Fusion, transfer and breakup of light weakly bound nuclei at near barrier energies.

P R S Gomes, J Lubian , J Rangel , D R O Otamar
Instituto de Física, Universidade Federal Fluminense, Av. Litoranea s/n, Gragoatá, Niterói,
R.J., 24210-340, Brazil

Abstract. We discuss interesting questions and results concerned with reactions involving
weakly bound nuclei at near barrier energies, particularly fusion, breakup, transfer and
scattering. We concentrate in the presentation and discussion of recent results, and so we
try to give a sort of state of art of this field at the present. PACS Numbers: 24.10Eq, 25.60Pj,
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1. Introduction

In the last decades, reactions between heavy ions at energies close to the Coulomb barrier have
been a subject of great and renewed interest. Particularly, the fusion process has been extensively
investigated. It is widely accepted that couplings to low lying collective states produce strong
enhancement of the fusion cross section at sub-barrier energies, especially when nuclei with
large static deformation, like $^{154}$Sm, are involved [1, 2, 3, 4, 5, 6]. Transfer reactions can also be
important doorway to enhance sub-barrier fusion cross sections [7, 8, 9, 10, 11, 12].

It has also been extensively investigated the elastic scattering between heavy ions at near
barrier energies. It is well accepted that the elastic scattering presents a behaviour of the energy
dependence of the interacting optical potential known as Threshold Anomaly (TA) [13, 14, 15],
corresponding to a rapid variation of the real and imaginary parts of this potential when the
energy decreases towards the Coulomb barrier energy. The real part of the potential shows a
localized peak, while there is a sharp decrease of the imaginary part of this potential at energies
close to the barrier. The decrease of the imaginary potential is due to the closure of the non-
elastic channels at energies below the Coulomb barrier. There is a connection between the
real and imaginary parts of the optical potential due to causality and subsequently they obey
the dispersion relation [16, 17]. As consequence, the real potential shows an increase at those
energies, in a bell shape form, when the imaginary potential decreases. The real potential can
be written as $V_{\text{eff}} = V_0 + \Delta V$, where $V_0$ is the real potential at higher energies and $\Delta V$ is
called polarization potential. So, it is found that the polarization potential is attractive, and it
has the effect of enhancing the fusion cross section at sub-barrier energies, since it decreases the
Coulomb barrier.

2. Reactions with weakly bound nuclei

The above situation may be different when weakly bound nuclei are involved in the reactions.
These nuclei have low breakup energy threshold and the breakup feeds states in the continuum.
Following breakup, different processes may occur: non-capture breakup (NCBU), when neither fragment fuses, incomplete fusion (ICF), when part of the fragments fuse and sequential complete fusion (SCF), when all the fragments fuse. Total fusion (TF) is the sum of direct and sequential complete fusion (CF) and ICF. Reactions with weakly bound nuclei, both stable and radioactive (some of them with halo properties) have been intensively studied in the last years, and there are some comprehensive reviews on this subject up to 2007 \cite{18, 19, 20}. In this paper we will concentrate on results which came out after those reviews, and so we will try to give a partial update of the status of art in this field, particularly based on works of ourselves and collaborators, but also on other reported important works.

One basic question in this field 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. Also one has to know whether the investigation is concerned with CF or TF. Other important questions are: What are the effects on different energy regimes and on different target mass regions? Does the breakup affect the elastic scattering and the usual threshold anomaly of the optical potential at near barrier energies? Do different breakup threshold energies affect the total reaction cross section significantly? How large is the \(\sigma_{NCBU}\) compared with \(\sigma_{CF}\) or \(\sigma_{CF+ICF}\)? How does it depend on the energy region and target mass? Is \(\sigma_{transfer}\) important for most weakly bound projectiles? Experimental aspects to be considered are, among others: What is it measured: \(\sigma_{CF}\) or \(\sigma_{TF}=CF+ICF\)? Can ICF be separated from transfer channels leading to the same compound nucleus? If not, instead of TF, one measures TF + transfer cross section? Recently it has been observed \cite{21, 22} that breakup following transfer of nucleons is also an important process and may predominate over the direct breakup at sub-barrier energies. Also, transfer channels were shown to be very important, at least for reactions like neutron-halo nuclei \cite{23, 24, 25, 26, 27}.

