Does the Break-up Process Influence the Fusion Cross Section?

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Received on 6 September, 2003

We give an overall picture of our present understanding of the effect of the break-up of stable weakly bound nuclei on their fusion cross section with light, medium and heavy mass nuclei, at energies above the Coulomb barrier. The discussion is based mostly on recent data obtained by our group in collaborative experiments with ANU, USP and Tandar Laboratories. We conclude that there is complete fusion suppression for heavy targets, due to the loss of flux, corresponding to the occurrence of incomplete fusion of one of the break-up fragments. For medium and light mass targets, the incomplete fusion is negligible and therefore is no complete fusion suppression.

Fusion of heavy ions is a subject that has been extensively studied in the last decades. For energies not too much above the Coulomb barrier (the so-called "region I"), the fusion process has the major contribution to the reaction cross section. As the bombarding energy increases, the competition with other reaction mechanisms decreases the fraction of the reaction cross section corresponding to the fusion cross section, that becomes saturated (the so-called "region II"). At energies close 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 couplings with elastic, inelastic and transfer channels. Simultaneous analyses of fusion and elastic scattering data[1, 2] have shown that the fusion process is decided at the Coulomb barrier position, or even outside the barrier. Transfer channels that have sharp form factors, and consequently a relative small average transfer distance, act as important doorway to fusion and enhance the fusion cross section at this energy regime[3, 4].

Nuclei that have small separation energies have a large probability of breaking-up when the colliding nuclei approach each other and their interactions convert potential and kinetic energy into relative kinetic energy between the two fragments. An important question that has been raised in the last years is: What is the effect of the break-up process on the fusion cross section? Although there has been many theoretical and experimental works on this subject, it is still far from being full understood. There is a special interest on this field due to the recently available radioactive beams of very weakly bound nuclei. Reactions of astrophysical interest are induced by weakly bound nuclei and, if the coupling with the break-up channel leads to remarkable enhancement of the fusion cross section, super-heavy nuclei could be more easily produced. Due to the low intensities of the radioactive beams, it is very convenient to produce fusion reactions with the high intensity stable beams that are weakly bound, and consequently should have a reasonable break-up probability. Such reactions are important reference for the understanding of reactions induced by radioactive proton and neutron rich beams, althoght the reactions with these stable nuclei do not cover all the physical processes related with radioactive beams. The suitable stable nuclei for this kind of study are ^{9}Be, ^{6}Li and ^{7}Li, that have threshold break-up energies from 1.48 MeV to 2.45 MeV, whereas the halo radioactive nuclei (^{11}Li, ^{11}Be and ^{6}He, for instance) have generally threshold break-up energies from 0.3 MeV to 1 MeV.

Theoretically [5-11] there are models with different answers to the question on the effect of the break-up on the fusion cross section. Some of them predict the fusion cross section enhancement, when compared with the fusion induced by tightly bound nuclei, due to the presence of low lying weakly-bound or unbound states, particularly important at sub-barrier energies, where the coupling effects on the fusion may be strong. However, it has been argued that although the soft dipole resonance of the halo nuclei may enhance the sub-barrier fusion, the break-up process leads to a continuum of states, in an irreversible path to fusion, and therefore, the break-up channel should inhibits the fusion cross section. So, some models suggest the hindrance of the complete fusion, due to the loss of incident flux in this channel, caused by the break-up, and consequently the so-called "region II" starts at energies very close to the Coulomb barrier. There are also predictions of fusion cross section enhancement at sub-barrier energies and fusion hindrance at above barrier energies.

Therefore, the usual questions concerning the effect of the break-up on the fusion process are: Does the break-up enhance or suppress the fusion cross section? Is this effect concerned with complete fusion or total fusion, the later including incomplete fusion, when one of the break-up fragments fuses? What are the effects on different energy regimes? What are the effects on different target masses? Does the value of the threshold break-up energy have an important effect on the fusion as it does for the direct break-up cross section?

