Why the complete fusion of weakly bound nuclei is enhanced at sub-barrier energies and suppressed above the barrier?

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Abstract. In this paper we explain the reasons for the systematic behaviour of enhancement of the complete fusion cross section of weakly bound systems at sub-barrier energies and its suppression above the barrier, when compared with predictions from calculations which do not take into account breakup and transfer channels. The methodology used is the study of dynamic polarization potentials. At above barrier energies the net polarization potential due to direct breakup is dominant and repulsive, consequently fusion is suppressed. At sub-barrier energies, the enhancement of fusion cross section is consistent with recent experimental observations that nucleon transfer leading to breakup is dominant compared to direct breakup and produces attractive polarization potential.

Keywords: Fusion, Transfer, Breakup, Weakly bound projectiles

The effect of the breakup of weakly bound nuclei, both stable and radioactive, on the fusion cross section has been a subject of great interest in the last years [1, 2, 3]. Several systems have been studied, both theoretically and experimentally, including stable weakly bound projectiles (⁶Li, ⁷Li and ⁹Be) and radioactive projectiles, like ⁶,⁸He, ⁷,¹¹Be, ⁸B, ¹⁷F, on targets with masses ranging from ⁷Li to ²³⁸U. The basic question is whether the breakup process enhances or hinders the fusion cross section. However, before one tries to answer this question, one should be clear about what one is talking about. First, it should be stated what is considered as fusion cross section. Is it the complete fusion of the projectile with the target (CF) or the total fusion (TF), defined as the sum of the complete fusion and the incomplete fusion (ICF), the latter being the fusion of part of the projectile fragments after the breakup with the target? Most of the fusion data reported in the literature are for TF, since it is very difficult to separate experimentally CF from ICF. Then, one should say whether the possible enhancement or suppression is considered in relation to which reference. Also, different breakup effects may occur, like static and dynamic effects. The first one is related with different barrier characteristics, when compared with those for similar tightly bound systems and the latter is related with the coupling of the breakup channel, which feed continuum states, and other direct reactions. In any situation, if one
compares data with theoretical predictions, the choice of the bare interacting potential plays a major role, and contradictory conclusions can be drawn with the same data set depending on the potential used [4].

So, if one wants to study fusion cross sections for weakly bound systems, it is required to start with a standard behaviour of the fusion cross section to which the data should be compared. As mentioned before, a reliable bare potential must be used in the calculations. However, if one uses double folding potentials with realistic densities of the colliding nuclei as the bare potential, the possible static effects of the weakly bound nuclei, specially halo nuclei, are already taken into account, and so the differences between data and calculations show only the dynamic effects of the channels not included in the calculations. Also, if one wants to plot the fusion excitation functions for different systems in the same graphic, a proper normalization method should be used, taking into account trivial factors to correct the cross sections and center of mass energies, like different sizes and Coulomb barriers of the systems. Usually, cross sections are divided by V_B and center of mass energies are divided by V_B, where R_B and V_B are the radius and height of the Coulomb barrier. Gomes et al [5] proposed a somehow alternative method when dealing with weakly bound nuclei, widely used nowadays, to perform this reduction. All those reduction methods aim to eliminate static and geometrical effects. However, it has been recently shown [6] that the traditional reduction procedures do not fully wash out geometrical effects.

Recently Canto et al [6] proposed the use of dimensionless quantities, which appropriately eliminates static effects, as a procedure to investigate dynamic effects on the fusion cross sections due to the breakup couplings. Furthermore, the proposed method allows reaching a systematic understanding of this subject, since it allows the comparison of any kind of system in the same graphic. This method uses a benchmark curve, called the universal fusion function (UFF), given by F_0(x) = ln1+ exp(2πx), where x = (E-V_B)/hω and F(x) = (2E_{c.m.}/πR_B^2hω) σ_{ fus}. hω is related to the barrier curvature, σ_{ fus} is the fusion cross section and F(x) is called fusion function. The fusion function would be system independent if the experimental fusion cross sections were well described by Wongs formula [7] \sigma_{ fus}^W = (πR_B^2hω/ 2E_{c.m.})ln1+exp(2π)(E-V_B)/hω. However, if we compared the experimental fusion function with the UFF, the differences would be caused by the dynamic polarizations altogether, such as all important low lying collective couplings, and not just breakup. Also, the Wong model is known for not being valid at sub-barrier energies for light systems, as it is the situation of some of those involving the above mentioned weakly bound projectiles. By these reasons, Canto et al [6] proposed to renormalize the experimental fusion functions to take into account the possible failure of the Wong model and the effects of inelastic couplings. In the coupled channel calculations to be performed in this renormalization, a reliable bare potential must then be used. These renormalized fusion functions are then compared with UFF. Now, after this renormalization, the differences are dynamic effects due to the channels left out of the coupled channel calculations, in this case, breakup and transfer reactions.