Concerning the elastic scattering, the energy dependence of the optical potential when weakly bound nuclei are involved has been shown, in several works, to have a different behaviour as that for tightly bound systems, namely, the TA and the attractive polarization potential owing to the couplings to inelastic and transfer channels. This is because the breakup channel may be important even below the barrier and produces repulsive polarization potential. So, the imaginary potential does not decrease at the barrier energy. Indeed, it may increase. Consequently, the real potential decreases at this energy region and fusion is suppressed owing to this effect. This behaviour is called breakup threshold anomaly (BTA) \cite{28, 29}. Of course, the imaginary potential must decrease and vanish at lower energies. A detailed investigation of this effect is rather difficult because one needs precise elastic scattering data at sub-barrier energies, where the scattering is almost of Rutherford type and almost insensitive to the nuclear potential. There are also several works where there is a simultaneous fit of fusion and elastic scattering data and the optical potential is divided in an inner part connected with fusion and a superficial part connected with direct processes like breakup and transfer. It is then observed a threshold anomaly behaviour for the fusion potential \cite{30}. A BTA behaviour for the direct reaction potential is usually found.

Other aspects of reactions with weakly bound nuclei have been investigated in the last years, such as the effect of breakup on inelastic scattering \cite{31}, quasi-elastic barrier distributions \cite{32} and the effect of breakup on total reaction cross sections by using two different methods \cite{33, 34}. However, in the following we will concentrate on the investigation of breakup effects on the fusion cross section.

3. Static and dynamic effects of breakup on the fusion cross section and the importance of the choice of the bare interaction potential

There are two main approaches to investigate this subject. The first one compares fusion data with predictions from some theory. For sure, the conclusions are strongly model dependent,
and so it is very important that a reliable bare potential must be used in the calculations. The difference between theoretical and experimental cross sections, $\Delta \sigma_F$, is attributed to the ingredients missing in the theory. The second approach compares fusion data for different systems, including tightly bound ones. In any case, there are two kinds of effects to be investigated. First, there are the static effects related with different barrier characteristics, when compared with those for similar tightly bound systems, since the longer tail of the nuclear density of the weakly bound nuclei, especially the halo ones, produces a more diffuse potential, with a lower barrier, and consequently enhances the fusion cross section. The second kind is the dynamical effects associated with the strong coupling between the elastic and the breakup channels. This is a much more difficult effect to be analyzed and, in our opinion, the most interesting one. 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 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.

When one compares data with theory, the comparison may be of different kinds: with single channel with standard densities of the nuclei ($\Delta \sigma_F$ is due to static + dynamic effects); single channel with realistic densities ($\Delta \sigma_F$ comes from couplings to all channels, but the static effect is already taken into account); coupled channel calculations taking into account all bound channels ($\Delta \sigma_F$ comes from the coupling to the continuum); Continuum Discretized Coupled Channel (CDCC) calculations taking into account also transfer channels ($\Delta \sigma_F$ should vanish). However, at the present it is not available the latter kind of calculations. The use of different interaction potentials may lead to controversies like for fusion of $^6$He + $^{208}$Bi [35] and $^6$He + $^{238}$U [23] data. Recently it has been shown [36] that there are no incompatibility between the two sets of data, which were originally analysed using different models. So, the choice of the bare interacting potential plays a major role in the analysis of the fusion cross section behaviour.

When one investigates the effect of breakup on the fusion cross sections for weakly bound systems, one must start with a standard behaviour of the fusion cross section to which the data should be compared. In order to do so, it is important to be able to compare different systems in the same graphic, what requires a proper normalization method to take into account trivial factors like different sizes and Coulomb barriers of the systems. Recently, Canto et al. [37] have shown that the traditional method of dividing cross sections by $\pi \frac{R_B^2}{B}$ 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 effects.

