# Fusion of $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni reactions

**Samiksha[1†], M S Gautam[2*], A Kumar[1] and Vijay[3]**

[1]Department of Physics, Chaudhary Ranbir Singh University, Jind (Haryana)-126102, India
[2]Department of Physics, Government College Alewa, Jind (Haryana)- 126102, India
[3]Department of Physics, Chaudhary Bansi Lal University, Bhiwani (Haryana)-127021, India

E-mails: [†]samikshasihan23@gmail.com

**Abstract.** The fusion of $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni systems are examined by opting SAGBD formalism. Wong estimations are appreciably deviated from experimental results and this suggests the importance of intrinsic channels. Therefore, influences of dominant channels for $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni in SAGBD model are empirically included via Gaussian type of weight function in Wong formula. Hence, present formalism adequately explains the fusion of $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni systems.

## 1. Introduction

Fusion process of heavy-ions have been thoroughly explored over the last 40 years in attempt to find out the origin of fusion enhancement in below barrier domain owing to channel couplings linked with internal channels of participants. In simple barrier penetration model (BPM), the internal channels of projectile-target pair are ignored. It is now believed that results from the coupling to additional channels besides from the relative motion of participants, known as sub-barrier fusion enhancement [1]. The complicated interaction between the kinetics of the reaction process and the internal channels of involved nuclei makes sub-barrier fusion quite interesting. However, many features of fusion reactions remain unknown, making it most difficult challenge in heavy-ion processes. The connection of interacting partners' internal channels with their relative motion effectively modifies tunnelling process & yields higher fusion cross-sections than results due to simple BPM in lower energy realm [1]. In present work, the fusion data for $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni reactions are theoretically analyzed within the preview of Wong formula [2] & SAGBD method [3]. The Wong based estimations fail drastically to retrieve experimental data while SAGBD model addresses fusion data of $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni systems [4].

## 2. Theoretical approach

The simplistic Wong formula [2] is given by following expression:

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

wherein, $V_{CB}$ is height, $\hbar\omega_B$ is curvature, and $R_B$ is position of nominal barrier. The standard Woods-Saxon potential is given below:

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

wherein $V_0$ denotes depth, $a_0$ denotes diffuseness and $R_0$ is radius parameter, which is connected with range parameter as:

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

In above equation, the range is represented by $r_0$ and $A_P$ is projectile's mass and $A_T$ is target's mass. The fusion cross-section predicted via SAGBD formalism is expressed as:

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

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

where, $D_f\,(V_{CB})$ is mathematically expressed as

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

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

and $V_{B0}$ & $\Delta$ are the mean barrier height & standard deviation of barrier distribution. For more deep insight of SAGBD formalism, one can read Ref. [3].

## 3. Results & discussion

**Table 1.** The nuclear potential parameters used for studied systems, are tabulated.

| Fusion reactions | Potential depth $V_0\ (MeV)$ | Diffuseness $a_0\ (fm)$ | Range $r_0\ (fm)$ | Reference |
|---|---|---|---|---|
| $^{16}O + ^{60}Ni$ | 150 | 0.65 | 0.940 | [3] |
| $^{18}O + ^{58}Ni$ | 150 | 0.65 | 0.995 | [3] |

**Table 2.** The Coulomb barrier characteristics used in SAGBD model for studied reactions, are tabulated.

| Fusion reactions | $V_{CB}\ (MeV)$ | $R_B\ (fm)$ | $\hbar\omega_B\ (MeV)$ | Reference |
|---|---|---|---|---|
| $^{16}O + ^{60}Ni$ | 34.60 | 8.60 | 4.0 | [3] |
| $^{18}O + ^{58}Ni$ | 32.91 | 9.09 | 3.6 | [3] |

The fusion excitation functions of $^{16}O + ^{60}Ni$ and $^{18}O + ^{58}Ni$ system were experimentally measured by authors of Ref. [4] and pointed out that $^{18}O$ dependency significantly affects the fusion dynamics of $^{18}O + ^{58}Ni$ system. Silva *et al* [4] performed coupled channel calculations and suggested that vibrational $2^+$ & $3^-$ excitation states in $^{60}Ni$-isotopes were needed to explain fusion process of $^{16}O + ^{60}Ni$ and $^{18}O + ^{58}Ni$ reactions. For $^{18}O + ^{58}Ni$ reaction, in addition to $2^+$ & $3^-$ vibrational states of $^{58}Ni$, one needs $2^+$ & $3^-$ states of states of $^{18}O$-isotope. The small deviation between so obtained calculation & experimental findings can be linked with positive *Q*-value neutron transfer channels (PQNT). The data of aforementioned reactions are analyzed by choosing SAGBD formalism and Wong formula. The potential parameters and corresponding barrier characteristics for $^{16}O + ^{60}Ni$ and $^{18}O + ^{58}Ni$ reactions are taken from Ref. [3] and are given in tables 1 and 2, respectively. Theoretical results predicted by Wong formula greatly underestimated with respect to data of $^{16}O + ^{60}Ni$ & $^{18}O + ^{58}Ni$ systems. The influences of internal channels of participants can be integrated into the SAGBD framework via weighted Gaussian function, and such framework-based predictions eliminate the inconsistencies between Wong based results and experimental outcomes. The multi-dimensional feature of nuclear potential lowers interaction barrier between fusing systems in the

