Search of a systematic behaviour for the weakly bound complete fusion suppression caused by breakup

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Abstract. We discuss the effect of breakup on the complete and total fusion cross sections of weakly bound nuclei, both stable and radioactive, at near barrier energies. We show that there is suppression of the complete fusion of non-halo nuclei and total fusion of neutron-halo nuclei at energies above the barrier, whereas there is some enhancement at sub-barrier energies. We investigate a systematic behaviour for this effect for several weakly bound systems.

Nuclear reactions involving weakly bound nuclei, both stable and radioactive, have been widely investigated in the last years[1]. Several processes can take place after the projectile breakup. One is the incomplete fusion (ICF) in which part of the fragments is absorbed by the target. When all the fragments fuse with the target, the process is called sequential complete fusion (SCF). From the experimental point of view, the SCF cannot be distinguished from the direct complete fusion (DCF) in which the whole projectile fuses with the target without breakup. Therefore, only the complete fusion (CF) cross sections, which includes both of the DCF and SCF cross sections, can be measured. The total fusion (TF) cross section, which includes both of the DCF and SCF cross sections,

\[ \sigma_{TF} = \sigma_{CF} + \sigma_{ICF} \, . \]

Experimentally, it is difficult to distinguish between residues from ICF and CF. Especially for light reaction systems, the excited compound nucleus emits charged particles during the process of its cooling. The residues from ICF cannot be distinguished from those from CF, and thence only the TF cross section can be measured. Particularly important is to study the effect of the breakup of those weakly bound nuclei on the complete fusion of the system at energies close to the Coulomb barrier. Recently it has been well accepted that breakup couplings suppress the complete fusion at energies close but above the Coulomb barrier and enhance fusion at sub-barrier energies. In this work we investigate a possible systematic behaviour of this suppression. The investigation of the effect of breakup on the fusion cross section can also be made using other approaches, such as the energy dependence of the optical potential in the elastic scattering of weakly bound nuclei. For tightly bound systems one observes the usual energy dependence of optical potential, namely the threshold anomaly, corresponding to the decrease of the imaginary potential when the bombarding energy decreases towards the barrier energy. This is explained by the closing of reaction channels at energies near the barrier and by the attractive polarization potential (its real part) produced by inelastic and transfer channels. For weakly bound systems a different behaviour is observed, called breakup threshold anomaly (BTA) [2]. The BTA occurs because the breakup cross section is still important at sub-barrier energies and it is possible to observe that the imaginary potential may even increase at energies close to the barrier, because breakup produces repulsive polarization potentials (real part) [3-5]. The analysis of quasi-elastic barrier distributions also shows that when the direct breakup coupling is included in
the calculations, the barrier height increases and the calculations have better agreement with the data, what confirms that the real part of the polarization potential produced by the direct breakup is repulsive [6-7].

Theoretically, the most suitable calculations involving breakup are the so-called CDCC (continuum discretized coupled channel) calculations, since the breakup feeds states in the continuum. It has been shown that if one wants to describe the behaviour of elastic scattering angular distributions of weakly bound nuclei, it is essential that continuum-continuum couplings are included in the CDCC calculations [4, 8]. However, if one wants to investigate the effect of breakup on the fusion cross section, it may be more interesting to perform much simpler coupled channel calculations which do not take into account the breakup, and so the difference between data and theoretical predictions should correspond to the breakup effect.

The starting point in the comparison of fusion cross section data with theoretical predictions is the choice of a systematic bare interaction potential. We adopt the double-folding parameter-free São Paulo potential (SPP) [9, 10], using reliable nuclear densities of the nuclei involved in the collisions [11,12]. This potential has described successfully several reactions with systems in different mass ranges, including weakly bound nuclei [13,14]. In order to compare data for several systems in a single plot, it is necessary to eliminate the differences associated with trivial factors, like sizes, charges and anomalous densities. Canto et al. [15, 16] proposed the use of dimensionless quantities, with a method, which 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 $F_0(x) = \ln[1 + \exp(2\pi x)]$, where $x = (E - V_B) / h\omega$ and $F(x) = \left(2 E_\text{c.m.} / \pi R_B^2 h\omega\right)\sigma_\text{fus}$. Here $V_B$, $R_B$ and $h\omega$ are the height, radius and curvature of the parabolic barrier, respectively, $\sigma_\text{fus}$ is the fusion cross section and $F(x)$ is called fusion function. This method was later extended for the analysis of total reaction cross section [17].