In order to answer these questions, many theoretical aspects should be considered, such as the study of different break-up processes (direct or elastic break-up related with low and high angular momenta; inelastic or sequential break-up, including the incomplete fusion (ICF) of one of the fragments and complete fusion following the break-up (CF^{BU})); the relative motion of the fragments, their interactions and their trajectories following the break-up; the boundary conditions assumed for the occurrence of complete fusion (CF); different coupling possibilities: bound-continuum states (with or without resonance) and continuum-continuum states; Coulomb and nuclear excitations and their coherent interferences etc. Different approaches are currently used, such as coupled channel calculations, continuum discretized coupled channel calculations, semiclassical trajectory models, survival probability from the break-up and dynamic polarization potentials.

In this paper we give an overall picture of the present understanding of the field, concerning stable weakly bound nuclei, for energies above the Coulomb barrier, based mostly on recent results on the fusion of the ^{9}Be + ^{208}Pb [12], ^{6,7}Li + ^{209}Bi [13], ^{6,7}Li, ^{9}Be + ^{27}Al, ^{64}Zn [14-18], ^{9}Be + ^{19}F [17] and ^{6,7}Li + ^{16}O, ^{12,13}C; ^{7}Li + ^{11}B; ^{9}Be + ^{9}Be [19, 20] systems and other systems involving tightly bound projectiles on the same targets and/or leading to the same compound nuclei.

The experiments discussed here were performed in collaborative experiments involving Australian National University-ANU at Canberra, Australia; University of São Paulo-USP at São Paulo, Brazil; and TANDAR Laboratory at Buenos Aires, Argentina. The results of Mukherjee et al.[19] on the fusion with low-Z targets are also discussed. Different experimental methods have been used in these studies, but they will not be described in this short paper, since they were already described in the corresponding specific papers.

The ^{6,7}Li + ^{209}Bi and ^{9}Be + ^{208}Pb CF and ICF cross sections were determined separately at ANU. Barrier distributions were also derived. The total fusion (CF + ICF) cross sections of ^{6,7}Li + ^{64}Zn, ^{27}Al and ^{9}Be + ^{27}Al were measured at the TANDAR. The fusion of ^{9}Be + ^{64}Zn was measured at USP, and the analysis of the data for this system showed that the ICF cross section was negligible. The total fusion of ^{19}F + ^{9}Be was measured at USP. Elastic scattering experiments for ^{6,7}Li on ^{64}Zn and ^{27}Al, and ^{9}Be on ^{27}Al were also performed at USP, allowing the derivation of reaction cross sections. The total fusion of the ^{12}C + ^{7}Li [20]system was measured at ANU.

Figure 1 shows the results of the CF cross sections for the ^{7}Li + ^{209}Bi system. Similar results were obtained for the ^{6}Li + ^{209}Bi and ^{9}Be + ^{208}Pb systems. For the three systems, single barrier penetration calculations (SBPC) and coupled channel calculations (CCC) including bound excited states, without the inclusion of any projectile break-up effect, predict values larger than the experimental ones at above barrier energies. Below the Coulomb barrier, the SBPC underpredict the experimental cross sections, whereas the CCC

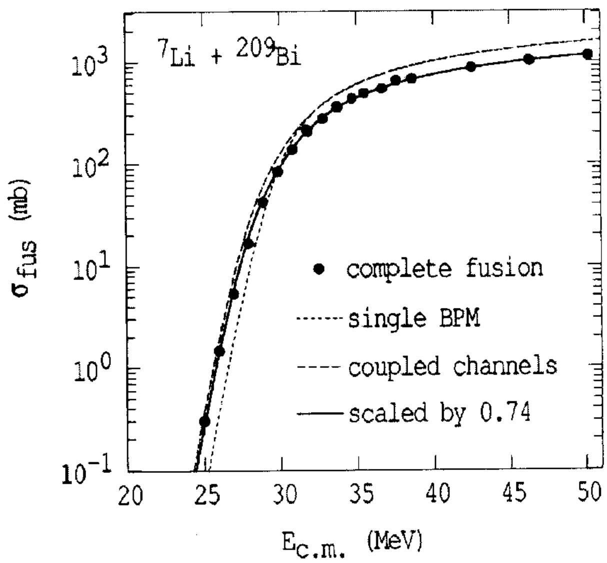

Figure 1. Complete fusion excitation function for the ^{7}Li + ^{209}Bi system. The SBPM and the CCC over-predict the complete fusion cross sections.

lead to reasonable fits of the data. The average barrier positions used in the calculations were constrained to match the ones obtained from the experimental barrier distributions. Agreement between the measured and calculated CF cross sections at high energies and the barrier distributions can only be obtained if the calculated cross sections are scaled by factors equal to 0.66 for ^{6}Li, 0.74 for ^{7}Li and 0.68 for ^{9}Be. Fig. 2 shows the suppression factors as a function of the energy, for the three systems. It is interesting to notice that although the suppression of the CF cross sections at high energies was found to be similar for the different systems, the strongest (smallest) CF suppression occurs for the ^{6}Li (^{7}Li) projectile, that has the smallest (highest) break-up separation energy among the three projectiles.