With this method, systematic behaviours of fusion cross sections were obtained [6, 8], by considering the available data for a large number of weakly bound systems. Complete fusion of stable weakly bound nuclei show suppression at energies above the barrier and enhancement below the barrier, when compared with the benchmark UFF curve. This behaviour was first verified by Dasgupta et al [9] for the \(^9\)Be + \(^{208}\)Pb system. Total fusion for those systems coincides with UFF at energies above the barrier. For neutron halo systems, the measured total fusion cross sections show suppression above the barrier and enhancement below the barrier. For the proton halo \(^{17}\)F fusion, the total cross section has the same behaviour as the stable weakly bound systems. It is important to mention that the enhancement of fusion cross section at sub-barrier energies, owing to dynamic breakup and transfer channels, is not so high as the ones found from couplings to low lying collective states when nuclei with large static deformation, like \(^{154}\)Sm, are involved [10, 11, 12, 13]. A quantitative systematic for the suppression of fusion of stable weakly bound systems at energies above the barrier, as a function of the target charge,
was investigated, but was not successful [14, 15]. For the $^{6,7}$Li + $^{209}$Bi systems, the complete fusion shows larger suppression above the barrier and larger enhancement below the barrier for the $^{6}$Li projectile than for $^{7}$Li [16], what can be understood, since $^{6}$Li has smaller breakup threshold than $^{7}$Li and no bound state, and so the breakup effects on complete fusion for $^{6}$Li might be more important than for $^{7}$Li. This effect could not be observed for the total fusion of $^{6,7}$Li + $^{59}$Co [17] at energies above the barrier (see figure 2 of that work), since the total fusion for these systems are not affected by breakup at this regime. Figure 1 shows the renormalized total fusion function for some of the systems involving neutron-halo nuclei. The linear scale is more appropriate to observe the effects above the barrier, whereas the usual logarithmic scale is better to investigate the sub-barrier energy regime.

![Renormalized fusion functions](image)

**Figure 1.** Renormalized fusion functions (see text) for total fusion of neutron-halo systems, plotted against $x = (E-V_B)/\hbar \omega$ for several systems. The full curves are the universal fusion function (UFF) obtained by using the prescription of [6].

One may ask whether all systems follow these systematic. The answer is no, since a few of them do not follow the behaviours mentioned above. Total fusion of $^{6,7}$Li + $^{12}$C, $^{9}$Be [18], $^{64}$Zn [19] and $^{59}$Co [17] show some suppression above the barrier. The total fusion of $^{6}$He + $^{197}$Au, for which the systematic says that it should be suppressed at this energy regime, does not show any effect [20] and the sub-barrier fusion of $^{6}$He + $^{206}$Pb [20] has a completely anomalous behaviour. Finally, the complete fusion of the proton halo $^{8}$B on $^{58}$Ni [21] is the only reported data for which it is observed enhancement at energies above the barrier. However, for some of those systems, other measurements were performed by other groups and methods, and the systematic behaviours were found for $^{7}$Li + $^{12}$C [22, 23], $^{6}$Li + $^{64}$Zn [24] and $^{6}$He + $^{206}$Pb [25]. So, in the following we will consider only the results from the systematic. The other systems may have special features.

Now we will try to explain the above mentioned systematic behaviours of complete fusion suppression above the barrier and enhancement at sub-barrier energies. This analysis is made into more details in another paper [26]. We use the approach of optical potentials, instead of explicitly including the couplings in coupled channel formalism. The effect of couplings is manifested through an energy dependent optical potential produced by complex dynamic polarization potentials (DPP). An advantage of this procedure is that the DPP can be derived from the elastic scattering measurements alone. The negative imaginary part accounts for the absorption of the incident wave, associated with non-elastic channels. So, the incident current is attenuated as the projectile approaches the fusion barrier, reducing fusion. The real part of
The polarization potential can be negative (attractive) or positive (repulsive), depending on the nature of the channel under consideration. Polarization potentials associated with couplings with transfer and inelastic channels were shown to be negative at energies near and below the Coulomb barrier.

The total nuclear potential, with an energy dependent polarization potential part, is obtained through fits to elastic scattering data. For reactions of tightly bound nuclei, it exhibits the so-called threshold anomaly (TA) [27, 28, 29], which corresponds to the decrease of the imaginary part of the potential, when the collision energy decreases towards the barrier, due to the closing of all non-elastic channels, while the real potential shows a bell shaped maximum, since the real and imaginary potentials are connected through the dispersion relation [30]. This behaviour occurs because the polarization potential is attractive just below the barrier. However, for weakly bound systems, the imaginary potential no longer decreases and may even increase when the bombarding energy decreases. This increase is accompanied by a decrease of the strength of the real part of the nuclear potential (that is, the total real potential is less attractive because the DPP is repulsive). This behaviour was called the breakup threshold anomaly (BTA) by Hussein et al [31] and it has been attributed to the repulsive DPP produced by the breakup channel. In literature one finds several weakly bound systems, both stable and radioactive, for which the BTA has been observed, especially for $^6$Li and $^6$He projectiles. Figure 2 shows the energy dependence of the optical potential for the $^6$He + $^{209}$Bi system [32, 33]. The dashed curves are extraplations at the low energy limit, all of them satisfying the dispersion relation.

