An Experimental Review on the Investigation of the Effect of Breakup of Weakly Bound Projectiles on Complete Fusion with Heavy Targets

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Abstract **In recent decades, reactions involving weakly bound projectiles have been investigated by several research groups working in the field of nuclear physics. Despite the many successes in addressing some reaction outcomes, many puzzling questions still remain. A relatively large number of reactions with weakly bound nuclei have been systematically investigated at the various laboratories around the world. This review discusses the various works, mainly experimental, reported so far with an aim to study the effect of breakup of the stable weakly bound projectiles, ^{6,7}Li and ^{9}Be on fusion with targets of heavy masses. For heavier systems, like ^{9}Be+^{208}Pb, ^{6,7}Li+^{209}Bi, ^{6,7}Li+^{197}Au, ^{9}Be+^{197}Au, ^{7}Li+^{165}Ho, ^{6}Li+^{144}Sm, ^{7}Li+^{144,152}Sm, ^{6,7}Li+^{159}Tb, ^{10}B+^{159}Tb, ^{6,7}Li+^{124}Sn *etc*., the compound nuclei decay predominantly by neutron evaporation, and so the evaporation residues (ERs) produced from complete fusion (CF) and incomplete fusion (ICF) processes are different, thereby making it possible to separate the CF and the ICF products. For such systems the measured CF cross sections were observed to be suppressed substantially ~ 30% at energies above the respective Coulomb barriers when compared with the predictions of the 1D BPM calculations. At energies below the barrier, there are indications of enhancement due to the breakup of loosely bound nuclei, but no strong conclusions have yet been drawn from the available data.**

Index Terms— **Heavy-ion Fusion, Weakly Bound Nuclei, Breakup, Heavy Mass Targets, Fusion Suppression.**

I. INTRODUCTION

The main goal of the present work in this field is to investigate nuclear reaction mechanisms for systems involving weakly bound projectiles. With the development of accelerators for heavy ions (defined as nuclei heavier than alpha particles) many studies have been carried out on heavy ion reactions at energies around the Coulomb barriers. The Coulomb field between the heavy ion and the target nucleus plays an important role, since classically the energy of the incident ion must be at least comparable to the Coulomb barrier for any nuclear reaction to occur. The fusion process between two interacting nuclei is one of the most important processes in nature. This process has been studied extensively, both theoretically and experimentally, over the last few decades.

When two approaching nuclei with relative energy sufficient to overcome the barrier collide, the nuclei get trapped in the pocket of the effective interaction potential to fuse and produce a highly excited equilibrated compound nucleus. However, fusion can also occur at energies below the barrier by the quantum tunneling process and is known as sub-barrier fusion. The excited compound nucleus formed following fusion, subsequently decays by successive particle emission to various residual nuclei and/or undergoes fission. The resulting residual nuclei, if in excited states, decay to their ground states by gamma-ray emission.

For energies not too much above the Coulomb barrier, the major contribution to the reaction cross section is the fusion process. As the bombarding energy increases the competitions with other reaction mechanisms sets in, thereby decreasing the fraction of the reaction cross section corresponding to the fusion cross section. At energies close to and below the Coulomb barrier, the study of the fusion mechanism is particularly interesting, due to its dependence on the nuclear structure of the colliding nuclei and to its strong coupling with elastic, inelastic and transfer channels [1].

The quantum mechanical one-dimensional barrier penetration model (1-D BPM) gives good agreement with the experimentally measured fusion cross sections σ_{fus} at below and near barrier energies, for reactions of light systems (e.g., ^{7}Li+^{12}C, ^{12}C+^{16}O etc.)

where the participants behave much like inert spherical nuclei. However, for reactions of heavy systems (e.g., $^{58}Ni+^{58}Ni$, $^{16}O+^{144}Sm$, etc.) where other degrees of freedom become important, the 1-D BPM does not adequately fit the experimental data at sub-barrier energies [2,3]. In fact, for heavier systems, the measured fusion cross sections at energies below the barrier show enhancements of several orders of magnitude compared to the predictions of 1-DBPM. In order to explain the observed sub-barrier enhancement of σ_{fus} [3-5], the results of Balantekin et al [6] suggests for the considerations of other degrees of freedom (e.g., static deformation, surface vibrations, rotation, transfer of nucleons between projectile and target) for the colliding nuclei.

The coupling of the radial motion between the projectile and target to the internal degrees of freedom such as rotation or vibration, effectively causes a splitting in the energy of the single, uncoupled fusion barrier. This gives rise to a distribution of barrier heights, some higher and some lower in energy than the uncoupled barrier and is manifested most obviously as an enhancement of the fusion cross sections at energies near and below the barrier [6,7]. This provides an explanation for the experimentally observed enhancement of fusion cross-sections at sub-barrier energies, compared to 1-DBPM (also called the single barrier penetration model) calculations. Systematic experimental and theoretical studies of the effect of coupling of the collective degrees of freedom on the fusion process, which lead to a significant enhancement of fusion cross sections when compared to the predictions of 1-DBPM calculations have been widely reported in the literature [4]. The role of dynamical processes such as inelastic excitation, transfer reaction leading to such enhancement seems to be well understood.

