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Angular Dependence of the Coherence Energy in Dissipative Reaction of $^{19}F+^{51}V$

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Excitation function fluctuation for projectile-like fragments from ^{19}F + ^{51}V dissipative reaction within the energies of 102.25-109.25MeV are reported in this paper. The statistical method is applied to the analysis of energy coherence in the cross-section fluctuations and the strong cross-correlation between exit channels is obtained. The dependencies of energy, and coherences on charge number and on mass number are presented. The relation between angular velocity damping and the rotational energy dissipation for the dinuclear system is discussed.

Key words: excitation function fluctuation, coherence energy, angular velocity of dinuclear system.

1. INTRODUCTION

Since the discovery of the excitation function fluctuation in deep inelastic collisions (DIC) by A. De Rosa [1], many papers have been devoted to experimental [2-5] and theoretical research [6-8] to explore the mechanism of the cross-section fluctuations in dissipative reactions. D.M. Brink [8]

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generalized the statistical theory of T. Ericson and made it suitable to analyze the excitation functions which have strong cross-correlations between different exit channels. In this theory, the coherence energy can be evaluated and the interaction time can be obtained according to the uncertainty principle $\tau = \hbar / \Gamma$. So the measurements of excitation functions provided a new way of experimental investigation of the time-space evolution in dissipative processes.

It is well known that the DIC is a multistep process. The projectile and target attract each other and form a metastable dinuclear system. If the incident energy is high enough, for example, $E = 1.5\ V_B$ (where V_B is the Coulomb barrier), the excitation energy of the intermediate dinuclear system is quite high and the dinuclear system populates the continual level region where the average level width is much greater than the level space. Strong overlaps occur among the intermediate levels. The coherence among the overlapped levels leads to the cross-section fluctuations. The dinuclear system rotates with an angular velocity in a semiclassical picture. So the coherence energy includes the information on the level width and on rotation of the intermediate dinuclear system.

In this paper, the excitation functions of the dissipative reaction $^{19}F + {}^{51}V$ are investigated. The spectrum density method (SDM) is employed to extract the coherence energies Γ for various projectile-like products. The coherence energies present dependence on ejectiles' charge number Z and on emission angles. The theoretical analysis shows that the dinuclear system rotation introduces a linear relationship between interaction time and emission angles, and the observed strong angular velocity damping is due to the rotational energy dissipation.

2. EXPERIMENTAL MEASUREMENT AND DATA ANALYSIS

The measurement was performed at the HI-13 tandem at CIAE (China Institute of Atomic Energy, Beijing, China). A self-supporting 70 $\mu g/cm^2$ ^{51}V target was bombarded by the $^{19}F^{8+}$ beams. The description of the setup and the performance of the telescopes are found in Ref. [9]. The data were written on magnetic tapes event by event by the JUHU data acquisition system and the off-line analysis was done by using the Vax-8350 computer at the Institute of Modern Physics. The energy losses in the target and in the entrance windows for each detector were taken into account in the analyzing processes. The linearity of detector electronics was calibrated with a precise pulse generator and the energy calibration was done by using the elastic scattering energies of 42.17, 77.17, and 102.0 MeV ^{19}F on ^{197}Au target. The cross sections were normalized by integrated charge value in the Faraday cup during the experimental run.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The DIC cross sections are obtained by integrating the damping part of energy spectra. The excitation functions for elements Li, Be, B, C, N, O, F, and Ne at laboratory angles of 36.1° and 40.5° are depicted in Fig. 1. The fluctuations in excitation functions are remarkable and far beyond the statistical errors. The statistical methods were used to calculate the cross-correlation coefficients between different Z products. The coefficients are normally larger than 0.5, a fact which implies strong channel-channel correlations exist between different excitation functions. The correlations between different final channels of fixed Z products should also exist. The fluctuations are different either from the fully statistical Ericson fluctuations or from the isolated resonance of intermediate levels. Since in our measurements the contributions of the unresolved final channels cannot be separated, the observed excitation functions are the average contributions of these final channels. So the dissipative cross-section fluctuations should be observed only in a lighter colliding system. The accumulated data which are focused on the lighter system with mass number $A_1 + A_2 \leq 100$ confirm the theoretical prediction.

