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Study of fusion of ^{8}B + ^{58}Ni System in near Barrier Energy Region

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Abstract. We have studied the fusion of ^{8}B with ^{58}Ni in the energy region around the barrier within the framework of quantum diffusion approach. The data are explained reasonably well except in the sub barrier region where the predictions overestimate the data. Further work is needed to remove the discrepancy in the sub barrier energy region.

1 Introduction

The availability of Radioactive Ion Beam (RIB) has made it possible to study the dynamics of reactions induced by weakly bound nuclei lying in the close proximity of drip lines [1-3]. Among the various possible reaction channels, the fusion of weakly bound nuclei is of utmost importance in conjunction with the process of nucleosynthesis and energy production in stars [2-3]. Owing to very low binding energy and the existence of an extended halo structure among some of these weakly bound nuclei, the fusion involving these nuclei differs fundamentally from those involving well bound stable nuclei [4-7]. The halo structure that is a large spatial extension leads to a reduction in Coulomb barrier and hence enhancements in fusion cross section in sub barrier energy region. Further because of very low binding energy the probability of breakup of a halo nucleus into its constituent fragments increases substantially and the dynamical effects arising due to coupling to breakup channel are quite important. Recent studies on fusion of neutron halo nuclei have show that there is a suppression of fusion cross section at energies above the barrier and enhancement at energies below the barrier, which indicates that static effect dominate over dynamical effects at energies below the barrier and vice-versa [8-11]. However, the proton halo structure due to the presence of Coulomb interaction between the valance proton and the remaining core is more complex than its neutron counterpart. Thus, it is quite tempting to investigate the static and dynamic effects on the fusion of proton halo nuclei. In the present work we have studied the fusion of one proton halo nucleus ^{8}B with ^{58}Ni in near barrier energy region by quantum diffusion approach. Very recently Aguilera *et al.* [12] have measured the fusion cross section of ^{8}B, ground state proton halo nucleus, on ^{58}Ni target at energies above and below the Coulomb barrier and analyzed the data using Wong formula with barrier height, radius and curvature as free parameters. Subsequently J. Rangel et al [13] analyzed these data through reliable calculation without any free parameters and found that experimental fusion cross section for ^{8}B + ^{58}Ni system could not be explained correctly. In the present work we have analyzed the fusion excitation function data of ^{8}B + ^{58}Ni system in near barrier energy region by quantum diffusion approach.

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2 Theoretical Formalism

The quantum diffusion approach is based on the quantum master equation for the reduced density matrix and model the coupling with various channels through the fluctuation and dissipation effects in collisions of heavy ions [14-17]. Within this approach, the collision of nuclei is treated in terms of two collective variables the relative distance R between the colliding nuclei and the canonically conjugate momentum P [16-19].The capture cross-section, the sum of partial cross section over possible values of angular momentum at a given centre of mass incident energy $E_{c.m.}$ for the formation of dinuclear system is written as

$$\sigma_c(E_{c.m.}) = \sum_L \sigma_c(E_{c.m.}, L) = \pi\lambdabar^2 \sum_L (2L+1) P_{cap}(E_{c.m}, L) \quad (1)$$

with $\lambdabar^2 = \hbar^2 / 2\mu E_{c.m}$ is the reduced de Broglie wavelength.

The partial capture probability P_{cap} which is defined as the passing probability of the potential barrier in the relative distance R between the colliding nuclei at a given L, is obtained by integrating an appropriate propagator from initial state at t = 0 to the final state at time t that is through the following expression

$$P_{cap} = \lim_{t\to\infty} \int_{-\infty}^{r_{in}} dR \int_{-\infty}^{\infty} dP\, G\left(R, P, t \middle| R_0, P_0, 0\right)$$

