Fusion hindrance investigation for $^{27}Al + ^{45}Sc$ system using Skyrme energy density formalism

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Introduction

Recently an experiment was performed at Argonne National Laboratory by Jiang and co-worker [1] using super-conducting linear accelerator ATLAS to measure the fusion cross-section for a positive Q-value $^{27}Al + ^{45}Sc$ system down to about 300 nb and calculations were done using coupled channel (CC), optical model and shallow model to reproduce the fusion data. Both CC, optical model calculations shows fusion hindrance for this system.

We use the Skyrme energy density formalism (SEDF) in semiclassical extended Thomas-Fermi approach to calculate the nucleus-nucleus interaction potential, where kinetic energy and spin-orbit densities are expanded up-to the second order and two parameter Thomas-Fermi density is used as nuclear density with its parameters taken from our earlier work [2]. The characteristics of the obtained interaction potential are used in Wong's formula to calculate the fusion cross-section as a function of center of mass energy.

Methods

Following our earlier work of [2, 3], the nuclear interaction potential between two spherical nuclei of central radii R_{01} and R_{02}, whose centers are separated by $R = R_{01} + R_{02} + s$, in the slab approximation is

$$V_N(R) = 2\pi\bar{R}\int_{s_0}^{\infty} e(s)ds, \qquad (1)$$

where $\bar{R} = R_{01}R_{02}/(R_{01} + R_{02})$ is the mean curvature radius and defines the geometry of the system, $e(s)$ is the interaction energy per unit area between two flat slabs of semi-infinite nuclear matter with surfaces parallel to the $x - y$ plane and moving in the z-direction and separated by distance s, is

$$\int_{s_0}^{\infty} e(s)ds = \int\{H(\rho,\tau,\vec{J}) - [H_1(\rho_1,\tau_1,\vec{J_1}) + H_2(\rho_2,\tau_2,\vec{J_2})]\}dz, \qquad (2)$$

where H is the Skyrme Hamiltonian density of the compound system (CS). Similarly, $\rho(=\sum_i \rho_i)$, $\tau(=\sum_i \tau_i)$ and $\vec{J}(=\sum_i \vec{J_i})$ are nuclear density, kinetic energy density and spin-orbit density, respectively for CS and i=1, 2 for two interacting nuclei (for detail see [2]). Since, both the kinetic energy density and spin-orbit density are function of nuclear density therefore $H(\rho,\tau,\vec{J}) \to H(\rho)$. The two parameter Fermi density in slab approximation with temperature dependence included [3] is

$$\rho_i(z_i,T) = \rho_{0i}(T)\left[1 + \exp\left(\frac{z_i - R_{0i}(T)}{a_{0i}(T)}\right)\right]^{-1} \qquad (3)$$

with $z_2 = R - z_1$ and central density is

$$\rho_{0i}(T) = \frac{3A_i}{4\pi R_{0i}^3(T)}\left[1 + \frac{\pi^2 a_{0i}^2(T)}{R_{0i}^2(T)}\right]^{-1}. \qquad (4)$$

The central radii R_{0i}, surface thicknesses a_{i0} and temperature dependence of these parameters is taken from [2]. The nuclear density ρ_i $(= \rho_{n_i} + \rho_{p_i})$ with neutron densities $\rho_{n_i} = (N_i/A_i)\rho_i$, and protons densities $\rho_{p_i} = (Z_i/A_i)\rho_i$, i=1, 2 for two nuclei.

Finally, adding Coulomb potential $V_C = \frac{Z_1 Z_2 e^2}{R}$ to the nuclear interaction potential $V_N(R)$, which includes nuclear proximity potential $V_P(R)$ and spin-orbit potential $V_J(R)$,

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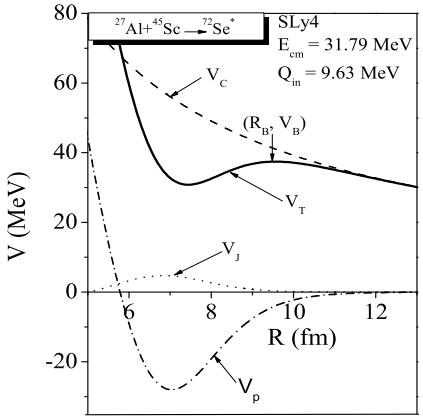

FIG. 1: The solid line, dashed line, dashed-dot line and dotted line shows respectively the total interaction potential, the Coulomb potential, proximity potential and the spin-orbit interaction potentials as a function of R, calculated using Skyrme energy density formalism, except Coulomb potential which is added directly.

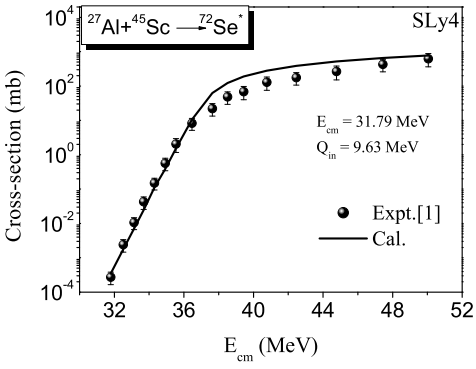

FIG. 2: The calculated fusion cross-section (solid line) is compared with the measured cross-section (solid sphere) as a function of E_{cm}. The data is taken from ref. [1]

gives the total interaction potential

$$V_T(R) = V_N(R) + V_C(R). \quad (5)$$

The fusion cross-section as a function of center of mass energy (E_{cm}) is calculated using Wong's Formula [4], given as

$$\sigma(E_{cm}) = \frac{\hbar\omega_0 R_B^2}{2E_{cm}} \ln\left[1 + e^{\left(\frac{2\pi}{\hbar\omega_0}(E_{cm}-V_B)\right)}\right]. \quad (6)$$

where barrier height V_B, barrier position R_B and curvature $\hbar\omega_0$ used in Eq. 6 are the characteristics of the total interaction potential $V_T(R)$.

Calculations and results

The nuclear potential is calculated using the Skyrme energy density formalism in semi-classical extended Thomas-Fermi approach for Skyrme force $SLy4$ at E_{cm} of 31.79 MeV for a positive Q-value system $^{27}Al+^{45}Sc$ as a function of inter-nuclear distance. In Fig. 1, the solid line shows the total nucleus-nucleus interaction potential $V_T(R)$, the dashed lines is for the Coulomb potential $V_C(R)$, the dashed-dotted line represent the nuclear proximity potential $V_P(R)$ and dotted line shows the spin-orbit density dependent potential $V_J(R)$, where $V_N(R) = V_P(R) + V_J(R)$.

The characteristics of potential shown in Fig. 1 are used in Eq. 6 to calculate the fusion cross-sections as a function of E_{cm}. The comparison of the calculated fusion cross-sections over center of mass energy range $31-50$ MeV with the fusion data of ref. [1] is shown in Fig. 2. Our calculated fusion cross-sections are in excellent agreement with the fusion data for energies below 36.4 MeV and above over-predicts by almost an order of magnitude. This means $^{27}Al+^{45}Sc$ system is not showing fusion hindrance with respect to the calculations of SEDF, as was seen for the CC and optical model calculations in ref. [1].

References

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