Influence of neutron transfer channels on fusion dynamics near the Coulomb barrier for ^{28}Si + ^{116,120,124}Sn systems

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Abstract.
The phenomenon of enhanced fusion cross-section as compared to the theoretical predictions of 1-D BPM has been extensively studied over the past few decades. However, the unambiguous role of neutron transfer channels on the sub-barrier fusion enhancement is still elusive in most cases. Fusion cross-section measurements $\approx 15\%$ below and above the Coulomb barrier were performed to elucidate the mechanisms responsible for the experimentally observed sub-barrier fusion enhancement. Coupled-channels calculations using CCFULL were used to decipher the reaction dynamics. CC calculations explained the fusion excitation function for ^{28}Si + ^{116,120}Sn systems after the inclusion of inelastic excitations along with a pair transfer. However, the observed behavior for the ^{28}Si + ^{124}Sn system could not be explained. The fusion barrier distribution has been extracted from the experimental data to unveil the various channels coupled in the concerned rection. A single uncoupled barrier was transformed into a distribution of barriers depicting the presence of different channels coupled in the reaction. The results indicate a significant effect from multi-neutron transfer channels on the fusion dynamics.

1. Introduction

Heavy-ion fusion cross sections well above the Coulomb barrier can be reproduced using quantum mechanical one-dimensional barrier penetration model calculations (1-D BPM). However, at energies around and below the barrier, a large discrepancy between the experimentally obtained fusion cross-sections and theoretical predictions has been observed. The major cause of these enhanced fusion cross-sections at sub-barrier energies has been attributed to the coupling of various nuclear intrinsic degrees of freedom viz. collective excitations, transfer channels, and neck formation with the relative motion of the interacting partners [1]. This coupling results in a splitting of a single one-dimensional barrier into a distribution of barriers with different heights and weights. The distribution of barrier heights around the uncoupled barrier causes an enhanced fusion cross section at the sub-barrier energies due to penetration through the lower

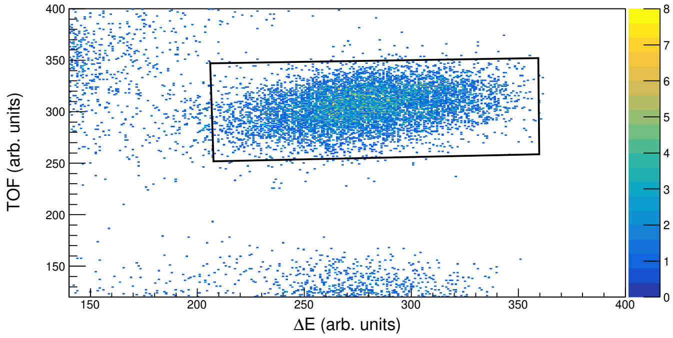

Fig. 1. Two-dimensional spectrum of energy loss (ΔE) vs Time of flight (TOF) for ^{28}Si + ^{116}Sn system at E_{lab} = 108 MeV. The region enclosed within rectangle indicates the evaporation residues reaching the focal plane detector MWPC.

barrier. Rowley *et al.* [2] proposed that the distribution of barriers can be extracted from the fusion excitation function by taking the second derivative of the product of the fusion cross-section and the center of mass-energy, ($E\sigma_{fus}$) with respect to E. The extracted fusion barrier distribution serves as a fingerprint to the mechanism involved in the nuclear reaction dynamics viz. nuclear structure of the participating nuclei and transfer channels involved in the reaction.

2. Experimental Details

The detailed experimental methodology adopted in the present work has been described in reference [3]. The experiment has been performed using the Heavy Ion Reaction Analyzer (HIRA) [4] facility at Inter-University Accelerator Centre, New Delhi, India. Enriched ^{116,120,124}Sn targets of thicknesses $\approx$ 200 μg/cm^2 with C backing of $\approx$ 20 μg/cm^2 were used in the target chamber of the HIRA. A ^{28}Si pulsed beam with a pulse separation of 2 μs and energy ranging from 88 MeV to 121 MeV was bombarded on the enriched Sn samples. Two silicon detectors at an angle of $\pm$ 15.5° with respect to the beam direction were placed inside the target chamber of HIRA for beam intensity monitoring. To detect the Evaporation Residues, a position-sensitive Multi-Wire Proportional Counter (MWPC) with an active area of 150 X 50 mm^2 was used at the focal plane of HIRA. The fusion cross-sections have been calculated using the yield of evaporation residues (ERs) which were separated from the beam-like particles at the focal plane using a 2-D spectrum between energy loss of ERs in MWPC versus time of flight (TOF). A raw spectrum obtained during the experiment for the ^{28}Si + ^{116}Sn system at E_{lab} = 108 MeV is shown in Fig. 1. The transmission efficiency of HIRA has been estimated using the semi-microscopic Monte-Carlo code TERS [5], which was found to be in the range 4 - 7 % .