II. MOTIVATION

However, in the reactions where at least one of the colliding nuclei is weakly bound, owing to its very low binding energy, it may break up in the field of the other nuclei and thereby can influence the fusion process. The effect of breakup of weakly bound nucleus on the fusion cross sections is still intriguing as the predictions of the theoretical models and experimental results are found to be conflicting.

Nuclei that have small separation energies have a large probability of breaking-up in the field of other nuclei. So, in collisions involving such weakly bound nuclei, the breakup becomes a significant channel. An important question that has been raised in the past few years is: What is the effect of the breakup process on the fusion cross sections? Although there have been many theoretical and experimental works on this subject, it is still far from being fully understood. There is a special interest in this field due to the recent availability of radioactive ion beams. The interest in the field of reactions with radioactive ion beams is focused on the understanding of the structure of halo nuclei and to investigate their unusual properties on reaction mechanisms. An understanding of these aspects is intimately related to the optimization of the production of new nuclei far-off the line of stability. Reactions of astrophysical interest are induced by loosely bound nuclei and if the coupling with the breakup channel leads to remarkable enhancement of fusion cross sections, super-heavy nuclei could be more easily produced. Besides, fusion reactions involving unstable nuclei that have a very low energy threshold against breakup have generated a lot of controversy which centers around the influence of breakup on fusion.

Beams of halo nuclei are produced in secondary reactions with intensities several orders of magnitudes smaller than the stable ones, with modest emittance and poor beam energy resolution. While experimental results from radioactive ion beam facilities are now becoming available [1], such measurements are still very difficult due to the low beam intensities. However, investigations of systems involving stable but weakly bound nuclei for which intense beams are available, can also shed light on the effect of breakup on the fusion process.

There are three suitable stable weakly bound nuclei for such kind of studies: ^{6}Li, ^{7}Li and ^{9}Be. Beams of these nuclei are easily produced and they have small separation energies.

This review will concentrate only on the fusion reactions studied so far with weakly bound stable nuclei in heavy mass systems only.

The present understanding of the breakup process of stable weakly bound nuclei and its effect on the fusion cross sections is still controversial. Theoretically there are models with different answers to the question on the effect of the breakup on the fusion cross sections. Depending on the theoretical approach, different predictions are made.

If fusion occur incoherently with possible breakup of the incoming particle, then it results in a loss of flux in the incident channel and a corresponding reduction of the fusion cross sections. On the other hand, due to the additional breakup channel, coupling to the states above the breakup threshold with the elastic channel will lead to an enhancement of the fusion cross sections, when compared with the fusion induced by the strongly bound nuclei. This enhancement should be particularly important at sub-barrier energies, where the coupling effects on the fusion may be strong because of the fact that due to coupling, entrance barrier fluctuation will lead to an effective lowering of this barrier. As breakup process leads to a continuum of states, very recently coupled channel calculations based on the coupling to the states in the continuum, which is split in discreate bin (continuum discretized coupled channel, CDCC) have been performed. These calculations predict the coexistence of both dynamical descriptions: a coherent process at sub-barrier energies leading to enhancement of fusion cross sections and reduction of fusion cross sections at above barrier energies due to a significant loss of flux in the entrance channel. However, in order to have a clear understanding of the effect of breakup on fusion, experimentally it is important to separate the complete fusion (CF, where all the charges of the projectile fragments fuse with the target) and incomplete fusion (ICF, where any of the breakup fragments fuse with the target) processes. Total fusion (TF) corresponds to the sum of the CF and ICF events. Usually residues following both processes (CF+ICF) are very similar or even identical; therefore, the measurement of residues using different techniques and/or particle identification devices (i.e., charged particle detectors, time of flight detectors, ionization chamber, delayed x-ray etc.) sometimes becomes difficult to distinguish them. This situation is even more dramatic for light systems in which the main evaporation channels includes charged particle (protons and alpha-particles). So even when the projectiles breakup into charged partitions, the ICF products in light systems are identical to the evaporation residues following charged particle emission from the compound nucleus, thereby making it almost impossible to separate the products of CF from ICF. This difficulty in separation of CF from ICF events in light systems, is particularly important at energies above the barrier, whereas at below barrier energies the lack of sufficient energy may prohibit ICF. Therefore, most of the available data on the light systems, like ^{6,7}Li+^{12,13}C, ^{6,7}Li+^{16}O [8-12] corresponds to the TF cross sections. But this is not the case for heavy systems, like ^{6,7}Li+^{209}Bi [13], where the compound nucleus decays predominantly by emitting neutrons, thereby making it convenient to separate CF from ICF products.

With this brief review, let us look into a few of the different experimental works reported so far in this field.

