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# Reactions with Weakly Bound Nuclei, at near Barrier Energies, and the Breakup and Transfer Influences on the Fusion and Elastic Scattering

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**Abstract** We present a brief review of the reaction mechanisms involved in collisions of weakly bound projectiles with tightly bound targets, at near-barrier energies. We discuss systematic behaviors of the data, with emphasis in fusion, breakup, nucleon transfer and elastic scattering. The dependence of the breakup cross section on the charge and mass of the target is discussed, and the influence of the breakup channel on complete fusion is investigated. For this purpose, we compare reduced fusion cross sections with a benchmark universal curve. The behaviors observed in the comparisons are explained in terms of polarization potentials and of nucleon transfer followed by breakup. The influence of the breakup process on elastic scattering is also discussed. Some apparent contradictions between results of different authors are explained and some perspectives of the field are presented.

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## 1 Introduction

The reaction mechanisms involved in collisions of weakly bound nuclei, both stable and radioactive, at near-barrier energies has been one of main fields in Low Energy Nuclear Physics research in recent years. Extensive experimental and theoretical efforts have been devoted to understanding the different processes taking place in the collision, including the important couplings between them. Some comprehensive review papers have been published on this subject [1–5]. 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. The couplings with continuum states may either enhance or suppress the fusion cross section.

Initially, the main motivation for investigations of fusion reactions with those exotic nuclei was the possible enhancement of the cross section, which might facilitate the production of super-heavy elements. The results so far reached do not corroborate the initial expectations. However very interesting results came out. The neutron and the proton halo nuclei, with extremely low breakup threshold energies and very exotic structure properties, are the ones which deserve the main attention. However, stable weakly bound nuclei, which have qualitatively some similar characteristics, have also attracted considerable interest. The reason is that it is much easier to perform experiments with stable beams, which are much more intense (by several orders of magnitude) than the currently available radioactive beams. In this way, the data for stable weakly bound nuclei, like $^{6,7}$Li or $^{9}$Be, tend to be much more precise.

To investigate the reaction mechanisms involved in collisions of weakly bound nuclei, one has to consider several different processes. Besides the usual direct fusion of the whole projectile with the target (DCF), transfer of nucleons and inelastic excitations, there are other processes following the breakup of the weakly bound projectile. They are listed below.

(a) non-capture breakup (NCBU): none of the projectile's fragments fuses with the target,
(b) incomplete fusion (ICF): at least one fragment, but not all, fuses with the target,
(c) sequential complete fusion (SCF): all the projectile's fragments fuse sequentially with the target.

From the experimental point of view, it is not possible to distinguish DCF from SCF, since they lead to the same compound nucleus. Only the complete fusion (CF) cross section, which is the sum of DCF and SCF, can be measured. Besides, it is hard to determine individual cross sections for the CF and the ICF process, either experimentally or theoretically. In most cases, only the total fusion cross section (TF), corresponding to the sum of CF and ICF, are available. Recently it has been observed experimentally [6,7] that reaction mechanisms involving weakly bound nuclei are even more complex than the above picture, because breakup following transfer of nucleons is also an important process and may predominate over the direct breakup at sub-barrier energies.

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 [8–13].

Another topic of intensive investigation is the behavior of the elastic scattering of weakly bound systems. Important characteristics of the scattering of such systems are very different from the scattering of tightly bound nuclei.

Some of the most basic questions on this subject are how the breakup process influences the fusion cross section; how the breakup cross section varies with the target mass and charge; how are the interferences between the Coulomb and nuclear components of the breakup; how the breakup affects the elastic scattering. The answers to these questions may change depending on the energy regime, above or below the Coulomb barrier. In this paper we will try to answer some of those questions, based mainly on results obtained by our group, but also by other experimental and theoretical research groups.

