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Abstract. Fusion excitation functions of stable odd-A targets ^{147,149}Sm with ^{16}O projectile are theoretically analyzed within view of the symmetric-asymmetric Gaussian barrier distribution (SAGBD) formalism. For the purposes of this study, we assumed that bombardment energies of the ^{16}O + ^{147,149}Sm reactions would be around nominal barrier. For these reactions, Wong based computations fails to retrace the fusion data whereas SAGBD predictions fairly retrace the fusion data in entire bombarding energy range. The evaluated values of channel coupling parameter (λ) and V_{CBRED} from SAGBD outcomes are found larger for heavier (^{16}O + ^{149}Sm) over lighter (^{16}O + ^{149}Sm) system, which suggests that heavier system possess extra fusion enhancement in sub-barrier domain. Present theoretical investigation highlights the significant contributions of intrinsic channels that emerges due to structure of reacting nuclei and such effects are empirically included in SAGBD method.

1. Introduction

The fusing process between two nuclei is extremely important on theoretical as well as experimental grounds because it is related with the involvement of inherent channels that arise because of structure of colliding nuclei during reaction dynamics [1,2]. For a larger number of heavy-ion events, experimental data at below Coulomb barrier energies are found to be too much larger over outcomes of simple barrier penetration model

(BPM) and such difference between theoretical and experimental results is termed as "fusion enhancement" [1,2]. In simple BPM, the internal structure of fusing nuclei is generally ignored and the theoretical estimations are done by considering the relative motion co-ordinate only. Numerous studies have been looked in past [1,2] for analyzing the importance of vibrational states and permanent shape deformations due to the structure of participants that might affect fusion cross-sections yields at energies lie below nominal barrier. Besides this, the function of surface rotational effects as well as the vibrational coupling effects of fusing nuclei are partially understood. In addition, several features of fusion reactions are still unknown, and hence motivates to examine the impacts of various inherent channels associated with the participants, on theoretical & experimental grounds.

Current work analyzes the fusion dynamics of stable odd-A targets ^{147,149}Sm with ^{16}O projectile in sub-barrier domain by using simple Wong formula [3] and SAGBD formalism [4]. Results due to Wong formula fails to replicate fusion data for both systems in sub-barrier domain, whereas above barrier data are explained by using such model. Conversely, SAGBD model automatically incorporates the impacts of intrinsic channels in theoretical estimations and appropriately recovers fusion data of ^{16}O + ^{147,149}Sm systems. Fusion data of odd-A Sm targets show same pattern of fusion enhancement to those of the adjacent even Sm-isotopes i.e., ^{144,148,150,152,154}Sm as pointed in literature [5]. The value of SAGBD parameters (λ and V_{CBRED}), that are used to evaluate the impacts of inherent channels couplings, are found to be larger for ^{16}O + ^{149}Sm than ^{16}O + ^{147}Sm reaction and hence fusion enhancement for ^{16}O + ^{149}Sm reaction comes out be larger over ^{16}O + ^{147}Sm reaction. The comparative analysis of SAGBD parameters for even-A target isotopes i.e.,^{144,148,154}Sm and odd-A target isotopes reveals that odd-A targets show similar impact on sub-barrier fusion enhancement of ^{16}O + ^{147,149}Sm systems as inferred from even-A Sm-isotopes with common projectile (^{16}O). The outcomes made by SAGBD calculations, quantitively and qualitatively explain the fusion cross-sections data of ^{16}O + ^{147,149}Sm systems.

2. Theoretical approach

Wong [3] proposed the following expression to evaluate the fusion excitation function around the Coulomb barrier (V_{CB}).

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

In above equation, $\hbar\omega_B$ designates to barrier curvature, R_B designates to barrier position & V_{CB} designates to barrier height. In SAGBD method, the role of internal channels is entertained by weighting one-dimensional Wong formula by a Gaussian function and the fusion excitation function due to present method is given by:

$$\sigma_{Fus}^{SAGBD}(E_{c.m.}, V_{CB}) = \int_0^\infty D_f(V_{CB})\sigma^{Wong}(E_{c.m.}, V_{CB})\, dV_{CB} \quad (2)$$

here, the normalized, continuous & symmetric function '$D_f(V_{CB})$' is termed as effective barrier distribution, which is expressed by Eq. (3).

$$D_f(V_B) = \frac{1}{N} exp\left[-\frac{(V_B - V_{B0})^2}{2\Delta^2}\right] \quad (3)$$

wherein $N = \Delta\sqrt{2\pi}$

In equation (3), Δ designates to standard deviation. In SAGBD approach, the quantitative contributions of internal channels of reaction partners are extracted by evaluating the channel coupling parameter (λ) and V_{CBRED}. The value of λ is defined by following relation:

$$\lambda = V_{CB} - V_{eff} \quad (4)$$

Mathematically, V_{CBRED} calculates the percentage reduction in the effective fusion barrier (V_{eff}) relative to nominal barrier and is expressed as:

$$V_{CBRED} = \frac{V_{CB} - V_{eff}}{V_{CB}} \times 100\% \quad (5)$$

The SAGBD parameters are extracted as described in details in Ref. [4].

