Importance of neutron transfer channels in sub-barrier fusion reaction mechanism

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Introduction

Heavy ion fusion reaction has been extensively studied for the last two decades. Fusion cross-sections show large enhancement with respect to theoretical prediction in sub-barrier energy region. It is well known that the enhancement occurs due to nuclear vibration, deformation and nucleon transfer. The influence of nuclear vibration and deformation is well described within the framework of coupled channel (CC) calculations . However, the role of neutron transfer is not yet explained.

Experimental investigations have shown that large enhancement in fusion cross-sections is due to neutron transfer channels with positive Q value [1]. But, few systems did not show any enhancement in spite of having positive Q value neutron transfer channels [2]. Hence, Q value is not the only criteria to infer the importance of neutron transfer on fusion. In a recent article, it was stated that enhancement is related to the increase in deformation of interacting nuclei after neutron transfer [3]. In other words, fusion will be weakly influenced by positive Q value neutron transfer channel if deformation of nuclei do not change or decrease after transfer. Moreover, it was recently reported that only valence neutrons i.e. 1n and 2n transfer channel with positive Q value has significant impact on sub-barrier fusion [4].

In order to examine above facts, a theoretical study has been carried out in the present paper for ^{40}Ca + ^{70}Zn and ^{28}Si + ^{94}Zr systems. Fusion excitation function for the two systems were measured at Inter University Accelerator Centre (IUAC), New Delhi [5, 6]. A pulsed beam was used to bombard the isotopically enriched targets of ^{70}Zn and ^{94}Zr. The measurements have been performed around Coulomb barrier using recoil mass separator, Heavy Ion Reaction Analyzer (HIRA) with angular acceptance of 5 mSr.

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Theoretical Analysis

Theoretical calculations were performed with CCFULL and empirical coupled channel (ECC) codes [7, 8]. CCFULL is a well established code for coupling inelastic excitations. However, role of multi-neutron transfer can not be studied using this code. ECC model was employed to include transfer channels. In the calculations, standard Akyuz-Winther parametrization was adopted to obtain Woods-Saxon potential parameters. Projectiles ^{40}Ca and ^{28}Si are doubly magic nucleus and deformed nucleus respectively. ^{40}Ca rule out the effect of deformation due to its doubly magic nature. Thus, calculations were performed assuming ^{40}Ca as vibrator, ^{28}Si as rotor and target nuclei (^{70}Zn and ^{94}Zr) as vibrator. Different inelastic excitations were included in the calculations to obtain best fit to the excitation functions. It can be seen from FIG. 1, 3^- state of ^{40}Ca, two phonons 2^+ state of ^{70}Zn gave a good agreement to the experimental data in above Coulomb barrier region. For ^{28}Si+^{94}Zr system, 2^+ state of ^{28}Si and 2^+ $(3^-)^2$ states of ^{94}Zr reproduced the data reasonably well in the energy region above Coulomb barrier as shown in FIG. 2. However, these inelastic excited states underestimated the experimental data at extreme low energies indicating perhaps the influence of transfer channels. System ^{40}Ca+^{70}Zn has eight neutrons pick up channel (except 1n channel) with positive Q value and ^{28}Si+^{94}Zr has positive Q value for upto four neutrons pick up channel.

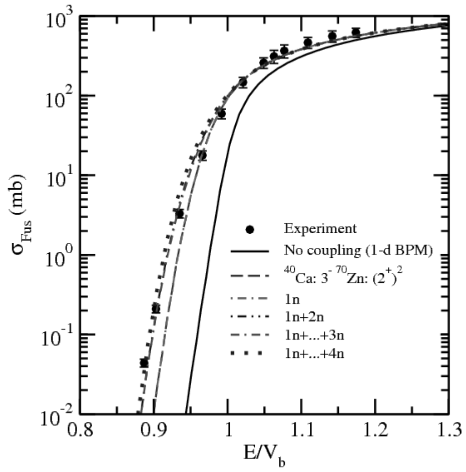

FIG. 1: Fusion excitation function along with coupled channel calculations for ^{40}Ca+^{70}Zn system.

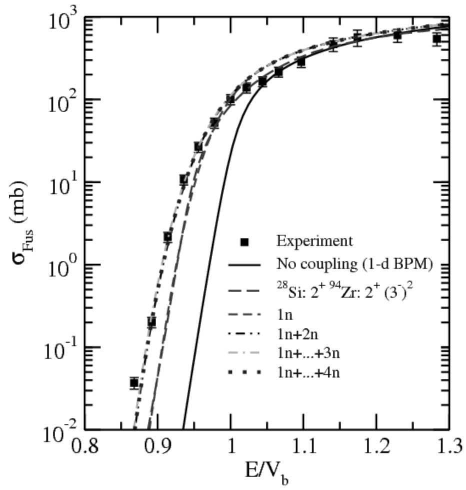

FIG. 2: Fusion excitation function along with coupled channel calculations for ^{28}Si+^{94}Zr system.

Hence, effect of multi-neutron transfer can be observed. Neutron transfer channels were successively added in the CC calculations. It is clear from the figures that 2n pick up channel enhanced the sub-barrier cross-sections significantly and could fit experimental data in the entire energy range for both systems. Transfer channel beyond 2n could not give any contribution to sub-barrier enhancement. Though systems have positive Q value for multi-neutron transfer, only two neutrons are sufficient to explain the fusion data. For both reactions, there is an increase in qudrupole deformation parameter (β_2) after 2n transfer, ^{40}Ca (β_2=0.123) + ^{70}Zn (β_2=0.228) $\rightarrow$ ^{42}Ca (β_2=0.247) + ^{68}Zn (β_2=0.205) and ^{28}Si (β_2=0.407) + ^{94}Zr (β_2=0.09) $\rightarrow$ ^{30}Si (β_2=0.315) + ^{92}Zr (β_2=0.1027). Therefore, observed enhancement may have attributed to the increase in deformation value which is in accordance with the observations of Sargsyan *et al.* [3]. But, this was not found to be true for system ^{28}Si+^{92}Zr in which deformation decreases and enhancement in cross-sections was observed after 2n transfer [6].

Conclusion

Upto two neutrons are sufficient to explain the enhancement in sub-barrier fusion cross-sections. It was also observed that contribution from four neutrons is negligible. The enhancement in cross-sections may have attributed to the overall increase in deformation parameter after transfer of two neutrons. However, contradiction has been found for system ^{28}Si+^{92}Zr in which noticeable enhancement has been observed, though there is decrease in deformation after 2n pick up.

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