## 2 Breakup and Transfer Processes

Measuring NCBU cross sections is a very difficult task. It requires very accurate exclusive experiments, with coincidences between the fragments, and then the conversion of events to integrated cross sections. A clear identification of the processes, including sequential breakup (breakup following transfer), is possible through the Q-values of the reactions [6]. However, the time-scale of the breakup process is of fundamental importance when one investigates the influence of breakup on fusion. One should distinguish *prompt breakup* from *delayed breakup*. The former takes place when the projectile approaches the target, as it reaches the interaction region. In this case, it is likely that the breakup process influences the fusion cross sections. On the other hand, delayed breakup corresponds to the situation where the interaction with the target excites a long lived state in the projectile, either in its original configuration or modified by nucleon transfer, and this state breaks up far from the target, on the outgoing branch of the trajectory. Thus, the dissociation of the projectile has no bearing on fusion. In fact, processes of this kind may influence fusion, but their influence would be analogous to those produced by inelastic or nucleon transfer channels. From the experimental point of view, prompt breakup can be distinguished from delayed breakup through the relative energy of the fragments. In prompt breakup, this energy tends to be large, whereas in delayed breakup it is small. The relative energy may be measured in some experiments where the trajectory of the fragments is determined [6].

Since the breakup feeds states in the continuum, the most suitable theoretical approach to describe breakup and its influence on fusion is the continuum discretized coupled channel (CDCC) method. However, the CDCC method is still far from giving a satisfactory description of collisions of weakly bound nuclei. In most cases it does not lead to individual CF and ICF cross sections. Furthermore, it cannot take into account bound and continuum states of the projectile simultaneously with nucleon transfer or inelastic channels in the target. For this reason, several works compare fusion data with calculations that neglect breakup and transfer channels. The differences between the data and the theoretical cross sections are then attributed to the processes not included in the calculations. That is, breakup and transfer. Transfer reactions are usually theoretically investigated through coupled reaction channel (CRC) or DWBA calculations.

A theoretical study of the breakup of $^6$Li in collisions with several targets has recently been reported [14]. The nuclear and the Coulomb contributions to the breakup cross sections were evaluated individually, and their interference was investigated. The dependence of those components on the target charge and mass was also investigated. The details of the calculations are described in Ref. [14]. To investigate separately the nuclear and Coulomb components of the breakup, the calculations were performed by switching on and off the Coulomb and nuclear components of the coupling interaction. The calculations have shown that for large scattering angles, corresponding to short range scattering, the nuclear breakup component may predominate over the Coulomb component, and that at energies above the barrier of light systems, the integrated nuclear component may also predominate. A very interesting result is the observation of a strongly destructive Coulomb-nuclear interference, since the Coulomb component is larger than the total breakup cross section at sub-barrier energies for heavy targets. This behaviour can be observed even at energies slightly above the barrier. Otomar et al. [14] have shown that the nuclear breakup cross section increases linearly with $A_t^{1/3}$, for the same $E_{\mathrm{c.m}}/V_{\mathrm{B}}$ energy, where $A_t$ and $V_{\mathrm{B}}$ are the target mass and height of the Coulomb barrier, respectively. For the Coulomb breakup, the cross section increases linearly with the $Z_t$. The results are shown in Fig. 1. The explanation for these behaviors was given by Hussein et al. [15]. We will come back to those results in Sect. 6.

The importance of neutron stripping cross sections for neutron-halo nuclei, especially at sub-barrier energies, may be dramatically observed in the data by Trotta et al. [16] and Raabe et al. [8], for the $^6\mathrm{He} + ^{238}\mathrm{U}$ system, obtained by the same group in two different experiments. In 2000, Trotta et al. reported as fusion cross section the data shown in Fig. 2a as full stars. In 2004, Raabe et al. performed a more refined experiment where they found out that most of the previously reported cross section was indeed related to neutron-transfer. The fusion cross section data is represented in Fig. 2a as the full circles.

Apart from neutron and proton halo nuclei, transfer cross sections were also found to have important cross sections, even larger than the fusion cross section at sub-barrier energies, for stable weakly bound systems like $^6$Li, $^7$Li and $^9$Be [17–21].

