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Fusion, Breakup and Scattering of Weakly Bound Nuclei at Near Barrier Energies

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Abstract: We discuss experimental and systematic results in the field of reactions with weakly bound nuclei at near barrier energies, particularly fusion, breakup and elastic scattering. The influence of breakup channels on the complete fusion of weakly bound systems is investigated in comparison with the benchmark curve called the Universal Fusion Function and the derived systematic behavior of fusion cross sections of weakly bound nuclei is explained in terms of polarization potentials. The systematic enhancement of the cross section at sub-barrier energies is consistent with recent experimental observations that nucleon transfer, often leading to breakup, is dominant compared to direct breakup in this energy regime. At energies above the barrier, the repulsive polarization potential due to direct breakup predominates and complete fusion is suppressed. We also discuss the relative importance of nuclear and Coulomb breakup as a function of the target charge and the destructive interference between them.

Keywords: Breakup reactions, elastic scattering, fusion reactions, halo nuclei, polarization potentials, transfer reactions, weakly bound nuclei.

1. INTRODUCTION

Heavy ion reactions involving weakly bound nuclei, at energies near the Coulomb barrier, have been extensively investigated in the last years [1-3]. In particular, the fusion process has been extensively studied, including the effect of the breakup of weakly bound and, especially, halo nuclei on this reaction mechanism. These nuclei have low energy threshold for breakup and the breakup feeds states in the continuum, which could either enhance or suppress the fusion cross section. In order to investigate the influence of breakup on the fusion cross section one has to consider several different processes which may occur with weakly bound nuclei: non-capture breakup, when neither fragment fuses, incomplete fusion (ICF), when at least one of the fragments fuses and sequential complete fusion, when all the fragments fuse. Total fusion (TF) is the sum of direct and sequential complete fusion (CF) and of ICF. In most experiments only TF can be measured. Of course, other reaction mechanisms which do not involve breakup also may occur, such as transfer reactions and inelastic scattering. Experimentally it is impossible to separate direct complete fusion from sequential complete fusion and it is very difficult to distinguish between CF and ICF and between ICF and direct transfer reactions leading to the same nucleus.

Maybe the most basic question on this subject is whether the breakup process enhances or hinders the fusion cross section. Before trying to answer this question, one should indicate whether the investigation is concerned with CF or TF. Also, the effects may be different depending on the energy regime and the target mass region.

Another type of study widely investigated is the elastic scattering between heavy ions at near barrier energies. For tightly bound systems, the energy dependence of the interacting optical potential has a behavior known as the Threshold Anomaly (TA) [4-6], corresponding to a rapid variation of the real and imaginary parts of this potential when the energy decreases towards the Coulomb barrier energy. There is a sharp decrease of the imaginary part of the potential at energies close to the barrier, due to the closure of the non-elastic channels at energies below the Coulomb barrier. As the real and imaginary parts of the optical potential are related due to causality, they obey the dispersion relation [7, 8]. Consequently the real potential shows an increase of bell-shaped form at these energies. The real potential can be written as $V = V_0 + \Delta V$, where V_0 is the constant real potential at high energies and ΔV is the energy-dependent part, called the polarization potential. The polarization potential is thus found to be attractive and has the effect of enhancing the fusion cross section at sub-barrier energies, since it decreases the Coulomb barrier. When the scattering involves at least one weakly bound nucleus, the TA usually is no longer present. It has been shown in several works that, for systems in which the breakup cross section is large even below the Coulomb barrier, the imaginary potential does not decrease at the barrier energy and may even increase. Consequently, the real potential decreases in this energy region and fusion is suppressed. This behavior was called the breakup threshold anomaly (BTA) [9]. This increase of the imaginary potential as the energy decreases is more clearly observed for neutron halo nuclei and ^{6}Li than for the less weakly bound ^{7}Li and ^{9}Be. Of course, the imaginary potential must decrease and vanish at lower

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energies, so that what actually happens is that the Coulomb barrier is no longer the threshold energy for such reactions. This threshold is below the barrier.