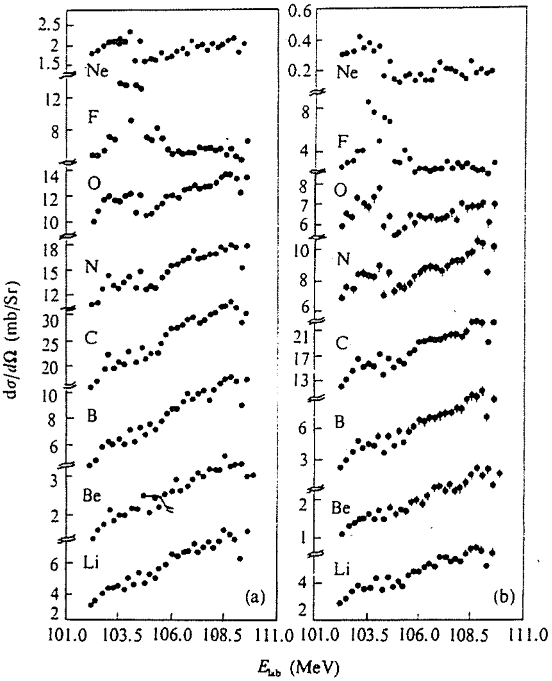

Fig. 1

The measured excitation functions for different elements in the reaction of $^{19}F + ^{51}V$.

(a) and (b) for laboratory angles of 36.1° and 40.5°, respectively.

In the generalized statistical theory, the energy self-correlation functions take the Lorentzian form

$$C(\varepsilon) = \frac{1}{N} \cdot \frac{\Gamma^2}{\Gamma^2 + \varepsilon^2}, \tag{1}$$

where N is the number of unresolved final channels, Γ is the coherence energy, and ε is the energy increase. By the Fourier transformation of energy self-correlation functions, the corresponding spectrum density functions [10] can be obtained

$$w(\alpha) = \frac{\pi}{N} \cdot \frac{\Gamma}{\Delta E} e^{-\frac{\Gamma}{\Delta E}\alpha}, \tag{2}$$

where $\alpha = m\pi / l$, l is the number of measured points in the excitation functions, $0 \leq m \leq l$, and ΔE is the energy step in which the excitation functions are measured. The $\ln w(\alpha)$ is a linear function of α and the coherence energy Γ can be extracted from the linear slope $\frac{\mathrm{d}}{\mathrm{d}\alpha} \ln w(\alpha) = -\frac{\Gamma}{\Delta E}$.

From the definition of energy self-correlation functions

$$C(\varepsilon) = \frac{\langle \sigma(E+\varepsilon) \cdot \sigma(E) \rangle^2}{\overline{\sigma(E)^2}} - 1, \tag{3}$$

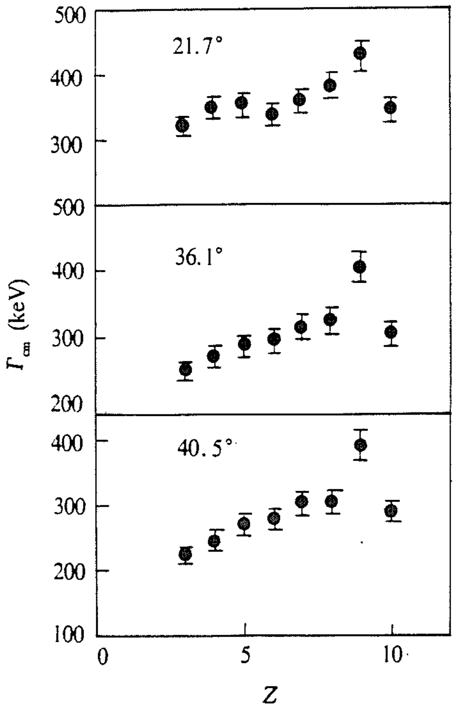

Fig. 2
Coherence energies versus atomic number at 21.7°, 38.1°, and 40.5°.

the experimental data of spectrum density functions are

$$w(\alpha) = \sum_k C(k\Delta E)\cos(k\alpha)\,, \tag{4}$$

where $\varepsilon = k\,\Delta\,E$. The coherence energy Γ can be obtained by using Eq.(2) to fit the data of Eq.(4). The error of Γ is mainly due to the finite range of data sample.

The SDM is employed to analyze the excitation functions in Fig. 1. Only one coherence energy is extracted for each element. The dependencies of coherence energy Γ on an ejectile's atomic number Z are presented in Fig. 2 at three angles. The coherence energy takes its maximum value while the charge number of the ejectiles is located at the projectile value and decreases as the difference between ejectile and projectile increases. A similar phenomenon was observed in previous experimental research. It can be normally interpreted as follows: The more nucleons that are transferred in a dissipative process and the greater the difference in the configuration from the initial system is formed, the more damping of the reaction is taking place towards equilibration and the more time is needed.