## 3 Comparison of Fusion Cross Section Data with Theoretical Calculations

Now we turn to the discussion of fusion cross sections, and the effect of the breakup channel on the fusion mechanism. This effect is usually expressed as an *enhancement* or a *suppression* of the fusion cross section. However, enhancement or suppression implies a comparison of the data with some standard cross section, used as a benchmark. Therefore, these terms are meaningless if this benchmark is not unambiguously specified. The use of different benchmarks may lead to conflicting conclusions. If this benchmark is a theoretical cross section obtained from a particular calculation, the conclusions are strongly model-dependent. The simplest benchmark would be the cross section obtained in single channel calculation for the system under study. In this case, one should use a reliable bare potential, obtained by some systematic procedure, like the folding model. In this case, the differences between the data and the standard cross section could be generically attributed to channel coupling effects. On the other hand, the benchmark could be the theoretical cross section obtained in a coupled channel calculation including all relevant inelastic channels. In this case, the differences between the

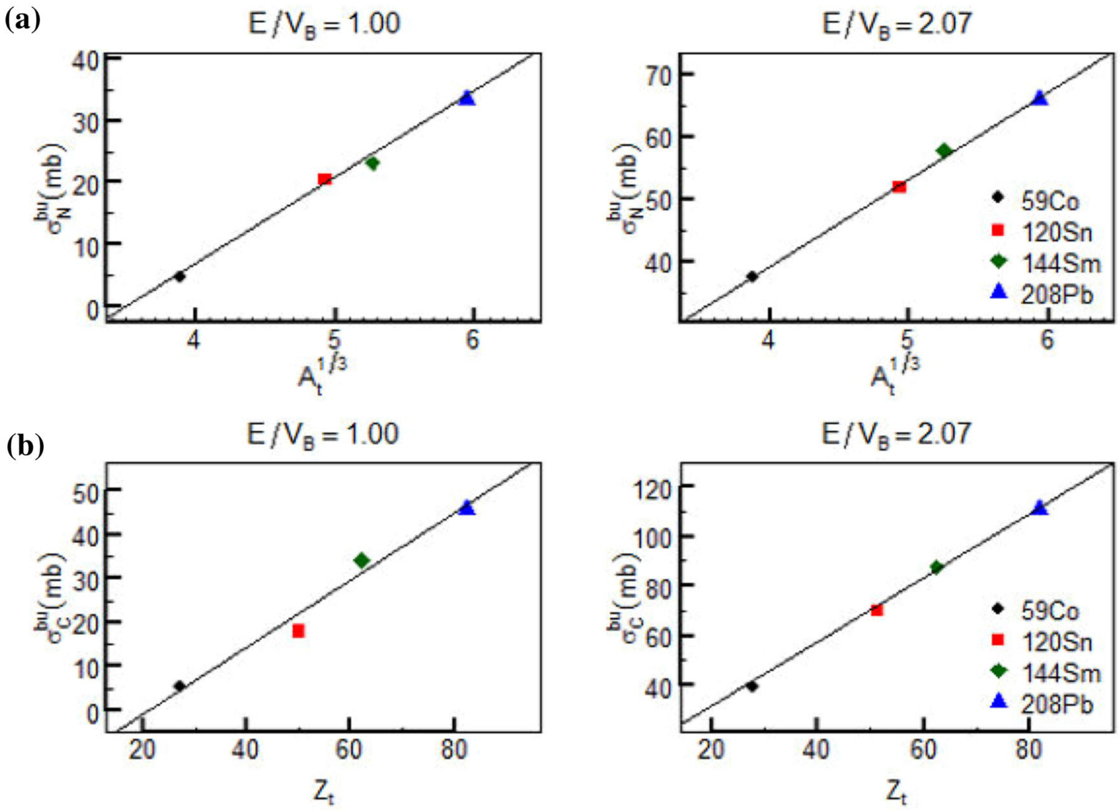

**Fig. 1** (Color online) Dependence of the nuclear and Coulomb components of the breakup of $^6$Li as a function of the target mass (*upper panel-a*) and charge (*bottom panel-b*), respectively. Figure adapted from Ref. [14]

