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IMPROTANCE OF TRANSFER CHANNELS IN SUB-BARRIER FUSION REACTIONS

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Abstract

The role of neutron transfer is investigated in the heavy-ion fusion reactions of ^{40}Ca+^{48}Ca and ^{40}Ca+^{124}Sn systems by using coupled-channel method. The calculated fusion cross sections and barrier distributions are compared with the experimental data. The calculations are performed with the inclusion of vibrational coupling for target nuclei in both systems. The calculated fusion cross sections with channel couplings give better agreement compare with no-coupling calculations. But extracted barrier distributions still deviate from the experimental data. The Q-values of two neutrons transfer reactions ^{48}Ca (^{40}Ca, ^{42}Ca) ^{46}Ca and ^{124}Sn (^{40}Ca, ^{42}Ca) ^{122}Sn show 2.621 MeV and 5.410 MeV, respectively. The inclusion of neutron transfer channel in the calculations reproduces the experimental fusion cross sections and barrier distributions.

Keywords: Heavy-ion fusion reactions, Coupled-channel method, Neutron transfer

Introduction

The process in which two colliding nuclei come close together to form a compound nucleus either by overcoming or by quantum tunneling through the potential barrier is known as nuclear fusion reaction. The simplest theoretical way to understand the fusion of the two nuclei is the one dimensional (1D) potential model, wherein the projectile is assumed to penetrate through potential barrier between two interacting nuclei and form a composite nucleus. However, at energies below the Coulomb barrier, the extensive experimental as well as theoretical studies have revealed that there is an anomalously large enhancement in the fusion cross section over the predictions of (1D) barrier penetration model. It indicates that the fusion of two nuclei is a complex rearrangement process which involves a large number of the degrees of freedom and a strong coupling between the projectile-target relative motion and the internal degrees of freedoms. As a result fusion reactions have become the most studied processes to explore the importance of structural as well as dynamical effects in the compound nuclear reactions.

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Moreover, the importance of neutron transfer in increasing the sub-barrier fusion probabilities was also established. The coupling to a transfer degree of freedom is in general weaker than couplings to collective excitations.

However, when the coupling is sufficiently large, e.g., for a transfer channel with a positive Q-value it expected that the transfer coupling leads to an extra enhancement of fusion cross sections below the Coulomb barrier. It has been known well that two-neutron transfer reactions provide a unique tool to study the pair correlation between nucleons. The effects of collective surface vibrations on fusion were also considered in a semi classical picture, again resulting in a distribution of fusion barriers. The experimental measurements of the fusion barrier distribution (BD) represent a new stage in the study of heavy-ion fusion. The fusion BD analysis is valuable tool to understand the fusion mechanism of two heavy nuclei and the role of their internal degrees of freedom leading to fusion. The fusion BD has been shown to be sensitive to the data related to the nuclear structure, such as the nuclear shapes, the multiple excitations, and the anharmonicity of nuclear surface vibrations etc. For this purpose, high precision measurements of the fusion cross-section data are required and have been reported for many systems.

The aim of the present work is to investigate the importance of neutron transfer channels on the calculations of the fusion cross section and the fusion barrier distribution for the systems $^{40}Ca+^{48}Ca$ and $^{40}Ca+^{124}Sn$.

Theoretical framework

Coupled-channels method

The effect of the nuclear structure can be taken into account in a more quantal way using the coupled-channels method. In this method, consider a collision between two nuclei in the presence of the coupling of the relative motion between the center of mass of the colliding nuclei, $\vec{\mathbf{r}} = (r, \hat{\mathbf{r}})$ to a nuclear intrinsic motion ξ. The total Schrödinger equation can be transformed to a set of coupled equations

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{d\,r^2} + V_0(r) - E \right] u_n(r) + \sum_m V_{n,m}(r)\, u_m(r) = 0 \qquad (1)$$

where,

$$V_{n,m}(r) = \varepsilon_n \, \delta_{n,m} + \int d\xi \, \varphi_n^*(\xi) \, V_{coup}(r,\xi) \, \varphi_m(\xi) \tag{2}$$

is the coupling matrix elements. These equations are called the coupled-channels equations and are solved by imposing the boundary conditions

$$u_n(r) \to e^{-ik_n r} \, \delta_{n,0} + R_n \, e^{ik_n r} \qquad r \to \infty, \tag{3}$$

$$\to T_n \, e^{-ik_n r} \qquad r \to -\infty, \tag{4}$$

where $k_n = \sqrt{2\mu(E - \varepsilon_n)/\hbar^2}$ is the wave number of the n-th channel and we have assumed that the intrinsic motion is in the ground state (n = 0) before the collision. T_n is interpreted as the transmission coefficient, the penetrability through the Coulomb barrier is given by

