The fusion of stable weakly bound nuclei

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We discuss our present understanding of the effect of the break-up of stable weakly bound nuclei on the fusion cross section of these projectiles with light, medium and heavy mass targets, at energies above the Coulomb barrier. The discussion is based mostly on data obtained by our group in collaborative experiments. We show that for heavy targets there is complete fusion suppression, corresponding to the occurrence of incomplete fusion of one of the break-up fragments, whereas for medium and light mass targets, there is no such effect, due to the negligible incomplete fusion process.

§1. The fusion versus break-up problem

Fusion reactions induced by weakly bound nuclei has been extensively studied in the last years. 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. The main question on this subject is: What is the effect of the break-up process on the fusion cross section? Although there has been many theoretical and experimental works, this subject is still far from being full understood. There is a special interest on this field due to the recent availability of radioactive beams of very weakly bound nuclei.\textsuperscript{1–6)} Reactions of astrophysical interest are induced by weakly bound nuclei and, if the great size of radioactive nuclei 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 induced by high intensity stable beams that are weakly bound, and consequently should have a reasonable break-up probability. The full understanding of the fusion and break-up processes induced by stable weakly bound nuclei is an important reference for similar studies involving radioactive proton and neutron rich beams. The suitable stable nuclei for this kind of study are \textsuperscript{9}Be, \textsuperscript{6}Li and \textsuperscript{7}Li, that have different structures and threshold break-up energies (from 1.48 MeV to 2.45 MeV). Measurements of fusion induced by these three nuclei may test theoretical models and may be useful when compared with fusion measurements involving unstable halo nuclei.

The main general questions which have to be answered concerning this subject are: (i) - Does the break-up channel (BU) enhance or suppress the fusion cross section? (ii) - Is this effect concerned with the complete fusion (CF) cross section or with the total fusion (TF) cross section, corresponding to the sum of the usual complete fusion (CF\textsuperscript{n}) cross section with the fusion cross sections following the break-up process (by one (ICF) or all (CF\textsuperscript{BU}) the BU fragments)? (iii) - What are the...
effects of the BU on the fusion at different energy regimes? (iv) - What are the effects of the BU on the fusion for different target masses? (v) - Does the value of the BU threshold energy strongly affect the fusion cross section as it does in the direct (or elastic) break-up (BU\textsuperscript{elast}) cross section?

Some general aspects of the heavy ion fusion involving tightly bound nuclei are relevant to the present subject. (i) - For energies from the Coulomb barrier to roughly twice this value (the so-called "region I"), the fusion process is the main component of the reaction cross section. As the bombarding energy increases, an important part of the incoming flux goes to other competing reaction channels, consequently decreasing the fraction of the reaction cross section associated with fusion (the so-called "region II"). A possible hindrance of the CF cross section at energies near the Coulomb barrier means that the BU may contribute to reduce the energy necessary to reach the "region II". (ii) - At energies below the Coulomb barrier, the fusion mechanism has strong couplings with elastic, inelastic and transfer channels. Is the BU channel another channel that, coupled to CF contribute to the usual sub-barrier CF cross section enhancement, compared with predictions of single barrier penetration models (SBPM), or does it compete with CF and suppress it, even for energies below the barrier? (iii) - It is widely assumed that the fusion absorptive potential has a small range ($r_f \cong 1.0 - 1.2$ fm), but there are some reports of simultaneous analysis of fusion and elastic scattering data\textsuperscript{7,8} that show that $r_f \cong 1.45$ fm, which means that the fusion process is decided upon the Coulomb barrier position. Transfer channels that have sharp form factors, and consequently a relative small average transfer distance, act as important doorways to fusion and enhance the fusion cross section at this energy regime,\textsuperscript{9} otherwise they do not affect the fusion process significantly.\textsuperscript{10} Therefore, it is very important to know whether the BU process occurs before or after the point of no return from fusion, in order to understand its effect on the CF.