The above reduction method has a simple meaning. For systems where channel coupling effects can be neglected and the fusion cross section is well approximated by Wong’s formula [18], $F(x)$ becomes the Universal Fusion Function (UFF). This method consists of using the UFF as the benchmark curve for comparisons with fusion data. First, one evaluates the barrier parameters for the particular system under study using the SPP potential. The experimental fusion function $F_{\exp}(x)$ is then determined from the experimental fusion cross section. $F_{\exp}(x)$ is then compared with $F_0(x)$. However, the above described procedure has two shortcomings: The first is that Wong's approximation is not valid for light systems at sub-barrier energies. The second is that a comparison of $F_{\exp}(x)$ with the UFF indicates the global effect of channel coupling on the fusion cross section. In this way, breakup couplings are entangled with couplings with other bound channels. In order to single out the effects of breakup coupling and eliminate deviations arising from the inaccuracy of Wong's formula at sub-barrier energies, it is necessary to renormalize the experimental fusion function by multiplying $F_{\exp}(x)$ by $F_0(x) / F_\text{CC}(x)$, where $F_\text{CC}(x)$ is the fusion function with isotope obtained from a coupled-channel calculation including couplings to all relevant bound channels.

In Figure 1, using the complete fusion data available in the literature we have the comparison between the UFF and the renormalized functions $F_{\exp}$ for fusion. For a clear view of the behaviours of the fusion functions above and below the barrier ($V_B$ corresponds to $x=0$), the results are displayed in linear and logarithmic scales. The results for total fusion of stable and proton halo systems are shown in Fig. 2. At above-barrier energies, the experimental fusion functions are very close to the UFF. One concludes that the breakup process does not significantly affect the total fusion cross section above the barrier. This means that fusion of one of the fragments with the target (incomplete fusion) is comparable with fusion of the whole projectile.

Inspecting Fig. 1(a), we conclude that the data for the $^6,^7\text{Li} + ^{209}\text{Bi}$ [19,20] and $^9\text{Be} + ^{208}\text{Pb}$ [20,21] systems at above-barrier energies are appreciably suppressed, as compared to the UFF. The
suppression corresponds to multiplying the experimental fusion function by the constant factor 0.7. Actually, one can observe that the attenuation factor is slightly larger for the $^6\text{Li} + ^{209}\text{Bi}$ system than for $^7\text{Li} + ^{209}\text{Bi}$, as observed in Refs. [19,20], where it is pointed out that the smaller the breakup threshold energy, the larger is the complete fusion suppression. For the $^7\text{Be}$, $^7\text{Li} + ^{238}\text{U}$ systems, similar results are observed [22]. The data in figure 2 are from Refs [20, 21, 23-25].

In Fig. 3, we show total fusion functions for the $^6\text{He} + ^{209}\text{Bi}$, $^6\text{He} + ^{238}\text{U}$ and $^{11}\text{Be} + ^{209}\text{Bi}$ systems. The data are from Refs. [23, 26-27]. Inspecting Fig. 3(a) we conclude that the results are rather similar to the ones for complete fusion of stable weakly bound projectiles, shown in Fig. 1(a).

We conclude that the complete fusion cross section is systematically suppressed at energies above the Coulomb barrier. The suppression is of about 30% of the complete fusion cross section. The influence of the breakup coupling on the total fusion cross section at above-barrier energies depends on the nature of the projectile. It has no appreciable effect in collisions of stable weakly bound projectiles. On the other hand, in collisions of neutron–halo nuclei, the total cross sections are suppressed by about 30%, similarly to the case of complete fusion of stable weakly bound nuclei. At sub-barrier energies, both the complete and total fusion cross sections are enhanced, owing to the coupling with the breakup channel.

It is very interesting to observe that for each weakly bound projectile, the complete fusion suppression factor is independent of the target mass [28]. An analytical relation of the suppression factor with the breakup threshold energy was recently derived by Wang et al. [28]. However, a physical explanation for that expression is still missing.

![Figure 1](image)

**Figure 1** - Comparison of the renormalized experimental complete fusion functions with the UFF, for stable and no-halo radioactive nuclei. See text for details.
Figure 2- Comparison of the renormalized experimental total fusion functions with the UFF, for stable and no-halo radioactive nuclei. See text for details.

Figure 3- Comparison of the renormalized experimental total fusion functions with the UFF, for neutron-halo radioactive nuclei. See text for details.

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