Fusion dynamics of ^{48}Ti + ^{60}Ni reaction

[1]Samiksha
Department of Physics,
Chaudhary Ranbir Singh University,
Jind (Haryana)-126102, India
samikshasihan23@gmail.com

[2]Manjeet Singh Gautam
Department of Physics,
Government College Alewa,
Jind (Haryana)-126102, India

[3]Anand Kumar
Department of Physics,
Chaudhary Ranbir Singh University,
Jind (Haryana)-126102, India

[4]Vijay Ghanghas
Department of Physics,
Chaudhary Bansi Lal University,
Bhiwani (Haryana)-127021, India

ABSTRACT

The fusion dynamics of ^{48}Ti + ^{60}Ni reaction is studied through simple Wong formula and Symmetric Asymmetric Gaussian Barrier Distribution (SAGBD) model. The fusion excitation function estimated by using Wong formula is significantly deviated from experiment data at sub-barrier energies, which demonstrates the significance of intrinsic channels associated with participants in fusion process. Simple Wong formula falls short of explaining the fusion data particularly at energies below the barrier but the SAGBD model explained data qualitatively as well as quantitatively for above reaction. The impacts of dominant channels on fusion process for the reaction ^{48}Ti + ^{60}Ni is examined in terms of channel coupling parameter λ and V_{CBRED}, which shows the decrease in height of fusion barrier resulting to increase in fusion cross section. The percentage reduction in height of effective barrier (V_{CBRED}) is due to involvement of nuclear structure effect. The non-zero values of these parameters indicated that the nuclear structural effects related with the fusing pair have significant impacts on the fusion process.

Keywords- Sub-barrier fusion; Fusion excitation function; Woods-Saxon potential; SAGBD model; channel coupling effect.

I. INTRODUCTION

Heavy-ion fusion reactions have been carefully explored in an effort to identify the cause of the fusion enhancement in the below-barrier domain from the last 40 years. When internal channels of the projectile target pair are not taken into account then explanation based on the simple barrier penetration model (BPM) give no fusion enhancement. So, we can say that the enhancement is an outcome from the coupling to additional degree of freedom besides the relative motion of participants and this is called sub-barrier fusion enhancement [1-3]. Sub-barrier fusion is quite intriguing due to the complex connection between the reaction's kinetics and the internal channels of the participating nuclei and has been analyzed by many authors [3-6]. The simply one concentrates on the issue of knowing the process leading sub-barrier fusion cross sections to increase in comparison to the one-dimensional barrier penetration model. The most challenging in heavy-ion processes is fusion reaction dynamics since so many aspects of these reactions are yet unknown. Vinodkumar *et al.* [5] carried out an experiment and extracted fusion data for the reaction ^{48}Ti + ^{60}Ni at Nuclear Science Centre (NSC), New Delhi, India by using a 15UD Pelletron accerlator in energy range 126-168 MeV. In present case, the fusion analysis for the reaction ^{48}Ti + ^{60}Ni has been carried out theoretically using simple Wong Formula [4] and SAGBD model [7-9]. The results from Wong formula are not able to address the fusion cross-section data usually at energies lower than the nominal barrier. However, for the above barrier data; Wong based calculations approximately explained fusion data as the effects of channel coupling are not significant. Within SAGBD model, a single Gaussian-function is weighted to simple Wong formula to account for the effects of inclusion of intrinsic degree of freedom of the colliding pairs [10], as the simple Wong formula doesn't account for the of intrinsic degree of freedom. In SAGBD approach; the effect of channel coupling for the reaction, which is accountable for enhancement of fusion excitation function; is defined in the terms of 'λ' and the percentage decrease of effective fusion barrier 'V_{CBRED}' with respect to Coulomb Barrier 'V_{CB}'.

