Fusion cross-sections for $^{6}Li +^{90} Zr$ reaction studied using Skyrme Energy Density Formalism

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Introduction

The investigation of nuclear reactions has been a topic of considerable interest as it assists in understanding nuclear structure, the underlying nuclear forces and related aspects. Besides this, the explicit study of nuclear reactions also holds importance as it aids in understanding various phenomena like fusion, fission, deep inelastic collision (DIC), quasi-fission (qf) etc. Moreover, in order to understand the existence of a nuclear system, the precise and systematic understanding of fusion process and the associated ion-ion interaction potential is essential.
In view of this, the fusion cross-sections for ^{6}Li-induced reaction have been analyzed in the framework of Skyrme Energy Density Formalism (SEDF). To study the dynamics of $^{6}Li+^{90}Zr \rightarrow^{96} Tc^{*}$ reaction, the Wong model [1] has been employed to estimate the fusion cross-sections using SIII Skyrme force accounted via semiclassical extended Thomas-Fermi (ETF) approach of SEDF. Apparently, the Wong model concentrates mainly on interaction barrier for s-wave, thus excludes the ℓ-dependent barrier modification. This requisite barrier component is included in the extended ℓ-summed Wong formula [2], which is employed to address the ℓ dependence of potentials involved in the calculations. It is relevant to mention that in one of our earlier work, the role of rotational energy and deformations was analyzed for $^{6}Li +^{90} Zr$ reaction in view of complete and incomplete fusion dynamics with in dynamical cluster decay model [3] using proximity potential of Blocki et. al.

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Methodology

In the present work, the nuclear proximity potential has been calculated by using the ETF approach within the framework of SEDF. The energy density formalism defines the nuclear interaction potential as

$$V_N(R) = E(R) - E(\infty) \qquad (1)$$

where, $E = \int H(\vec{r})d\vec{r}$ with H as the Skyrme Hamiltonian density.
Thereafter, the barrier characteristics (V_B^{ℓ}, R_B^{ℓ}, and $\hbar\omega_B^{\ell}$) obtained for $\ell = 0$ are used to calculate the fusion cross-sections within Wong approach, which reads as

$$\sigma(E_{c.m.},\theta_i) = \frac{R_B^{02}\hbar\omega}{2E_{c.m.}} \ln\left[1 + exp\left(\frac{2\pi}{\hbar\omega}(E_{c.m.} - V_B^0)\right)\right] \qquad (2)$$

On the other hand the fusion cross-sections, in terms of ℓ partial waves of two deformed and oriented nuclei lying in same plane, can be estimated using extended ℓ-summed Wong formula, which is given as follows

$$\sigma(E_{c.m.},\theta_i) = \sum_{\ell=0}^{\ell_{max}} \sigma_\ell = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}} (2\ell+1)P_\ell(E_{c.m.},\theta_i) \qquad (3)$$

with $k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}}$, and μ as the reduced mass. Here, P_ℓ is the transmission coefficient for each ℓ which describes the penetration of barrier given by,

$$V_T^{\ell}(R) = V_c(R,Z_i,\beta_{\lambda i},T,\theta_i) + V_N(R,A_i,\beta_{\lambda i},T,\theta_i) + V_\ell(R,A_i,\beta_{\lambda i},T,\theta_i) \qquad (4)$$

Hence, the fusion cross-section integrated over the angles θ_i is obtained as

$$\sigma(E_{c.m.}) = \int_{\theta_i=0}^{\pi/2} \sigma(E_{c.m.},\theta_i)\sin\theta_i d\theta_i. \qquad (5)$$

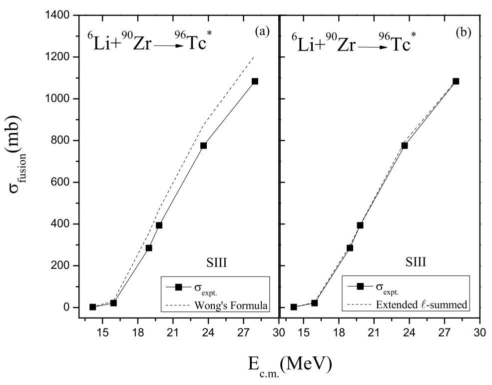

FIG. 1: Comparison of fusion cross-sections calculated for $^6Li+^{90}Zr$ reaction using Skyrme force SIII, with the experimental data [4] for the use of (a)Wong's formula (b) extended ℓ-summed Wong formula.

TABLE I: The Wong formula and extended ℓ-summed Wong's formula based fusion cross-sections for $^{96}Tc^*$ using SIII force, over a wide range of $E_{c.m.}$, compared with the experimental data [4]. Also, tabulated are the ℓ_{max}-values at corresponding $E_{c.m.}$ energies.

$E_{c.m.}$	T	ℓ_{max}	σ_{fus}(mb)		
(MeV)	(MeV)	($\hbar$)	Wong formula	ℓ-summed Wong	Expt.
14.17	1.45	3	2.44	1.65	1.95
15.94	1.51	4	31.32	24.92	21.45
18.94	1.59	7	356.31	297.31	285.11
19.82	1.61	8	471.06	394.52	393.89
23.59	1.71	13	874.28	794.54	775.89
27.96	1.81	17	1207.72	1086.47	1084.06

Results and Calculations

In a recent experiment [4] on the fusion of ^6Li projectile with medium mass ^{90}Zr nucleus, the complete fusion cross-sections have been measured over a wide range of incident energies varying from $E_{c.m.} = 14.17 - 27.96MeV$, spread across the Coulomb barrier. The reaction under study is of great interest as it involves light weakly bound projectile ^6Li induced on medium mass target ^{90}Zr having neutron shell closure and proton sub-shell closure, which may influence the fusion cross-sections. In view of this, the cross-sections of $^{96}Tc^*$ nucleus have been studied using Skyrme force SIII, for the use of Wong [1] and ℓ-summed Wong [2] formula using Skyrme Energy Density approach for addressing nuclear interaction potential. Firstly, the fusion cross-sections were calculated using Wong formula and compared with experimental results. Fig.1 shows the fusion cross-sections of ^6Li-induced reaction over a wide range of $E_{c.m.}$, using SIII force. One may notice that, at above barrier energies, the fusion cross-sections calculated using Wong model are enhanced as compared to the experimental data. This discrepancy in the calculated and the measured fusion cross-section may be attributed to the fact that Wong formula is solely dependent on the interaction barrier of s-wave ($V_B^{\ell=0}$). Moreover, the variation in the magnitude of the barrier height due to temperature effects is found to be very minimal, under semiclassical approach [5]. As a possible remedy of this issue, the cross-sections are calculated using extended Wong formula, i.e. ℓ-summed Wong model. It has been observed that due to ℓ-summation procedure the fusion cross-sections calculated using extended Wong model for the use of SIII Skyrme force find nice agreement with experimental data. The cross-sections calculated at all energies for the Wong and ℓ-summed Wong model have been tabulated in Table I, and compared with experimental data. It is clearly evident from fig1 and Table I that the comparison with the experimental data improves significantly after the mechanism of ℓ-dependence in the barrier characteristics is employed, and the ℓ-summed Wong approach seems equally good for addressing the fusion of loosely bound reaction.

References

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