Study of fusion in reactions populating Erbium and Thulium as compound nucleus

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The study of fusion reactions at near Coulomb barrier energies has been a topic of great interest in recent years. Nuclear fusion is a complex process involving a complete rearrangement of quantum systems with many degrees of freedom. Although fusion at energies above the Coulomb barrier can be explained using classical treatments, the dynamics become increasingly complicated at sub-barrier energies where quantum effects are significant. Fusion reactions at near barrier energies are dramatically influenced by the internal structure and entrance channel parameters of the interacting nuclei. It was known long back that the fusion cross sections in sub-barrier regions were enhanced by several orders of magnitude over the predictions of one-dimensional barrier penetration models (1D-BPM) [1]. It is now well known that the coupling of various internal degrees of freedom of the colliding nuclei such as static deformation, collective vibration, nucleon transfer channels, etc. contribute to the observed enhancement in fusion cross sections at sub-barrier energies. These couplings lead to a distribution of barriers and favor fusion at sub- barrier energies. The coupling of static deformation and inelastic channels were proven with a great success. However there are ambiguities in the role of transfer of few nucleons in enhancing the fusion cross sections, in this region.

Though tremendously successful in describing the data at near barrier energies, coupled channels theories fail to describe the fusion at deep sub-barrier and well above barrier energies. Alternate theories proposed recently also could not give a reasonable explanation to the experimental observations till date.

The experiments were carried out in two runs at Inter University Accelerator Centre (IUAC), New Delhi, using the 15 UD Pelletron accelerator. In the first experiment pulsed beams of ^{16}O with a pulse separation of 4 μs was used to bombard the isotopically enriched ^{142}Nd and ^{150}Nd targets. The measurements were performed in the beam energy range of 60 to 104 MeV and 56 to 104 MeV, for the ^{16}O+^{142}Nd and ^{16}O+^{150}Nd reactions, respectively. The low energy ERs produced in the fusion reactions were separated from other possible scattered particles using the Heavy Ion Reaction Analyser (HIRA) [2] and are detected in the focal plane using a two-dimensional position-sensitive multi wire proportional counter (MWPC) with an active area of 150 mm x 50 mm. Two silicon surface barrier detectors were placed inside the target chamber to measure elastically scattered beam particles and to get absolute normalization of ER cross sections. The ERs were selected through the two-dimensional spectrum of ER energy loss (ΔE) vs ER TOF.

In the second experiment with ^{19}F+^{142,150}Nd reactions, a similar experimental set up and methodology was used to get the ERs in the focal plane of the spectrometer. The measurements were performed in the beam energy range of 66 to 96 MeV and 62 to 96 MeV, for the ^{19}F+^{142}Nd and ^{19}F+^{150}Nd reactions, respectively.

Coupled channels calculations (CCFULL) have been used to analyse the measured fusion cross sections for the two reactions. Nuclear potential parameters V$_0$, r_0 and a were first fixed using the Akyüz-Winther parameterisation. The measured excitation function is found to be significantly enhanced relative to the 1D-BPM. The vibrational coupling of

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2^+ and 3^- states of ^{142}Nd is found to explain the sub-barrier fusion enhancement in ^{16}O+^{142}Nd reaction. Vibrational effects of ^{16}O seem to play no role in sub-barrier fusion in this reaction. The degree of fusion enhancement is larger for the ^{16}O+^{150}Nd reaction, compared to ^{16}O+^{142}Nd. Rotational couplings (2^+ and 4^+) of the deformed target nucleus reproduced the fusion cross sections reasonably well in ^{16}O+^{150}Nd reaction at sub- and near barrier energies. Though CC calculations assuming AW potential parameters reasonably reproduce the fusion cross sections at below barrier energies, they over predict fusion at energies well above the barrier. This difference is observed to increase with increasing beam energy. Careful analysis indicates that the observed difference is not due to fission or particle emission. Diffuseness parameter in the range 1.0-1.1 fm is required to fit the cross sections. These values are significantly larger than the values obtained from elastic scattering measurements. The inadequacy of AW potential parameters hints at the role of dynamical effects in fusion at higher energies [3].

In the second project, we studied the reactions ^{19}F+^{142,150}Nd where the ER excitation function is measured from around 15% below the barrier to 30% above the barrier. There was a significant enhancement seen in the sub-barrier fusion cross sections relative to the 1D-BPM even for these reactions. Vibrational coupling of 2^+ and 3^- states of ^{142}Nd alone is not sufficient to explain the sub-barrier fusion enhancement in the ^{19}F+^{142}Nd reaction. Incorporating the inelastic coupling of ^{19}F could successfully reproduce the experimental fusion cross sections. The quadrupole ($\beta_2 = 0.43$) and hexadecapole ($\beta_4 = 0.12$) deformation parameters are taken from Oyamada *et al.,*[4]. ^{19}F nuclei is considered as a pure rotor and the calculations are performed considering the states corresponding to $J^\pi = 0^+$, 2^+ and 4^+. Significant enhancement in the cross section is observed by the inclusion of first excited state (2^+) of the ^{19}F nuclei. Further enhancement in the cross section and a reasonable agreement with the experimental values have been noticed when both 2^+ and 4^+ states along with the target excitations are inluded in the calculation.

A significant effect of the inelastic excitation of the projectile is observed in these reactions which were not seen in the case of reactions using the ^{16}O projectile. This could be due to the low-lying first excited state in the case of the ^{19}F nucleus. The barrier distribution for the ^{19}F+^{142,150}Nd reaction is extracted and the distribution of the barrier is observed, which could be related to the observed fusion enhancement in the sub-barrier region.

In summary, we have measured the fusion excitation function over a wide range of energies around the Coulomb barrier populating Erbium and Thulium isotopes as the compound nucleus. The enhancement observed in the sub-barrier cross sections compared to 1D-BPM is explained by incorporating the inelastic excitation of the target nuclei alone in case of reaction with ^{16}O as projectile. In the reaction with ^{19}F as projectile, the collective excitations of the projectile also had to be incorporated to explain the observed enhancement. There was a hindrance in the fusion cross section seen well above (Ecm/ V_b $> 30\%$) the barrier compared to the theoretical calculations which could be explained by the use of a larger value of the diffuseness parameter. The reason for the difference could be the onset of the dynamical effects which sets in for very high excitation energies. The present study strongly recommends a revised theoretical approach incorporating dynamical effects to understand heavy ion fusion.

References

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