\section{2. Theoretical aspects to be considered and some predictions.}

There are several theoretical aspects to be considered when one wants to study the influence of the break-up (BU) process on the fusion cross section. For example, one has to consider different reaction mechanisms related with the BU, such as the elastic or direct break-up (BU\textsuperscript{elast}) and the inelastic or sequential break-up, including incomplete fusion (ICF) of one of the fragments and complete fusion (CF\textsuperscript{BU}) of all the fragments. One has also to study the relative motion of the fragments and their interactions, in order to describe their trajectories following the BU. It is very important to specify which are the boundary conditions used for the occurrence of complete fusion, such as the distance where the fusion is decided and definitions of CF and ICF related to bound and unbound states. Calculations have to be performed by considering bound states-continuum couplings, with or without resonance states, discretized continuum states and continuum-continuum couplings, Coulomb and nuclear excitations have to be considered, as well as their interference. So far, there is no such complete theoretical study in this field.

In the following we try to summarize very briefly some of the main theoretical
The fusion of stable weakly bound nuclei works in this field. In 1991, Takigawa and Sagawa\cite{11} studied the nuclear interaction potential for the $^{11}\text{Li} + ^{208}\text{Pb}$ system, taking into account the halo effect and the coupling of the soft resonance at 0.2 MeV, but ignoring the BU process. They predicted a strong sub-barrier fusion enhancement, compared with SBPM calculations and with reactions induced by the other Li isotopes, and no effect at energies well above the barrier. Similar conclusions were earlier reached by Hussein,\cite{12} who was the first to point out the potential relevance of neutron-rich nuclei to the production of the super-heavy elements. Later, in 1992, Hussein et al\cite{13} extended the study by the inclusion of the BU channel and neglecting the real part of the polarization potential and the Coulomb BU. They predicted that the BU channel leads to a fusion surviving probability smaller than one, and decreases the large sub-barrier CF enhancement, whereas it suppress the CF cross section at above barrier energies. In 1993, Takigawa, Kuratani and Sagawa,\cite{14} using a semiclassical approach, where the BU is introduced through an imaginary local dynamic polarization potential, drew similar qualitative conclusions at energies below the barrier, although the effect of the BU was smaller. For energies above the barrier, they predicted that the total fusion should not be affected by the BU. In 1994, Dasso and Vitturi\cite{15} predicted a TF enhancement due to the BU below and above the barrier, due not only to the soft resonance but also to the BU channel. The Brazilian group\cite{16} questioned those results by arguing that the BU cannot be considered a single coupling channel, but rather a continuum of states corresponding to an irreversible path to fusion. Canto et al\cite{17} included the Coulomb BU previously neglected and, considering that there is no CF following the BU, concluded that the Coulomb BU has an effect similar to an effective increase in the height of the Coulomb barrier, and therefore decreases the CF in the whole energy range. In 1996, using a semiclassical approach with quantum fluctuations, Dasso et al\cite{18} assumed that if the BU occurs inside the nuclear well, it will be followed by CF. They predicted once more the enhancement of the CF cross section in the whole energy range. From 1997 the calculations were extended to stable weakly bound nuclei. Canto et al\cite{19} used the formalism of ref. 16 to predict the hindrance of the fusion of light systems at energies above the barrier. In 2001, Keeley et al,\cite{20} using CDCC, a cluster-folding model and Coulomb and nuclear BU, predicted no effect of the BU on the fusion, for similar systems. In 2000, Hagino et al\cite{21} studied the $^{11}\text{Be} + ^{208}\text{Pb}$ system by using CDCC. In this work, CF is associated with the flux at the entrance channel (absorption from bound states), separated inside the barrier by incoming wave boundary conditions (IWBC) from the ICF, that corresponds to the flux of the BU (unbound states) channels. Without taking into account the continuum-continuum and bound state couplings, they predicted the enhancement of CF cross section at sub-barrier energies, when compared with bare potentials, and its hindrance at energies above the barrier. Both, the usual CF enhancement as for tightly bound nuclei, and the reduction of flux in the bound channels due to the BU before reaching the fusion barrier, are present at all energies, but each one dominates at different energy regions, below and above the barrier. More complete and precise studies performed by Diaz Torres and Thompson,\cite{22} including high order continuum-continuum couplings, predict the hindrance of CF and TF below and above the barrier (except for energies far below the barrier),
due to the reduction of flux penetrating the barrier.