The ICF cross sections were measured for the three systems, and were found to be important in the whole energy range studied, as can be seen from Fig. 3. One has to point out that what is being called incomplete fusion cross section is actually the sum of this value with eventual direct transfer channel cross sections leading to the same final products. Fig. 4 shows the total fusion (TF = CF + ICF) reduced excitation functions for the three systems. Their behaviors are similar and agree with the predictions of SBPM and CCC, indicating that the total fusion cross section is not affected by the break-up process.

The measured cross sections for the ^{6,7}Li + ^{209}Bi systems were also compared with a three-body classical trajectory model[13] that follows the path of the break-up fragments. The model reproduces the data well, and a remarkable prediction is that, at energies just above the Coulomb barrier, roughly half of the total CF cross section comes from the complete fusion following the break-up (CF^{BU}). As the energy increases, the contribution of this process to the CF decreases. On the other hand, the ICF cross section is important in the whole energy range studied.

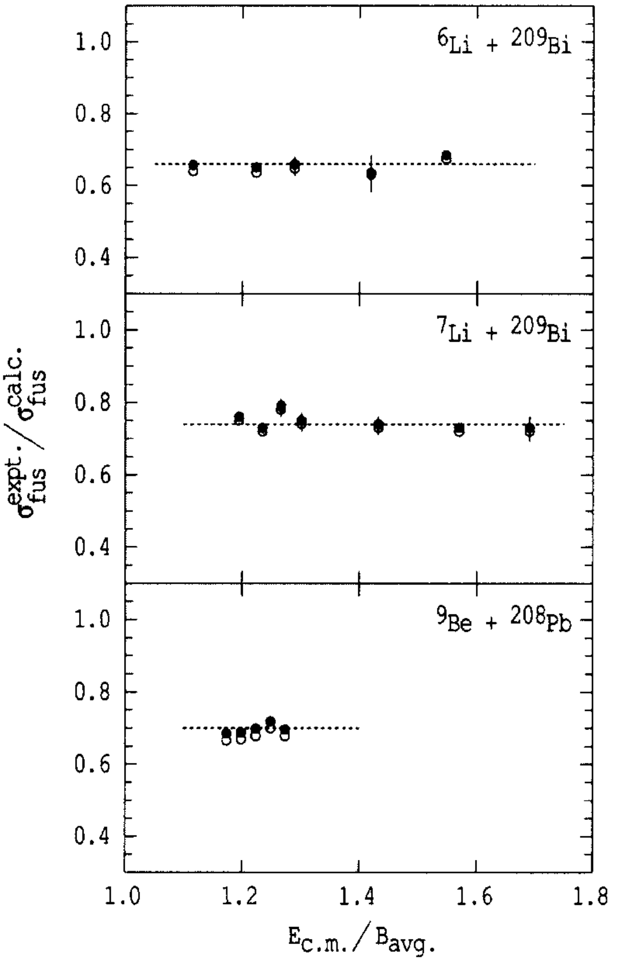

Figure 2. Complete fusion suppression factors, due to the break-up, as a function of the energy, at the above barrier energy regime for the ^{6,7}Li + ^{209}Bi and ^{9}Be + ^{208}Pb systems.

