Cold rotation in the reaction $^{19}F+^{51}V$*

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Abstract Excitation functions of the dissipative products in the reaction $^{19}F+^{51}V$ have been measured from 102.25 to 109.50 MeV in a step of 250 keV at θ_l=21.7°. Nuclear temperature of the system is extracted and discussed by using a concept of cold rotation.

Keywords Nuclear temperature, Dissipative reactions, Excitation functions, Rotation levels

1 Introduction

Heavy ion deep inelastic collision (DIC), more generally termed as the dissipative reactions, is a reaction mechanism between the direct interaction and the compound nucleus formation. The interpretation about 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 and the orbital momentum are transformed into the intrinsic excitation energy and the intrinsic angular momentum of the system, respectively. The average properties of DIC, such as the relaxation process of energy, mass, charge and angular momentum, have been well studied for many years. In recent years some measurements of excitation functions of dissipative reactions have been performed and the cross section fluctuation in them has been found. The universality of the fluctuation in DIC has been confirmed for systems with lighter masses ($A_1 + A_2 \leq 100$).[1~3]

It is well known that the IDS formed in DIC carrys high excitation energy and the corresponding excited levels are overlapped. The Ericson theory[4], for the case of the strongly overlapped compound nuclear states, has been extensively applied to the analysis of the experimental fluctuation in DIC. In this way, the energy coherence width Γ can be extracted from the energy autocorrelation functions (EAF) of the reaction products, and then the average lifetime τ of the IDS can be obtained by using the uncertainty principle $\tau = \hbar/\Gamma$, which is essential for understanding the time evolution process of DIC. However, the IDS does not reach statistical equilibrium within its lifetime. As a consequence, by comparison between the experimental results and the prediction of the Ericson theory, it can be found that there exist lots of different behaviours. For example, Γ extracted from the experimental data depends on the emitting angle θ and the charge number Z of the reaction products while the Γ values keep constant in the frame of Ericson theory; the EAFs show a quasiperiodic oscillating feature in DIC instead of the Lorentzian shape in the overlapped compound nuclear states.

Several models[5,6] taking into account the angular momentum effect have been proposed to understand and reproduce the fluctuation phenomenon in DIC. Some average properties and fluctuation features in DIC can be explained reasonably by these models, such as the focusing angular distribution, the quasiperiodic structure in the EAF and the rotation as macroscopic quasimolecular states in IDS. Especially, it is quite noticeable that the rotation of the IDS plays a very important role in DIC process. This paper is devoted to study of the rotation of IDS in the dissipative reaction $^{19}F+^{51}V$.

2 Experimental

The measurement of excitation functions of the projectile-like fragments (PLF) in reaction $^{19}F+^{51}V$ has been performed at the HI-13 Tandem Accelerator National Laboratory, Beijing. The incident energies of the $^{19}F^{8+}$ beam

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were selected from 102.25 to 109.50 MeV in a step of 250 keV. A self-supporting ^{51}V foil of 70 $\mu g/cm^2$ was used as a target. The experimental setup and some previously results have been described in Refs.[7,8]. A detection system combining time-of-flight measurement (TOF) with $\Delta E - E$ technique was employed to identify the charge number Z and the mass number A of the PLF simultaneously.

3 Results and discussion

By the datum analysis, the mass resolution $A/\Delta A \approx 50$ and the charge resolution $Z/\Delta Z \approx 30$ for the system were obtained, respectively. The excitation functions of the PLF, corresponding to the elements C, N, O, F and their several isotopes, were extracted from the damped part of energy spectra. An obvious fluctuation behaviour characterizing the DIC process has been observed in all of the excitation functions. The dependence of Γ on the degrees of freedom A and neutron excess N/Z were discussed for the products in the dissipative reaction.

