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Asymmetric barrier model for heavy ion fusion and its relation to channel coupling

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Abstract. A new asymmetric parabolic effective fusion barrier model for heavy ion fusion is developed.

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1. Introduction

One expects that coupling effects in the mechanism of heavy ion (HI) fusion may dramatically change the shape of the barrier particularly in the region r interior to the Coulomb barrier position $R_{\rm B}$ such that there is a sharp fall of the potential in the interior region which results in an asymmetric barrier. Based on the exact transmission coefficient across an asymmetric parabolic barrier derived by Zafar Ahmed [1] and the ideas used earlier in our effective fusion barrier transmission model [2] we develop a new asymmetric parabolic effective fusion barrier model for heavy ion fusion. The expected change of shape of the barrier is represented by a variable curvature parameter ω_2 whereas the outer curvature ω_1 is kept unchanged.

2. Formulation

We explicitly use an asymmetric parabolic type barrier given by the potential

$$V(x) = \left(V_1 - \frac{1}{2}\mu\omega_1^2 x^2\right)\theta(x) + \left(V_2 - \frac{1}{2}\mu\omega_2^2 x^2\right)\theta(-x). \tag{1}$$

$\theta(x)$ is a step function such that $\theta(x) = 1, x > 0$ and $\theta(x) = 0, x \leq 0$. V_i and $\omega_i, i = 1, 2$ indicate the height and the curvature factors, respectively, and μ stands for the reduced mass. The potential barrier can be used to simulate the Coulomb barrier for any partial wave in the neighborhood of $R_{\rm B}$ which is taken to be at the origin in this particular expression (1). In a fusion calculation we set $V_1 = V_2 = V_{\rm B}$.

By defining $\alpha_i = (V_{\rm B} - E_{\rm cm})/\hbar\omega_i, i = 1, 2$ and an asymmetric parameter $\eta = \sqrt{\omega_2/\omega_1}$ the transmission coefficient [1] at center of mass energy $E_{\rm cm}$ is given as

$$T(E_{\rm cm}) = \frac{1}{\frac{1}{4}\sqrt{1+{\rm e}^{2\pi\alpha_1}}\sqrt{1+{\rm e}^{2\pi\alpha_2}}\left[\eta\left(\frac{f_1}{f_2}\right)+\frac{1}{\eta}\left(\frac{f_2}{f_1}\right)\right]+\frac{1}{2}\left[{\rm e}^{\pi\alpha_1}\,{\rm e}^{\pi\alpha_2}+1\right]}, \tag{2}$$

where $f_1 = f(\alpha_1)$ and $f_2 = f(\alpha_2)$. The function $f(\alpha) = \left|\Gamma\left(\frac{1}{4}+i\frac{\alpha}{2}\right)/\Gamma\left(\frac{3}{4}+i\frac{\alpha}{2}\right)\right|$, can be approximated by $f_{\rm approx}(\alpha) = 1/\sqrt{\gamma}(1+1/8\gamma)$, where $\gamma = \sqrt{(1/16)+(\alpha^2/4)}$.

In order to consider the Coulomb barriers generated by different partial waves l, we need to replace the height $V_{\rm B}$ of the effective barrier by

$$V_{\rm B}^l = V_{\rm B} + \frac{\hbar^2}{2\mu}\,\frac{l(l+1)}{R_{\rm B}^2}.$$

The quantities $V_{\rm B}, R_{\rm B}$ and the outer region $(r > R_{\rm B})$ curvature factor ω_1 can be obtained using the following global formulae:

$$R_{\rm B} = r_0\left(A_1^{1/3}+A_2^{1/3}\right)+2.72\,{\rm fm}, \quad V_{\rm B} = \frac{Z_1Z_2e^2}{R_{\rm B}}\left(1-\frac{a}{R_{\rm B}}\right)$$

and

$$(\hbar\omega_1)^2 = \frac{Z_1Z_2e^2\hbar^2}{\mu R_{\rm B}^2}\left(\frac{1}{a}-\frac{2}{R_{\rm B}}\right),$$

where $a = 0.63$ fm and $r_0 = 1.07$ fm, $A_j, Z_j, j = 1, 2$ denote the mass number and proton number of the two colliding nuclei, respectively. We control the inner region $(r < R_{\rm B})$ curvature factor ω_2 by varying the parameter $\eta = \sqrt{\omega_2/\omega_1}$.

Using the above specifications we adopt the expression (2) to calculate transmission coefficient $T_l(E_{\rm cm})$ for different l's as a function of incident energy. This is then used to obtain the results for $\sigma_F^l, \sigma_F, \langle l\rangle$ and $D(E_{\rm cm})$ given by the formulae:

$$\sigma_F^l = \frac{\pi}{k^2}(2l+1)T_l, \quad \sigma_F = \sum_{l=0}^{\infty}\sigma_F^l,$$

$$\langle l\rangle = \frac{\sum_{l=0}^{\infty} l\sigma_F^l}{\sigma_F} \;\text{ and }\; D(E_{\rm cm}) = \frac{{\rm d}^2(E\sigma_F)}{{\rm d}E^2},$$

where $k = \sqrt{(2\mu/\hbar^2)E_{\rm cm}}$.