Recently it has been observed experimentally [10, 11] that breakup following transfer of nucleons is also an important process and may predominate over the direct breakup at sub-barrier energies. Moreover, as the time scale of the breakup could be observed in those works, it was realized that an important part of the breakup cross section is related with delayed breakup, which occurs when the projectile is already moving away from the target, a mechanism that cannot influence the fusion cross section. Only prompt breakup, which occurs when the projectile is approaching the target, can influence the fusion probability. In several other works it has been shown that transfer channels can also have large cross sections, even larger than fusion cross sections, at least for reactions with neutron-halo nuclei at sub-barrier energies [12-16].

Among other kinds of studies with weakly bound nuclei, one may mention the effect of breakup on fusion and quasi-elastic barrier distributions and the effect of breakup on total reaction cross sections.

In this paper we will be concerned with the investigation of breakup effects on the fusion cross section.

2. DISENTANGLING THE STATIC AND DYNAMICAL EFFECTS OF BREAKUP ON THE FUSION CROSS SECTION

There are two kinds of breakup effects on the fusion cross section. There is the static effect related with different barrier characteristics when compared with those for similar tightly bound systems: since the longer tail of the nuclear density of weakly bound nuclei, especially halo ones, produces a more diffuse potential with a lower barrier, the static effect consequently enhances the fusion cross section of weakly bound nuclei. The other effect is the dynamical one associated with the strong coupling between the elastic and the breakup channels. When double folding potentials with realistic densities of the colliding nuclei are used as the bare potential, the possible static effects of the weakly bound nuclei are already taken into account, so that the differences between data and calculations show only the dynamical effects of the channels not included in the calculations. The static effects are, therefore, disentangled from the dynamical ones. If the calculations could take into account all channels, there should be no differences between data and calculations. However, this is not the present situation. The most reliable calculations related to the breakup process, which feeds states in the continuum, are the Continuum Discretized Coupled Channel (CDCC) calculations. These can still not take into account transfer channels, however, nor can they differentiate between complete and total fusion. In any kind of calculation, the choice of the bare interacting potential plays a major role in the analysis of the behavior of the fusion cross section. When a not very reliable bare potential is used in the calculations, the conclusions concerning comparison of data and calculations may change drastically [17].

If one investigates the effect of breakup on the fusion cross section, one must start with a reference behavior of the fusion cross section to which the data should be compared. It is also very important to be able to compare different systems in the same figure, containing data for both tightly and weakly bound nuclei. This requires a reduction method to take into account trivial static factors such as the different sizes and heights of the Coulomb barriers of the systems. Canto *et al*. [18] have shown that the traditional and widely-used method of dividing cross sections by πR_B^2 and center of mass energies by V_B, where R_B and V_B are the radius and height of the Coulomb barrier, does not fully eliminate these geometrical (or static) effects. They proposed a reduction procedure that can eliminate static effects, through the introduction of a dimensionless function F (x), called the Fusion Function, and energy variable x, defined as $F(x) = 2E\ \sigma_F / \hbar\omega\ R_B^2$ and $x = E - V_B / \hbar\omega$, where $\hbar\omega$ is related to the barrier curvature, when the top of the Coulomb barrier is approximated by a parabola. The fusion function was inspired by Wong's formula [19].

3. THE BENCHMARK UNIVERSAL FUSION FUNCTION (UFF) AND THE SYSTEMATICS OF THE DYNAMICAL BREAKUP EFFECT ON FUSION CROSS SECTION