3. Results and Discussion

The experimentally measured fusion excitation functions for ^{28}Si + ^{116,124}Sn systems are shown in Fig. 2. It has been observed from the fusion excitation function plots that the fusion cross-sections for all three Sn isotopes are enhanced by a substantial amount as compared to 1-D BPM predictions. The coupled-channels [6] formalism explained the fusion cross-sections for ^{28}Si + ^{116,120}Sn systems (Fig. 2(a)) after including the effects of inelastic and transfer channels. However, for ^{28}Si + ^{124}Sn system, a large deviation has been observed even after the inclusion of a pair transfer channel along with the inelastic excitations of the participating nuclei in the CC calculations (Fig. 2(b)). The ^{28}Si + ^{124}Sn system has multi-neutron positive Q-value transfer channels, which might be responsible for the additional enhancement in this case. The detailed data analysis along with the theoretical calculations using coupled-channels formalism

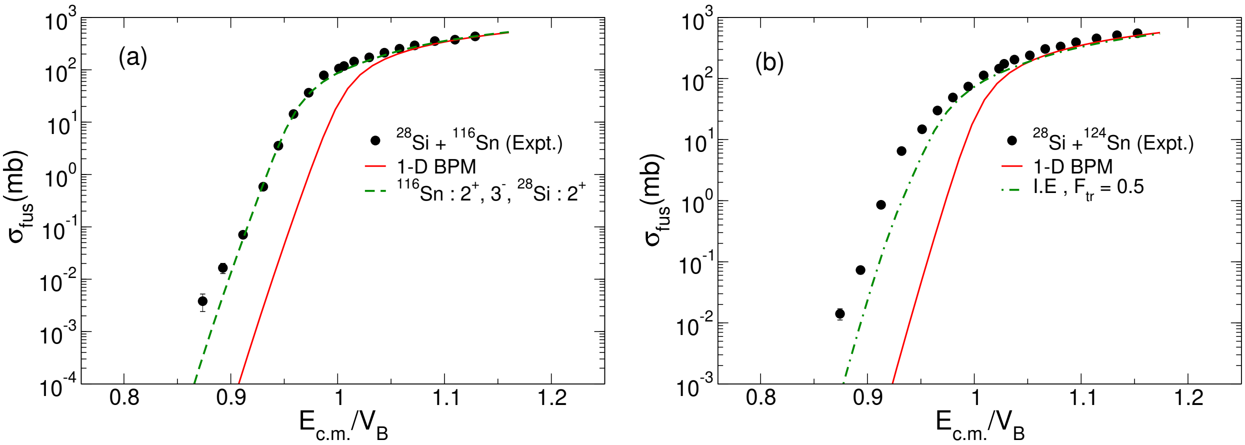

Fig. 2. Fusion excitation function for the (a) ^{28}Si + ^{116}Sn, and (b) ^{28}Si + ^{124}Sn systems along with uncoupled (1-D BPM) and coupled-channels calculations using CCFULL program.

is reported in reference [3]. Furthermore, to understand the underlying reaction dynamics and relevant channels coupled in the reaction, the fusion barrier distribution was extracted from the experimental data. The expression for extracting the barrier distribution at energy $E = (E_1 + 2E_2 + E_3)/4$, is given by

$$\frac{d^2(\sigma E)}{dE^2} = 2\left[\frac{(E\sigma)_3 - (E\sigma)_2}{E_3 - E_2} - \frac{(E\sigma)_2 - (E\sigma)_1}{E_2 - E_1}\right]\frac{1}{(E_3 - E_1)} \tag{1}$$

where $(E\sigma)_i$ have been evaluated at energies E_i. For data with equal energy steps, i.e. $\Delta E = (E_2 - E_1) = (E_3 - E_2)$,

$$\frac{d^2(\sigma E)}{dE^2} = \frac{(E\sigma)_3 - 2(E\sigma)_2 + (E\sigma)_1}{\Delta E^2} \tag{2}$$

Here ΔE is the energy step taken for extracting the second derivative. In the present analysis, an energy step of 1.5 MeV has been used around the Coulomb barrier and 2 MeV below the barrier for extraction of barrier distribution. The statistical error δ_c associated with the second derivative at energy E is approximately given by

$$\delta_c \simeq \left(\frac{E}{\Delta E^2}\right)[(\delta\sigma)_1^2 + 4(\delta\sigma)_2^2 + (\delta\sigma)_3^2]^{1/2} \tag{3}$$

where $\delta\sigma_i^2$ are uncertainties in the corresponding absolute cross sections.