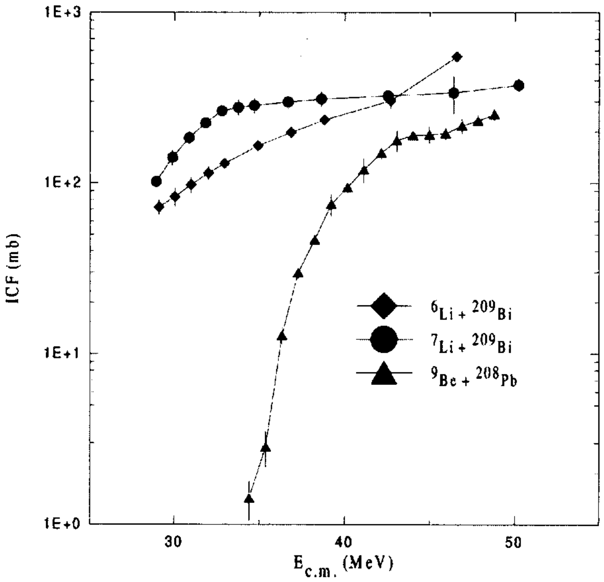

Figure 3. Measured incomplete fusion cross sections for the ^{6,7}Li + ^{209}Bi and ^{9}Be + ^{208}Pb systems.

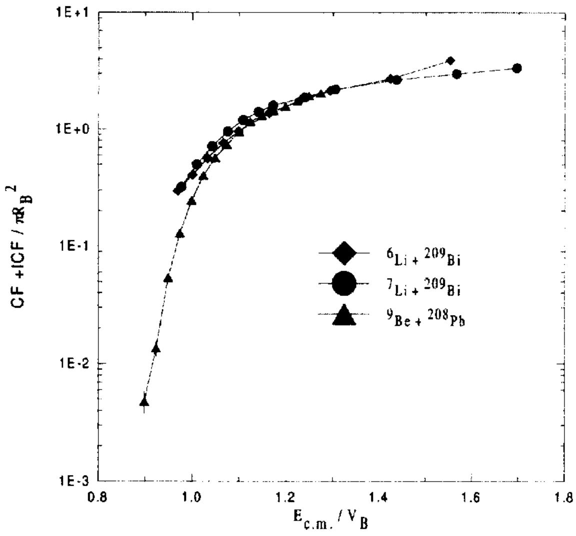

Figure 4. Reduced total fusion cross sections for the ^{6,7}Li + ^{209}Bi and ^{9}Be + ^{208}Pb systems.

From these results for energies above the Coulomb barrier, the following conclusions can be drawn: the break-up process inhibits about 30 % the CF cross section at this energy regime and there is a signature that the suppression factor increases slightly as the break-up separation energy decreases; the TF cross section is not affected by the break-up process; the ICF is important and it is the mechanism responsible for the CF cross section suppression; at sub-barrier energies, the situation is not so clear, due to the competition between the enhancement of the CF due to couplings and suppression due to the break-up. The net result is some CF cross section enhancement.

Although we observe differences in the fusion cross sections for the three systems, they are not so remarkable as the differences in the break-up threshold energy and in the elastic break-up cross sections of similar systems (^{6,7}Li + ^{208}Pb [21], ^{9}Be + ^{209}Bi [22], ^{9}Be + ^{208}Pb [23], ^{6}He + ^{209}Bi [24]) might suggest. These cross sections were found to be larger than the fusion cross sections at sub-barrier energies, and depend strongly on the break-up threshold energy. The reaction cross sections derived for some of these systems are in agreement with the sum of break-up and total fusion cross sections, and also increase strongly when the projectile break-up threshold energy decreases. However, the large difference between the break-up cross sections for different weakly bound projectiles are not reflected in the fusion cross section values.

From these arguments and data, we believe that a simple picture of this subject can be given at the moment, for energies above the Coulomb barrier and heavy targets. The break-up corresponding to large partial waves is related to the measured elastic break-up cross sections, and does not affect the CF cross section, since these mechanisms are concerned with different partial waves. The fusion cross section should be affected by processes and interactions that take place near the nuclear surface of the colliding nuclei, where the fusion is decided. Our results show that the sum of ICF + CF cross sections correspond to the predictions of CCC and SBPC, without the inclusion of the break-up process. Therefore, the break-up process that occurs near the Coulomb barrier radius leads predominantly to the absorption, by the target nucleus, of one or all the fragments. The results from the classical trajectory calculations predict that the absorption of all the fragments, leading to CF, is important at energies close to the Coulomb barrier, corresponding to the need of closer approach of the projectile, in order to convert kinetic and potential energies in relative energy. As the energy increases, the probability of CF following the break-up decreases. On the other hand, the probability that only one of the fragments fuses with the target, leading to ICF is likely to occur at any energy above the barrier, for heavy targets. This is the mechanism responsible for the CF suppression at energies above the barrier, corresponding to a significant fraction of the total fusion cross section (of the order of 30%). Those conclusions are qualitatively in agreement with the picture of long range fusion absorptive potential, of the order of the position of the Coulomb barrier[1, 2], and with the effect of sharp transfer form factor channels on the fusion of tightly bound nuclei mentioned at the beginning of this paper[3, 4].