For systems in which channel coupling effects can be neglected and the fusion cross section can be described by Wong's formula, the fusion function F(x) becomes system independent and can be written as a Universal Fusion Function (UFF)

$$F_0(x) = \ln [1 + \exp (2\pi x)].$$

The UFF can then be used as a benchmark for comparisons with fusion data $F_{exp}(x)$. However, there are two important shortcomings if one wants to compare experimental fusion functions with the UFF. The first is that if one does this, the differences between the UFF and the fusion data could be due to the couplings not considered in the calculations, such as all important low-lying collective channels, whereas one is actually interested in the breakup effects, or at least in the combined breakup plus transfer effects on the fusion cross section. The second shortcoming is that it is well known that the Wong model is not valid at sub-barrier energies for light systems, as is the case of several systems involving light weakly bound projectiles. Canto *et al*. [18] thus proposed to renormalize the experimental fusion functions to take into account the possible failure of the Wong model and the effects of inelastic couplings. These renormalized experimental fusion functions are then compared with the UFF, so that the observed differences are now dynamical effects due to the channels left out of the coupled channel calculations. For weakly bound systems these channels are breakup and transfer reactions.

This method was applied to the complete and total fusion cross sections of tens of tightly and weakly bound systems. When the renormalized experimental fusion functions were compared with the benchmark UFF curve, a systematic behavior could be found [18, 20]. In the following we show some examples of the systematics. The figures are shown in linear and log scales. The linear scale is better to observe the behavior at energies above the barrier, whereas the log scale is more suitable for sub-barrier energies. Fig. (**1**) shows the

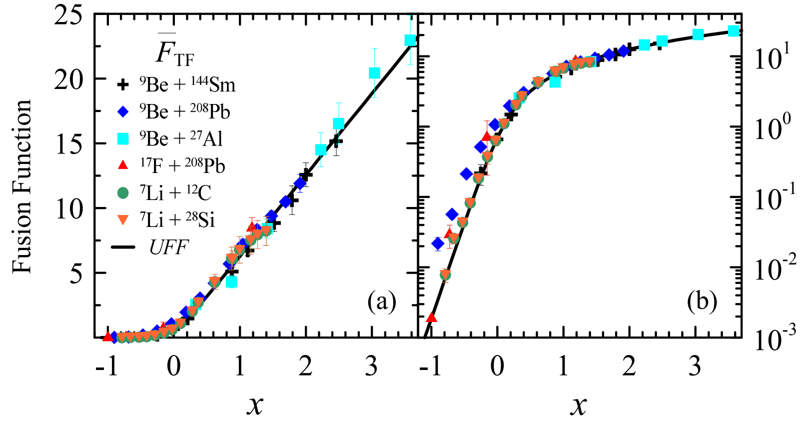

Fig. (1). Renormalized fusion functions for total fusion of several stable weakly bound projectiles and the proton-halo nucleus ^{17}F (in the excited state), plotted against x = (E-V_B) / ω. The full curve is the universal fusion function (UFF).

total fusion cross section for several stable weakly bound systems (fusion induced by ^{6}Li, ^{7}Li and ^{9}Be) [21- 26] and for the ^{17}F + ^{208}Pb system [27], where ^{17}F is a proton-halo nucleus in its excited state. For all systems, there is neither suppression nor enhancement above the barrier, a behavior similar to that obtained for fusion of tightly bound systems. At sub-barrier energies there is some enhancement compared to the UFF curve. Fig. (**2**) shows the complete fusion cross section for several stable weakly bound nuclei. Data are from Ref. [22, 23, 28, 29]. The systematics shows that complete fusion cross sections for such systems are suppressed by about 30% at above barrier energies, when compared to the UFF, at least for heavy targets. There are no data for the complete fusion of stable weakly bound light systems. One concludes that the combined effect of breakup and transfer channels is to suppress fusion above the barrier. At sub-barrier energies one also observes some enhancement in comparison with the UFF. It is important to mention that although at sub-barrier energies all systems show some enhancement, they are not as large as those of the well-known low-lying excitations of deformed nuclei. Fig. (**3**) shows the fusion for several halo systems. Data are from Ref. [12, 14, 30-33]. For neutron-halo systems, complete fusion and total fusion are considered to be the same, because experimentally one defines complete fusion as the fusion of the total charge of the projectile. The systematic result is similar to the one obtained for the complete fusion of stable weakly bound nuclei, that is, some suppression above the barrier and some enhancement below the barrier.

