

Evolution of fusion hindrance for asymmetric systems at deep sub-barrier energies



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ABSTRACT

Measurements of fusion cross-sections of ^7Li and ^{12}C with ^{198}Pt at deep sub-barrier energies are reported to unravel the role of the entrance channel in the occurrence of fusion hindrance. The onset of fusion hindrance has been clearly observed in $^{12}\text{C} + ^{198}\text{Pt}$ system but not in $^7\text{Li} + ^{198}\text{Pt}$ system, within the measured energy range. Emergence of the hindrance, moving from lighter ($^6,^7\text{Li}$) to heavier (^{12}C , ^{16}O) projectiles is explained employing a model that considers a gradual transition from a sudden to adiabatic regime at low energies. The model calculation reveals a weak effect of the damping of coupling to collective motion for the present systems as compared to that obtained for systems with heavier projectiles.

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1. Introduction

Fusion reactions in the vicinity of the Coulomb barrier have been investigated in the past to explore the mechanism of tunneling through multidimensional barriers, thereby giving an insight into the role of different intrinsic properties of the entrance channel. Recent efforts towards developing new methods to precisely measure very low fusion cross-sections have stimulated new activities, distinct to energies deep below the barrier. Fusion data at these low energies can be uniquely used to interpret the reaction dynamics from the touching point to the region of complete overlap of the density distribution of the colliding nuclei, not accessible through any other reaction [1,2]. This opens up the possibility to study effects of dissipative quantum tunneling, which has relevance in many fields of physics and chemistry [3]. The data in this energy range was shown to have strong implications on the fusion with light nuclei of astrophysical interest [2].

At deep sub-barrier energies, a change of slope of the fusion excitation function compared to coupled-channels (CC) calculations

was observed initially in symmetric systems involving medium-heavy nuclei and was referred to as the phenomenon of fusion hindrance [4,5]. The models suggested to explain this behavior have different physical basis. The model proposed by Mişicu and Esbensen is based on a sudden approximation [6], where a repulsive core is included to take into account the nuclear compressibility arising due to Pauli exclusion principle when the two nuclei overlap. On the other hand at low energies, the nucleus–nucleus interaction potentials extracted from the microscopic time-dependent Hartree–Fock theory indicate that after overlap of two nuclei, internal degrees of freedom reorganize adiabatically [7]. The model proposed by Ichikawa et al. [8] to explain the deep sub-barrier fusion data is based on such an adiabatic picture. Here a damping factor imposed on the coupling strength as a function of the inter-nuclear distance, takes into account a gradual change from the sudden to the adiabatic formalism [9,10]. A recent work, applying the random-phase-approximation (RPA) demonstrates that the fusion hindrance originates from damping of quantum vibrations when the two nuclei adiabatically approach each other [11,12]. The role of quantum de-coherence that effectively causes a reduction in coupling effects has also been investigated [13,14].

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In all the above models, fusion hindrance is a generic property of heavy-ion collision below certain threshold energy. Due to challenges involved with measurement of low cross-section ($\sim \text{nb}$), there are only a limited number of studies involving fusion hindrance. As discussed in a recent review article [2], these studies have mainly concentrated around medium-heavy ($A \sim 100$), medium ($A \sim 50$) and light ($A \sim 10$) symmetric systems [4,5,15–21], covering a wide range of reduced masses, Q -values and nuclear structure properties. Most of the measurements employed recoil mass analyzers and hence are restricted to symmetric or nearly symmetric systems. In such cases the evaporation residues have sufficient recoil velocities for being detected at the focal plane of the spectrometer. The data corresponding to asymmetric systems, presently scarce, are vital to establish the generic nature of the fusion hindrance and for the improvement of current theoretical models. The only exception being the two systems $^{16}\text{O} + ^{208}\text{Pb}$ [14] and $^6\text{Li} + ^{198}\text{Pt}$ [22] that used different methods for fusion cross-section measurements. The presence of fusion hindrance was clearly shown in $^{16}\text{O} + ^{208}\text{Pb}$ system [14]. The shapes of the logarithmic derivative and astrophysical S -factor for this asymmetric system were found to be different, compared to those for the symmetric systems [1,2]. In the case of a more asymmetric system $^6\text{Li} + ^{198}\text{Pt}$ [22], an absence of fusion hindrance was reported at energies well below the threshold energy (E_T) computed from both the sudden and adiabatic models. For reactions induced by protons, intuitively one would not expect fusion hindrance. In this case, the projectile maintains its identity and the sudden approximation would be appropriate. This should be the case for alpha particle as well, which can be treated as a rigid nucleus. On the other hand for heavier projectiles, such as ^{12}C and ^{16}O , one may expect a neck formation at low energies when the colliding nuclei follow the minimum energy path allowing for the readjustment of the densities as a function of the collective variables. Deviation from a simple sudden picture is expected to occur for nuclei heavier than ^4He .

The present work investigates the evolution of the fusion hindrance with increasing mass and charge of relatively light projectiles (^6Li , ^{12}C , ^{16}O) on heavy targets. For this purpose we have performed new measurements at deep sub-barrier energies with ^7Li and ^{12}C projectiles on a ^{198}Pt target. The current results along with the available data for different entrance channels have been studied to understand the origin of the fusion hindrance.