The coherence energies for different products presented in Fig. 2 also show their dependence on emission angles. The angular dependence for products far away from the projectile is much more obvious, while for products close to the projectile a relatively weak angular dependence is found. Generally, the coherence energies decrease as the emission angles increase. This feature can be attributed to the rotation of the dinuclear system.

For the macrorotation of the dinuclear system, the following estimation can be done. The orbital momentum of inertia can be written as

$$I_{\mathrm{rel}} = \mu\,(R_1 + R_2)^2, \tag{5}$$

Table 1

The extracted angular velocity for various ejectiles.

Ejectile	Li	Be	B	C	N	O	F	Ne
$\omega_{exp} \times 10^{21}\ s^{-1}$	0.53 ± 0.03	0.62 ± 0.04	0.85 ± 0.06	1.25 ± 0.08	1.31 ± 0.09	1.32 ± 0.09	3.97 ± 0.21	1.65 ± 0.09

where μ is the reduced mass of projectile and target, $R_i = r_0 A_i^{1/3}$ and $r_0 = 1.3$ fm. For $^{19}F + ^{51}V$ system, a value of $I_{rel} = 9.93 \times 10^{-42} MeV \cdot s^2$ is obtained. The average angular velocity is

$$\omega = \hbar L_{rel} / I_{rel} , \tag{6}$$

when the relative angular momentum L_{rel} is assumed equal to l_{gr}, the angular velocity is $\omega = 3.68 \times 10^{21}\ s^{-1}$ and the corresponding rotation period is $T = 1.71 \times 10^{-21}s$. If the difference of Γ, $\Delta\Gamma = \Gamma(\theta_2) - \Gamma(\theta_1)$, is caused by the time needed by the dinuclear system rotating at an angle of $\Delta\theta = \theta_2 - \theta_1$, the corresponding angular velocity can be estimated as

$$\omega_{exp} = \frac{\theta_2 - \theta_1}{\hbar\left[\dfrac{1}{\Gamma(\theta_2)} - \dfrac{1}{\Gamma(\theta_1)}\right]} . \tag{7}$$

When the intermediate dinuclear system is assumed to rotate with a fixed angular velocity ω_{exp}, the relation between $\Gamma(\theta)$ and emission angles θ is

$$\Gamma(\theta) = \left[\frac{\theta - \theta_0}{\hbar\omega} - \frac{1}{\Gamma(\theta_0)}\right]^{-1} . \tag{8}$$

According to Eqs.(7) and (8), a linear relationship between interaction time evaluated from coherence energies Γ and emission angles θ can be expected. The behavior of coherence energies with emission angles for ejectiles of $Z = 3\text{-}10$ is shown in Fig. 3(a). The trend of interaction time which is obtained through the uncertainty principle versus the emission angles θ_{cm} is depicted in Fig. 3(b), where θ_{cm} is the emission angle in the rest frame of center of mass (C.M). Under the assumption of binary reaction, which means to neglect the influence of light particle evaporation and sequential decay of the primary dissipative products, a channel-by-channel C.M. transformation of the damped region of the spectra in the lab system is performed. The mean emission angle is determined as a weighted average value of C.M. angles within the measured energy region for each exit product.

A linear least-squares fit is applied to the data and the results are shown in Fig. 3(b) as the solid lines. The deduced angular velocities for different products are listed in Table 1. The angular velocities present a strong damping character. When the ejectile is the same as the projectile, the extracted angular velocity is comparable with the calculated one from Eq.(6). The corresponding rotational period is $T = 1.58 \times 10^{-21}s$, which is very close to the mean lifetime of the dinuclear system. So the rotation causes very little variation of coherence energy for $Z = 9$ product. While for products close to the projectile, e.g., elements N, O, and Ne, some damping occurs in angular velocity and the rotational period is longer than the mean lifetime of the dinuclear system. The rotation of the dinuclear system may lead to the trend of Γ decrease with the increase of the emission angle. For the ejectiles far from the projectile, e.g., elements Li, Be, B, and C, strong damping of angular velocities is observed and the coherence energy Γ depends on the emission angle more strongly than in the previous two cases. The general trend is that the greater the difference the ejectile is from the projectile, the more nucleons are transferred, and the more damping of the angular velocity occurs. This trend

