Long-range angular correlation in dissipative reaction of $^{27}Al+^{27}Al$

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Abstract Angular correlation of excitation functions in dissipative heavy ion collision $^{27}Al+^{27}Al$ has been measured. The incident beam energies ranged from 114 MeV to 127 MeV in steps of 200 keV. The angular analysis region was continuous from 50° to 90° in the center of mass system. An angular coherent width, at least 40°, was obtained. This long-range angular correlation could not be interpreted in the framework of the standard statistical reaction theory with state of equilibrium or near equilibrium, maybe it reveals the formation of a new kind of dissipative structure in the reaction of $^{27}Al+^{27}Al$ with the state that is far from equilibrium.

Keywords Dissipative heavy ion collision, Long-range angular correlation, State far from equilibrium, Dissipative structure

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1 INTRODUCTION

One of the most important results on the study of heavy ion physics is discovery of the so-called deep inelastic collision (DIC). The interpretation of the DIC is based on a picture of the formation and decay of an intermediate dinuclear system (IDS). Within the lifetime of IDS, the relative kinetic energy is transformed into the intrinsic excitation energy of the system and the orbital momentum into intrinsic angular momentum of the system. The transformation is a dissipative process and the DIC is also called the dissipative heavy ion collision (DHIC). The IDS formed at the early stage of the collision can not reach complete statistical equilibrium and decays into a projectile-like fragment and a target-like fragment. A series of non-equilibrium features appear in the DHIC. For example, the energy spectrum is the bell-like shape and the angular distribution of the products is asymmetric with respect to 90° in the center of mass system (C.M.).

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Recently, a noticeable development in DHIC is to measure the excitation functions,[1~5] to study both average and fluctuation properties, and moreover, to study the evolution process of the IDS with time. IDS formed in DHIC carries high excitation energy corresponding to excited overlapping levels ($\Gamma \gg D$, Γ is the average width of the levels and D their spacing). The structure width of the energy fluctuation in excitation functions of DHIC is about 1 MeV. It is different from either the gross structure with a width of 3~5 MeV induced by the potential scattering, or the fine structure characterized by a width of ≤ 0.1 MeV corresponding to the Ericson fluctuation. The fluctuation in the DHIC is also not the intermediate structure coming from the isolated level molecular resonance with $\Gamma < D$.

It is interesting that the fluctuation structure in the DHIC can not be smoothed out in spite of the high intrinsic excitation and a great number of final micro-channels. Especially, summing the excitation functions of the different dissipative products, the feature of the nonself-averaging is still kept. In addition, anomalous large angular correlation has been reported between the fragments at 60°, 120° and 160° in the DHIC of $^{19}F+^{89}Y$[2]. In order to examine the phenomenon of the long-range angular correlation, an experiment has been carried out for the first time to measure the angular correlation of the excitation functions at the wide continuous angles in the DHIC of $^{27}Al+^{27}Al$. Some results and discussions are presented in this paper.

2 EXPERIMENTAL RESULTS

An experiment of $^{27}Al+^{27}Al$ has been performed event by event. The beam $^{27}Al^{8+}$ was provided by the Tandem accelerator at LNS (the Laboratorio Nazionale del Sud), INFN (Istituto Nazionale di Fisica Nucleare), Catania, Italy. The incident beam energies were from 114 to 127 MeV in steps of 200 keV. An aluminium foil of 38 $\mu g/cm^2$ was used as the target. The beam intensity was about 50 nA. A total of 300 h beam time was used in order to get sufficient statistics.

In the experiment, three sets of $\Delta E - E$ gas-solid state telescopes were used to identify the charge number Z of the fragments emitted from the reaction. The ΔE detector is an ionization chamber filled with C_4H_{10} gas at a pressure of 4kPa, the residual energy E is deposited in a Si position sensitive detector. The detector system covered a wide range of continuous angles from 10.4° to 57.4° in the laboratory system. A semiconductor detector was set at 5.8° to monitor the beam. A Farady cup collecting the beam charge was placed at 0° to normalize the product counts.

The angular correlation coefficient was calculated through the expression,

$$C(\theta,\theta') = \left\langle \left[\frac{\sigma(E,\theta)}{\overline{\sigma}(E,\theta)} - 1\right]\left[\frac{\sigma(E,\theta')}{\overline{\sigma}(E,\theta')} - 1\right]\right\rangle_E \tag{1}$$

and the normalized angular correlation function (NACF) for the fixed angle θ is defined as

$$C_n(\theta,\theta') = C(\theta,\theta')/[C(\theta,\theta)C(\theta',\theta')]^{1/2} \tag{2}$$

where the big bracket $< >$ stands for the arithmetic average over the measured energy range and $\overline{\sigma}(E,\theta)$ represents the average cross section curve. Table 1 lists the angular correlation coefficients and Fig.1 plots the NACF of the Al-like products (summing from $Z=11$ to $Z=15$) emitted from the DHIC of $^{27}Al+^{27}Al$. The angular analysis region is continuous from 50° to 90° in the C.M. and the angular resolution is about 4°. The errors are due to the finite size of the data sampling.[6]

