Analysis of barrier distributions data for $^{16}$O + $^{64}$Zn reaction at sub-barrier energies

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Abstract. The barrier distribution data for the $^{16}$O + $^{64}$Zn reaction at energies spanning around the nominal barrier are examined by employing symmetric-asymmetric Gaussian barrier distribution (SAGBD) approach. The cumulative role of dominant channel couplings in the SAGBD method are determined in terms of the channel coupling parameter $\lambda$ and percentage decrease of fusion barrier $V_{CBRED}$ with reference to nominal Coulomb barrier. The non-zero and positive values of these parameters for the studied system quantitively measure the influences of dominant intrinsic channels originated from the structure of the participants. The barrier distribution data of $^{16}$O + $^{64}$Zn reaction is quantitatively as well as qualitatively explained by SAGBD outcomes.

Keywords: Barrier distribution, channel coupling effects, heavy-ion fusion, SAGBD model, Woods-Saxon potential.

1. Introduction

The fusion process, wherein two or more light mass nuclei are fused to form a heavy mass compound nucleus with emission of large amount of energy along-with few nucleons and nucleosynthesis in sun and other stars, is one of the most exciting field in the nuclear and astrophysics. The sun and perhaps other stars with masses less than 1.5 times that of the sun, for example, emit energy primarily by the proton-proton cycle. The nuclear fusion process plays a key role for understanding the path of energy production in sun and other stars and such process is of astrophysical interest. Furthermore, heavy-ion fusion reactions may give an excellent insight into the mechanics involved in understanding the nature of nuclear forces [1,2]. Nuclear structure effects such as dynamical and static deformations, neck formation, entrance channel mass asymmetry and/or nucleon transfer channels along with relative motion of colliding nuclei strongly affects the fusion process at sub-barrier realm[3-9]. As a result of channel coupling, the single barrier gets modified into distribution of barriers [10]. The barrier distribution (BD) can be extracted from experimentally measured fusion data by employing three-point difference method. This concept of extracting BD from fusion excitation function data ($\sigma_{Fus}$) was
initially introduced by Rowley et al. [10]. In other words, according to Rowley et al. [10], one can extract BD by taking second derivative of quantity $\left( E_{\text{c.m.}} \sigma_{\text{Fus}} \right)$ corresponding to center-of-mass energy ($E_{\text{c.m.}}$). The BD is quite helpful to identify the nature of dominant coupling participated in the fusion process. By using the concept of BD, one can also analyze the fusion data at deep energies lying in sub-barrier realm with considerable accuracy.

Huiza et al. [11] experimentally measured the barrier distribution for $^{16}\text{O} + ^{64}\text{Zn}$ reaction by using 8 UD Pelletron accelerator at university of Sao Paulo at energies lying between $E_{\text{lab}} = 30 - 50\text{MeV}$. Authors concluded that single-phonon quadrupole and octupole states of $^{64}\text{Zn}$ were important to retrieve the shape of barrier distribution in sub-barrier energy domain. In this work, the BDs for $^{16}\text{O} + ^{64}\text{Zn}$ reaction are examined within the groundwork SAGBD model [12,13]. The simple Wong formula is weighted by the single Gaussian function in order to incorporate the aforementioned effects in the SAGBD approach. The theoretical predictions are made by using SAGBD model adequately reflected the barrier distribution of chosen reaction. This unambiguously reflected that the impacts of dominant channel couplings are properly included in the SAGBD model. The influences of the dominant channel couplings at sub-barrier domain for the fusion partners are expressed in terms of $\lambda$ and $V_{\text{CBRED}}$. The details of SAGBD model are briefly given in section 2, while the result and discussion for the present work is given in section 3. The conclusions of this work are given in section 4.

2. Theoretical approach

The simple Wong formula [14] used to calculate fusion cross-sections is expressed by following relation:

$$\sigma^{\text{Wong}}(E_{\text{c.m.}}, V_{\text{CB}}) = \frac{\hbar \omega_{R} R_{g}^{2}}{2 E_{\text{c.m.}}} \ln \left[ 1 + \exp \left( \frac{2 \pi}{\hbar \omega_{R}} \left( E_{\text{c.m.}} - V_{\text{CB}} \right) \right) \right]$$  \hspace{1cm} (1)

where, $V_{\text{CB}}$, $\hbar \omega_{R}$ and $R_{g}$ are the barrier height, barrier curvature and barrier position, respectively. This Wong formula does not include the contribution from nuclear structure of the reactants and just consider the relative motion between them as the only degree of freedom. As a result, the predictions made via such simple formula would not be able to reproduced the experimental data especially in below barrier domain. Stelson [15] and Wilczynska & Wilczynska [16] suggested that the Wong formula can be weighted by a Gaussian type of weight function in order to address the channel coupling effects. Keeping this in mind, to include the influences of nuclear structure linked with the fusion partners, the Wong formula is weighted by a single Gaussian function i.e.

