Study of fusion reactions deep below the barrier

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Coupled-channels (CC) formulation has been quite successful in explaining the enhancement of sub-barrier fusion cross-sections. With the availability of precise measurement techniques using advanced recoil separators, measurements were extended down to deep sub-barrier energies to understand the stellar nucleosynthesis. Such reactions occur at energies a few orders below the Coulomb barrier. In doing so, a steep fall in fusion cross sections was observed deep below the barrier, which was termed as *fusion hindrance* [1]. The standard CC calculations over-predicted the cross sections at the lowest energies. Following the first observation of fusion hindrance, many other light ion-induced and heavy ion-induced reactions were studied. A systematic trend was observed for the threshold energy at which onset of fusion hindrance occurred [2]. Based on the logarithmic derivative of the energy-weighted cross section, $L(E)$ and the S-factor, an empirical relation was established to evaluate the threshold energy for hindrance which depended on the parameter $\zeta = Z_1 Z_2 \sqrt{\mu}$, where Z_i are the atomic number of the participating nuclei and μ is the reduced mass. Systems with deformed nuclei or positive Q-value neutron transfer (PQNT) channels were observed to show a delayed or no onset of hindrance. The empirical relation enables us to predict the threshold energy for the systems for which measurement of fusion cross sections at low energies are experimentally challenging. This difficulty can be addressed by measuring the quasi-elastic (QEL) scattering at centre of mass (c.m.) angle $\theta_{\rm c.m} = 180°$, which is complementary to fusion, since at this angle, the angular momentum, $\ell = 0$ [3].

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The aim of this thesis is to investigate fusion hindrance in asymmetric systems in different mass regions and also the role of entrance channel mass asymmetry. The reaction products from asymmetric systems pose an additional challenge in detection due to very low energy of evaporation residues (ERs). The ERs are unable to penetrate the mylar foil at the entrance of the gas-based detector system. The reactions chosen in this work did not have any PQNT channels which could compete with the hindrance. ^{16}O was chosen as the projectile due to its double closed shell structure, which is likely to facilitate onset of fusion hindrance. The results from the experiments were compared with systems, studied earlier, having similar values of ζ.

The experiment was performed in two runs using the Heavy Ion Reaction Analyzer (HIRA) [4] at IUAC, New Delhi. A pulsed beam of ^{16}O ions (pulse separation of 4 μs), was obtained from the 15UD Pelletron accelerator. Isotopically enriched ^{142}Ce and ^{116}Cd targets of thickness 121.7 μg/cm^2 [5] and 20 μg/cm^2, respectively, were used. Beam energy ($E_{\rm lab}$) were varied between 42 –76 MeV, in steps of 1 MeV. Two solid state silicon detectors (SSSDs) were placed at $\theta_{\rm lab} = 15°$ for beam monitoring and normalization. Two additional SSSDs were placed at backward angles of $\theta_{\rm lab} = 138°, 150°$ inside the target chamber to detect back-scattered projectile-like ions. The HIRA was operated at $\theta_{\rm lab} = 0°$ with an opening aperture of 5 mSr. A thin ($\sim 10\mu$g/cm^2) graphite charge-reset foil was placed in front of the opening aperture of the HIRA. A Multi-Wire Proportional Counter (MWPC) with dimensions 150 mm in χ and 50 mm in y was placed at the focal plane of the HIRA. The HIRA fields were set alternately for detection of ERs and target-like recoils (TRs) originating from fusion and QEL reactions, respectively, for each target at statistically viable energies. Energy loss (ΔE) information was obtained from the cathode of the MWPC. Two separate Time-to-Amplitude Converters (TACs) were set up to measure time-of-flight (TOF) of the ERs and TRs through the HIRA.

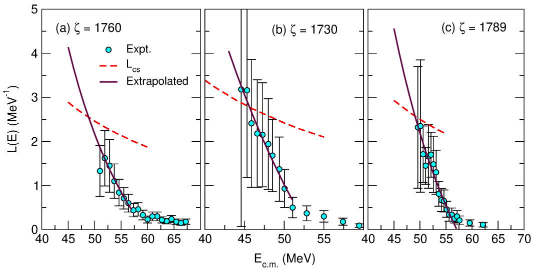

FIG. 1: Logarithmic slope (blue circles), logarithmic slope at S-factor maxima (L_{CS}, as red dashed line) and extrapolated logarithmic slope (maroon solid line) for (a)^{16}O+^{142}Ce, (b)^{28}Si+^{64}Ni and (c)^{40}Ca+^{40}Ca.

The ER yields at the focal plane of the HIRA were extracted from the ΔE-TOF spectra for both reactions. Relative abundance of ER channels were calculated using a statistical model for the decay of the compound nucleus (CN). Transmission efficiency of the ERs were determined using a semi-microscopic Monte Carlo code TERS [6]. $L(E)$, S-factor and barrier distributions were extracted from measured fusion excitation functions for both the systems, with the first two quantities being used to determine the threshold energy for fusion hindrance.

The yields of TRs at $\theta_{\text{lab}} = 0°$ (corresponding to yields of projectile-like ions at $\theta_{\text{c.m.}} = 180°$) were obtained from the χ-TOF spectra of TRs at the focal plane of the HIRA. The measured spectra were compared with spectra simulated by a semi-microscopic Monte Carlo code [7, 8]. This ensured unambiguous identification of the TRs. The differential QEL scattering cross-sections were calculated following the methodology presented in Ref. [8]. Barrier distributions were extracted from measured QEL scattering excitation functions. The differential QEL scattering cross-sections from back-scattered projectile-like ions were obtained from the energy spectra of the two SSSDs placed at backward angles. Reaction products with Q-value up to -10 MeV were considered in the calculation of cross sections. Centrifugal correction was applied to $E_{\text{c.m.}}$ to obtain the effective energy which was used in plotting the excitation functions and barrier distributions.

It has been observed from Fig. 1(a) that the system ^{16}O+^{142}Ce ($\zeta = 1760$) shows a clear sign of hindrance. The threshold energy lies at the point of intersection of the extrapolated $L(E)$ with the logarithmic slope at S-factor maxima ($L_{CS}(E) = 0.495\zeta/E^{3/2}$), the value of which matches with the empirical value [9]. The observations are in agreement with the observation of hindrance in the symmetric systems ^{40}Ca+^{40}Ca ($\zeta = 1789$) [10] and ^{28}Si+^{64}Ni ($\zeta = 1730$) [11] as shown in Fig. 1. In case of ^{16}O+^{116}Cd ($\zeta = 1440$), the non-monotonous rising trend of $L(E)$ at lower energies is not enough to conclude about the onset of fusion hindrance. Similar trend in $L(E)$ was also observed in the symmetric system ^{36}S+^{48}Ca ($\zeta = 1451$), in which presence of fusion hindrance was reported due to absence of PQNT channels [12].

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