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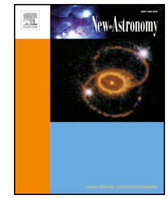

Fusion cross sections for nucleonic-halo systems in solar systems

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A B S T R A C T

The behavior of total fusion cross sections for proton and neutron-halo systems at near and sub-barrier energies have been studied using coupled-channel calculations. We have done the fusion distribution by considering phonon excitations and rotational deformation. Comparing with available experimental data represents a good agreement for neutron halo systems. A comparison between the reduced fusion cross sections of these systems shows different behavior in sub-barrier energies.

1. Introduction

In recent years, the cross sections of fusion reactions at sub-barrier energies have been investigated (Dasgupta et al., 1998). Experimental data along with theoretical studies have demonstrated that coupling of the relative motions of the reaction nuclei to several nuclear intrinsic motions effects intensively on the fusion reactions at some energy around the coulomb barrier (Beckerman, 1988). Sub-barrier fusion reaction of heavy ion is a phenomenon which shows quantum tunneling despite nuclear physics' coupling (Hagino et al., 1999). Recently, some investigations of nuclear interactions on exotic neutron-halo nuclei have been done both experimentally and theoretically (Canto et al., 2006; Keeley et al., 2009 2007). Researches on neutron-rich light projectile nuclei in fusion process has been done lately (Di Pietro et al., 2004; Kolata et al., 1998; Lemasson et al., 2009; Raabe et al., 2004; Scuderi et al., 2011; Signorini et al., 2004; Yoshida et al., 1996) nevertheless, studies on proton rich nuclei in fusion process are scarce. Already, only one fusion measurement at sub-barrier energies on ^{8}B + ^{58}Ni was reported (Aguilera and Kolata, 2012). Many studies in nuclear astrophysics have explored the structure of ^{8}B due to the fact that in the sun ^{8}B is thought to be produce via the reaction ^{7}Be (p,γ) ^{8}B. The subsequent β decay of this ^{8}B gives a spectrum of neutrinos. The only direct probe of the condition at the heart of the sun is provided by these neutrinos (Filippone et al., 1983a,b). ^{8}B has only one bound state and just a small one-proton separation energy, Sp = 137 keV (Motobayashi, 2001). ^{15}C is a neutron halo nucleus with one-neutron separation energy (1.218 MeV), and is next to the closed-neutron shell ^{14}C which is a spherical projectile (Alcorta et al., 2011). So it is interesting to study the behavior of proton and neutron halo nuclei in fusion reactions. the aim of this work is to study the behavior of the fusion cross sections of three halo systems (^{8}B + (^{28}Si, ^{58}Ni), ^{15}C + ^{232}Th) by using coupled channel calculations, and to show that whether charge of the halo will influence on the fusion cross section or not.

2. Fusion cross section and fusion barrier distribution

For heavy ion fusion reactions, a useful approximation is isocentrifugal approximation, which one can use the total angular momentum J instead of the relative motion angular momentum of the channel (Hagino et al., 1995; Lindsay and Rowley, 1984). The coupled-channel equations are given by (Hagino et al., 1999):

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{J(J+1)\hbar^2}{2\mu r^2}+V_{\mathrm{N}}^{(0)}(r)+\frac{Z_P Z_T e^2}{r}-E+\varepsilon_n\right]\varphi_n(r) + \sum_m V_{nm}(r)\varphi_m(r)=0 \tag{1}$$

where r is the radial component of the relative motion, μ is the reduced mass, E and ε_n are the center of mass incident energy and the n'th channel excitation energy, respectively. V_{nm} is the Coulomb and nuclear matrix component of the coupling Hamiltonian. $V_{\mathrm{N}}{}^{(0)}$ is the Woods–Saxon nuclear potential in the entrance channel, the Hamiltonian of nuclear coupling is defined as follows:

$$V_{\mathrm{N}}(r,\hat{\mathrm{O}}) = -\frac{V_0}{1+\exp\left(\frac{r-R_0-\hat{\mathrm{O}}}{a}\right)} \tag{2}$$

where $\hat{\mathrm{O}}$ is a rotational (vibrational) coupling operator, for example in a rotational mode of target nucleus:

$$\hat{O} = \beta_2 R_{\mathrm{T}} Y_{20} + \beta_4 R_{\mathrm{T}} Y_{40} \tag{3}$$

where β_2 and β_4 are deformation parameters (quadrapole and hexadecapole), and R_{T} is define as $r_{\mathrm{coup}}A_{\mathrm{T}}^{1/3}$, in which A_{T} is the target mass