When the nucleus-nucleus potential V is approximated by an inverted parabola, the propagator G is Gaussian and is given by Ref. [20]

$$G = \frac{1}{\pi}\left|\det \Sigma^{-1}\right|^{1/2} \exp\left(-q^T \Sigma^{-1} q\right) \tag{2}$$

with $q_R(t) = R - \overline{R(t)}, q_P(t) = P - \overline{P(t)}$,

$\overline{R(t=0)} = R_0, \overline{P(t=0)} = P_0$,

$\sum_{ij}(t) = 2\overline{q_i(t) q_j(t)}$,

$\sum_{ij}(t=0) = 0$, and $i, j = R, P$

Use of some simple matrix algebra and the standard integration $erfc(z) = \frac{2}{\pi}\int_z^{\infty} e^{-t^2} dt$ leads to the following simple expression for partial capture probability

$$P_{cap} = \lim_{t\to\infty} \frac{1}{2} erfc\left[\frac{-r_{in} + \overline{R(t)}}{\sqrt{\Sigma_{RR}(t)}}\right] \tag{3}$$

If the coupling between the collective and internal subsystem is linear in momentum then the quantities first moment, $\overline{R(t)}$, and the variance, $\Sigma_{RR}(t)$ in the co-ordinate acquires the following expressions

$$\overline{R(t)} = A_t R_0 + B_t P_0$$

$$\Sigma_{RR}(t) = \frac{2\hbar^2 \tilde{\lambda} \gamma^2}{\pi} \int_0^t d\tau' B_{\tau'} \int_0^t d\tau'' B_{\tau''} \int_0^{\infty} d\Omega \frac{\Omega}{\Omega^2 + \gamma^2} \times \coth\left[\frac{\hbar\Omega}{2T}\right] \cos\left[\Omega(\tau' - \tau'')\right] \tag{4}$$

With

$$B_t = \frac{1}{\mu}\sum_{i=1}^{3} \beta_i (s_i + \gamma) e^{s_i t}$$

$$A_t = \sum_{i=1}^{3} \beta_i \left[s_i(s_i + \gamma) + \hbar\tilde{\lambda}\gamma/\mu\right] e^{s_i t}$$

Above $\beta_i = \left[(s_i - s_j)(s_i - s_k)\right]^{-1}, \quad i, j, k = 1,2,3$ and $i \neq j \neq k$ and s_i are the real roots of

$$(s + \gamma)(s^2 - \omega_0^2) + \hbar\tilde{\lambda}\gamma s/\mu = 0 \tag{5}$$

where γ, ω_0 and $\tilde{\lambda}$ are the internal excitation width, renormalized frequency and parameter related to the strength of linear coupling.

Combining equations (3) and (4) one obtains

$$P_{cap} = \frac{1}{2} erfc\left[\left(\frac{s_1(\gamma - s_1)}{2\hbar\tilde{\lambda}\gamma}\right)^{1/2} \times \frac{\mu\omega_0^2 R_0/s_1 + P_0}{\left[\frac{s_1\gamma}{\pi(s_1+\gamma)}\left(\psi\left(1 + \frac{\gamma}{2\pi T}\right) - \psi\left(\frac{s_1}{2\pi T}\right)\right) - T\right]^{1/2}}\right] \tag{6}$$

Where $\psi(z)$ is the digamma function.

For sub barrier fusion using equation (4) we have

$$P_{cap} = \frac{1}{2} erfc\left[\left(\frac{\pi s_1(\gamma - s_1)}{2\mu\hbar(\omega_0^2 - s_1^2)}\right)^{1/2} \frac{\mu\omega_0^2 R_0/s_1 + P_0}{\left[\gamma \ln(\gamma/s_1)\right]^{1/2}}\right] \tag{7}$$

For further details of the model see Ref. [14]. In the present work we have used this expression for calculating P_{cap} and hence the fusion excitationfunction for the system considered. Theparameter R_0 is very crucial and strongly depends on the separation of the region of pure Coulomb interaction and that of Coulomb nuclear interference, we here propose a very simple expression for its determination which takes into account the spatial extension of the nucleus through R_{int}. If the value of r_{ex}, the position of external turning point, is larger than the interaction radius R_{int}, we take $R_0 = R_{\text{int}}(\exp(-(E_{c.m.} - E_{\text{int}})/V_b))$ and $P_0 = 0$ while for $r_{ex} < R_{\text{int}}$ we take $R_0 = R_{\text{int}}$ and P_0 is equal to the kinetic energy at that point. The quantity E_{int} corresponds to the incident energy for which the r_{ex} and R_{int} coincides.