Our next question is: Can we extend the previous conclusions for medium and light mass targets? We answer this question in the following.

The influence of the break-up on the fusion cross section with medium - light mass nuclei was investigated by the comparison of the fusion excitation functions of several systems, at above barrier energies: the weakly bound ^{6,7}Li and ^{9}Be, and the tightly bound ^{16,17,18}O, ^{14}N, ^{12}C and ^{11,10}B nuclei as projectiles and the ^{19}F, ^{27}Al, ^{29}Si and ^{64}Zn nuclei as targets. The inverse reaction ^{12}C + ^{7}Li was also measured. Several light systems measured by the gamma ray spectroscopy method by Mukherjee et al.[19] were also analyzed. Only the CF + ICF cross sections were determined for all the systems, except for the ^{9}Be + ^{64}Zn and the light systems measured by Mukherjee, for which the CF cross sections were measured and the ICF cross section was found to be negligible. We believe that the ICF is also not important for similar systems.

Each fusion excitation function was fitted by SBPC. If the break-up process had an important influence on the fusion cross section, the derived barrier parameters should have anomalous values. However, reasonable fits were obtained for all the systems, and the barrier parameters agree with the values from systematic, within the usual fluctuations around the average values.

The reduced fusion excitation functions for the ^{6,7}Li, ^{9}Be, ^{16}O + ^{64}Zn systems coincide, regardless of the presence or absence of weakly bound nuclei. The same behavior is found when we compare the excitation functions of the ^{6,7}Li, ^{9}Be, ^{11}B, ^{16}O + ^{27}Al systems; ^{9}Be + ^{27}Al, ^{29}Si and ^{11}B + ^{27}Al systems (the last one leads to the same compound nucleus as ^{9}Be + ^{29}Si); ^{18}O + ^{10}B, ^{17}O + ^{11}B, ^{19}F + ^{9}Be (all the three leading to the same compound nucleus); ^{19}F + ^{9}Be and ^{19}F + ^{12}C.

Therefore, the fusion excitation functions, which we expect to correspond to CF, for the medium-light systems do not seem to be influenced by the break-up process and do not show any dependence on the projectile separation energy, within the $\sim$10% uncertainties of the measurements.

We have also investigated the behavior of the ratio fusion / reaction cross sections for some of those systems, and it does not follow any systematic dependence with the separation energies either.

Therefore, we believe that there are strong signatures that there is no total fusion cross section hindrance, at above barrier energies, for these medium mass systems, and there are also some evidence that the ICF process is negligible at this mass range. Our data for the for the ^{12}C + ^{7}Li reaction, measured in inverse kinematics in order to minimize the problems of transmission of the low energy residues through the detector window, agree with those from the gamma spectroscopy method, where no fusion suppression could be detected at energies above the Coulomb barrier.

These results for light systems are in agreement with the continuum discretized coupled channel calculations performed by Keeley et al.[25], for the ^{6,7}Li + ^{16}O systems. They also agree with the predictions of Hinde et al.[23] and Hussein et al.[26], leading to suppression factors for the CF of ^{9}Be + ^{64}Zn equal to 0.13 and 0.037 for the ^{9}Be + ^{19}F, consistent with our measurements.

The low values of the ICF, for medium and light mass targets might be probably due to the weak Coulomb potential and the need of a closer approach of the colliding nuclei before the break-up occurs. At such small distance the point of no return from fusion had already been reached and the whole flux go to CF, even after the break-up. Therefore, there is no CF cross section suppression for those light systems, for stable weakly bound nuclei, at energies above the Coulomb barrier. The conclusions related to the negligible ICF cross section for medium and light mass targets may not be a priori extended to halo nucleus projectiles, due to their abnormal large radii.

Ackowledgements

The authors would like to thank the CNPq, CAPES and FAPERJ for their financial support.

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