III. EXPERIMENTAL WORKS

To investigate the effect of the loosely bound neutrons, fusion excitation functions in the barrier region were measured for the systems ^{9,11}Be+^{238}U [14] and ^{9,10,11}Be+^{209}Bi [15], where the reaction with the stable ^{9}Be beam was done for comparison. The fusion cross sections for ^{10,11}Be+^{209}Bi at energies near and below the barrier were found to be similar to those for ^{9}Be, while above the barrier, the ^{9}Be induced reaction gave the lowest fusion yield. It is not clear whether this is due to differing enhancement or suppression for the stable and unstable projectile. ^{11}Be is a two-neutron halo nucleus. In order to investigate the effect of coupling related to unstable neutron-rich halo nuclei on fusion, it is necessary to reliably predict the expected fusion cross sections in the absence of halo. Thus, in the above cases definite conclusions are difficult unless fusion with ^{9}Be is well understood.

Both complete and incomplete fusion cross sections have been measured for the heavy systems ^{9}Be+^{208}Pb [16], ^{6,7}Li+^{209}Bi [13], ^{7}Li+^{165}Ho [17], ^{6,7}Li+^{159}Tb [27-29], ^{6,7}Li+^{197}Au [30], ^{6}Li+^{144}Sm [25], ^{7}Li+^{144,152}Sm [26], ^{6,7}Li+^{124}Sn [31,32] *etc*. Some of the silent findings for these heavy systems are discussed below.

The complete fusion cross sections for ^{6,7}Li+^{209}Bi and ^{9}Be+^{208}Pb [13,16], defined as the sum of the Rn *xn* evaporation residue cross sections and fission cross section at each energy are shown in Fig. 1.

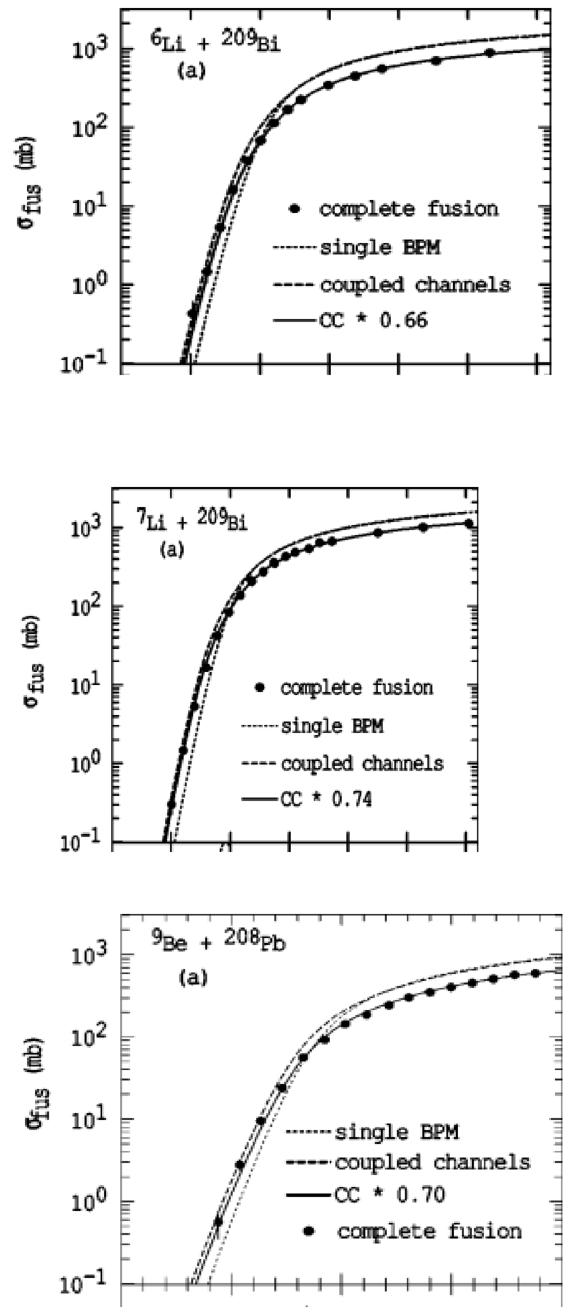

Fig. 1. *The measured and calculated complete fusion excitation function for the fusion of ^{6,7}Li with ^{209}Bi and for the fusion of ^{9}Be with ^{208}Pb. The short-dashed lines are the predictions of a single barrier penetration model, and the long-dashed lines are the results of a coupled channels calculation. The full line is the latter calculation multiplied by the indicted factor.*

Theoretically to predict the fusion cross sections, realistic coupled-channel calculations were performed using a Woods-Saxon form for the nuclear potential. These calculations are shown in Fig. 1 by dashed lines. It is found that the calculated values are considerably larger than those measured. This is in contrast to fusion with tightly bound projectiles such as ^{16}O and ^{40}Ca [19-22, 23], where calculations give an extremely good fit to the experimental cross sections. Agreement between the measured and calculated quantities can be obtained if the calculated fusion cross sections are scaled by 0.73 and 0.68 for ^{7}Li and ^{9}Be induced reactions respectively. The suppression of complete fusion cross sections at energies above the barrier, observed in both the reactions, is attributed to the reduction of flux in the incident channel due to the large breakup probability for ^{7}Li and ^{9}Be before they reach the fusion barrier. The evidence for the high breakup probability is the large incomplete fusion cross sections which were observed in this experiment. It is also interesting to notice that although the suppression of the CF cross sections at high energies was found to be similar for both the systems, the strongest (smallest) CF suppression occurs for the ^{6}Li (^{7}Li) projectile, that has the smallest (highest) breakup separation energy among the three projectiles. It is also found that total fusion cross section is not affected by the breakup process. From these results the conclusion is for energies above the Coulomb barrier, the breakup process inhibits about 30% of the CF cross section and there is a signature that the suppression factor increases slightly as the breakup threshold energy decreases. At sub-barrier energies, the situation is not so clear, due to the competition between the enhancement of the CF due to the coupling and suppression due to the breakup. The net result is some CF cross section enhancement.