One may ask why breakup suppresses the complete fusion of weakly bound systems at energies above the barrier and enhances it at sub-barrier energies. Recently Gomes *et al*. [34] gave a possible explanation for the behavior of fusion cross sections based on the formalism of polarization potentials. Before that paper, all available calculations of polarization potentials for weakly bound systems found in the literature considered only direct breakup and found that the real part of this potential is repulsive [35-38]. As consequence, the barrier height increases, and suppresses the fusion cross section. The increase in the barrier height for the quasi-elastic scattering of ^{8}B + ^{58}Ni, when breakup coupling was taken into account in the calculations, was clearly shown for the quasi-elastic barrier distribution of this system in Ref. [39]. On the other hand, it is well accepted that transfer and inelastic channels produces attractive polarization potentials, lowering the barrier and consequently enhancing the fusion cross section. Gomes *et al.* [34] proposed that at energies above the barrier, the direct breakup predominates over the attractive polarization potential, consequently suppressing

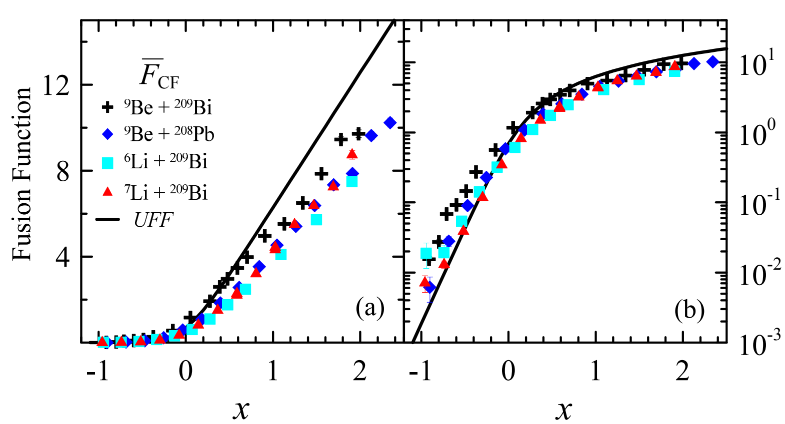

Fig. (2). Renormalized fusion functions for complete fusion of some stable weakly bound systems, plotted against x = (E-V_B) / ω. The full curve is the universal fusion function (UFF).

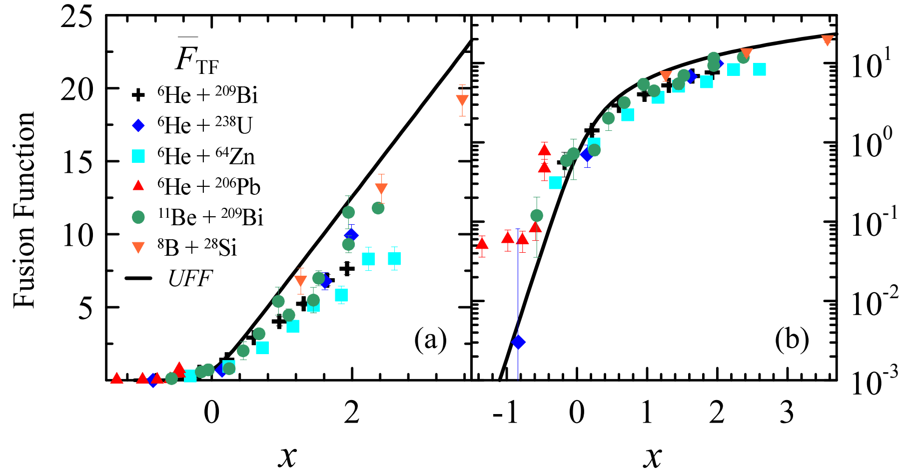

Fig. (3). Renormalized fusion functions for total fusion of halo systems, plotted against x = (E-V_B) / ω. The full curve is the universal fusion function (UFF).