4. Fusion functions, the UFF benchmark curve and systematic of fusion cross section of weakly bound systems

Recently, Canto et al. [37] have proposed a reduction procedure that can eliminate static effects, by the introduction of dimensionless function $F(x)$, called Fusion Function, and energy variable $x$, defined as $F(x) = \frac{2E\sigma_F}{\hbar \omega R_B^2}$ and $x = \frac{E-V_B}{h \omega}$. Here, $V_B$, $R_B$ and $h \omega$ are the barrier height, radius and the curvature, appearing in the parabolic approximation of the Coulomb barrier. For systems where channel coupling effects can be neglected and the fusion cross section can be approximated by Wong’s formula [38], $F(x)$ becomes system independent and can be written as a Universal Fusion Function (UFF) written as $F_0(x) = \ln[1 + \exp(2\pi x)]$. UFF is then used as the benchmark for comparisons with fusion data $F_{exp}(x)$. However, if one compares experimental fusion functions with the UFF, the differences would be due to the ingredients not considered in the calculations, such as all important low lying collective couplings, and not just breakup plus transfer. Also, the Wong model is known for not being valid at sub-barrier energies for light systems, as it is the situation of some those involving the above mentioned weakly bound projectiles. By these reasons, Canto et al. [37] 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. In their coupled channel calculations, the double folding Sao Paulo potential (SPP) was used [39]. This potential has been widely and successfully used in the last years, for a large variety of systems and energy ranges [40, 41], including fusion barrier distributions for weakly bound nuclei and fusion of halo nuclei [42, 43].

Complete and total fusion for tens of systems, both tightly and weakly bound (stable and neutron-halo), were compared with UFF and then a systematic behaviour could be observed [37, 44, 45, 46]. In figure 1 we show, as example, the comparison of the renormalized experimental fusion function for some representative systems. Data are from Ref. [23, 24, 25, ?; 12, 48, 49, 50, 51, 52]. We will discuss the results for fusion of the proton-halo $^8$B [51, 52] in the next section. The linear scale is better to observe the behaviour at energies above the barrier, whereas the log scale is more suitable for sub-barrier energies. The reached systematic shows that complete fusion cross sections for stable weakly bound systems and total fusion cross sections for neutron-halo systems are around 30% suppressed at above barrier energies, when compared with UFF. So, the combined effect of breakup and transfer channels is to suppress fusion above the barrier. For total fusion of stable weakly bound system and for the $^{17}$F + $^{208}$Pb system [47], there is neither suppression nor enhancement above the barrier. Very recently, Fang et al. [53] were able to disentangle total fusion induced by $^9$Be from transfer of one-neutron, and only if one adds both mechanisms the total fusion coincides with the UFF. Maybe in some works where total fusion was reported to have been measured, actually what was measured was the sum of total fusion plus transfer channels. At sub-barrier energies, all systems show some enhancement, although they are not as large as for low-lying excitations of deformed nuclei.

One may ask whether all systems investigated obey the systematic behaviour mentioned above. The answer is no. Among the tens fusion functions investigated from the available data in literature, only very few of them do not follow the systematic. Possible explanations for these anomalous behaviours might be either something very special with those systems or something wrong with the data or with the standard coupled channel calculations. Actually, some of those systems were measured again by other groups and/or experimental methods and the new measurements give results compatible with the systematic.

The puzzle concerning the explanation why the complete fusion is suppressed by the breakup at above barrier energies and enhanced at sub-barrier energies has been investigated recently by Gomes et al [54], in terms of polarization potentials. They have shown that at energies above the barrier, the direct breakup which produces repulsive polarization potential predominates over the attractive polarization potential originated by transfer channels, whereas at sub-barrier energies, where the breakup following transfer predominates over the direct breakup, a net attractive polarization potential which enhances the fusion cross section occurs. Indeed, recent calculations [55, 56, 57] show that the direct breakup produces repulsive polarization potentials, owing to the couplings among continuum breakup states (continuum-continuum couplings), whereas the breakup following transfer produces attractive polarization potential [54]. Those explanations are in agreement with experimental results for sub-barrier breakup [21, 22, 58]. Those results are also consistent with the polarization potentials derived from elastic scattering at lower energies, as can be observed in all extrapolations to low energies of the real polarization potential 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 polarization potential which enhances the fusion.