3. Results and discussion

In figure 1(a) and (b) (upper panel) we show by solid curve the variation of σ_F and $\langle l\rangle$, respectively, with energy for ^{40}Ca + ^{46,48,50}Ti systems. $E_{\rm lab}$ indicates energy in the laboratory frame. From these figures it is clear that fit to the experimental data is good. Values

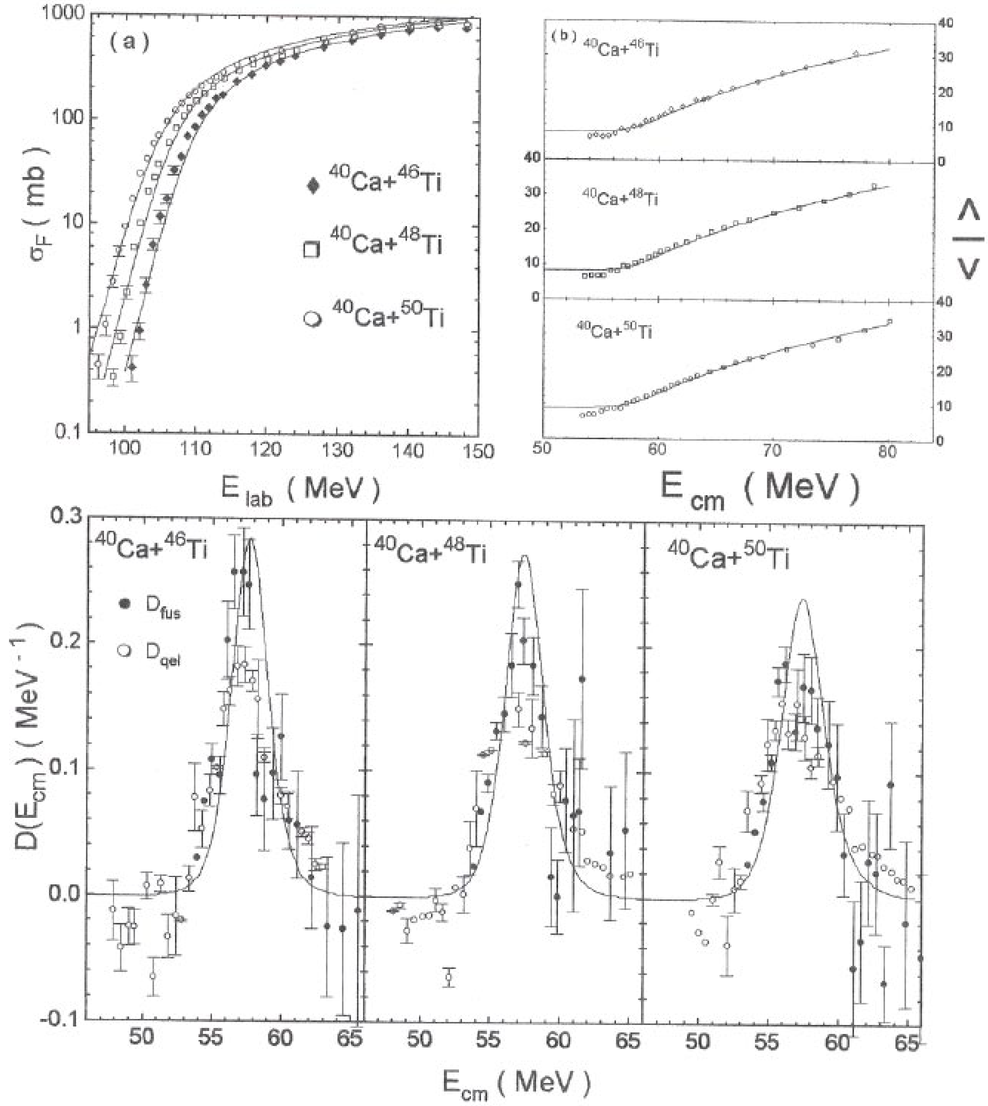

Figure 1. Upper panel shows the variation of (**a**) σ_F and (**b**) $\langle l \rangle$ with energy for ^{40}Ca + ^{46,48,50}Ti systems. Lower panel shows the variation of $D(E_{\rm cm})$ with $E_{\rm cm}$. Solid curves represent the results of present calculation. The experimental data are taken from ref. [4].

of $V_{\rm B}$, $R_{\rm B}$, $\hbar\omega_1$ and η used in the calculation for these systems are listed in table 1. In the lower panel of figure 1, we show the results for $D(E_{\rm cm})$ obtained by using point-difference formula used in ref. [3] for the ^{40}Ca + ^{46,48,50}Ti systems. The fit to the experimental data in these cases is impressive. If one examines D, the D variation curve becomes broader and shorter in height for larger η as in the case of ^{40}Ca + ^{50}Ti system (see table 1) where more channels are involved.

Table 1. Systems and s-wave barrier radius R_B, its height V_B, curvature factor $\hbar\omega_1$ and the asymmetry parameter η.

System	R_B (fm)	V_B (MeV)	$\hbar\omega_1$ (MeV)	η
^{40}Ca + ^{46}Ti	10.32	57.65	4.02	1.4
^{40}Ca + ^{48}Ti	10.37	57.36	3.96	1.5
^{40}Ca + ^{50}Ti	10.39	57.76	3.91	1.8

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