§3. Experimental aspects to be considered.

A first aspect to be considered when one performs experiments to measure fusion cross sections is if one is able to identify the CF process separated from the ICF. Usually the residues following both processes are very similar or identical, and therefore the measurement of residues by charged particle detectors is not able to distinguish them. This is even more dramatic for light systems for which the main evaporation channels include charged particles. Therefore, most of the data available in the literature correspond to the total fusion cross section. When the compound nuclei evaporate mainly by neutrons, the detection of decay alpha particles or X-rays following electron capture may be used to separate CF and ICF processes. Similarly, it is very difficult to separate experimentally the CF from the fusion of all the charged BU fragments with the target, what leads to obtain the cross section of the sum of these two processes, instead of the pure CF. These restrictions are particularly important when one wants to measure the CF cross sections using $^6$He $^{1,2}$, $^9$Be and $^{11}$Li as projectiles. The derived cross section may be much larger than the actual CF cross section. Of course, there is no way to distinguish experimentally between the usual complete fusion (CF) and the complete fusion following break-up, namely the sequential absorption of all the fragments by the target after the BU has occurred (CF$^{BU}$).

Another important aspect to be considered is that one can not distinguish experimentally the ICF from direct transfer channels leading to the same compound nucleus. Q-value considerations and exclusive experiments may help to distinguish them, but if the two processes are present, a misinterpretation of the data may come out.

Finally, we would like to strength the importance of a clear definition of what is considered a fusion cross section enhancement or suppression, otherwise different interpretations may arise from the same data.

§4. Fusion cross section data obtained by our group in collaborative experiments

In this paper we give an overall picture of our 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, $^6$Li + $^{11}$B, $^9$Be + $^{27}$Al, $^{64}$Zn, $^9$Be + $^{19}$F, $^{12}$C + $^7$Li, and $^{12}$C + $^7$Li. Systems measured by other authors are also analyzed, such as $^6$Li + $^{59}$Co and $^6$Li + $^{16}$O, $^{12,13}$C, $^7$Li + $^{11}$B, $^9$Be + $^9$Be. Comparisons with other systems involving tightly bound projectiles on the same targets and/or leading to the same compound nuclei are also made.

The experiments discussed here were performed in collaborative experiments involving Australian National University-ANU, Canberra, Australia; São Paulo University-USP, Brazil; and TANDAR Laboratory, Buenos Aires, Argentina. Different experi-
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mental methods have been used in these studies, but they will not be described in this short paper, since this was done in the corresponding specific papers.

The $^6,^7\text{Li} + ^{209}\text{Bi}$ and $^9\text{Be} + ^{208}\text{Pb}$ fission, CF and ICF cross sections were determined separately at ANU, by the measurement of on-line and off-line alpha particles.\cite{23}-\cite{25} Barrier distributions were also derived. The total fusion (CF + ICF) cross sections of $^6,^7\text{Li} + ^{64}\text{Zn}$, $^{27}\text{Al}$ and $^9\text{Be} + ^{27}\text{Al}$ were measured at TANDAR by either time of flight\cite{29},\cite{33} or ionization chamber techniques.\cite{32} The fusion of $^9\text{Be} + ^{64}\text{Zn}$ was measured at USP by the in-beam and off-beam gamma ray spectroscopy methods,\cite{30},\cite{31} and it was derived that the ICF cross section was smaller than 10% of the CF. The total fusion of $^{19}\text{F} + ^9\text{Be}$ was measured at USP,\cite{32} with one ionization chamber. Elastic scattering experiments for $^6,^7\text{Li}$ on $^{64}\text{Zn}$ and $^{27}\text{Al}$, and $^9\text{Be}$ on $^{27}\text{Al}$ were also performed at USP, allowing the derivation of reaction cross sections. The total fusion for the $^{12}\text{C} + ^7\text{Li}$ system was measured at ANU,\cite{34} with a large multi-anode ionization chamber.