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number. In a vibrational mode of target nucleus we have:

$$\widehat{O} = \frac{\beta_\lambda}{\sqrt{4\pi}} R_T (a_{\lambda 0}^{\dagger} + a_{\lambda 0}). \tag{4}$$

In the vibrational coupling, λ is the multipolarity of vibrational mode and also $a_{\lambda 0}$ and $a_{\lambda 0}^{\dagger}$ are the annihilation and creation operators of the phonon, respectively. Then we should get matrix elements of coupling Hamiltonian between phonon states (vibrational mode) (Kermode and Rowley, 1993). The CCFULL code (Hagino et al., 1999) calculates the eigenvalues and eigenvectors of this operator and evaluates the nuclear matrix elements of coupling Hamiltonian by diagonalising the matrix $\widehat{O}$, then we can obtain the fusion cross section of compound nucleus by:

$$\sigma_{fus}(E) = \frac{\pi}{k^2} \sum_J (2J+1) P_J(E) \tag{5}$$

where

$$P_J(E) = \sum_n |T_n^J|^2 \tag{6}$$

In the above equation T_n^J is the transmission coefficient that is attained by considering proper boundary conditions.

It should be noted that the role of collective modes on fusion barrier distributions has well been recognized and Fusion barrier distribution is defined by using a simple point difference method at energy $(E_1 + 2E_2 + E_3)/4$ as follows (Leigh et al., 1995):

$$\frac{d^2(E\sigma_{fus})}{dE^2} = 2\left(\frac{(E\sigma_{fus})_3 - (E\sigma_{fus})_2}{E_3 - E_2} - \frac{(E\sigma_{fus})_2 - (E\sigma_{fus})_1}{E_2 - E_1}\right)\left(\frac{1}{E_3 - E_1}\right) \tag{7}$$

The second derivative statistical error in case energy increments are equal, is given by:

$$\delta_c \approx \frac{E_n}{(\Delta E)^2} \sqrt{(\delta\sigma_{fus})_1^2 + 4(\delta\sigma_{fus})_2^2 + (\delta\sigma_{fus})_3^2} \tag{8}$$

where $(E\sigma_{fus})_i$ are figured out at energies E_i, and $(\delta\sigma_{fus})_i$ are the cross section errors.

A meaningful approach to compare fusion cross section for different systems is composed of reducing the cross section and the energy. In this method the barrier parameters (V_b,R_b,$\hbar\omega$) are extracted from a realistic bare potential, then reduced cross section and energy are characterized by these parameters (Canto et al., 2009a,b; Gasques et al., 2004; Prasad et al., 1996). Universal fusion function (UFF) is derived from the cross section analytic expression $\sigma^w(E)$ (Wong, 1973).

$$\sigma_{Red}^w(E_{Red}) = \frac{2E}{\hbar\omega R_b^2}\sigma^w(E) = Ln[1 + \exp(2\pi E_{Red})] \tag{9}$$

3. Results and discussion

In this section coupled reaction channels calculations are availed by using the CCFULL code to get fusion cross section for the systems ^{8}B + (^{28}Si,^{58}Ni), ^{15}C + ^{232}Th, as well as the fusion barrier distribution for the ^{15}C + ^{232}Th . ^{15}C and ^{8}B projectiles are assumed to have no vibrational mode (inert) and the low-ling states in the target nuclei are collective states. Although the target nuclei are considered to be inert at first, and their fusion cross sections are calculated, then their multiple excitations were added to calculations. For the system ^{15}C + ^{232}Th, the target nucleus has coupling 3^- of low lying vibrational states with deformation parameter $\beta = 0.085$, and rotational deformation parameters $\beta_2 = 0.205$ and $\beta_4 = 0.103$. For ^{8}B + ^{28}Si reaction, vibrational and rotational parameters are $\beta = 0.401$, $\beta_2 = -0.363$, $\beta_4 = 0.187$ respectively. The system ^{8}B + ^{58}Ni is a little different, there is no rotational coupling and its vibrational parameter for 2^+ low lying states is $\beta = 0.1768$ (http://nrv.jinr.ru/nrv/).The Woods-Saxon parameters which obtained by A–W potential parametrization, are given in Table 1 (http://nrv.jinr.ru/nrv/). The results of these calculations for ^{15}C + ^{232}Th reaction have been shown in Fig. 1. This Fig. presents the effect of coupled channels calculations in sub-barrier energies, since the barrier height V_b of ^{15}C + ^{232}Th reaction is 61.48 MeV (Hagino et al., 1999), the rotational coupling of ^{232}Th, affects the fusion cross section at sub-barrier energies (below 61.48 in Fig. 1) and enhances the fusion cross sections and this enhancement is sensitive to the deformation parameter.

