

Fusion in sub barrier energies in $^{19}\text{F}+^{158}\text{Gd}$ reactions

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Introduction

Heavy-ion induced fusion reactions have been extensively studied over the past four decades, particularly following the experimental findings of fusion enhancement below the Coulomb barrier. Heavy-ion fusion reactions provide valuable insights into the synthesis of heavy and superheavy elements, and also have astrophysical implications [1]. One-dimensional barrier penetration models (1DBPM) have been unable to fully explain the theory of heavy-ion fusion, particularly the effects of coupling, the vibrations and quadrupole and octupole deformations of projectile and target nuclei, and also positive Q value neutron transfer (PQNT) [2,3]. During a nuclear collision, as the interacting nuclei approach each other, one or more neutrons may be transferred from the projectile to the target, or vice versa, prior to or in the course of the fusion process. However, there were a few fusion measurements in which the systems with PQNT does not show any effect of neutron transfer in fusion. To address this, we analysis the fusion mechanism in $^{19}\text{F}+^{158}\text{Gd}$ reactions using coupled channel code CCFULL [4].

Methods

It is found several measurements that the fusion cross section below barrier was substantially larger than the 1DBPM predictions. This has been attributed to the coupling of various degrees of freedom such as deformations, vibrations and transfer effects. The coupled-channel equations are given by[5]:

$$-\frac{\hbar^2}{2\mu} \frac{d^2}{dr^2} + \frac{J(J+1)\hbar^2}{2\mu r^2} + V_N^{(0)}(r) + \frac{Z_P Z_T e^2}{r} + \epsilon_n - E\psi_n(r) + \sum_m V_{nm}(r)\psi_m(r) = 0 \quad (1)$$

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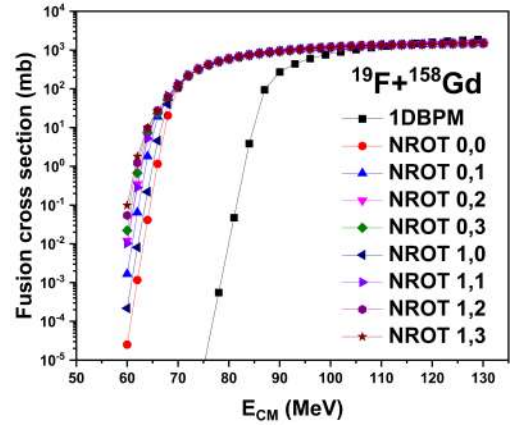


FIG. 1: The fusion cross section of $^{19}\text{F}+^{158}\text{Gd}$ compared with the theoretical predictions considering with different rotation coupling of both projectile and target.

where, μ is the reduced mass, r is the internuclear distance, J is the total angular momentum, $V_N^{(0)}(r)$ is the bare nuclear potential, $\frac{Z_P Z_T e^2}{r}$ is the Coulomb potential between projectile and target, ϵ_n is the excitation energy of the intrinsic state n , E is the total energy in the center-of-mass frame, $V_{nm}(r)$ represents the couplings between channels n and m , $\psi_n(r)$ is the radial wave function for channel n . The wave function solution $\psi_m(r)$ in each channel is expressed as a linear combination of functions $\chi_{nm}(r)$:

$$\psi_m(r) = \sum_n T_n \chi_{nm}(r) \quad (2)$$

where, $\chi_{nm}(r)$ be the wave function of the m^{th} channel and T_n is the transmission coefficient.

Result and Discussion

The fusion excitation function for the system $^{19}\text{F}+^{158}\text{Gd}$ has been calculated using the coupled-channel code CCFULL. The two-neutron pickup

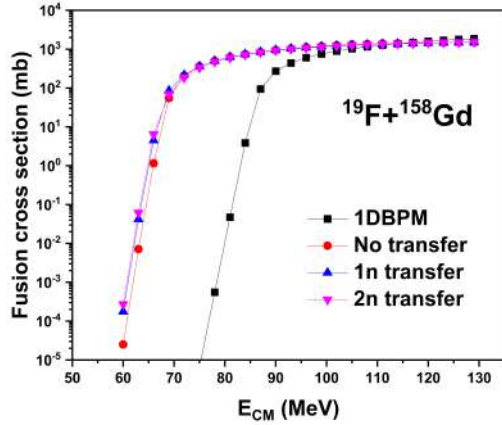


FIG. 2: The fusion cross section of $^{19}\text{F} + ^{158}\text{Gd}$ compared with the theoretical predictions considering with different neutron transfer.

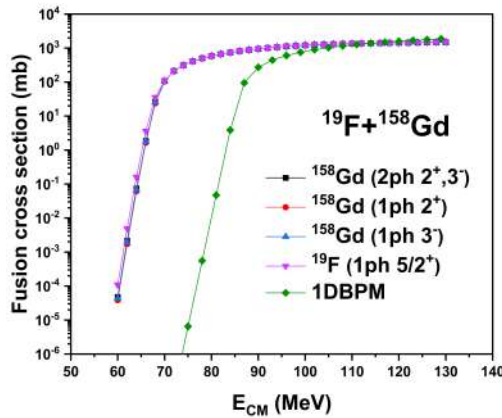


FIG. 3: The fusion cross section of $^{19}\text{F} + ^{158}\text{Gd}$ compared with the theoretical predictions considering with different vibrational state.

transfer channel has a positive Q-value and produces a much larger enhancement compared to both the one-neutron transfer and the no-transfer cases. When rotational excitations of the target and projectile are included, the fusion cross section shows significant enhancement at sub-barrier energies. The inclusion of additional rotational couplings further increases the enhancement at lower

energies. The fusion excitation function for the system $^{19}\text{F} + ^{158}\text{Gd}$ has been calculated, with vibrational excitations of both projectile and target nuclei included. The one-dimensional barrier penetration model (1DBPM) underpredicts the fusion cross sections at sub-barrier energies, showing a steep rise only at higher E_{CM} . In contrast, the coupled-channel calculations that incorporate the low-lying vibrational states of ^{158}Gd (2^+ , 3^-) and ^{19}F ($5/2^+$) reproduce the experimental-like enhancement of fusion cross sections at energies below the Coulomb barrier. The inclusion of single-phonon and two-phonon excitations of ^{158}Gd leads to significant sub-barrier fusion enhancement compared to the 1DBPM prediction, indicating the strong role of target vibrational couplings. Similarly, the coupling to the $1\text{p}h\ 5/2^+$ state of ^{19}F further contributes to the enhancement, producing nearly identical results across the considered channels.

Conclusion

Rotational couplings in ^{158}Gd play a dominant role in fusion dynamics by fragmenting the single barrier into a distribution of barriers, thereby lowering the effective barrier height and enhancing the fusion probability. The inclusion of additional rotational states systematically increases the sub-barrier fusion cross sections. Coupled channel effects significantly enhance fusion probabilities below the barrier, while positive Q neutron transfer (PQNT) provides further enhancement relative to the no transfer case. The study confirms that coupling to vibrational excitations of both the target (^{158}Gd) and projectile (^{19}F) plays a crucial role in enhancing the sub-barrier fusion probability, in contrast to the strong suppression predicted by the simple 1DBPM.

References

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