Results for the cross section for complete fusion at energies around the Coulomb barrier are presented for ^{7}Li with ^{165}Ho [17] shown in Fig. 2. Comparison of the cross sections with a one-dimensional barrier penetration model, using a potential consistent with the measured elastic scattering, showed a reduction above the barrier and an enhancement below it. It is found that these results together with a reanalysis of existing data conclusively demonstrate that the effect of breakup on fusion is coherent, like coupling to any nonelastic channel.

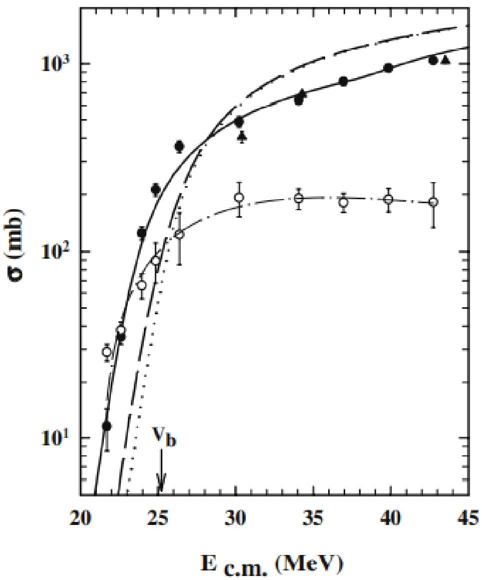

Fig. 2. *Complete and partial breakup fusion cross section (filled and open circles) as a function of the center of mass energy for the $^{7}Li+^{165}Ho$ system. The dotted curve is the prediction of a 1D-BPM calculation. The dashed and solid curves are the results of a coupled channel calculation including the effect of coupling to the ground state rotation band of the deformed target and only the breakup channel, respectively. The solid triangles are the complete fusion cross sections for the $^{6}Li+^{165}Ho$ system.*

For the systems $^{11,10}B$ + ^{159}Tb Complete fusion excitation functions have been measured [24] at energies around the respective Coulomb barriers, and the existing complete fusion measurements for ^{7}Li + ^{159}Tb have been extended to higher energies shown in Fig. 3. The measurements show significant reduction of complete fusion cross sections at above-barrier energies for both the reactions, ^{10}B + ^{159}Tb and ^{7}Li + ^{159}Tb, when compared to those for the strongly bound system ^{11}B + ^{159}Tb. The comparison shows that the extent of suppression of complete fusion cross sections is correlated with the α-separation energies of the projectiles (Fig. 4). Also, the two reactions, ^{10}B + ^{159}Tb and ^{7}Li + ^{159}Tb were found to produce incomplete fusion products at energies near the respective Coulomb barriers, with the α-particle emitting channel being the favored incomplete fusion process in both the cases.