Fig. 3 shows a single uncoupled peak (red continuous line) transformed into a distribution with varying probabilities resulting from the coupling of various channels in the vicinity of the barrier which evidently provides a better fit to the data. The barrier distributions are defined within the uncertainties at low energies, but at the near barrier and higher energies, uncertainties in the extracted distribution are high due to irregular energy step and errors getting transported to second order in the procedure of extraction of the fusion barrier distribution. Similar to fusion excitation function results, barrier distribution for the ^{28}Si + ^{116}Sn system can be explained after the inclusion of inelastic coupling into the CC calculations. However, no set of couplings could describe the entire barrier distribution for ^{28}Si + ^{120,124} Sn systems which might be due to the presence of multi-neutron positive Q-value transfer channels as is also reflected in the fusion excitation function plots. The height of the barrier resulting due

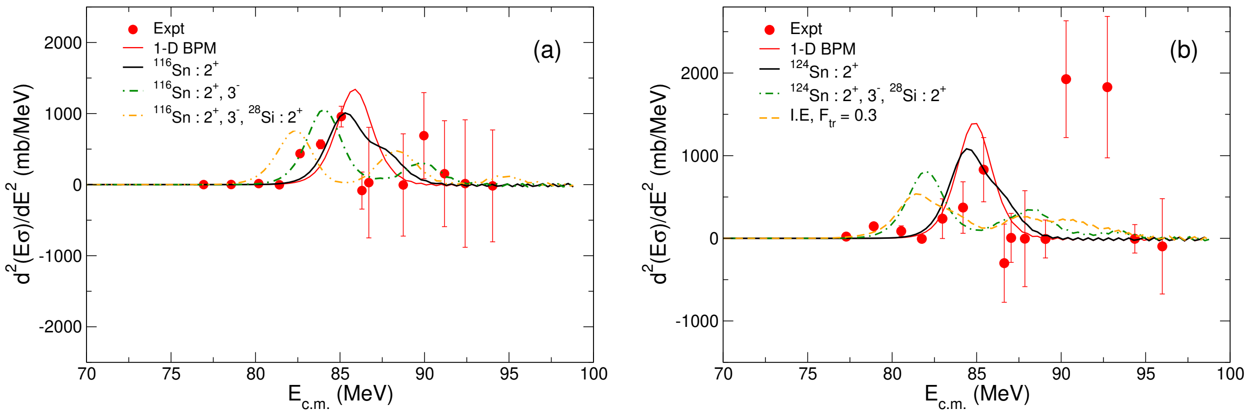

Fig. 3. Fusion barrier distribution for (a) ^{28}Si + ^{116}Sn, and (b) ^{28}Si + ^{124}Sn systems obtained using CCFULL program with low-lying inelastic excited states and one pair transfer channel coupling.

to coupling with the neutron transfer channel is less than that it would be if there was only coupling to inelastic excitations, which might result in enhancement in the fusion cross-section at sub-barrier energies due to transfer channels. Further, it has been observed that the extracted barrier distributions are slightly wider in the ^{28}Si + ^{124}Sn system as compared to its isotopic counterparts, which may indicate the presence of multi-neutron transfer channels in the system. More precise experimental data with minimum uncertainty in energy measurements along with smaller energy intervals would be beneficial to decipher and validate any inferences from the extracted barrier distributions.

4. Summary and Conclusions

The fusion cross-section measurements have been performed for ^{28}Si + ^{116,120,124}Sn systems in the vicinity of the Coulomb barrier to apprehend the influence of multi-neutron transfer channels in fusion reaction dynamics. The experimentally obtained fusion excitation functions for ^{28}Si + ^{116,120}Sn systems could be well explained within the coupled-channels framework. However, no set of couplings could describe the fusion excitation function in the entire energy domain for the ^{28}Si + ^{124}Sn system. The fusion barrier distribution extracted from the experimental data showed the distribution of a single uncoupled barrier into multiple barriers with varying weights and heights. The significance of multi-neutron transfer channels on sub-barrier fusion enhancement has been emphasized.

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