident energy is measured for $^{64}Zn+^{58}Ni$ reactions at 35–79 MeV/u. An azimuthally isotropic emission of particles is observed at the incident energy of 50–60 MeV/u [8]. However, at the energies between 10 and 35 MeV/u, few experiments are performed to study this azimuthally anisotropic emission and rotational effect. In this paper, we report our measurements for $^{40}Ar+^{197}Au$ reactions at 25 MeV/u.

2. EXPERIMENTAL SET-UP

The experiment was performed at the heavy ion research facility at Lanzhou (HIRFL), using a ^{40}Ar beam with beam energy of 25 MeV/u and beam intensity of 10 nA bombarding on ^{197}Au target. The charged particles and light fragments were measured by an array of thirteen $\Delta E-E$ telescopes, each consisting of a 300 μm-thick Si detector as ΔE and a 50 mm-thick BGO scintillator as E measurement. Each telescope was located at a distance of 580 mm from the target and each telescope had a detective area of ϕ17 mm. The center of the array was positioned at laboratory polar angle θ = 20° relative to the beam axis and at the laboratory azimuthal angle θ = 0°. The maximum polar angle of the telescope was 27° and the minimum was 13°. Particle identification was done by measuring both

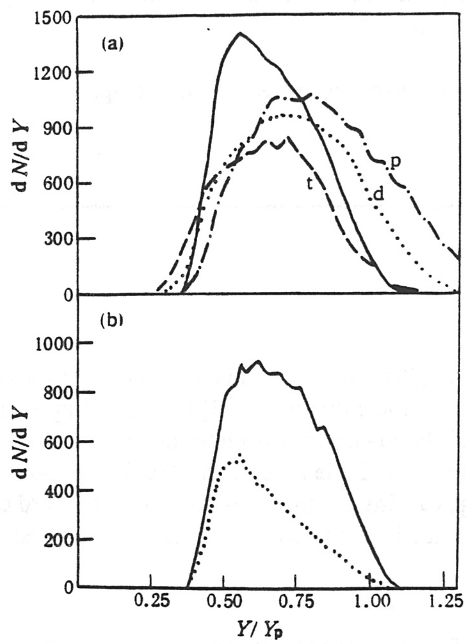

Fig. 1

(a) The rapidity distributions of light particles emitted from binary fission. (b) the rapidity distributions of the in-plane (solid line) and out-of-plane emission (dashed line) of α particles.

the energy loss in ΔE and energy deposition in E. A clear element identification for α, Li, Be, B, C, etc., as well as all hydrogen isotopes (p, d, t), was obtained for all telescopes.

In addition, two fission fragments were detected by four position sensitive parallel plate avalanche counters (PPAC) placed symmetrically around the beam axis with solid angle coverage of θ_{Lab} = 30°–90° and φ = 0°–360°. The out-of-plane emission of particles was measured via the telescope array, PPAC 1# (52°–128°) and PPAC 3# (232°–308°); while the in-plane emission of particles via the array, PPAC 2# (147°–210°) and PPAC 4# (−26°–26°). The accurate time and position (r, θ, φ) measurements, as well as energy loss ΔE measurement, were obtained by four PPACs.

3. IN-PLANE AND OUT-OF-PLANE EMISSION OF LIGHT PARTICLES

Up to now several methods of reaction-plane determination were proposed [9]. In this paper, the fission plane methods is employed. For each event, the azimuthal angle Φ of the reaction plane determined by two fission fragments is defined as [10]:

$$\Phi=\frac{1}{2}\left(\varphi_{f_1}+\varphi_{f_2}+180^\circ\right), \tag{1}$$

where φ_{f_1} and φ_{f_2} denote the azimuthal angles of the two fission fragments, respectively. The azimuthal angle (Φ) of the particle with respect to the reaction plane is calculated to determine the in-plane or out-of-plane emission of particle, i.e., the particles with $|\Phi+90^\circ|\le 25^\circ$ or $|\Phi-90^\circ|\le 25^\circ$ are accumulated as out-of-plane emission; while the particles with $|\Phi|\le 25^\circ$ or $|\Phi-180^\circ|\le 25^\circ$ as in-plane emission, where an azimuthal angle bin of 25° is used to accumulate sufficient statistics.

Figure 1(a) shows the rapidity distributions of p, d, t, and α particles measured by thirteen telescopes. The rapidity Y is defined as

$$Y=\frac{1}{2}\ln\left[\frac{1+\beta}{1-\beta}\right]. \tag{2}$$

It is shown in Fig. 1(a) that the light particles emitted from target-like source with rapidity $Y/Y_p < 0.3$ are not detected (where Y_p is the rapidity of the projectile), since these low-energy particles are stopped in the 300 μm-thick ΔE detector. To distinguish between the mid-rapidity particles and the particles from the projectile-like fragment (i.e., high-rapidity particles), the particles are divided into two groups according to the rapidity: high rapidity group ($Y/Y_p>0.7$) and mid-rapidity group ($0.3\le Y/Y_p\le 0.7$). Figure 1(b) shows the α rapidity distributions of in-plane and out-of-plane emission. An in-plane enhancement is clearly observed for high-rapidity and mid-rapidity particles. To study the in-plane and out-of-plane emission as a function of the particle mass, particle energy, and impact parameter, the ratio of out-of-plane to in-plane emission is used [6]:

$$R=\frac{N(90^\circ)+N(-90^\circ)}{N(0^\circ)+N(180^\circ)}=\frac{N_{out}}{N_{in}}. \tag{3}$$