$$P(E) = \sum_n \frac{k_n}{k_0} \left| T_n \right|^2. \tag{5}$$

Then, the fusion cross section is given by

$$\sigma_{fus}(E) = \frac{\pi}{k^2} \sum_J (2J+1) P^J(E). \tag{6}$$

Pair-transfer coupling

For the two-particle transfer couplings, the macroscopic form factor for the transfer between the ground states is usually used

$$F_{trans}(r) = F_{tr} \, \frac{dV_N(r)}{dr} \tag{7}$$

where F_{tr} is the coupling strength parameter and $V_N(r)$ is the nuclear potential for the system.

Fusion barrier distribution

The first derivative of the product of fusion cross section σ and the centre of mass energy E with respect to the energy $d(E\sigma)/dE,$ is proportional to the penetrability of the s-wave scattering

$$\frac{d(E\sigma)}{dE} = \frac{\pi r_B^2}{1+\exp[-\frac{2\pi}{\hbar\Omega}(E-V_B)]} = \pi R_B^2 P_0(E). \qquad (8)$$

This equation immediately leads to a relation between the first derivative of the penetrability and the fusion cross section

$$\frac{d^2(E\sigma)}{dE^2} = \pi r_B^2 \frac{2\pi}{\hbar\Omega} \frac{e^{2\pi(E-V_B)/\hbar\Omega}}{\left(1+e^{2\pi(E-V_B)/\hbar\Omega}\right)^2} = \pi R_B^2 \frac{dP_0(E)}{dE}. \quad (9)$$

This quantity, which is conventionally called fusion barrier distribution, is peaked at the height of the Coulomb barrier for the *s*-wave scattering.

Results and Discussion

^{40}Ca+^{48}Ca System

The coupled-channels calculation of fusion cross section as well as fusion barrier distribution for heavy-ion fusion reaction of ^{40}Ca+^{48}Ca system by including the 3^- (octupole) state of ^{40}Ca, [P:(3^-)] and the 2^+ (quadrupole) and 3^- (octupole) states of ^{48}Ca, [T:(2^+) (3^-)].

The results of coupled-channels calculations performed by using the CCFULL code are compared with the experimental data in Fig (1.a) and (1.b). The left panel is the fusion cross section and the right panel is the fusion barrier distribution. The dashed line represents the calculations of without including the coupling effects, i.e., the target and the projectile are assumed to be inert in which the calculations of the fusion cross section fail to reproduce the experimental data at and below the Coulomb barrier. The calculations including the coupling effects without neutron transfer channel [P:(3^-) ; T:(2^+) $(3^-)^3$] is shown by dotted line which underestimated the experimental data.

The solid line represents the coupling effects with neutron transfer channel [P:(3^-); T:(2^+) (3^-)^3 + 2n], where the calculated fusion cross section agrees with the experimental data. We can see in this figure, the calculations with neutron transfer channel coupling reproduce the experimental data for the fusion cross section as well as the fusion barrier distribution. The Woods-Saxon parameters are taken to be V_0 = 68.05 MeV, r_0 = 1.16 fm, and a_0 = 0.66 fm. The Q-value of the neutron pick-up channel of the 2n-transfer reaction ^{48}Ca (^{40}Ca, ^{42}Ca) ^{46}Ca is 2.621 MeV. The low-lying excitations energies and the deformation parameters are E_3 = 3.737 MeV, and $\beta_3 = 0.411$ for ^{40}Ca and, E_2 = 3.831 MeV, E_3 = 4.506 MeV, $\beta_2 = 0.10$, and $\beta_3 = 0.18$ for ^{48}Ca.

^{40}Ca+^{124}Sn System

The calculations of the fusion cross section and fusion barrier distribution are presented in Fig (2.a), and (2.b). For ^{40}Ca+^{124}Sn case, the coupling to the 3^- state of ^{40}Ca, [P:(3^-)] and the 2^+ and 3^- states of ^{124}Sn, [T:(2^+) (3^-)] were included. The dashed line in Fig (2.a) and (2.b) represents the calculations without including the coupling, i.e., both projectile and target are inert. The coupling without neutron transfer and with neutron transfer channels are defined by dotted and solid lines. The results of fusion cross section which include the coupling with neutron transfer channel agree well with the experimental fusion cross section, and the corresponding fusion barrier distributions reproduce the experimental barrier distribution than those of without neutron transfer channel. The Q-value of the 2n-transfer reaction ^{124}Sn (^{40}Ca, ^{42}Ca) ^{122}Sn is 5.410 MeV. The Woods-Saxon parameters are taken to be V_0 = 98.05 MeV, r_0 = 1.2 fm, and a_0 = 0.66 fm. The low-lying excitations energies and the deformation parameters are E_3 = 3.737 MeV, and $\beta_3 = 0.411$ for ^{40}Ca and E_2 = 1.132 MeV, E_3 = 2.603 MeV, $\beta_2 = 0.096$, and $\beta_3 = 0.106$ for ^{124}Sn.