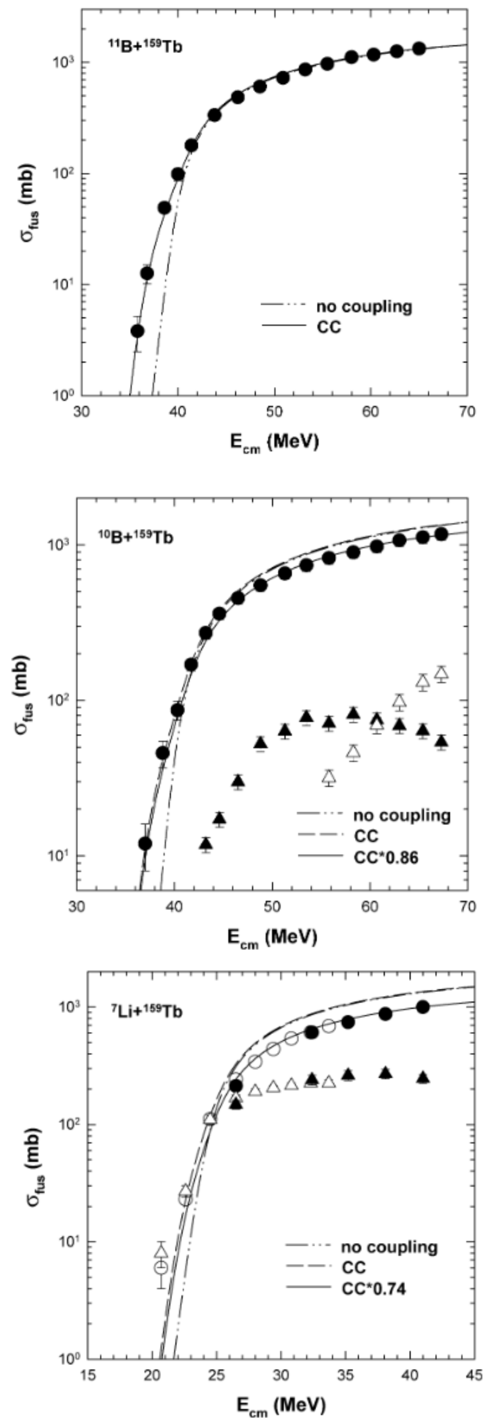

Fig 3: *Fusion excitation function for the ^{11}B + ^{159}Tb system (upper) and for ^{7}Li + ^{159}Tb and $^{10}B+^{159}Tb$ systems (lower). The dot-dot-dashed and the solid lines are the uncoupled and coupled channels calculations performed with the code CCFULL [23] for ^{11}B + ^{159}Tb. The dot-dot-dashed and the dashed lines are the uncoupled and coupled channels*

calculations performed with the code CCFULL for $^{7}Li + ^{159}Tb$ and $^{10}B+^{159}Tb$ systems. The solid line shows the coupled channels calculations scaled by the factor 0.86 and 0.74 respectively for $^{10}B+^{159}Tb$ and $^{7}Li + ^{159}Tb$ systems.

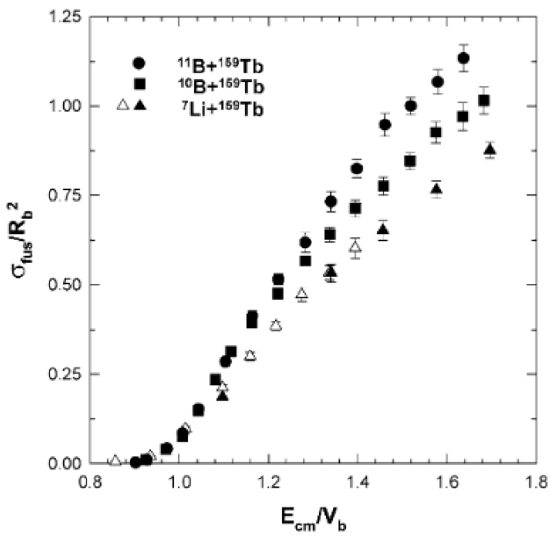

Fig. 4. *Reduced complete fusion excitation functions for the $^{11,10}B+^{159}Tb$ and $^{7}Li+^{159}Tb$ systems.*

Complete fusion excitation function for the $^{6}Li+^{144}Sm$ reaction [25] has been measured at near barrier energies by the activation technique shown in Fig. 5. Coupled-channel calculations show an enhancement in fusion cross section at energies below the barrier compared to the one-dimensional barrier penetration model calculation, but they overpredict it in the entire energy range compared to the experimental data. Reduced fusion cross sections for the present system at energies normalized to the Coulomb barrier were also found to be systematically lower than those with strongly bound projectiles forming a similar compound nucleus. These two observations conclusively show that the complete fusion cross section, at above barrier energies, is suppressed by ~32% in the $^{6}Li+^{144}Sm$ reaction. Re-analyses of existing fusion data for $^{7}Li+^{165}Ho$ and $^{7}Li+^{159}Tb$ also show a suppression compared to those with strongly bound projectiles, which contradicts earlier conclusions. The fusion suppression factor seems to exhibit a systematic behavior with respect to the breakup threshold of the projectile and the atomic number of the target nucleus.

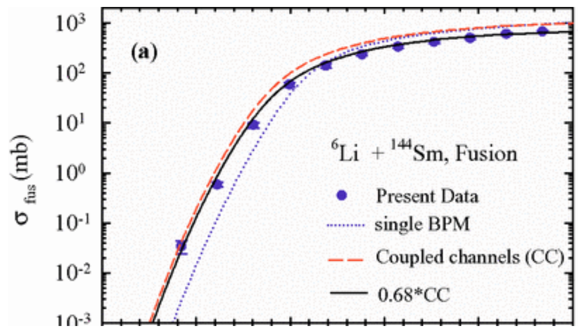

Fig. 5. *Complete fusion cross section (filled circles) for $^{6}Li+^{144}Sm$ compared with coupled (dashed lines) and uncoupled (dotted lines) results from CCFULL calculations. Solid lines are obtained by multiplying the coupled results by a factor of 0.68.*

Complete fusion cross sections for $^{7}Li+^{144,152}Sm$ reactions [26] have been measured at energies around the Coulomb barrier by the offline γ-counting technique. Measured cross sections shown in Fig. 6 for the above two reactions are found to be similar at energies well above the Coulomb barrier, however, at sub-barrier energies the cross sections for the $^{7}Li+^{152}Sm$ system are much higher compared to the $^{7}Li+^{144}Sm$ system, manifesting the effect of target deformation. Cross sections for the present reactions at above-barrier energies are found to be larger than previously measured reactions involving ^{6}Li projectile with the same targets, possibly due to smaller breakup probability of ^{7}Li than ^{6}Li. Coupled-channels calculations show that the experimental fusion cross sections for both the systems are enhanced at sub-barrier energies and suppressed at above-barrier energies compared to the respective one-dimensional barrier penetration model predictions. The calculations by different models show that the measured complete fusion cross sections at above-barrier energies are suppressed up to ~ 25% compared to the theoretical predictions. It also reveals that a large part of the suppression could be due to inelastic and transfer coupling.