Figure 2(a) shows the radio R of mid-rapidity particles as a function of θ angle. The R values are all smaller than 1 for p, d, t, and α particles, which indicates that in-plane emission is enhanced. At incident energy of 25 MeV/u, the interaction is dominated by the nuclear mean field. BUU calculation on the Ar+Al reaction has shown that the mean field effect produces this in-plane enhancement [11]. On the other hand, since such an in-plane enhancement is also produced in the de-excitation emission of a nucleus with a large angular momentum, this effect is also called a rotational effect. This

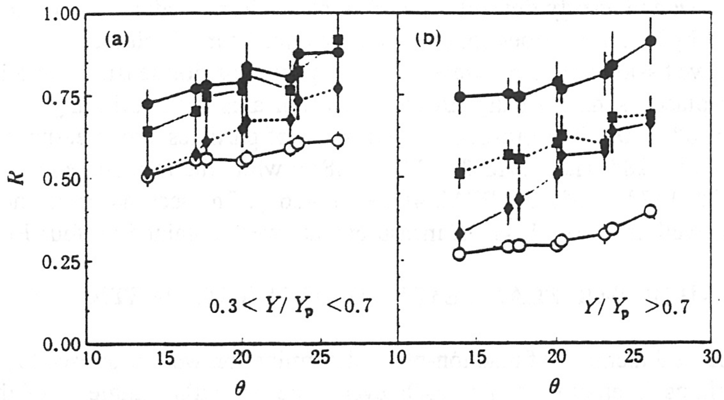

Fig. 2
The ratio R of light particles as a function of θ angle.
●: p; ■: d; ◆: t; ○: α.

rotational effect has been observed for the rather light system of Ar+V at 35 MeV/u [7]. Therefore, the in-plane enhanced emission observed in our results is caused by the mean field effect. The attractive mean field interaction causes the rotation of the reaction system around an axis perpendicular to the reaction plane. De-excitation of the rotational system produces the in-plane emission of light particles. This is opposite to the squeeze-out effect seen at high incident energies where the compressed nuclear matter in the reaction system produces the out-of-plane enhanced emission.

Figure 2(a) also shows that the R values dramatically decrease with the increasing mass of particles (i.e., rotational effect dramatically increases with the increasing mass of particles). This effect is also observed in the study of in-plane collective flow where the in-plane flow of light particles increases dramatically with the increasing mass of particles [1,2]. This effect is attributed to the role of thermal motion which tends to reduce the alignment into the reaction plane due to collective motion: in the limit of complete thermalization, the thermal energy of a cluster is the same whatever its mass, i.e., the thermal energy per nucleon is lower for heavy clusters than for nucleon, and their flow parameter is less reduced. It supports the fact that α particles are more suitable for the study of flow than protons. Figure 2(a) also shows the R value slightly increases with increasing θ angle.

Figure 2(b) shows the ratio R of high-rapidity particles as a function of θ angle. Compared with mid-rapidity particles, the R values are more smaller than 1. The in-plane emission of projectile-like particles dominate and there are few out-of-plane emission particles. The out-of-plane emission of high-rapidity particles decreases with the mass increasing of particles; the R value for α particles is 0.3, while the R value for p is about 0.8. This is also attributed to the affection due to the large thermal energy per nucleon of the particles. In the particle-particle correlation measurements for Ar+Au reaction at 25 MeV/u, the excited states of unstable nuclei (such as the 3.04 MeV excited state of ^{8}Be and the 4.63 MeV excited state of ^{7}Li) were also observed in the projectile-like fragments, indicating that the large thermal energy also exists in the high-rapidity particles from projectile-like fragments.

4. IMPACT PARAMETER DEPENDENCE OF ANISOTROPIC EMISSION

To sort the events according to impact parameter b, the linear momentum transfer (*LMT*) is estimated event by event by converting the angles, masses, and velocities of two fission fragments into the velocity of the recoiling nucleus. *LMT* ranges from 0 for peripheral collisions to about 1 for central collisions. Figure 3 shows the rapidity distributions of α particles at $LMT = 0.45$, $LMT = 0.6$, and $LMT = 0.8$, respectively. In the central collisions ($LMT = 0.8$), α particles mainly come from the

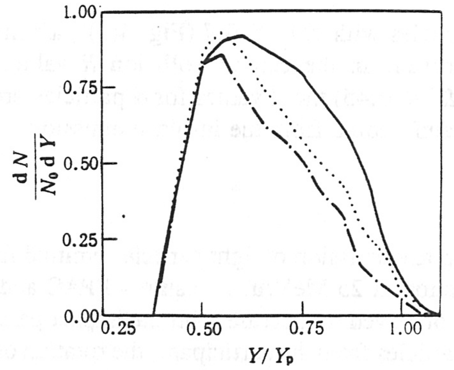

Fig. 3

The rapidity distributions of α particles at three bins of *LMT*.