3. Results and discussion

Nuclear component of total nucleus-nucleus potential is taken to be of Woods-Saxon form in this study, and the values of parameters for this potential chosen in such a way that simple Wong formula-based predictions replicate the experimental results at above nominal barrier energies. This is due to fact that the above-barrier data is insensitive to inherent channels of reaction participants. The evaluated values of Woods-Saxon parameters for ^{16}O + ^{147}Sm (^{16}O + ^{149}Sm) systems are V_0 (potential depth) $= 150\ (150)\ MeV$, a_0(diffuseness) and r_0(range), respectively are $0.87\ (0.87)\ fm$ and $0.967\ (0.980)\ fm$. The barrier characteristics for the ^{16}O + ^{147}Sm (^{16}O + ^{149}Sm) systems are $V_{CB} = 63.31\ (62.41)\ MeV$, $R_B = 10.29\ (10.44)\ fm$ and $\hbar\omega_B = 3.303\ (2.938)\ MeV$ and the so obtained characteristics are also depicted in figure 1. These barrier characteristics are used in SAGBD calculations to estimate the fusion data for studied reactions and the results are shown in figure 2.

According to literature [5], in comparison with the even-A Sm isotopes, the odd-A Sm isotopes almost show similar fusion enhancement. Coupled channel calculations due to authors of Ref. [5] pointed out the importance of 2^+ & 3^- inelastic surface excitations in the fusion mechanisms of studied reactions. Authors suggested that one-dimensional BPM calculations for odd-A isotopes that incorporates the influences of quadrupole deformation (β_2) show the similar behaviour as established by the even-A isotopes. In other words, the parameter $\beta_2 = (0.13, 0.156)$ evaluated for odd-A $^{147,149}Sm$ isotopes, respectively fairly fit the data with similar trend of β_2-values evaluated for even-A Sm isotopes, which sets an increasing trend of strong collectivity as neutrons are added to ^{144}Sm-isotope. This unambiguously pointed out that there are shape transition effects from spherical symmetry for ^{144}Sm to a well deformed nucleus ^{154}Sm as one moves from lighter (^{144}Sm) to higher isotope (^{154}Sm).

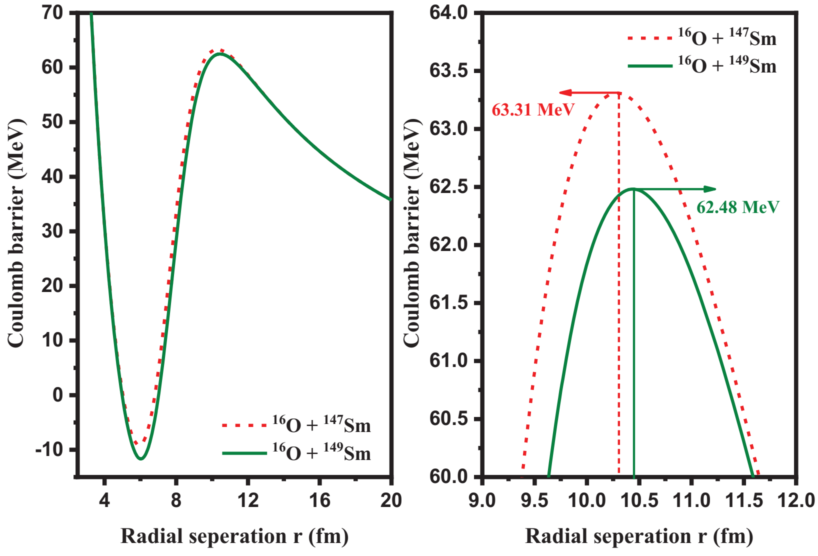

Figure 1. Coulomb barrier is a function of radial separation co-ordinate for ^{16}O + $^{147,149}Sm$ systems.