\section{Discussion of the effect of the break-up on the fusion cross section}

We start by the analysis of the CF for the three systems involving heavy targets: $^6,^7\text{Li} + ^{209}\text{Bi}$ and $^9\text{Be} + ^{208}\text{Pb}$. For all of them SBPC and CCC including bound excited states, without the inclusion of any projectile break-up effect, predict larger values than the experimental ones at above barrier energies. Below the Coulomb barrier, the SBPC underpredict the experimental cross sections, whereas the CCC 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 from 0.66 to 0.74. The strongest CF suppression occurs for the $^6\text{Li}$ projectile, that has the smallest break-up separation energy, and the smallest occurs for the $^7\text{Li}$, for which this value is the highest among the three projectiles. The ICF cross sections for the three systems were found to be important in the whole energy range studied. One has to point out that what is being called ICF cross section is actually the sum of this value with eventual direct transfer channel cross sections leading to the same final products. The TF reduced excitation functions for the three systems have similar behaviors and agree with the predictions of SBPM and CCC, indicating that the total fusion cross section is not affected by the BU process. When we compare the experimental data of two pairs of systems,\cite{25} leading to the same compound nuclei (i) $^7\text{Li} + ^{209}\text{Bi}$ and $^{18}\text{O} + ^{198}\text{Pt}$; (ii) $^9\text{Be} + ^{208}\text{Pb}$ and $^{13}\text{C} + ^{204}\text{Hg}$), we observe that while the CF of the systems with weakly bound nuclei are reduced by the same suppression factors discussed before, when compared with the systems with tightly bound projectiles, the total fusion excitation functions, on the other hand, coincide. Figure 1 shows the results for one of those two pairs of systems. The cross sections for the $^6,^7\text{Li} + ^{209}\text{Bi}$ systems were also compared with a three-body classical trajectory model\cite{24} that follows the path of the break-up fragments and predicts 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.

The influence of the BU on the fusion with medium and light mass nuclei was investigated by the comparison of the fusion excitation functions of several systems, at above barrier energies: the weakly bound $^6$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 reaction $^{12}$C + $^7$Li was also measured. Several light systems measured by the gamma ray spectroscopy method$^{35}$–$^{38}$ were also analyzed. Only the CF + ICF cross sections were determined for all the systems, except for the $^9$Be + $^{64}$Zn, for which the CF cross sections were measured and the ICF cross section was found to be smaller than 10% of the CF (within the experimental error bars).$^{31}$ Figure 2 shows the CF cross sections for the $^9$Be + $^{64}$Zn and $^{14}$N + $^{59}$Co systems, leading to the same compound nucleus. A possible CF suppression of the $^9$Be + $^{64}$Zn is within the experimental uncertainties. We suppose that the ICF is also not important for similar systems. The reduced fusion excitation functions for the $^6$Li, $^9$Be, $^{16}$O + $^{64}$Zn systems coincide.$^{30,33}$ The same behavior is found when we compare the excitation functions of the $^6$Li, $^9$Be, $^{11}$B, $^{16}$O + $^{27}$Al systems; $^9$Be + $^{27}$Al, $^{29}$Si and $^{14}$B + $^{27}$Al systems (the last one leads to the same compound nucleus as $^9$Be + $^{29}$Si); $^{18}$O + $^{18}$B, $^{17}$O + $^{11}$B, $^{19}$F + $^9$Be (leading to the same compound nucleus); $^{19}$F + $^9$Be and $^{19}$F + $^{12}$C.$^{32,33}$ The data for the for the $^{12}$C + $^7$Li reaction,$^{34}$ 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,$^{35}$–$^{39}$ where no fusion suppression could be detected at energies above the Coulomb barrier. Therefore, we believe that there are strong signatures that the BU process does not affect the TF cross section, at above barrier energies, for these medium and light mass systems, and there are also some evidence that the ICF process is negligible, within the 10% uncertainties of the data, at this mass range.

