Facets of fusion and fission dynamics investigated via heavy-ion reactions around the Coulomb barrier

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Nuclear reactions have been essential to understanding fundamental forces and the universe, driven by advances in experimental techniques and theory. Massive investments in the development of advanced detection setups, upgraded accelerator facilities, software support along with data analysis, and invaluable collaborative efforts around the world have deepened insights into the dynamics of heavy-ion (HI) induced nuclear reactions, nuclear structure, and related phenomena in a better way. The emergence of multiple distinct processes, like complete fusion (CF), incomplete fusion (ICF), few nucleon transfers, pre-equilibrium (PEQ) emissions, fusion-fission, etc., brings in added complexity in understanding fusion of two heavy-ions. Also, the role of coupling to various degrees of freedom in fusion reactions has generated renewed interest in both experimental as well as theoretical investigations. The focus has been on new developments in fusion studies with weakly bound nuclei on one front and the fusion-induced fission studies of the nuclei (A $<$ 200) on the other, both serving to be topics providing new and exciting physics [1, 2]. These have additionally driven the application of HI reactions for societal good, industrial requirements, and interdisciplinary research.

The present thesis is focused on studying the dynamics of reaction perpetrated by weakly bound nuclei ^{6,7}Li on ^{63,65}Cu and ^{181}Ta targets. Furthermore, these reactions have been explored for the production of radioisotopes for relevant utilization in medical and industrial applications. In addition to this, the effect of shell closures on the fissioning profile of ^{192}Hg (which exists in the newly discovered region of asymmetric fission) has been studied via ^{32}S+^{160}Gd reaction.

All the experiments have been performed at the 14-UD BARC-TIFR Pelletron and LINAC facility, Mumbai. The Li induced reactions were performed using the stack irradiation and offline γ-ray measurement technique. Stacks created by foils of interested target interspersed with Al foils were irradiated by Li beams for a specific duration of time. They were then carried to a separated place for off-beam γ counting using a HPGe detector. After studying the decay characteristics of the evaporation residues, cross sections were calculated [3]. However, for the fission measurements, pulsed ^{32}S (with a repetition rate of 104.7 ns) beam were impinged on thin ^{160}Gd target. Two MWPC detectors having an active area of 12.5 cm $\times$ 7.5 cm were placed at folding angles to make coincident fission fragment detection. The time-of-flight information from the MWPC and RF of the beam were then used to deduce the mass and total kinetic energy of the fission fragments.

In the first work, we have analyzed the cross section data of different evaporation channels of ^{6}Li+^{63,65}Cu reaction (in 2.3–7.1 MeV/A energy range) with the help of PACE4, ALICE20, EMPIRE-3.2 theoretical model codes. All three model codes provide a statistical description of the nuclear reaction process. Here PACE4 only provides equilibrium treatment, however, ALICE20 and EMPIRE-3.2 also include pre-equilibrium process. We put forth in this work that majority of the reaction channels are described well with an admixture of EQ and PEQ process. No significant evidence of ICF in the p/α-channel was observed in

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this reaction, possibly due to the low-Z target. The deduced nuclear potential parameters from the measured total residue cross section are in consonance with those estimated theoretically from the Bass model [3]. In the follow up work, we have explored the reaction dynamics of ^{7}Li+^{63,65}Cu. A similar analysis like for the previous measurement reveal that here too both EQ and PEQ process contribute in the production of the evaporation residues. We also note that, there was no substantial evidence of ICF in the p/α-channel, however, we observe a deviating trend between measured data and model calculated ones for ^{67}Ga. This deviation is attributed mostly to inadequacies of model predictions to properly account for nuclear level density of ^{67}Ga. Coupled channel analysis of the fusion data reveals that the inelastic couplings in the projectile play much vital role than those in the target [4]. The production possibility of ^{67}Ga and ^{68}Ga has also been put forth using these two reactions. This projects HI-induced reactions as an alternative to produce medically relevant radionuclides.

To gauge the effect of target charge and mass on reactions induced by Li beams, ^{6}Li+^{181}Ta reaction was studied in 4.5–7.1 MeV/A energy range. The n-channel cross sections are explained satisfactorily by EMPIRE-3.2 calculations with GSM level density. However, the 2p/α- channel cross section show orders of magnitude enhancement over the theoretical calculations. This enhancement is attributed to incomplete fusion and n-transfer around the Coulomb barrier. The ICF fraction if found to vary parabolically with energy near the barrier which indicates contribution from one n-transfer process. CRC calculations using FRESCO demonstrates that ^{180}Ta residue is produced majorly by one n-stripping. Furthermore, the isomeric cross section ratio of ^{183m,g}Os isomeric pair reveals role of angular momentum in the population of the two states [5]. In continuation to this, yield estimates of residues from ^{6}Li+^{181}Ta reaction are reported. The theoretical yields of Os and Re isotopes estimated by EMPIRE-3.2.2 model code show good agreement with the experimental ones. Special attention has been paid to ^{183}Os whose experimental yields when compared for ^{6}Li- and ^{7}Li-induced reaction on ^{181}Ta in a similar energy range shows that ^{6}Li reaction is a better candidate for its production. Thick target yields have also been calculated for the residues produced in this reaction [6].

The fission measurements were performed for ^{32}S+^{160}Gd system at E^{*}_{CN} = 54.2, 64.6, and 74.3 MeV. The fragment masses and TKE deduced from the TOF information have interesting features. The M-TKE spectrum confirms no contamination from quasi-fission. However, we note a mass distribution typical of asymmetric fission at the lowest excitation energy. The mass distribution then changes slowly to flat topped and then to single peaked (peculiar feature of LDM) at the highest E^{*}_{CN}. The different fission modes S, A1, A2, and A3 obtained from fitting TKE distribution for different mass ranges fit well the mass distribution at different E^{*}_{CN}. The corresponding neutron and proton numbers to these modes reveal that these fission modes are driven by proton shells, Z $\sim$ 36, 46, and Z = 28/50 [7].

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