

## Complete fusion of weakly bound cluster-type nuclei near barrier energies

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**Abstract.** We consider the influence of breakup channels on the complete fusion of weakly bound cluster-type systems in terms of dynamic polarization potentials. It is argued that the enhancement of the cross section at sub-barrier energies may be consistent with recent experimental observations that nucleon transfer, often leading to breakup, is dominant compared to direct breakup. The main trends of the experimental complete fusion cross sections are analysed in the framework of the Dynamic Polarization Potential approach. The qualitative conclusions are supported by CDCC calculations including a sequential breakup channel, the one-neutron stripping of  ${}^7\text{Li}$  followed by the breakup of  ${}^6\text{Li}$ .

The fusion and breakup of weakly bound, cluster-type, nuclei, both stable and radioactive, have 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 ( ${}^6\text{Li}$ ,  ${}^7\text{Li}$  and  ${}^9\text{Be}$ ) and radioactive halo-type projectiles, like  ${}^{6,8}\text{He}$ ,  ${}^{7,11}\text{Be}$ ,  ${}^8\text{B}$  and  ${}^{17}\text{F}$ , on targets with masses ranging from  ${}^7\text{Li}$  to  ${}^{238}\text{U}$ . The basic question is whether the coupling to the breakup process enhances or hinders the fusion cross section. 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 with a fragment of the projectile after breakup on 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. One may compare a particular result to a well-defined reference calculation to find an enhancement or suppression. Also, different breakup effects may occur, like static and dynamic effects. The first one is related to different barrier characteristics, when compared with those for similar tightly bound systems, and the latter is related to the coupling to breakup channels, which feed continuum states, and to other direct reactions. Therefore, if one compares data with theoretical predictions, the choice of the bare interaction potential plays a major role, and contradictory conclusions can be drawn with the same data set, depending on the potential used [4].

The accepted picture of the fusion and breakup of a cluster-type nucleus on a certain target, is based on the following decomposition of the different processes involved: (1) the complete capture of the whole projectile by the target (complete prompt fusion), (2) the breakup of the projectile followed by the sequential capture of both fragments (complete sequential fusion), (3)



the breakup of the projectile followed by the capture of one of the fragments, while the other fragment flies on (incomplete fusion), and (4) the breakup of the projectile with no capture of any of the fragments (non-capture breakup). The above processes compete and affect each other. In particular, the study of the complete fusion, defined as the sum of (1) and (2), and the total fusion, defined as the sum of (1), (2) and (3), are in general very much influenced by the coupling to the non-capture breakup process (also called ‘elastic’ breakup). In this contribution we discuss the above processes and supply evidence of the occurrence of yet another process, which we may call (5) transfer followed by breakup. This has been confirmed recently by the Canberra group [7], and should be considered as another process to reckon with in discussing fusion of weakly bound stable or radioactive nuclei.

In the analysis of experimental data, the usual procedure has been to define the background or benchmark cross section, which describes the tunnelling of the given system with due reference given to its general overall geometrical features, as well as its charge and mass. This is accomplished through what has been known as the Universal Fusion Function (UFF), introduced and discussed extensively in [5, 6]. This function hinges on an appropriate rescaling of the Wong formula for fusion [8], given by

$$\sigma_F = \frac{R_B^2 \hbar \omega}{2E} \ln \left[ 1 + \exp \left( \frac{2\pi}{\hbar \omega} (E - V_B) \right) \right].$$

The Wong cross section is useful in describing the fusion of structureless nuclei, in the vicinity of the Coulomb barrier, and fails at energies well below the barrier owing to the parabolic (symmetrical) barrier used in its derivation. The actual Coulomb barrier is quite asymmetrical. The limits of the Wong formulae are well known. At above-barrier energies it reduces to the geometrical formula,

$$\sigma_F = \pi R_B^2 \left[ 1 - \frac{E}{V_B} \right],$$

and, as expected, no reference to the curvature of the barrier is maintained. At below-barrier energies, the Wong formula reduces to the usual exponential tunnelling form,