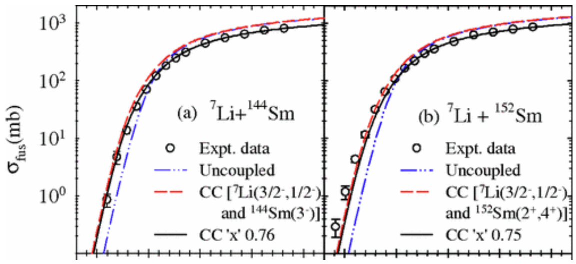

Fig: 6. *Shown are (a) and (b) the measured complete fusion cross sections (open circles) for ^{7}Li+^{144}Sm and ^{7}Li+^{152}Sm. Dash-dot-dot and dashed lines represent the results of coupled-channels calculations for the no-coupling case and with full couplings, respectively. Solid lines are obtained by normalizing the coupled results by 0.76 and 0.75 for ^{7}Li+$^{144,152}Sm$ reactions, respectively.*

Complete and incomplete fusion cross sections for ^{6}Li + ^{159}Tb [28,29] have been measured at energies around the Coulomb barrier by the γ-ray method. The measurements show that (Fig. 7) the complete fusion cross sections at above-barrier energies are suppressed by ~ 34% compared to the coupled-channel calculations.

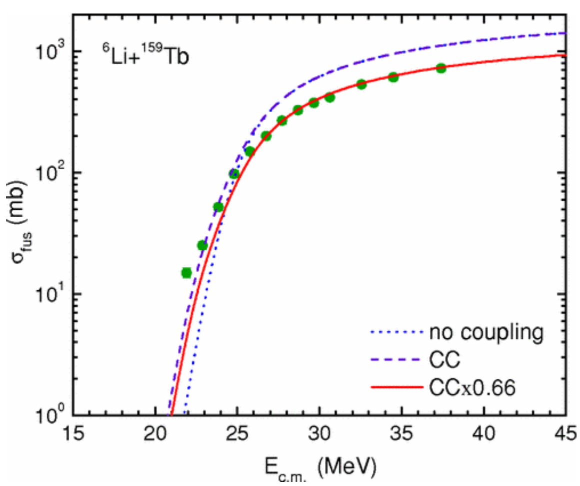

Fig. 7. *Complete fusion cross sections as a function of the centre-of-mass energy for the reaction ^{6}Li+^{159}Tb. The dotted and dashed lines show the uncoupled and coupled-channel calculations, respectively performed with the code CCFULL. The solid line is the coupled-channel calculation multiplied by a factor of 0.66.*

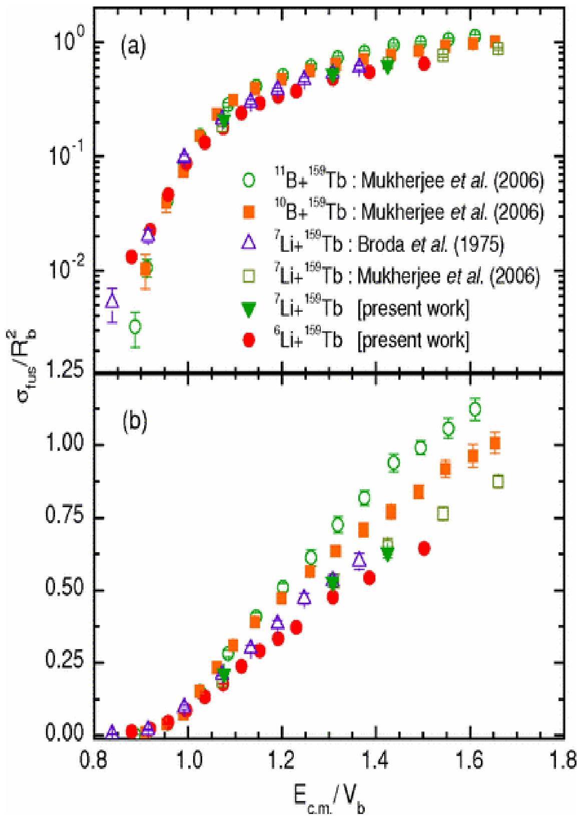

Fig. 8. *A comparison of the reduced complete fusion excitation functions for the systems $^{10,11}B$ + ^{159}Tb and ^{7}Li + ^{159}Tb with those of the present measurements for $^{6,7}Li$ + ^{159}Tb.*

A comparison (shown in Fig. 8) of the complete fusion cross sections at above-barrier energies with the existing data for ^{11,10}B + ^{159}Tb and ^{7}Li + ^{159}Tb shows that the extent of suppression is correlated with the α separation energies of the projectiles.

Fusion measurements have been carried out for ^{6,7}Li+^{197}Au systems [30] in the energy range E/V_b ~ 0.7 to 1.5. Coupled-channel calculations including coupling to inelastic states of the target and projectiles are able to explain an enhancement in measured fusion cross sections at energies below the barrier. At energies above the barrier the complete fusion cross sections are found to be suppressed compared to the coupled-channel predictions for both systems (Fig. 9).