$$\sigma_{f} = \int_{0}^{\infty} D_{f}(V_{g}) \sigma^{\text{Wong}}(E_{\text{c.m.}}, V_{g}) dV_{g}$$  \hspace{1cm} (2)

with $D_{f}(V_{g})$ obeys the normalization condition $\int D_{f}(V_{g}) dV_{g} = 1$ and is given by

$$D_{f}(V_{g}) = \frac{1}{N} \exp \left[ -\frac{(V_{g} - V_{0})^{2}}{2\Delta^{2}} \right]$$  \hspace{1cm} (3)

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

where, $V_{0}$ and $\Delta$ denotes mean barrier height and standard deviation, respectively. Because of the contributions from different channel coupling effects, the value of $V_{\text{eff}}$ will come out to be always lesser than that of the $V_{\text{CB}}$ and approximately given as
Quantitative contributions of dominant channels are extracted in terms of channel coupling parameter $(\lambda) \& V_{\text{CBRED}}$ and defined as
\[
\lambda = V_{\text{CB}} - V_{\text{eff}}
\]
and $V_{\text{CBRED}}$ measures the percentage decrease of effective fusion barrier in comparison to $V_{\text{CB}}$.

3. Results and discussion

In present work, the Woods-Saxon potential (WSP) has been used to obtain theoretical results. The WSP parameters for $^{16}\text{O} + ^{64}\text{Zn}$ reaction which have been used for the theoretical barrier distribution are potential depth $(V_0) = 150 \text{MeV}$, diffuseness $(a_0) = 0.67 \text{fm}$, and range $(r_0) = 1.05 \text{fm}$. Using these potential parameters, the barrier characteristics emerge out as: Coulomb barrier $(V_{\text{CB}}) = 33.57 \text{MeV}$, barrier curvature $(\hbar \omega_b) = 3.19 \text{MeV}$ and barrier position $(R_B) = 9.50 \text{fm}$. The potential parameters mentioned above are used for theoretical predictions and SAGBD results.

![Figure 1](image_url)

**Figure 1.** The barrier distribution for $^{16}\text{O} + ^{64}\text{Zn}$ system are obtained by using SAGBD approach. The theoretical outcomes are also correlated with experimental BD[11].

In figure 1, the experimental and theoretical barrier distribution for $^{16}\text{O} + ^{64}\text{Zn}$ system are depicted. The height and height of BD are very sensitive to the channel coupling effects and the coupled channel study of different projectile-target configurations in the literature showed that theoretical calculations cannot reproduced the shape of BD data without the incorporation of such effects [13,17]. Huiza et al. [11] experimentally measured the barrier distribution data from quasi-elastic measurements and authors pointed out that the theoretical barrier distribution which has been obtained by coupled channel analysis with inclusion of deformation parameter $(\beta_2 = 0.311)$ and $(\beta_2 = 0.333)$ for target reasonably explained the experimental barrier distribution data. Authors also emphasized that the octupole collective state of projectile does not affect the shape of barrier distribution. This is because of the fact that the excitation energy corresponding to octupole state of
projectile was higher than that of the barrier curvature. This can only result in the renormalization of the peak of BD with respect to energy. However, the single-phonon quadrupole and octupole states of $^{64}$Zn are very important for retrieving the shape of BD in sub-barrier energy domain. Theoretical results estimated from SAGBD model have fairly retrieved the shape of BD at energies spanning around the nominal barrier. The close relation between predicted barrier distribution and experimental barrier distribution clearly indicates that SAGBD predictions entertain the influences of all dominant channel couplings in the fusion process of $^{16}$O + $^{64}$Zn system. The impacts of channel couplings are quantitatively described in terms of $\lambda$ and $V_{CBRED}$. The parameter $\lambda$ measures the influences of nuclear structure associated with the fusing partners and hence measures the difference between effective fusion barrier and the uncoupled Coulomb barrier. The larger difference in above quantities directly measures the role of the channel couplings in the fusion process. The parameter $V_{CBRED}$ directly measures the magnitude of decrease of the fusion barrier because of intrinsic structure of the fusing nuclei. The value of $\lambda$ and $V_{CBRED}$ for chosen reaction are 1.19 and 3.54% of $V_{CB}$, respectively. The non-zero and positive value of $\lambda$ and $V_{CBRED}$ pointed out that the significant impacts of nuclear structure in the fusion process of $^{16}$O + $^{64}$Zn reaction. This further suggests that larger barrier modifications are required to reproduced the BD of studied system.

4. Conclusion
The experimental barrier distributions for $^{16}$O + $^{64}$Zn system are analyzed by using the SAGBD approach. The SAGBD approach adequately reproduced the experimental barrier distribution of the chosen reaction which clearly highlights the impacts of dominant channel couplings have been incorporated in the present calculations. The role of the internal structure of participants are quantitatively analyzed in terms of $\lambda$ and $V_{CBRED}$. The large positive values of $\lambda$ (1.19) and $V_{CBRED}$ (3.54%) pointed out that intrinsic structure of participants display significant impacts on the fusion dynamics of $^{16}$O + $^{64}$Zn system. Hence, the larger barrier modifications are required in order to address the experimental BD of chosen reaction.

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