II. THEORETICAL APPROACH

The simple Wong formula [4] for the fusion cross section is given by the expression:

$$\sigma^{Wong}(E_{c.m.},V_{CB}) = \frac{\hbar\omega_B R_B^2}{2E_{c.m.}} \ln\left[1+\exp\left(\frac{2\pi}{\hbar\omega_B}(E_{c.m.}-V_{CB})\right)\right], \tag{1}$$

where, V_{CB}, $\hbar\omega_B$ and R_B are barrier heights, barrier curvature and barrier position of nominal barrier respectively. $E_{c.m.}$ is the center of mass energy. In this work, we have taken the Woods-Saxon potential form of nucleus-nucleus potential and given by:

$$V_N(r) = \frac{-V_0}{\left[1+\exp\left(\frac{R-R_0}{a_0}\right)\right]}, \tag{2}$$

where V_0 is the depth, a_0 is the diffuseness and R_0 is the radius parameter of the nucleus-nucleus potential. Here, the radius parameter is defined as:

$$R_0 = r_0\left(A_P^{1/3} + A_T^{1/3}\right), \tag{3}$$

Here, the range for Woods-Saxon potential is denoted by r_0. A_P and A_T are the mass of projectile and target. The total fusion cross-section can be evaluated in the SAGBD model [7-9] by weighting the Wong formula with single Gaussian function [11]. The total weighted fusion cross-section is given by the expression:

$$\sigma^{SAGBD}(E_{c.m.},V_{CB}) = \int_0^\infty D_f(V_{CB})\sigma^{Wong}(E_{c.m.},V_{CB})dV_{CB}, \tag{4}$$

and $\int D_f V_{CB} dV_{CB} = 1,$

where, $D_f(V_{CB})$ represents the effective barrier distribution, which is given by following relation

$$D_f(V_{CB}) = \frac{1}{N}\exp\left[-\frac{(V_{CB}-V_{B0})^2}{2\Delta^2}\right], \tag{5}$$

with $N = \Delta\sqrt{2\pi}$,

here, Δ & V_{B0} are the standard deviation and mean barrier height of barrier distribution of selected system. In this work, the effects of inherent channels linked with the fusing nuclei are determined by evaluating the channel coupling parameter (λ) and V_{CBRED}. Mathematically, the value of λ is given as:

$$\lambda = V_{CB} - V_{eff}, \tag{6}$$

where, V_{eff} represents the effective fusion barrier. The parameter V_{CBRED} mathematically evaluates the percentage decrease in the effective fusion barrier relative to V_{CB}.

$$V_{CBRED} = \frac{V_{CB}-V_{eff}}{V_{CB}} \times 100\% \tag{7}$$

For more details of SAGBD formalism, readers can read the Refs. [7-9].

III. RESULT AND DISCUSSION

For the exploration of the system ^{48}Ti + ^{60}Ni theoretically, we have used the Woods-Saxon potential. The different parameters for the Woods-Saxon potential such as depth, diffuseness and range have values 110 MeV, 0.87 fm and 1.00 fm respectively. The potential barrier between fusing nuclei using SAGBD model are shown in figure 1. The fusion cross-section estimated with the help of simple Wong formula and SAGBD model are also shown in figure1. Figure 1 (a) shows the Coulomb barrier for the selected system, which is under study. The barrier characteristics such as Coulomb barrier (V_{CB}), barrier curvature ($\hbar\omega$) and barrier position (R_B) are also calculated using Woods-Saxon potential. These barrier characteristics as $V_{CB} = 82.89\ MeV$, $\hbar\omega = 3.33\ MeV$ and