3 Results and Discussions

Besides the parameters related to nucleus-nucleus, friction co-efficient and internal excitation width the average value of R_0 at t=0 is an important input parameter needed for the calculation. It is quite intuitive that the quantity R_0 strongly depends on the incident energy. In fig.1, the variation of R_0 with the incident energy is shown. The R_0 decreases with the increasing energy as the two nuclei come more and more close to each other at high energies. The interaction radius R_{int} is considered here as the upper limit for the value of relative separation at t=0. Since for events with R_0 larger than R_{int} the two nuclei do not interact with each other and hence fusion does not occur.

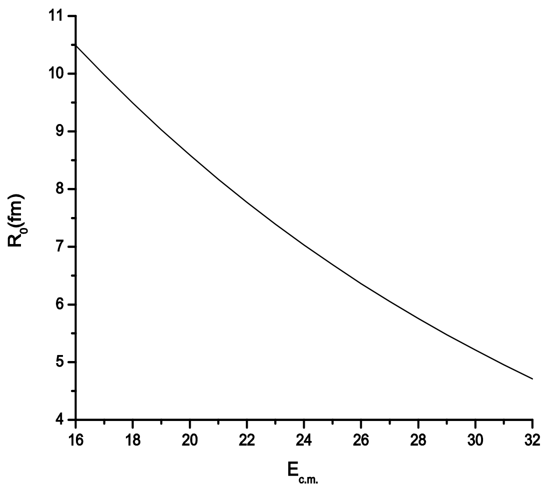

Figure 1. The average separation at t = 0 (R_0) between the colliding nuclei is plotted as a function of incident beam energy ($E_{c.m.}$)

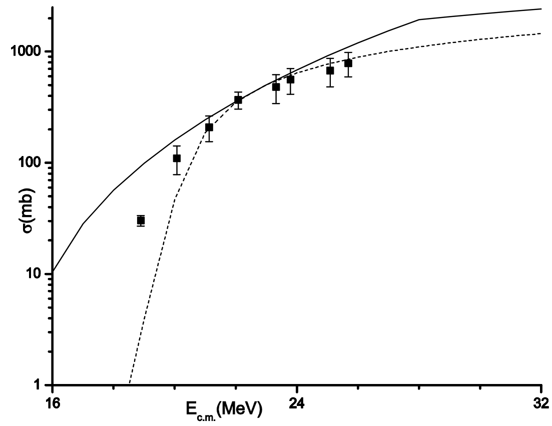

Figure 2. The fusion excitation function of $^8B+^{58}Ni$ system calculated by quantum diffusion approach (solid line) and by Wong formula (dotted line) is compared with the experimental data (solid square) taken from Ref. [21].

Using this energy variation of R_0 we have calculated the fusion excitation function of ^8B +^{58}Ni system in the near barrier energy region and have compared with the corresponding data taken from Ref.[21]. The comparison is shown in Fig.2, wherein the results of calculation made by Wong formula using 20.8 MeV, 9.2 fm and 4.0 MeV as barrier height, radius and curvature respectively are also included [22]. It may be clearly observed from this figure that in the sub barrier energy region, the predictions of quantum diffusion approach overestimate the measured fusion cross section while that of Wong formula underestimate it. In the above barrier energy region the data and the result of quantum diffusion approach and of Wong formula are almost similar since at energies higher than the barrier energy the channel coupling effects are negligibly small. However slight overestimation of data points by quantum diffusion approach may be removed by using more realistic model parameters. In order to understand the discrepancy between data and predictions of quantum diffusion approach in the sub barrier region, the effects of halo structure and of high probability of breakup on various parameters involved in the approach are needed to be properly incorporated.

4 Summary

The quantum diffusion approach is applied to study the capture cross section of weakly bound one proton halo nucleus ^8B by ^{58}Ni. A reasonable agreement between experimental data and theoretical predictions except in sub-barrier energy region is found. The discrepancy between the data and predictions in sub barrier energy region needs further investigation.

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