Comparing with experimental data one can find out that coupled channel calculations for energies beyond the coulomb barrier are not so important because in sub-barrier energies the coulomb barrier heights is distributed and the quantum tunneling is more probable, and this is a direct result of collective surface modes in heavy nuclei. In Fig. 2 the barrier distribution with coupling calculations of ^{15}C + ^{232}Th reaction

Table 1
Wood–Saxon parameters used in the calculations for ^{15}C + ^{232}Th, ^{8}B + ^{28}Si and ^{8}B + ^{58}Ni reactions (http://nrv.jinr.ru/nrv/).

Reactions	V_0(MeV)	a_0(fm)	r_0(fm)
^{15}C + ^{232}Th	59.359	0.657	1.179
^{8}B + ^{28}Si	39.693	0.594	1.164
^{8}B + ^{58}Ni	45.314	0.610	1.169

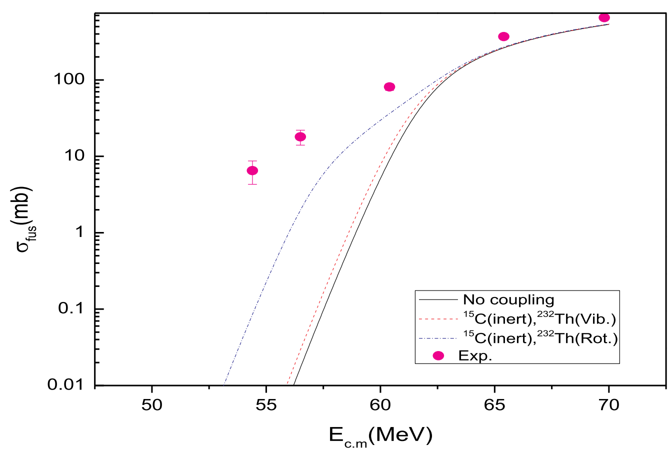

Fig. 1. Fusion cross section for the ^{15}C + ^{232}Th system as a function of center of mass energy. The solid line shows the bare (no- coupling) calculation, the dash line including vibrational coupling, the dash-dot line including rotational coupling and the circle symbols show experimental data on Ref. Alcorta et al. (2011).

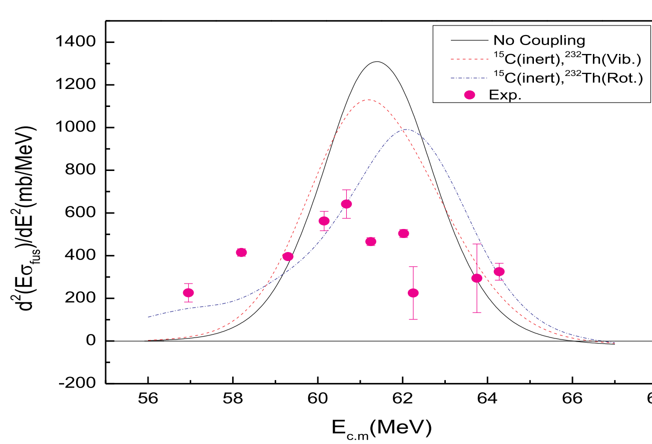

Fig. 2. fusion barrier distribution for ^{15}C + ^{232}Th reaction as a function of center of mass energy. The solid line shows the bare (no-coupling) calculation, the dash line includes vibrational coupling, the dash-dot line includes rotational coupling and the circle symbols show experimental data that calculated based on Ref. Alcorta et al. (2011) for energy and cross section data.