§6. Conclusions

From these results for energies above the Coulomb barrier, the following conclusions can be drawn: For heavy targets, the BU process inhibits the CF cross section, by 30%, 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. 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, because there may be competition between the enhancement of the CF due to couplings and a possible suppression due to the loss of flux to the break-up channel. The net result is some CF cross section enhancement. The differences in the fusion cross sections for the three systems, are not so remarkable as the differences in the BU threshold energy and in the BU$_{elast}$ cross sections of similar systems ($^6$Li + $^{208}$Pb,$^{40}$ $^9$Be + $^{209}$Bi,$^{41}$ $^9$Be + $^{208}$Pb,$^{42}$ $^6$He + $^{209}$Bi$^3$) 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 \( BU^{elast} \) and TF cross sections, and also increase strongly when the projectile BU threshold energy decreases. However, the large differences between the \( BU^{elast} \) cross sections for different weakly bound projectiles are not reflected in the fusion cross section.

From these arguments and data, we believe that a simple picture of this subject emerges at the moment, for energies above the Coulomb barrier and heavy targets. The \( BU^{elast} \) 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 corresponds to the predictions of CCC and SBPC, without the inclusion of the BU process. Therefore, the BU process that occurs near the Coulomb barrier radius leads predominantly to the absorption, by the target nucleus, of one or all the fragments. The absorption of all the fragments, leading to CF (\( CF^{BU} \)), may be important at energies very close to the Coulomb barrier, corresponding to the need of closer approach of the projectile, in order to convert total mechanical energy into binding and excitation energies. 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 TF 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,\(^7\),\(^8\) and with the effect of sharp transfer form factor channels on the fusion of tightly bound nuclei mentioned at the beginning of this paper.\(^9\),\(^10\)

Concerning the medium and light mass targets, the ICF is negligible, at least within the experimental error bars of the measured fusion cross sections (of the order of 10%), probably due to the weak Coulomb potential and the need of a closer approach of the colliding nuclei before the BU 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 BU. Therefore, there is no CF cross section suppression for those light systems, for stable weakly bound nuclei, at energies above the Coulomb barrier.

The occurrences of the BU very close to the Coulomb barrier radius were derived by exclusive \(^9\)Be \( BU^{elast} \) measurements.\(^42\) 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.

These results for light systems are in agreement with the continuum discretized coupled channel calculations performed by Keeley et al\(^20\) for the \(^6,7\)Li + \(^16\)O systems and Diaz-Torres et al for the \(^6,7\)Li + \(^59\)Co systems.\(^43\) They are also consistent with the predictions of Hinde et al\(^42\) and Hussein et al,\(^44\) leading to suppression factors of 0.13 for the CF of \(^9\)Be + \(^64\)Zn and 0.037 for the \(^9\)Be + \(^19\)F.

As perspectives for new experiments, we believe that one needs additional fusion data at sub-barrier energies and more exclusive experiments on separated elastic break-up, elastic scattering, complete fusion, incomplete fusion and transfer reac-
tions, in order to understand the overall reaction mechanisms, and obtain precise information for the calculations. For sure, there is a strong need to extend the experiments using radioactive beams.

References

30) P.R.S. Gomes et al; Heavy Ion Phys.11, 361 (2000)

Fig. 1. Reduced complete fusion cross sections for $^9$Be + $^{208}$Pb and $^{13}$C + $^{204}$Hg$^{25}$ systems, leading to the same compound nucleus.
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Fig. 2. Reduced complete fusion cross sections for $^9\text{Be} + ^{64}\text{Zn}$ and $^{14}\text{N} + ^{59}\text{Co}$ systems, leading to the same compound nucleus.