Influence of low-lying excitation states and higher order deformations in sub-barrier fusion enhancement

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Heavy-ion fusion reactions are the most familiar examples of multi-dimensional quantum tunneling and are the most effective tool for investing the complex interplay of internal structure and reaction kinetics of collision partners. Such process reveals the important information about the nature of nuclear interactions and also shed light on the form of nuclear potential. Several heavy-ion systems have shown a significant increase in the fusion excitation function over the assumptions made via simple barrier penetration model (BPM) in sub-barrier domain. Based on the existing research, one can infer that the couplings to intrinsic degrees of freedom of fusing partners with their relative motion increases the fusion probability, which increases the fusion excitation function, especially at sub-barrier domain [1-4].

This work analyzed the fusion cross-sections of $^{16}O + ^{76}Ge$ system by opting coupled channel code 'CCFULL' [5] and symmetric-asymmetric Gaussian barrier distribution (SAGBD) approach [6-8]. To handle the multi-dimensional nature of nuclear potential, we follow the idea of Stelson [9] and Swiek-Wilczynska and J. Wilczynska [10] and the fusion excitation function is described as

$$\sigma_F = \int_0^\infty D_f(V_B)\,\sigma^{Wong}(E_{c.m.},V_B)\,dV_B \qquad (1)$$

here, $\sigma^{Wong}(E_{c.m.},V_B)$ and $D_f(V_B)$ is the Wong formula [11] and the effective barrier distribution, respectively. The $D_f(V_B)$ follows normalization condition and described by following relation

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

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

wherein, Δ denotes standard deviation and V_{B0} denotes and mean barrier height, respectively.

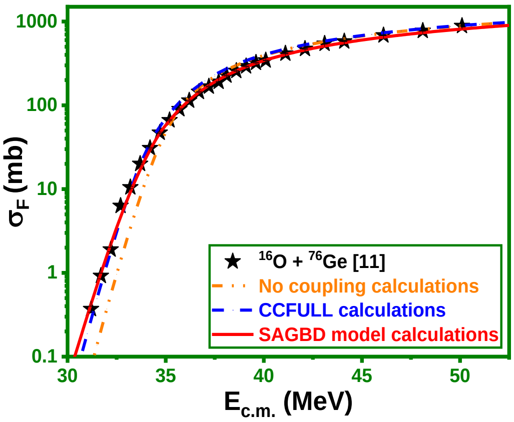

Fig. 1 The fusion cross-sections of $^{16}O + ^{76}Ge$ system obtained by opting CCFULL code and SAGBD approach.

In order to extract theoretical outcomes, the spherical form of standard Woods-Saxon potential (WSP) has been adopted. The parameters of typical WSP and barrier characteristics for the $^{16}O + ^{76}Ge$ system are taken from the Ref. [7]. These parameters are used in SAGBD approach to obtain the theoretical outcomes and the results are shown in Fig. 1.

The authors of Ref. [12] experimentally determined the fusion excitation functions for the $^{16}O + ^{76}Ge$ system. For chosen system, the ^{16}O nucleus has been considered as spherical in shape in its ground state. While ^{76}Ge nucleus has been considered as prolate deformed. Authors of Ref. [13] used the statically deformed shape and higher order deformation for ^{76}Ge-nucleus and hence appropriately addressed the magnitude of fusion cross-sections. In present work, computations of no coupling scheme estimate significantly smaller fusion cross-sections in below barrier domain. While, such estimations reasonably recovered the above barrier data. The dissimilarity between experimental data and no coupling results can be visualized in terms of dominant couplings linked with the nuclear shape of the reaction partners. The considerations of inelastic excitation states of 2^+ and 3^- types of the ^{76}Ge-nucleus produce larger fusion enhancement than that of no coupling calculations at sub-barrier realm. However, such calculations unable to reproduce the reported the fusion data of ^{16}O + ^{76}Ge system. As mentioned in literature [11,12], the ^{76}Ge-nucleus is a statistically deformed nucleus in its ground state. The inclusion of $\beta_2(=0.27)$ & $\beta_4(=0.02)$ for the ^{76}Ge-nucleus in the coupled channel analysis along with 3^- vibrational states of ^{16}O fairly recover the experimental data in sub-barrier domain. By using coupled channel model, the authors of Ref. [12-14] also arrived at similar conclusions.

The remarkable similarity among experimental evidence and SAGBD based results demonstrates that the contributions of all dominant channel couplings are inherently included in the model computations. For the ^{16}O + ^{76}Ge reaction, the channel coupling parameter $\lambda = 1.38$. The parameter V_{CBRED} specifies the percentage reduction in the fusion barrier by 3.78% of V_{CB} and thus indicates greater barrier modulations are needed to address the fusion data of the selected system.

In brief, the coupled channel estimations extracted by opting the 'CCFULL' code [5] for the investigated reactions clearly show that the couplings to rotational states and hexadecapole deformation (β_4), are necessary for the entire addressal of the sub-barrier fusion enhancement of ^{16}O + ^{76}Ge system. The SAGBD computations fairly addressed the fusion excitation functions of the ^{16}O + ^{76}Ge system and hence indicates that the shortcomings of one-dimensional barrier penetration can be overcome by choosing the Gaussian type of weight function.

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