$R_B = 9.65\,fm$ are used in Wong formula and SAGBD approach for the theoretical calculations. Figure 1 (b) shows the fusion excitation function for the reaction ^{48}Ti + ^{60}Ni. The symbol indicates the experimental fusion cross section data; the dash line shows the Wong calculations and the solid line gives result of calculations due to SAGBD approach. The fusion cross-section data were experimentally measured by the author of Ref. [5]. Theoretical calculations using Wong formula are considerably lower than the experimental data at specific barrier energies. It is due to involvement of only one channel i.e., relative motion of colliding nuclei in simple Wong formula and hence the multidimensional behavior is absent. Vinodkumar *et al.* [5], explained fusion data by considering coupled channel calculations by using the code CCMOD [12]. The calculations were done by authors including the effect of lowest 2^+ and 3^- vibrational states of fusing nuclei. In current work, Wong based calculations are incapable to retrieve the fusion data at below energies realm. Although, the SAGBD model calculations replicate the fusion excitation function at all range of incident energies. In SAGBD model, the effects of intrinsic channels related to the reaction partners are explained in the forms of channel coupling parameter (λ) and V_{CBRED}.The value of λ and V_{CBRED} for the reaction ^{48}Ti + ^{60}Ni is 4.59 and 5.54% of V_{CB}. The decrease in effective barrier is due to participation of nuclear structural effect of the colliding nuclei and this involvement further enhances the fusion cross section relative to simple Wong formula specially at below barrier energies as seen in the SAGBD prediction.

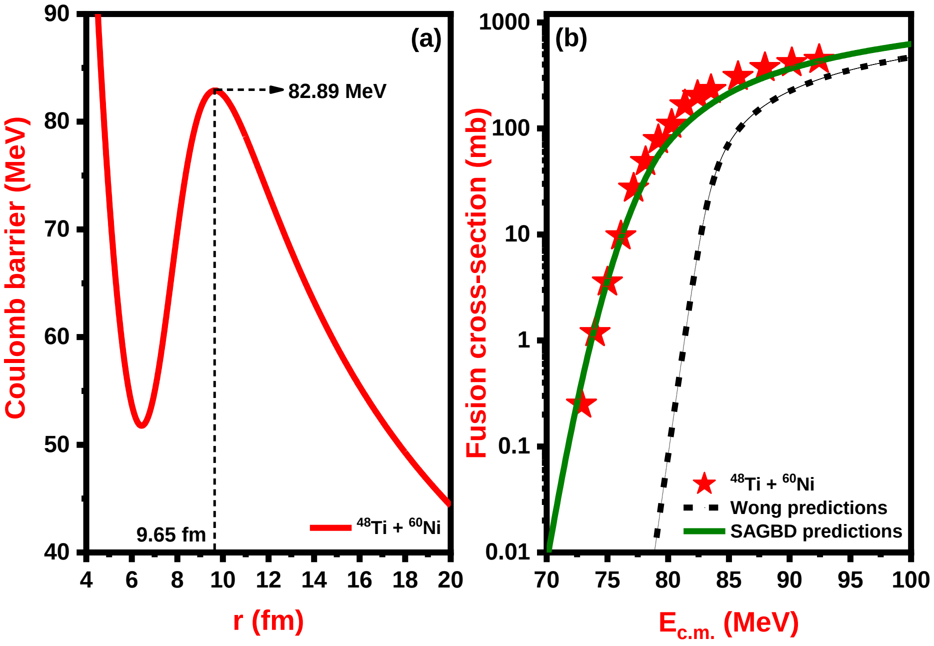

Figure 1: (a) Radial dependence of the fusion barrier for ^{48}Ti+^{60}Ni reaction and (b) Fusion excitation function for the system ^{48}Ti + ^{60}Ni obtained by using SAGBD model as a function of center of mass energy. The calculations are contrasted with Wong formula based calculations and the theoretical results are also compared with experimental results obtained from Ref. [5].

IV. CONCLUSION

The excitation function for the fusion reaction ^{48}Ti + ^{60}Ni is explored at sub energies using simple Wong formula and SAGBD model. The fusion cross-section estimated using simple Wong formula remain significantly deviated with reference to the experimental outcomes at below barrier energies. Although, the SAGBD approach reproduces fusion excitation function for the system ^{48}Ti + ^{60}Ni .The parameters λ and V_{CBRED} determines quantitative involvement of the channel coupling effects in the fusion process. The larger value of both the parameters suggests the participation of nuclear structure of colliding nuclei in fusion is significant.

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