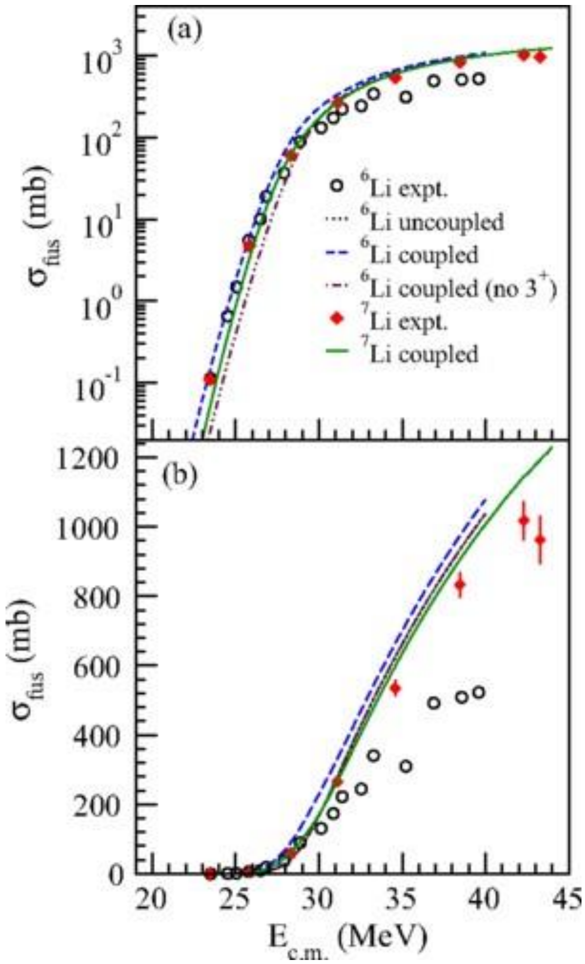

Fig. 9. *Measured complete fusion excitation function for $^{6,7}Li+^{197}Au$ (open and filled symbols, respectively) together with CCFULL calculations. The dashed (solid) line represents the results of CC calculations for ^6Li (^7Li). Cross sections obtained from CCFULL for $^6Li+^{197}Au$ without inclusion of the coupling to the 3^+ state of ^6Li is shown by the dash-dot-dotted line, and those without any coupling are shown by the dotted line. Errors are within the symbol size. (b) Same as (a), but on a linear scale.*

For the ^{7}Li+^{124}Sn reaction [31], the complete and incomplete fusion cross sections were measured using online and offline characteristic γ-ray detection techniques. The complete fusion (CF) cross sections at energies above the Coulomb barrier were found to be suppressed by ∼26% compared to the coupled channel calculations (Fig. 10). This suppression observed in complete fusion cross sections is found to be commensurate with the measured total incomplete fusion (ICF) cross sections. There is a distinct feature observed in the ICF cross sections, i.e., *t* capture is found to be dominant compared to α capture at all the measured energies. A simultaneous explanation of complete, incomplete, and total fusion (TF) data was also obtained from the calculations based on the continuum discretized coupled channel method with short range imaginary potentials. The cross section ratios of CF/TF and ICF/TF obtained from the data as well as the calculations showed the dominance of ICF at below-barrier energies and CF at above-barrier energies.

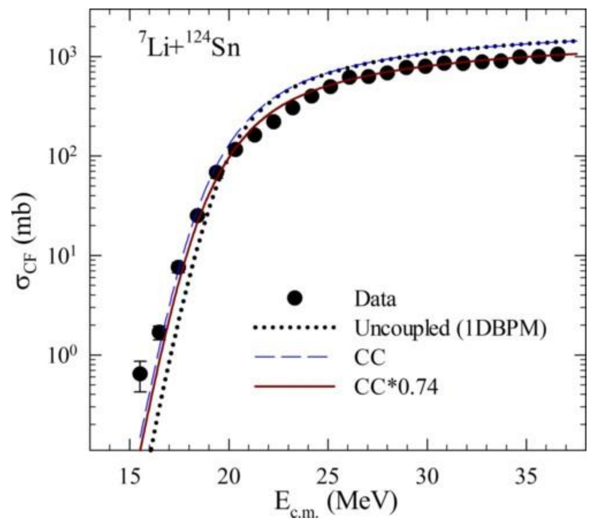

Fig. 10. *Complete fusion cross section (filled circles) for the $^7Li+^{124}Sn$ reaction compared with coupled (dashed lines) and uncoupled (dotted lines) results from CCFULL calculations. Solid lines were obtained by multiplying the coupled results by a factor of 0.74.*