Table 1 Angular correlation coefficients of the Al-like products in DHIC of $^{27}Al+^{27}Al$

$\theta_{c.m.}/(°)$	52°	56°	60°	64°	68°	72°	76°	80°	84°	88°
52°	1	0.96	0.97	0.99	0.97	0.93	0.81	0.58	0.53	0.48
56°		1	0.98	0.95	0.97	0.95	0.88	0.71	0.65	0.58
60°			1	0.95	0.97	0.95	0.88	0.71	0.66	0.60
64°				1	0.97	0.93	0.78	0.55	0.49	0.45
68°					1	0.98	0.89	0.70	0.64	0.59
72°						1	0.93	0.76	0.70	0.66
76°							1	0.92	0.89	0.84
80°								1	0.97	0.94
84°									1	0.96
88°										1

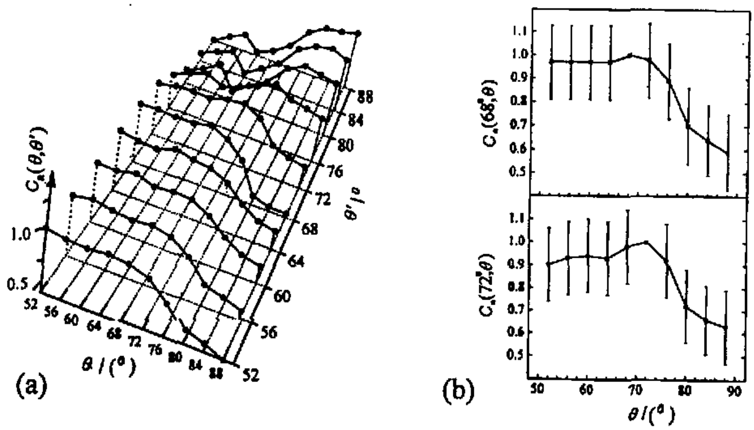

Fig.1 Plots of NACF of the Al-like products in the DHIC of $^{27}Al+^{27}Al$

3 DISCUSSIONS

From Table 1 and Fig.1, the angular coherent width of the Al-like products in the DHIC of $^{27}Al+^{27}Al$ is at least 40° and the NACF shows an asymmetry relative to the C.M. reference angles. The most of correlation coefficients are more than 0.5 and strong long-range angular correlation is obvious.

In the framework of the standard compound nuclear reaction statistical theory, Brink *et al*[7] predicts that the angular coherent width $\theta_c = 1/L_{gr}$, where L_{gr} is the grazing momentum. In the case of the $^{27}Al+^{27}Al$ reaction, $L_{gr} \cong 38\hbar$ and θ_c is about

3°. It is much smaller than 40°. In fact, the basic features of the DHIC are the non-equilibrium of IDS and the strong correlation between channels, whereas the above θ_c reflects only the size of the particle itself and there is no correlation considered.

Taking into account the angular momentum correlation between **S**-matrix elements, Hartmann *et al*[8] proposed a formula to find the angular coherent width:

$$\theta_c = 1.67(\Delta^2 + \delta^2)^{1/2}/\Delta^2 \tag{3}$$

where Δ is the width of the reaction l-window and δ the angular momentum correlation length. In the DHIC, $\delta < \Delta$ and $\Delta \geq 5 \sim 10$, and whatever δ and Δ are, always $\theta_c < 30°$. The experimental results about the long-range angular correlation in the reactions of $^{19}F+^{89}Y$ and $^{27}Al+^{27}Al$ can not be well fitted by this model that is based on the state of near equilibrium either.

According to the famous dissipative structure theory suggested by Prigogine *et al*, in the state far from equilibrium, non-equilibrium is not only the reason of disorder, but is especially the origin of the order too. In this case, there is a new kind of coherence which does not exist in the state of equilibrium or near equilibrium and a long-range correlation can be formed because of this new kind of coherence. At this point, the fluctuation can not be neglected, and it plays a very important role in the formation of the dissipative structure. As mentioned by Kun,[9] the IDS formed in the DHIC is far from equilibrium. The experimental facts of the nonself-averaging excitation functions and the long-range angular correlation reveal probably the formation of a new order dissipative structure in DHIC. The asymmetry of NACF relative to the C.M. angle can be considered as the space localization. The localization is due to a small fluctuation in the state far from equilibrium. It is spontaneous space symmetry breaking. A further analysis is in progress.

4 CONCLUSION

There is a long-range angular correlation in the dissipative heavy ion collision of $^{27}Al+^{27}Al$. The long-range angular correlation can not be interpreted by the standard compound nuclear reaction statistical theory and by the model based on the condition of near equilibrium. Maybe the long-range angular correlation reveals the formation of a new dissipative structure in the DHIC with the state that is far from equilibrium.

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