SAGBD calculations, which then addresses fusion processes of $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni systems as shown in figure 1(a). In SAGBD results, the role of inherent channels associated with reaction partners are analyzed in terms of $\lambda$ & $V_{CBRED}$. The calculated values of $\lambda$ ($V_{CBRED}$) for $^{16}$O + $^{60}$Ni & $^{18}$O + $^{58}$Ni reactions are 1.29 (3.73% of $V_{CB}$) & 1.34 (4.07% of $V_{CB}$), respectively [3]. The extracted values of aforesaid parameters are found larger for $^{18}$O + $^{58}$Ni reaction than $^{16}$O + $^{60}$Ni reaction, which suggested that $^{18}$O + $^{58}$Ni reaction shows additional fusion enhancement which may be attributed to PQNT channel. Hence, SAGBD results adequately describes the shape of fusion cross-sections data.

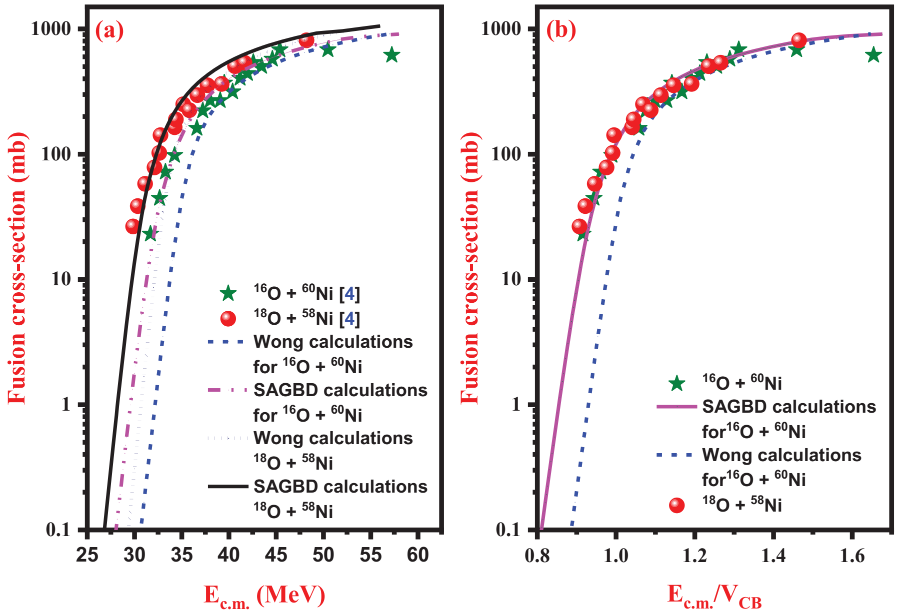


**Figure 1.** (a) Fusion cross-sections as a function of $E_{c.m.}$ for $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni systems predicted by SAGBD method and Wong formula. (b) Fusion data in reduced scale for $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni systems.

The fusion data of $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni systems and Wong based predictions & SAGBD outputs are picturized as a function of $E_{c.m.}/V_{CB}$ in figure 1(b). In this figure small additional enhancement is observed for $^{18}$O + $^{58}$Ni reaction over $^{16}$O + $^{60}$Ni reaction, which reflects presence of PQNT channel in $^{18}$O + $^{58}$Ni reaction. On the other hand, such channel is absent in $^{16}$O + $^{60}$Ni reaction. Despite of the fact that both events have different entrance channels, yet produce same composite nucleus i.e., $^{76}$Kr. According to the published literature [3], higher mass asymmetry (η) increases possibility to happen fusion in sub-barrier realm. The values of η for $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni reactions are 0.579 and 0.526, respectively [3]. Besides smaller value of η, $^{18}$O + $^{58}$Ni reaction exhibits greater fusion enhancement that can be connected with PQNT channel.

## 4. Conclusions

The SAGBD computations reproduced fusion data of $^{16}$O + $^{60}$Ni and $^{18}$O + $^{58}$Ni reactions, while Wong based results underestimate with reference to the data. It emphasizes that SAGBD method involves barrier modifications that greatly decreases the height of the nominal barrier, thereby offering a credible addressal for the fusion of $^{16}$O + $^{60}$Ni & $^{18}$O + $^{58}$Ni events. The positive and large values of $\lambda$ & $V_{CBRED}$ clearly demonstrated that impacts due to the inherent channels are properly taken into account in the predictions in

SAGBD approach. In $^{16}O$ + $^{60}Ni$ reaction only target's inherent channels are supposed to explain enhancement as suggested in literature. In contrast, $^{18}O$ + $^{58}Ni$ reaction results in a considerable enhancement over $^{16}O$ + $^{60}Ni$ due to participation of inelastic surface excitations in $^{18}O$ & $^{58}Ni$. As SAGBD approach retrieve the fusion data of both reactions, therefore model predictions inherently consider the influences of vibrational states and/or particle transfer channel.

**Acknowledgement**
The author Samiksha acknowledges to CSIR, India for providing Junior Research fellowship under grant number 09/1347(16516)/2023-EMR-I.

**References**

[1] Balantekin A B and Takigawa N 1998 *Rev. Mod. Phys.* **70** 77-100
[2] Wong C Y 1973 *Phys. Rev. Lett.* **31** 766-769
[3] Vijay *et al* 2022 *Phys. Scr.* **97** 045305
[4] Silva C P *et al* 1997 *Phys. Rev. C* **55** 3155-58