Study of effect of weakly bound projectile breakup on Heavy-ion fusion

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Introduction

Heavy-ion reactions involving weakly bound nuclei may result in CF or ICF (*x*) where *x* is only part of the projectile fragments which are captured [1]. The projectile may also get scattered without breakup (NBUS) or after breakup (NCBU). In a coincident measurement of breakup fragments of $^{6-7}$Li, it is observed that direct processes such as nucleon transfer leading to breakup of the remaining projectile contribute significantly to the ICF processes [2].

None of the models such as CDCC [3], semi-classical CC [4] or the Classical trajectory models [5] account for breakup following direct reactions in the ICF processes. We have developed a new multi-body 3S-CMD model [6, 7] for study of heavy-ion collisions involving weakly-bound projectiles. Apart from demonstrating CF, ICF, is also able to account for a process equivalent to direct reactions leading to ICF process.

In the present thesis we have presented the dynamical evolution of ^{6}Li with ^{209}Bi and ^{144}Sm in order to specifically investigate the effect of the extent of reorientation of deformed weakly-bound ^{6}Li.

The detailed study of the effect of breakup and transfer on CF and ICF is carried out by calculating various event fractions and event probabilities for various possible events, such as SCF, DCF and ICF etc., as a function of impact parameter (*b*) and the collision energy (E_{CM}).

Cross sections are calculated and studied using the Wong's formula [6] for CF, ICF and TF events for $^{6-7}$Li+^{209}Bi and $^{6-7}$Li+^{144}Sm reactions for the systematic relaxation of the rigid-body constraints on the projectile and target.

Calculation Details

In this model both the target and the projectile are treated as 3-dimensional bodies consisting of point nucleons. Weakly-bound nuclei are constructed as a cluster of the tightly bound nuclei. The interaction between the projectile fragments is generated self-consistently. Weakly-bound ^{6}Li is constructed by making use of the stable ^{2}H and ^{4}He with the potential energy between them equal to -1.47 MeV and a soft-core Gaussian NN potential between all the nucleons as in ref. [6]. Similarly, ^{7}Li is constructed by the stable ^{3}H and ^{4}He with the potential energy between them -2.47 MeV [6]. The ground state configuration of nucleons in the stable ^{2}H, ^{3}H, ^{4}He, ^{209}Bi [15] and ^{144}Sm are generated by a potential energy minimization code *STATIC* [8].

The model calculations take care of the long-range Coulomb reorientation of the deformed nuclei as well as possible excitations of target and projectile fragments in the appropriate stages. This model while treats the dynamics classically, it calculates fusion cross sections semi-classically by accounting for quantum tunneling through the generated fusion barriers by use of the Wong's formula for fusion cross sections.

The collision process is carried out in the model [8,9] in the following 3-stages: (1) Rutherford trajectory calculation up to R_{CM}= 2500 fm for given E_{CM} and *b*; (2) thereafter, assuming $^{6-7}$Li and ^{209}Bi as rigid bodies, using CRBD model calculation; (3) the rigid-body constraints are relaxed at about R_{CM}=13 fm and the trajectories of all the nucleons are computed as in CMD model calculation. In the present calculation one of the projectile fragments (^{4}He) is further constrained to be rigid and it is dynamically evolved as in the CRBD-model calculation.

Event fractions, F(*b*) [10] for given E_{CM} and *b* and event probabilities *P*(E_{CM}) [10] for given E_{CM} are calculated for $^{6-7}$Li+^{209}Bi and ^{6}Li+^{144}Sm reactions.

The calculations are carried out for the three cases of a systematic relaxation of the rigid-body constraints, ie., (a) Treating the entire projectile as rigid, (b) Relaxing the bond be-

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tween the projectile fragments while maintaining the rigidity constraint on the fragments themselves; and (c) Relaxing the rigidity constraint on one of the projectile fragment and allowing its own breakup was carried out in all the reactions.

Results and Discussion

The dynamical evolution of ^{6}Li with ^{209}Bi clearly shows the significant importance of extent of reorientation in heavy-ion reaction involving weakly-bound nuclei which are light and deformed.

From the study of *F(b)* and $P(E_{CM})$ for $^{6-7}$Li+^{209}Bi reaction it is observed that when the rigidity constraint on the bond between clusters in ^{6}Li (d & α) [7] and ^{7}Li (t & α) is relaxed then at highest collision energy as b increases the events following breakup (ICF+NCBU) events increases. Beyond a certain value of b the trajectories do not come very close to the target and the $F(b)$ for events following breakup again decreases. Thus, both the field of the target nucleus and the angular momentum of the projectile are responsible for breakup of ^{6}Li and ^{7}Li.

When the rigid-body constraint on ^{2}H cluster of ^{6}Li is also relaxed in stage-3 of the model, the breakup events especially, ICF(α+n) events further increases due to 1n- stripping reactions [7]. Similarly, when rigid-body constraint on ^{3}H cluster of ^{7}Li is relaxed, the ICF(n) and ICF(2n) events significantly increases which cause the F(b) for DCF events to decrease [10].

Thus, the probability of complete fusion and incomplete fusion events increases as the collision energy is increased. Moreover, the probabilities of breakup events are also increased for given collision energy for the systematic relaxation of rigid-body constraints on the bond between the projectile fragments.

The complete fusion cross sections (σ_{CF}), incomplete fusion cross sections (σ_{ICF}) and the total fusion cross sections (σ_{TF}) are also calculated for ^{6,7}Li+^{209}Bi [6,7] and ^{6,7}Li+^{144}Sm reactions for the collision energies spanning the fusion barrier; ranging from sub-barrier energy to far above the barrier energies using the Wong's formula at b=0 fm as well as at critical impact parameter (b_{cr}).

All the reactions studied in this thesis reveal the same trend for CF cross sections as listed: (i) Enhancements of σ_{CF} for case-(b) compared to case-(a) at lower energies due to the projectile excitations, with (ii) Some suppression at higher energies due to projectile breakup, similarly (iii) suppressions of σ_{CF} at lower energies as well, in case-(c) is seen as compared to case-(b) due to opening up of additional breakup channels arising from breakup of ^{2}H or ^{3}H cluster also, leading to further increase in the flux for ICF events and consequent suppression in CF events in case-(c).

Although, CF and TF fusion cross sections calculated in the present study do not agree well with the experimental cross sections in some of the reactions, but the present study does reproduces correctly the experimental trend in all the reactions. A systematic comparative study of the relaxations of the rigid-body constraints on the involved nuclei clearly brings out the importance of excitations of the target and projectile on fusion. It also emphasizes on the importance of the breakup of the projectile into its fragments. More significantly, the importance of the direct reaction processes such as nucleon-stripping reactions arising from one of the weakly-bound projectile fragment itself is also emphasized in this thesis. The effect of the projectile breakup energy and charge and mass of the target nuclei on fusion is also demonstrated through a systematic choice of the various target and projectile combinations in the present study.

Acknowledgments

I am grateful to my supervisor Prof. S. S. Godre for his valuable guidance and support and I am also grateful for providing me financial assistance by DAE-BRNS under a project grant no. 2009/37/20/BRNS.

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