Indeed, recent calculations [34, 35, 36] show that the direct breakup produces repulsive DPP, owing to the couplings among continuum breakup states (continuum-continuum couplings) [35]. Figure 3 is an example, for the $^8$B + $^{58}$Ni system, at three energies (above, near and below the Coulomb barrier). This repulsive real DPP increases the barrier height and suppress fusion. However, there are recent experimental evidences [37, 38, 39, 40] which show that breakup triggered by nucleon transfer may predominate over the direct breakup, at least at sub-barrier energies. So, the polarization potentials for each one should be evaluated separately and the
results summed. Thus, the suppression of complete fusion above the Coulomb barrier should result from the real part of the DPP associated with direct breakup.

Figure 3. Repulsive polarization potential for the direct breakup of $^8\text{B}$ on $^{58}\text{Ni}$.

Now, a puzzle that we propose to consider is how to explain the enhancement of complete fusion at sub barrier energies after the above arguments used to explain the suppression above the barrier. Again, the real parts of the DPP for transfer followed by breakup and direct breakup should be evaluated and the results summed. However, so far there are no reported calculations for the DPP of transfer followed by breakup, considering all important transfer channels. Very recently we have performed [26] Coupled Channel Born Approximation (CCBA) calculations to evaluate the sequential breakup of $^7\text{Li}$ on the $^{144}\text{Sm}$ target, by considering only one of such channels: transfer of one neutron from $^7\text{Li}$ to the ground state of the target, followed by the breakup of $^6\text{Li}$ into $\alpha+d$. The reason to include only the transfer to the ground state of $^{145}\text{Sm}$ lies on the fact that the Q-values of this transfer reaction is negative, but near to zero (Q-value = -0.493 MeV). For the $^{145}\text{Sm}(g.s.)|^{144}\text{Sm}(g.s.)$ overlap, the spectroscopic factors were taken from Ref.[41] as equal to 0.735 and 0.657, respectively. For the $^{7}\text{Li}(g.s.)|^{6}\text{Li}(g.s.)$ overlap, the spectroscopic factor used was 0.60 [42]. In the calculations we used the double folding Sao Paulo potential (SPP) [43] without any free parameter as the real part of the optical potentials. The computer code FRESCO [44] was used in the calculations. These can be considered as qualitative calculations, since we are not able yet to perform calculations involving all important channels simultaneously, such as direct breakup, several transfer channels and furthermore, several transfer channels followed by breakup. Earlier [45], the direct breakup polarization potential was calculated for the same system, by means of CDCC calculations where, besides the continuum states of the projectile, only inelastic excitations of the interacting nuclei were considered. Using the cluster model, the projectile $^7\text{Li}$ was considered to breakup into $\alpha+t$, as it is usually reported in the literature. The computer code FRESCO [44] was also used in the calculations. Detailed descriptions of both calculations can be found in refs [45, 26]. The results of both calculations show that the real parts of the DPP due to direct breakup and breakup after transfer have opposite signs. The latter is attractive while the former is repulsive. Figure 4 shows the results of the real DPP for the transfer of one-neutron from $^7\text{Li}$ followed by the breakup of $^6\text{Li}$, for the $^{144}\text{Sm}$ target, for three different energies: below, near and above the barrier. In every situation the DPP is attractive. As the systematic results for complete fusion data show enhancement at sub-barrier energies, we argue that at this energy regime the attractive DPP due to sequential breakup predominates over the repulsive one produced by direct breakup. This argument is compatible with the experimental evidences that the former breakup process has larger cross section than the later at sub-barrier energies [37, 38, 39, 40].

Those results are also consistent with the DPP derived from elastic scattering at lower energies, as can be observed in all extrapolations to low energies of the real DPP in several
works. In those works usually there are no data at deeper sub-barrier energies, since the elastic scattering can hardly be distinguished from Rutherford scattering. However, in every case it is obvious that the imaginary part of the energy dependent optical potential has to vanish at very low energies, since all reaction channels will be closed at energies too much below the Coulomb barrier. So, due to the dispersion relation, the real part of the potential has to show the typical bell shape maximum at this energy range, corresponding to an attractive DPP which enhances the fusion. Figure 2 shows some possible extrapolations of the energy dependent optical potential at energies below the barrier.

The present explanations can be generalized for other weakly bound projectiles, like neutron halo nuclei like $^6$He, $^8$He and $^{11}$Be, for which it has been shown that neutron transfer is more important than fusion and direct breakup at sub-barrier energies [46, 47, 48, 49, 50].

In conclusion, we have explained the systematic behaviour found for experimental complete fusion cross sections in terms of polarization potentials. The suppression of complete fusion observed above the Coulomb barrier is attributed to the absorption of the incident flux resulting from direct breakup. The enhancement of complete fusion at sub-barrier energies is associated with the barrier lowering resulting from intermediate transfer channels. This interpretation is supported by recent experiments showing that the breakup triggered by nucleon transfer dominates the breakup cross sections at sub-barrier energies.

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