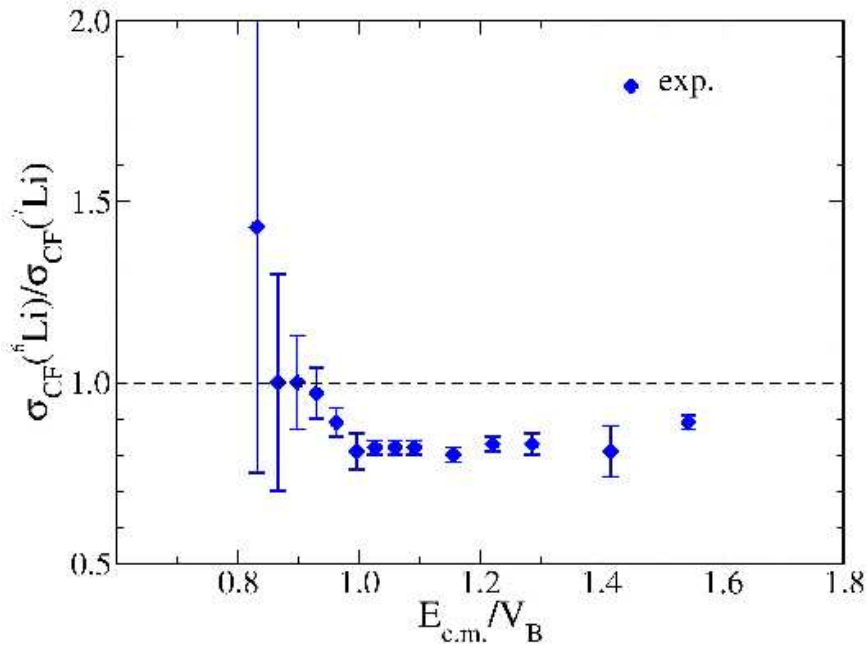
$$\sigma_F = \frac{R_B^2 \hbar \omega}{2E} \exp \left( \frac{2\pi}{\hbar \omega} (E - V_B) \right).$$

Again we remind the reader that the above formula is not appropriate since the barrier is not an inverted parabola. An appropriate use of the correct classical action should be employed at these sub-barrier energies [1].

The rescaling of the Wong formula is done by defining the variable  $x = (E - V_B)/(\hbar \omega)$  and defining the UFF through

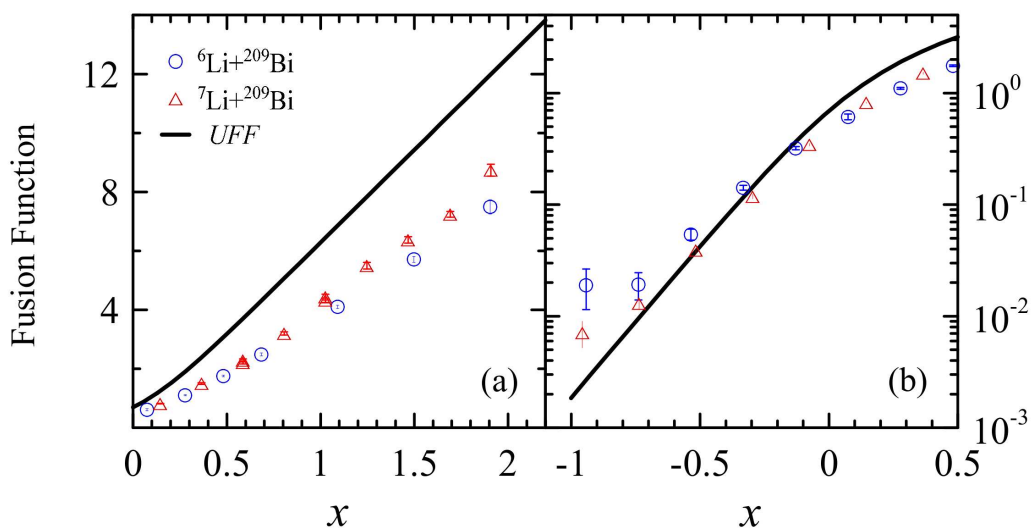
$$F_0(x) = \frac{2E}{R_B^2 \hbar \omega} \sigma_F = \ln[1 + \exp(2\pi x)].$$

Note that  $F_0(x) \rightarrow 2\pi x$  even for small positive  $x$ . The function  $F_0(x)$  is universal in the sense that no specific reference to the system is made. The experimental  $F(x)$  is defined [6] as  $F(x) = F_{exp}(x) \frac{F_0(x)}{F_{CC}(x)}$ , with  $F_{CC}(x)$  being the CC fusion function which includes couplings to all important bound channels. The deviations of  $F(x)$  from the UFF ( $F_0(x)$ ) is traced to the breakup and transfer couplings not included in the coupled-channels (CDCC) calculation,  $F_{CC}(x)$ . A large body of data have been analysed using the above picture [6]. In the following we consider the particular data for collisions of  ${}^6, {}^7\text{Li}$  projectiles incident upon a  ${}^{209}\text{Bi}$  target, which have been measured with high precision [10].