—— *LMT* = 0.45, ······ *LMT* = 0.6, —·—·— *LMT* = 0.8.

mid-rapidity particles and pre-equilibrium emission particles. In the peripheral collisions (*LMT* = 0.45), not only mid-rapidity contributions but also the contributions from projectile-like fragments exist in the rapidity distributions. The *R* values for p and α particles are shown in Fig. 4 as a function of *LMT*. The *R* values for d and t particles are not shown in the figure since they are between those of p and α particles. Because of the limitation of the PPAC detection angle coverage, peripheral collision events with *LMT* < 0.4 are missed.

Figure 4(a) shows the *R* values for mid-rapidity particles as a function of *LMT*. In the central collisions (*LMT*$\geq$0.75), the *R* values are around 1 and the azimuthal isotropic emission is observed. The *R* decreases dramatically with decreasing *LMT* (increasing impact parameter). In the mid-peripheral collisions (*LMT*$<$0.6), $R < 0.5$, the in-plane emission of particles dominated. The decreasing of *R* values with the increasing impact parameter implied that the rotational effect of the system gets stronger with the increasing impact parameter. This is because the rotational energy of system increases with the increasing impact parameter. This effect is similar to the observation in the study of in-plane collective flow of light particles: the in-plane flow increases from central to mid-central collisions and is maximum at mid-peripheral collisions, then it begins to decrease in peripheral collision. This suggests that mid-central and mid-peripheral collisions provide a good probe for the study of collective flow.

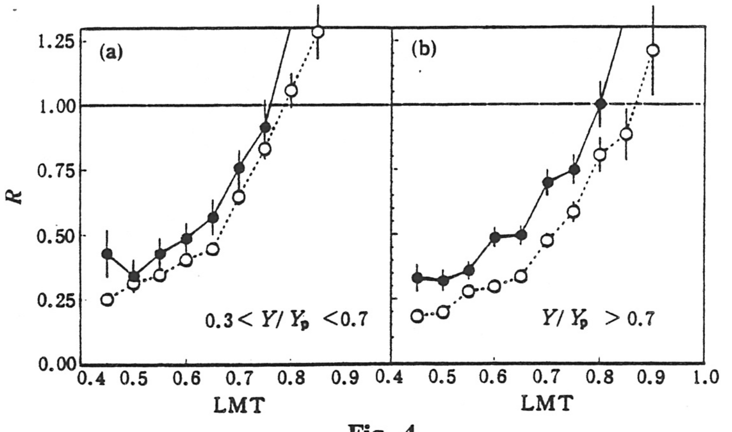

Fig. 4

The ratio *R* of light particles as a function of *LMT*.

●: p; ○: α.

For the high-rapidity particles with $Y/Y_p > 0.7$ (Fig. 4(b)), a similar variation of R values with the impact parameter is observed. In the central collision R values are around 1; while in the mid-peripheral collisions ($LMT < 0.45$) the R values for α particles are smaller than 0.2, indicating that high-rapidity particles mainly come from the in-plane emission.

5. CONCLUSION

The in-plane and out-of-plane emission of light particles emitted from binary fission events were measured for $^{40}Ar+^{197}Au$ reaction at 25 MeV/u, by using 4 PPAC and 13 telescopes. The emission of projectile-like fragments is observed to increase with the impact parameter, and in-plane emission dominates. For mid-rapidity particles from the participant, the rotation of the emission source produces the in-plane enhanced emission of particles. In the central collisions, the rotational effect is not obvious, but the rotational effect becomes stronger with the increasing impact parameter. This rotational effect also increases with the increasing mass of particles.

REFERENCES

[1] J.P. Sullivan *et al.*, *Phys. Lett.*, **B249**(1990), p. 8.
[2] He Zhiyong *et al.*, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **18**(1994), p. 800.
[3] He Zhiyong, *Trends in Nucl. Phys.*, **12**(1995), p. 26.
[4] He Zhiyong, *Chinese Journal of Nuclear Physics*, **16**(1994), p. 313.
[5] H.M. Xu., *Phys. Rev. Lett.*, **67**(1991), p. 2769.
[6] H.H. Gutbrod *et al.*, *Phys. Rev.*, **C42**(1990), p. 640.
[7] W.K. Wilson *et al.*, *Phys. Rev.*, **C41**(1990), R1881.
[8] R. Popescu *et al.*, *Phys. Lett.*, **B311**(1994), p. 285.
[9] He Zhiyong *et al.*, *Chinese Journal of Nuclear Physics*, **16**(1994), p. 207.
[10] M.B. Tsang *et al.*, *Phys. Rev.*, **C44**(1991), p. 2065.
[11] Y.G. Ma *et al.*, *Phys. Rev.*, **C48**(1993), p. 1492.