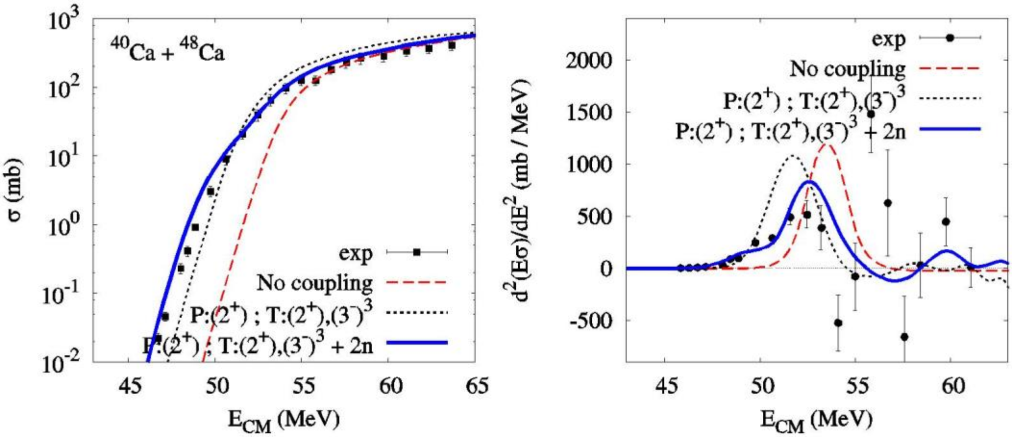

Figure1: The results of the coupled-channels calculations for ^{40}Ca+^{48}Ca system for the fusion cross section (left panel) and the corresponding fusion barrier distribution (right panel), respectively. The experimental data are taken form.

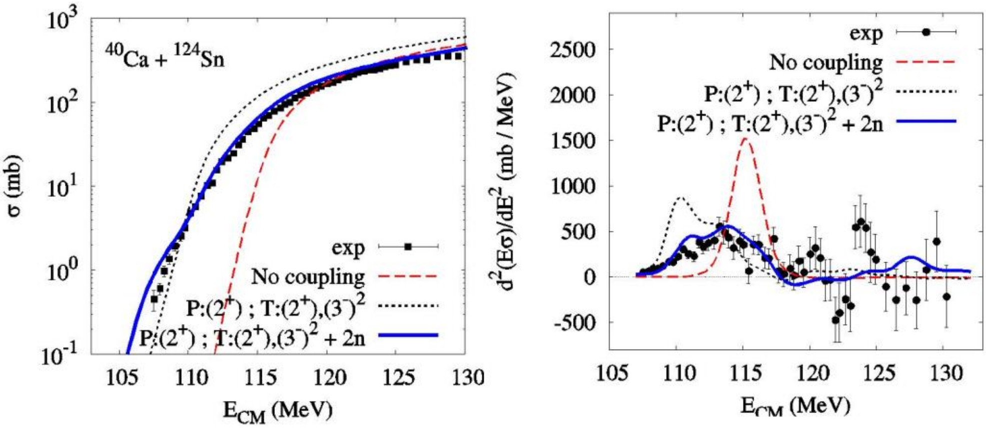

Figure 2: The results of the coupled-channels calculations for ^{40}Ca+^{124}Sn system for the fusion cross section (left panel) and the corresponding fusion barrier distribution (right panel), respectively. The experimental data are taken from.

Conclusion

The importance of transfer channels are investigated for the systems $^{40}Ca+^{48}Ca$ and $^{40}Ca+^{124}Sn$. It can be concluded that coupling of the low lying states with neutron transfer channels in ^{48}Ca and ^{124}Sn target nuclei are very essential and leads to enhance the fusion cross section calculations and also leads to reasonable agreement with the experimental fusion barrier distributions. Furthermore, the enhancement of fusion cross sections can be observed at low energies below the Coulomb barrier due to the positive Q-value neutron transfer effect. Therefore, the two nucleon transfer enhancement of sub-barrier fusion reactions is very important for these two cases.

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