**Figure 1.** Ratio between the complete fusion cross section of the  ${}^6\text{Li} + {}^{209}\text{Bi}$  system and of the  ${}^7\text{Li} + {}^{209}\text{Bi}$  system, as a function of the centre-of-mass energy, divided by the fusion barrier, obtained from the measured fusion barrier distributions [10]. Data from Ref. [10].

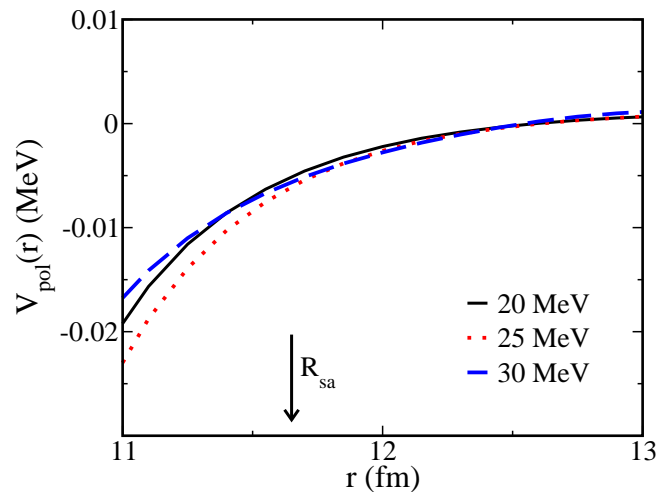
Figure 1 shows the ratio between the complete fusion cross sections of the  ${}^6\text{Li} + {}^{209}\text{Bi}$  and of the  ${}^7\text{Li} + {}^{209}\text{Bi}$  reaction, as a function of the centre-of-mass energy divided by the fusion barrier energies, obtained from the measured fusion barrier distributions [10]. Above the barrier, the



**Figure 2.** Renormalized fusion functions (see text) for complete fusion plotted against  $x = (E - V_B)/\hbar\omega$  for the two systems. The reduced data  $F$  are constructed from [10] and the full curves are the universal fusion functions (UFF),  $F_0$ , given in the text.

stronger the couplings that lead to prompt breakup, the larger is the suppression. Below the barrier, the couplings lower the barrier height. Because of the exponential dependence of the tunnelling probabilities on the barrier energy, this outweighs the linear reduction in cross-section due to prompt breakup. The behaviour seen by plotting the ratio of the cross sections for the two reactions (Fig. 1) is consistent with this picture.

Figure 2 shows the renormalized experimental complete fusion function,  $F(x)$ , for these two systems. These  $F(x)$ 's are obtained by using the São Paulo potential [11] for  $F_{CC}(x)$ . One can observe that the renormalized experimental complete fusion functions are below the UFF (full curve),  $F_0$ , at energies above the barrier. The main features of the data are summarized as follows: (i) the CF cross sections are suppressed by about 30% at energies above the barrier; (ii) the CF cross sections at sub-barrier energies are enhanced; (iii) the above two effects are more pronounced for  ${}^6\text{Li}$  than for  ${}^7\text{Li}$ . The behaviour below the barrier can be traced to the afore-mentioned process (5), transfer followed by breakup. This can be seen in Fig. 3, where the real part of the dynamic polarization potential (DPP) is calculated for this process, and it shows a significant increase in attraction, resulting in a lower barrier.



**Figure 3.** Real part of the DPP around the strong absorption radius for  ${}^7\text{Li} + {}^{144}\text{Sm}$  at laboratory energies above (30 MeV), below (20 MeV) and close to the barrier (25 MeV) for breakup of  ${}^6\text{Li}$  into  $\alpha + d$  following the one-neutron stripping of  ${}^7\text{Li}$ .

Thus, the inclusion of the neutron pickup (transfer) followed by breakup can explain the below-barrier enhancement seen in the fusion of  ${}^6\text{Li}$  on a  ${}^{209}\text{Bi}$  target. The content of this contribution is a summary of a recent publication [12].

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