5. Recent measurements of fusion cross sections for the proton-halo $^8$B nucleus

Very recently, the first fusion cross section involving proton-halo nucleus, $^8$B, was measured [51]. The results were very unexpected, since they show enhancement of the fusion cross section at energies above the barrier in relation with theoretical predictions which do not have any free parameter and with the UFF [59], as shown in figure 1. When one fits the data with free parameters [51] or in a simultaneous fit of fusion and elastic scattering data [60], the potential required to fit the data have an unusual long range. This leads to the conclusion that there is a special effect of proton-halo nuclei, different from those of neutron-halo nuclei, on the fusion cross section. This is particularly unexpected, because there are several works on the breakup of the $^8$B on the presence of the $^{58}$Ni target [61, 62, 63, 64] which show that the polarization potential produced by the breakup of $^8$B is repulsive, what should lead to the suppression of fusion cross section. Also, the work on the elastic scattering for this systems, performed by Gomez Camacho et al. [65] shows the presence of the BTA, compatible with repulsive polarization potential and suppression of the fusion cross section above the barrier. However, it just came out a new paper reporting the fusion of $^8$B with $^{28}$Si [?], and the results agree very well with the systematic. So, more data on other proton-halo fusion are required to further investigate the possible existence of special proton-halo effect on the fusion or some problems with the derivation of fusion cross section for one of the mentioned systems.

6. Systematic of breakup and its effect on fusion, as a function of the charge of the target.

It is usually accepted that the Coulomb breakup increases with the charge of the target, and so it predominates over the nuclear breakup for heavy systems. Consequently, the breakup effects on the fusion cross section, such as the suppression of complete fusion at energies above the barrier, should be more important for heavier targets than for the light ones. This subject has already been investigated, but a systematic behaviour for the dependence of the complete fusion suppression as a function of the target mass, for the same projectile, has not yet reached [66, 67].

![Figure 1](image_url)

Figure 1. (color on line) Experimental renormalised fusion functions for total fusion of several weakly bound, proton-halo and neutron-halo systems. The curve is the universal fusion function. $x$ is a reduced energy parameter. For details see the text and Ref. [37].
Very recently, Otomar et al. [68] investigated the dependence of Coulomb, nuclear and total breakups of $^6\text{Li}$ on different targets, by performing CDCC calculations, which agree with the elastic scattering of those systems. It was shown that the nuclear breakup increases linearly with $A_1^{1/3}$ whereas the Coulomb breakup increases linearly with $Z_T$. However, a very interesting result of that work is that the Coulomb and nuclear breakups interfere destructively in such intense way that the total breakup is smaller than the Coulomb breakup for some energies. This result is shown in figure 2 for the $^{144}\text{Sm}$ and $^{208}\text{Pb}$ targets. In the same work [68], it was shown that the total breakup cross section is much smaller than the fusion cross section above and below the Coulomb barrier for light targets, like $^{59}\text{Co}$, but that for heavier targets, like $^{144}\text{Sm}$ and $^{208}\text{Pb}$, the breakup cross section is much larger than the fusion cross section at sub-barrier energies.

7. Systematic of total reaction cross sections for halo, weakly bound and tightly bound systems.

From the fits of elastic scattering angular distribution data, total reaction cross sections can be derived. A possible systematic behaviour for the total reaction cross section of weakly bound nuclei has been investigated in the last years, involving tens of systems (tightly bound, weakly bound and halo projectiles on targets with mass varying from light to heavy ones), and reported in a large amount of works. All of those papers use one or both of the presently two reduction methods used to compare different systems in the same graphic: the one proposed in 2005 by Gomes at al. [33] and the one proposed more recently by Shorto et al. [34], as an extension of the fusion function proposed by Canto et al. [37]. Both methods lead to qualitative similar results: the total reaction cross sections induced by halo nuclei are larger than for stable or non-halo weakly bound nuclei, which are similar or slightly larger than for tightly bound nuclei. A comprehensive work on this systematic was very recently published [69], using the latter method.

Figure 2. (color on line) Contribution of the Coulomb, nuclear and combined interactions to the NCBU cross section for the $^6\text{Li} + ^{144}\text{Sm}, ^{208}\text{Pb}$ systems at near barrier energies. For details see the text and Ref. [68].

8. Conclusions

In conclusion, we can see that this fascinating subject is very alive, with a lot of interesting results coming out very recently. Several questions have already been answered, a lot has been
learned, but there are still much to be done and learned, both experimentally and theoretically.

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