2. Experimental details and results

The experiments were performed at the Pelletron-Linac Facility, Mumbai, using beams of ^7Li (20–35 MeV) and ^{12}C (50–64 MeV) on a ^{198}Pt target with beam current in the range of 10 to 35 pA. The targets were foils of ^{198}Pt (95.7% enriched, $\sim 1.3 \text{ mg/cm}^2$ thick) followed by an Al catcher foil of thickness $\sim 1 \text{ mg/cm}^2$. The cross-sections have been extracted using a sensitive and selective offline method employing KX- γ ray coincidence [22,23]. Two efficiency calibrated HPGe detectors – one with an Al window for detection of γ -rays and another with a Be window for detection of KX-rays, having an active volume $\sim 180 \text{ cc}$ were placed face to face for performing KX- γ -ray coincidence of the decay radiations from the irradiated sample. The irradiated targets were mounted at $\sim 1.5 \text{ mm}$ from the face of each detector. The measurements were performed in a low background setup with a graded shielding (Cu, Cd sheets of thickness $\sim 2 \text{ mm}$ followed by 10 cm Pb). The evaporation residues from complete fusion were uniquely identified by means of their characteristic γ -ray energies and half-lives which correspond to $^{205-207}\text{Po}$ in case of $^{12}\text{C} + ^{198}\text{Pt}$ and $^{200-202}\text{Tl}$ in case of $^7\text{Li} + ^{198}\text{Pt}$ systems. The γ -ray yields of the daughter nuclei at lowest energies were extracted by gating on their KX-ray transi-

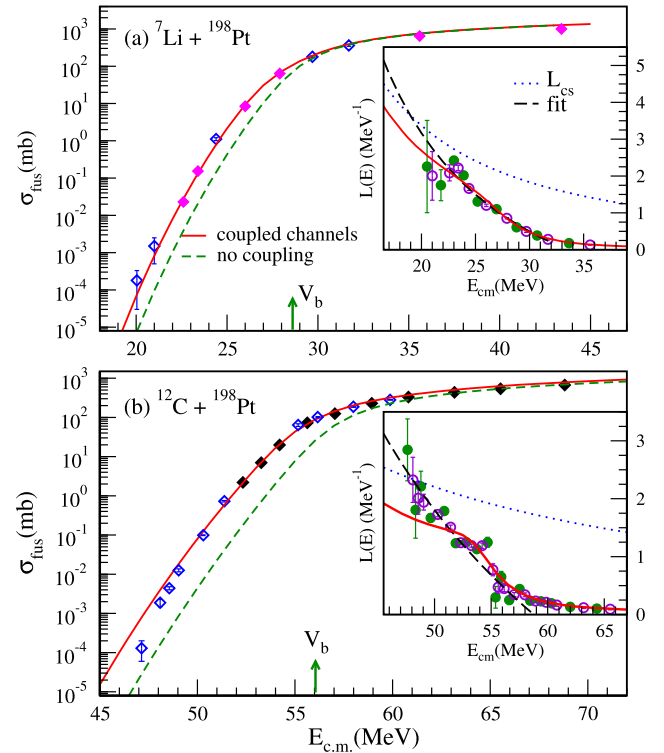


Fig. 1. (Color online.) Fusion excitation function and its logarithmic derivative (inset) for (a) $^7\text{Li} + ^{198}\text{Pt}$ and (b) $^{12}\text{C} + ^{198}\text{Pt}$ systems. The arrow indicates the value of the Coulomb barrier (V_b). The cross-sections from Refs. [25,27] are shown as filled diamonds. The $L(E)$ values shown as closed and open circles were obtained from two consecutive data points and least-squares fits to three successive data points, respectively. The results of the coupled-channels calculations (solid line) along with single channel calculations (dashed line) using the code CCFULL are also shown. The $L(E)$ values fitted to an expression and that corresponding to a constant S -factor ($L_{cs}(E)$) are shown as long dashed and dotted curves, respectively (see text).

tions. Further details on the method can be found in Ref. [23]. Due to the increased sensitivity of the KX- γ -ray coincidence method, cross-section down to 130 nano-barns could be measured. The fusion cross-sections were obtained from the sum of the measured evaporation residue cross-sections. In case of $^{12}\text{C} + ^{198}\text{Pt}$ system, the fission cross-section was also taken into account using data from Ref. [25], up to the beam energy where fission cross-section was $\sim 0.5\%$ of the fusion cross-section. The statistical model calculations for the compound nuclear decay were performed using PACE [24] with parameters from Refs. [22,25] which reproduce the residue cross-sections well for both the systems. The estimation of errors for low counting rates was made assuming Poisson statistics and using the method of maximum likelihood [26]. The present results are shown in Fig. 1, together with the cross-sections obtained in Refs. [25,27]. The error on the data points in Fig. 1 is only statistical in nature.

Plotted in the inset of Fig. 1(a) and (b) are the logarithmic derivatives of the fusion cross-section ($L(E) = d[\ln(\sigma_f)]/dE$), determined using two consecutive data points and also performing a least square fit to a set of three data points. This representation provides an alternate way to illustrate any deviations in the slope of the fusion excitation function independent of the weight of the lowest barrier [2]. The $L(E)$ values fitted to the expression $(A + B/E^{3/2})$ and that corresponding to a constant astrophysical S -factor ($L_{cs}(E)$) [28] are shown as long dashed and dotted lines respectively. The cross-over point between the $L(E)$ and $L_{cs}(E)$ corresponds to peak of the S -factor and can be related to the threshold energy for observing fusion hindrance [28].

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