At below barrier energies, Wong formula is not capable to address inherent channels of participants and as a result evaluated fusion excitation functions are strongly undervalued with respect to fusion data. Conversely, the SAGBD results estimates notably larger fusion excitation functions (see figure 2) and fairly retrace experimental findings. In present approach, the relevant channel couplings are automatically incorporated into the theoretical estimations. The evaluated values of SAGBD parameters (λ and V_{CBRED}) for ^{16}O + $^{147,149}Sm$ reactions are tabulated in table 1. From this table an increasing trend of parameters i.e., λ and V_{CBRED} is found for all Sm-isotopes, which clearly reflects that odd-A Sm-isotopes do not possess any extraordinary fusion enhancement with respect to neighboring even-A Sm-isotopes with common projectile as expected due to odd number of nucleons. The present results are in close resemblance with the outcomes due to DiGregorio *et al.* [5]. Also, the larger values of aforesaid parameters are found for ^{16}O + ^{149}Sm system over ^{16}O + ^{147}Sm system and hence, the heavier system possess larger sub-barrier fusion enhancement.

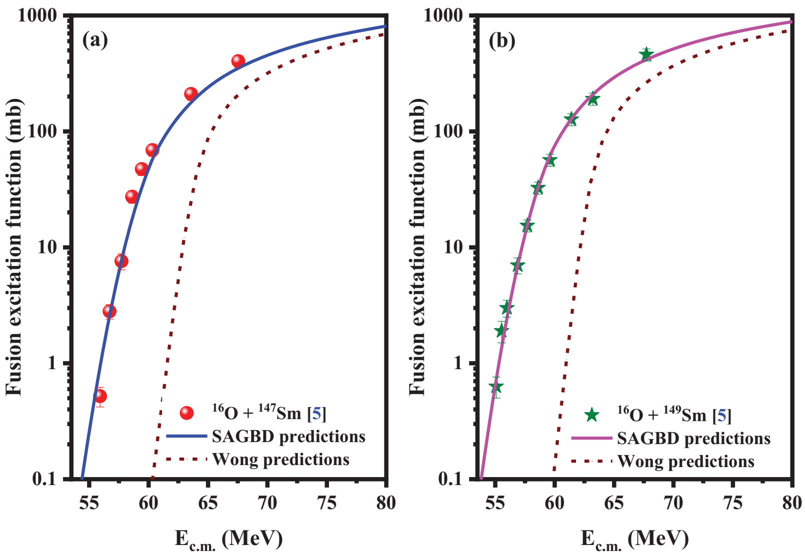

Figure 2. Fusion cross-sections versus energy in center of mass frame for (a) ^{16}O + ^{147}Sm and (b) ^{16}O + ^{149}Sm reactions.

Table 1. The value of λ and V_{CBRED} for various reactions extracted from SAGBD calculations.

Fusion reaction	λ	V_{CBRED}	Reference
^{16}O + ^{144}Sm	3.42	5.30 % of V_{CB}	[4]
^{17}O + ^{144}Sm	3.46	5.44 % of V_{CB}	[4]
^{16}O + ^{147}Sm	3.48	5.49 % of V_{CB}	Present work
^{16}O + ^{148}Sm	3.49	5.54 % of V_{CB}	[4]
^{16}O + ^{149}Sm	3.50	5.60 % of V_{CB}	Present work
^{16}O + ^{154}Sm	3.55	5.72 % of V_{CB}	[4]

4. Conclusions

The present paper examined fusion dynamics of ^{16}O + ^{147,149}Sm reactions within the framework of simple Wong formula and SAGBD formalism. Wong formula-based calculations fail to retrace fusion data. However, the SAGBD results quantitatively as well as qualitatively ascribed the fusion mechanisms of ^{16}O + ^{147,149}Sm systems. This holds the fact that present model includes barrier alteration effects that significantly decreases the height of nominal barrier and hence give a fair description to the fusion mechanism of systems under study. The evaluated values of parameters λ & V_{CBRED} suggest the significant influences of various channel couplings in sub-barrier domain. The order of fusion enhancement follows the increasing trends as the number of neutrons in Sm-isotopes increases and no additional sub-barrier fusion enhancement due to odd-A structure for ^{147,149}Sm-isotopes is observed. The SAGBD outcomes predict larger fusion enhancement of ^{16}O + ^{149}Sm system at sub-barrier realms over ^{16}O + ^{147}Sm system as the values of λ & V_{CBRED} parameters

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are found larger for heavier system. This in turn, suggests that effects of relevant channel couplings play a vital role in enhancing excitation functions in the fusion dynamics of ^{16}O + $^{147,149}Sm$ systems.

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