the fusion cross section, whereas at sub-barrier energies, where breakup following transfer has been shown experimentally to predominate over the direct breakup [10, 11, 40], the net polarization potential is attractive, enhancing the fusion cross section in this energy regime. To justify these explanations, Gomes *et al*. [34] performed Coupled Channel Born Approximation (CCBA) calculations to study the sequential breakup of ^{7}Li on the ^{144}Sm target. They considered only one channel, that of one-neutron stripping followed by the breakup of ^{6}Li into α+d. The bare potential used in the calculations was the double-folding Sao Paulo potential (SPP) [41] with no free parameter, as the real part of the optical potential. The computer code FRESCO [42] was used to perform the calculations. The direct breakup polarization potential was earlier [43] calculated for the same system, within continuum discretized coupled channel (CDCC) calculations, by taking into account the continuum states of the projectile and inelastic excitations of the interacting nuclei. Detailed descriptions of both calculations can be found in refs [34, 43]. The results of both calculations show that the real parts of the polarization potentials due to direct breakup and breakup after transfer have opposite signs. The latter is indeed attractive while the former is repulsive. As the systematic results for complete fusion data show enhancement at sub-barrier energies, Gomes *et al.* [34] claim that in this energy regime the attractive polarization potential due to sequential breakup predominates over the repulsive one produced by direct breakup.

So far we have discussed the systematic behavior of fusion cross sections of weakly bound systems. We should also say something about systems which do not follow the systematics. Indeed, one finds in the literature a few systems with a behavior different from the systematic already mentioned. Possible explanations for these anomalies might be either something very special with those systems or something wrong with the data or with the standard coupled channel calculations. In Fig. (**4**) we show the behavior of several of these systems. The total fusion of ^{6,7}Li + ^{64}Zn, ^{59}Co [44, 45] are suppressed at energies above the barrier, when the systematic predicts neither enhancement nor suppression. Fusion of ^{6}He + ^{197}Au [46] coincides with the UFF curve above the barrier, when the systematic predicts some suppression. The total fusion of ^{8}B + ^{58}Ni [47] shows enhancement above the barrier when the systematic predicts some suppression or coincidence with the UFF curve. Actually, for the ^{6,7}Li + ^{64}Zn and ^{8}B + ^{58}Ni systems, there are several indications [20, 48, 49] of possible problems with the data.

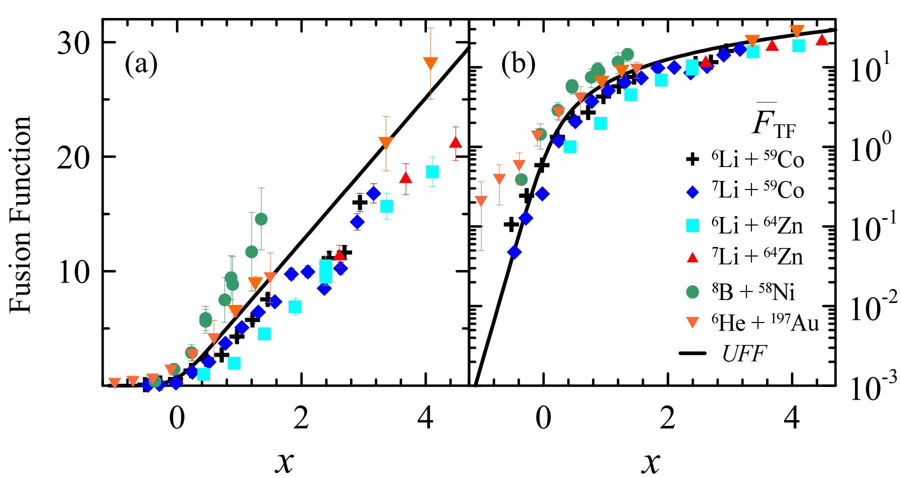

Fig. (4). Renormalized fusion functions for several systems that do not follow the systematics, plotted against x = (E-V_B) / ω. The full curve is the universal fusion function (UFF).