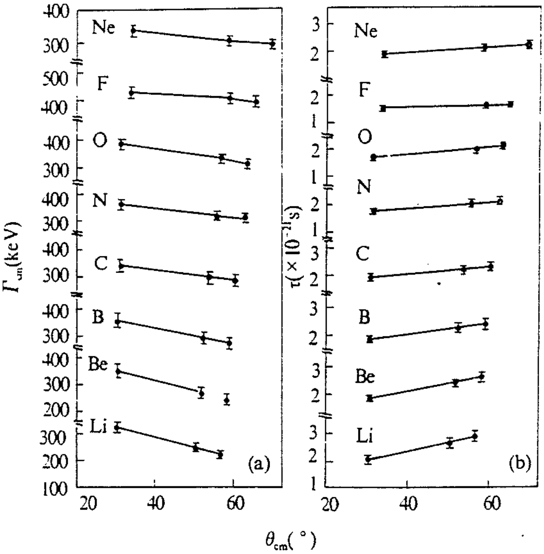

Fig. 3
Coherence energies (a) and reaction times (b) versus emission angles.

reflects the transition feature of the dissipative reaction which means the evolution from pre-equilibrium direct reaction to fully equilibrium compound nucleus formation. The damping of angular velocity is relevant to the relative kinematic energy dissipation. For the $^{19}F + ^{51}V$ system, the average reaction time is of the order of 2×10^{-21}s to 3×10^{-21}s. Within this time scale, the equilibration of some degrees of freedom is not attained and the dissipation of the rotational energy $E_{rot} = L_{rel}^2 / 2I_{rel}$ is undergone. According to the sticking model, the transferred angular momentum is $L_{rel} = L(1 - I_{int} / I_{tot})$, where $I_{tot} = I_{int} + I_{rel}$ and $I_{int} = \frac{2}{5} r_0 A_i^{\frac{5}{3}}$. From all configurations of the intermediate system, only 30% angular momentum is dissipated. The angular velocity damping is near to one order of magnitude. So the damping is mainly determined by the shape of the dinuclear system and is weakly relied on in the angular momentum dissipation. It should be noted that the coherence energy Γ carries the information not only on the mean level widths of the intermediate system but also on the rotation time of the dinuclear system. In order words, two time scales dominate the time evolution of the reaction process. One is the mean lifetime of decaying states of the dinuclear system and the other is the rotation time which is determined by the angular velocity ω; however, in the statistical compound nucleus reaction only the lifetime of levels plays such a role.

4. CONCLUSION

The fluctuations in the excitation functions, which are measured in the dissipative reaction of $^{19}F + ^{51}V$ around the energies $E \sim 2.5V_B$, are observed. The fluctuations present strong cross-correlation between different exit channels. The statistical method is applied to analyze the fluctuations and the coherence energies Γ are extracted. The coherence energies show pronounced differences with Z of ejectiles and dependence on emission angles due to the rotation of the dinuclear system. Under the assumption of a linear function between rotation times and emission angles, the angular velocity of the dinuclear system is obtained. The angular velocities have stronger damping as the difference between the ejectiles and the projectiles increases. This phenomenon is attributed to the rotational energy dissipation. The investigation of the dependence of coherence energy on emission angles makes it possible to obtain a deeper understanding of the reaction mechanism and to attain the information on the time evolution of the colliding system.

REFERENCES

[1] A. De Rosa, *et al.*, *Phys. Lett.*, **160** (1985): p. 239.
[2] A. Glaesner, *et al.*, *Phys. Lett.*, **169B** (1986): p. 153.
[3] T. Soumijarvei, *et al.*, *Phys. Rev.*, **C36** (1987): p. 181.
[4] G. Cardella, *et al.*, *Z. Phys.*, **336A** (1990): p. 387.
[5] G. Pappalardo, *Nucl. Phys.*, **A488** (1988): p. 395c.
[6] S. Yu Kun, W. Norenberg, and M. Papa, *Phys. Lett.*, **B298** (1993): p. 273.
[7] G. Pappalardo, *et al.*, *Perspectives in Heavy Ion Physics*, edited M. Di Toro and E. Migneco (SIF, Bologna, 1993).
[8] D.M. Brink and K. Dietrich, *Z. Phys.*, **326A** (1987): p. 7.
[9] Xu Hushan, *et al.*, *Chin. Jour. of Nucl. Phys.*, **17** (1995): p. 225.
[10] A. De Rosa, *et al.*, *Il Nuovo Cimento*, **68A** (1982): p. 205.