The complete and incomplete fusion along with one neutron stripping and pickup cross sections for the ^{6}Li+^{124}Sn system [32] are measured using online and offline characteristic γ-ray detection techniques. The complete fusion (CF) cross sections at energies above the Coulomb barrier are found to be suppressed by ∼ 34% compared to the coupled channel calculations (Fig.11). This suppression observed in complete fusion cross sections is found to be commensurate with the measured total incomplete fusion (ICF) cross sections. There is a distinct feature observed in the ICF cross sections, i.e., *d* capture is found to be dominant than α capture at all the measured energies, contrary to the data available for ^{6}Li+^{209}Bi,^{197}Au systems [13,30]. The total fusion cross section ratio between ^{6}Li and ^{7}Li induced reactions shows an increasing trend as the energy decreases below the barrier while it remains unity at above-barrier energies. A simultaneous explanation of complete, incomplete, and total fusion (TF) data is also obtained from the calculations based on the continuum discretized coupled channel method with short-range imaginary potentials. The cross section ratios of CF/TF and ICF/TF obtained from the data as well as the calculations shows the dominance of ICF at below-barrier energies and CF at above-barrier energies.

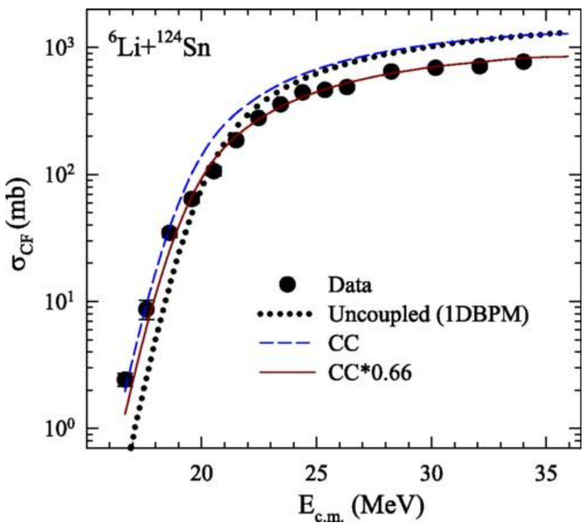

Fig. 11. *Complete fusion cross section (filled circles) for the $^{6}Li+^{124}Sn$ system compared with coupled (dashed lines) and uncoupled (dotted lines) results from CCFULL calculations. Solid lines were obtained by multiplying the coupled results by a factor of 0.66.*

Very recently F. Gollan et al., [33] have reported measurement of complete and incomplete fusion cross sections for the ^{9}Be+^{197}Au system over a wide range of energies around the Coulomb barrier by the offline γ-ray detection method. The reduced complete and total fusion were found to be hindered above and enhanced below the Coulomb barrier compared with the universal fusion function due to the breakup plus transfer effects (Fig. 12).

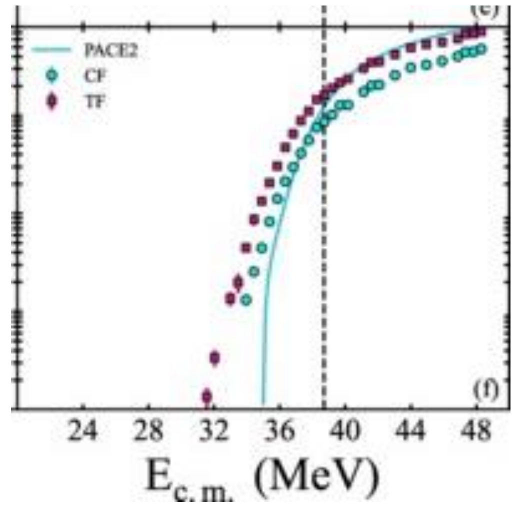

Fig. 12. *Experimental cross sections (full symbols) for the CF, TF measured for the $^{9}Be+^{197}Au$ system. In solid lines, PACE2 calculations are included for the CF neutron evaporation channels.*

IV. SUMMARY

This review discusses the various works, mainly experimental, reported so far with an aim to study the effect of breakup of the stable weakly bound projectiles, ^{6,7}Li and ^{9}Be on fusion with targets of heavy masses.

For heavy mass targets ^{208}Pb and ^{209}Bi, at energies above the Coulomb barrier, complete fusion cross sections were suppressed due to breakup effect by around 30% compared to fusion with tightly bound nuclei such as ^{16}O, ^{40}Ca. however the total fusion (CF+ICF) cross sections were almost unaffected by the breakup process. For heavier systems, like ^{9}Be+^{208}Pb [16], ^{6,7}Li+^{209}Bi [13], ^{7}Li+^{165}Ho [17], ^{6}Li+^{144}Sm [25], ^{7}Li+^{144,152}Sm [26], ^{6,7}Li+^{159}Tb, ^{10}B+^{159}Tb [24,27,28], ^{6,7}Li+^{197}Au [30], ^{6,7}Li+^{124}Sn [31,32], ^{9}Be+^{197}Au [33] *etc*., the compound nuclei decay predominantly by neutron evaporation, and so the ERs produced from CF and ICF processes are different, thereby making it possible to separate the CF and the ICF products. For such systems the measured CF cross sections were observed to be suppressed substantially ~30% at energies above the respective Coulomb barriers when compared with the predictions of the 1D BPM and/or coupled channels calculations. At energies below the barrier, there are indications of enhancement due to the breakup of loosely bound nuclei, but no strong conclusions have yet been drawn from the available data.

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