4. DEPENDENCE OF COULOMB AND NUCLEAR BREAKUP ON THE CHARGE OF THE TARGET

Coulomb breakup is expected to increase with the charge of the target, and it should thus predominate over nuclear breakup for heavy systems. Therefore, one expects that the breakup effects on the fusion cross section discussed previously should be more important for heavier targets than for the light ones. However, the systematic behavior for the dependence of the complete fusion suppression as a function of the target mass has not yet been obtained [50, 51].

The interference between Coulomb and nuclear breakup may be quite important and is a subject that requires quantitative investigation. Recently, Otomar *et al.* [52] investigated the dependence of Coulomb, nuclear and total breakup of ^{6}Li on different targets by performing CDCC calculations. They have shown that at energies below the barrier, Coulomb breakup predominates over the nuclear breakup, which is expected due to the short range of the nuclear potential. At energies above the barrier, Coulomb breakup predominates at forward angles, whereas the nuclear breakup predominates at large angles, corresponding to small distances within the range of the nuclear potential. The angle at which the two contributions cross each other increases as the collision energy decreases and below a critical energy the Coulomb breakup predominates over the whole angular range. An unexpected result is that this crossing angle is almost independent of the target. Also, they have shown that the nuclear breakup increases linearly with $A_T^{1/3}$ whereas the Coulomb breakup increases linearly with Z_T. Moreover, it has been shown that the Coulomb and nuclear breakup strongly interfere destructively in such a way that the total breakup is smaller than the Coulomb breakup, especially at energies below the Coulomb barrier. Table **1** shows an example of this strong destructive interference for the ^{6}Li + ^{208}Pb system, where the cross sections refer to breakup cross sections.

Table 1. Coulomb, Nuclear and Total Breakup Cross Sections for the ^{6}Li + ^{208}Pb System, at Energies Close to the Coulomb Barrier

$E_{c.m.} / V_B$	σ^{BU}_{Coul} (mb)	σ^{BU}_{Nucl} (mb)	$\sigma^{BU}\sigma_{total}$ (mb)
0.89	34.9	8.8	29.3
0.96	46.8	22.8	37.2
1.09	66.8	38.7	82.5

5. CONCLUSIONS AND PERSPECTIVES

In conclusion, we observe a systematic behavior of the dynamical effect of breakup on the fusion of weakly bound nuclei, with suppression of complete fusion of stable weakly bound nuclei and of total fusion of halo nuclei above the Coulomb barrier and some enhancement below the barrier. This behavior is explained in terms of the net polarization potential due to inelastic and transfer channels (attractive) and direct breakup (repulsive), which oppose each other below and above the barrier energy. A very strong destructive interference between Coulomb and nuclear breakups was observed, especially at low energies.

We have seen that several important questions have already been answered in this field. However, there is still much to be done and learned, both experimentally and theoretically. As examples of what has yet to be done, we mention:

- Need of additional data in the sub-barrier energy regime. One still does not fully understand this important energy regime, very important for nucleosynthesis and production of super heavy elements.
- Need of more data with radioactive beams. One needs better data with smaller error bars.
- More fusion cross section measurements for proton-halo nuclei, because there are conflicting results between the only two systems investigated.
- More separated CF and ICF data, especially for light and medium mass systems.
- Disentanglement of ICF and transfer reactions leading to the same nucleus.
- More data on sub-barrier total fusion for light targets.
- Disentanglement of CF and ICF data for light systems, below and above the barrier. Is ICF negligible for these systems?
- Measurement of more CF and ICF data for medium mass targets, in order to investigate how the suppression varies with the mass of the target.
- New and reliable cross sections for non-capture breakup, for any projectile, from light to heavy target mass, below and above the barrier, to determine the corresponding time scale of prompt and delayed breakup.
- More complete and quantitative calculations are required, such as CDCC calculations including transfer and breakup following transfer.

ABBREVIATIONS

ICF = Incomplete fusion
TF = Total fusion
CF = Complete fusion
TA = Threshold anomaly
BTA = Breakup threshold anomaly
UFF = Universal fusion function
CCBA = Coupled Channel Born Approximation
SPP = Sao Paulo potential
CDCC = Continuum discretized coupled channel
BU = Breakup

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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