In this paper, some experimental results, the values Γ_{exp} and N_{eff} of the products C, N, O and F in dissipative reaction of $^{19}F + ^{51}V$ at $\theta_l = 21.7°$, are presented in columns 2 and 3 of Table 1. These values were obtained by using the EAF method developed by D. M. Brink and K. Dietric[5]:

$$C(\varepsilon) = \frac{< \sigma(E)\sigma(E+\varepsilon) >}{< \sigma(E) >^2} - 1 \qquad (1)$$

where ε is the energy interval between two steps and the brackets $< >$ stand for the arithmetic average over the measured energy range. By the approximation of a Lorentzian form, it can be got

$$C(\varepsilon) = \frac{1}{N_{eff}} \frac{\Gamma_{exp}^2}{\Gamma_{exp}^2 + \varepsilon^2} \qquad (2)$$

where $N_{eff} = 1/C(0)$ is the effective number of concerned energy levels of IDS leading to the final channel. Γ_{exp} was extracted at the half maximum of $C(0)$ in $C(\varepsilon)$ function. The errors stem from the finite size of the datum sampling.[9]

Based on the values of Γ_{exp} and N_{eff}, the important effect of the rotation in IDS will be discussed in the following by taking the concept of nuclear temperature. The so-called nuclear temperature is a scale to represent the various intrinsic excitation level densities of a nuclear system. In a simple form, the temperature T equals $(E^*/a)^{1/2}$, where E^* is the excitation energy of the system and the level density parameter $a = A/8$ is taken as usual, in which A is the mass number of the system.

For our experiment, the level densities ρ of the IDS can be estimated by the relation [10]

$$\Gamma_{exp} = \frac{N_{eff}}{2\pi\rho} \qquad (3)$$

then values of the excitation energy E^* and the system's nuclear temperature T_{exp} can be obtained according to the Fermi gas model formulated by A. Bohr and B. Mottelson [11]. The values of T_{exp} obtained for dissipative products C, N, O and F in reaction $^{19}F+^{51}V$ are listed in column 4 of Table 1.

Table 1 Some experimental results and the nuclear temperature values for elements C, N, O and F in dissipative reaction $^{19}F+^{51}V$ at θ_l=21.7°

elements	Γ_{exp}/keV	N_{eff}	T_{exp}/MeV	T_{the}/MeV	T_{fit}/MeV
C	311±62	193±39	1.55±0.16	2.21	1.54
N	302±60	159±32	1.40±0.14	2.34	1.40
O	354±70	178±35	1.29±0.13	2.16	1.27
F	394±78	60±12	1.10±0.11	2.24	1.12

Assuming that the PLF coming from the IDS were fully relaxed in our experiment, we have the excitation energy of the IDS, $E^* = E_{cm} + Q_{gg} - V_c$, where E_{cm}, Q_{gg} and V_c are the incident energy in the center-of-mass system, the Q value in the ground state and the Coulomb barrier of the IDS, respectively. The theoretical nuclear temperature values T_{the} for the present colliding system are also listed in column 5 of Table 1. There is a remarkable dif-

ference between the T_{exp} and the T_{the}. How to understand the difference? In fact, at the early stage of the DIC, the IDS is formed as a rotation system. The experimental analysis shows[6] that the rotation levels of the IDS as the macroscopic quasimolecular states will be preferably excited. The rotation energy is defined by the orbiting cluster model:[12]

$$E_{rot} = E_b + V_c + J(J+1)\hbar^2/2I \qquad (4)$$

where E_b is the binding energy, V_c the Coulomb energy and I the moment-of-inertia of the IDS. It is necessary to point out that the actual intrinsic excitation energies of the IDS should be the difference between the ground state molecular band defined by equation (4) and the excited one given by[13]:

$$L_{gr} = \left(\frac{E_{cm} - V_c}{E_R}\right)^{1/2} \qquad (5)$$

where $E_R = \hbar^2/2\mu R^2$, μ is the reduced mass and R the interaction radius.

In fact, for the dissipative reaction $^{19}F+^{51}V$, the actual intrinsic excitation energy obtained from Eqs.(4) and (5) is not so high as expected. A similar result is also observed in the reaction $^{28}Si+^{48}Ti$[3]. In our case, the nuclear temperature values T_{fit} to which these E^* correspond are listed in column 6 of Table 1. It is clear that the values of T_{exp} can be reproduced very well by T_{fit} for all of elements C, N, O and F.

4 Conclusion

In summary, the IDS is formed in the DIC. The relative kinematic energy is transformed into excitation energy of the IDS within its lifetime. IDS carries high excitation energy which consists of two parts, the rotation energy and the intrinsic one. In our case, the former is considered to be much larger than the latter. Therefore, the actual intrinsic excitation energy of the IDS is low, that is to say, the IDS is in a cold rotation state and its state density is not high. This is the reason why the fluctuation structure in DIC cross section is still visible.

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