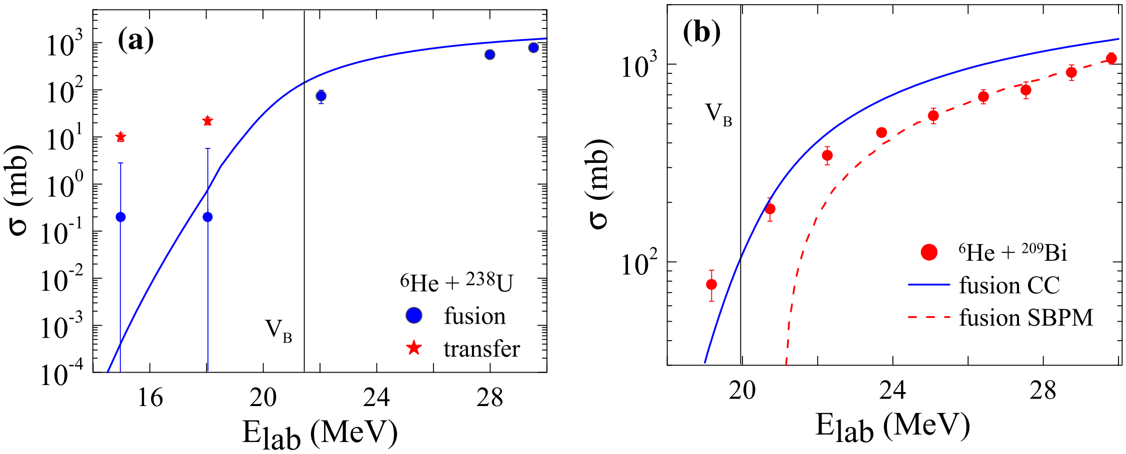

**Fig. 2** (Color online) Fusion excitation functions of the neutron-halo $^6$He projectile with the $^{238}$U (left) and $^{209}$Bi (right) targets. Data are from [8] and [22], respectively. The figure is adapted from [23]. The full *curves* (*blue* online) are predictions form the Sao Paulo potential[24, 25], including target excitation couplings. *The dashed curve* in the *right panel* is the prediction using the potential from the original paper [22]. The stars (*red online*) in the *left panel* correspond to the sum of fusion and neutron transfer cross section [8, 16]

theoretical cross section and the data could be attributed to couplings with the breakup and transfer channels, which were left out of the calculations.

There are two kinds of effects to be investigated in the fusion of weakly bound nuclei. First, there are the static effects, related with their different barrier characteristics. Owing to the contribution from the weakly bound particles, the nuclear density has a longer tail and this leads to a lower Coulomb barrier. The reduction of the height of the barrier gives rise to larger fusion cross sections at sub-barrier energies. This reduction is particularly important in the case of halo nuclei, where the breakup threshold is very low. This effect is taken into account in calculations based on realistic bare potentials, like the ones calculated by the folding model with realistic densities. The second kind is the dynamical effect associated with the strong coupling between the elastic and the breakup channels. They can be taken into account in CDCC calculations.

As we have mentioned, the use of different interaction potentials may lead to controversies. One important example is the conflicting conclusions reached in Refs. [22] and [8] about the behavior of the fusion of $^6$He with heavy targets. This is illustrated in Fig. 2. On panel (a) we show the experimental fusion cross section of Ref. [22] for the $^6\mathrm{He}+^{238}$U system. The data are compared with the cross section of a calculation based on a double-folding potential [24,25] using realistic densities [23]. One observes that the data at above-barrier energies are suppressed in comparison with the theoretical predictions. At sub-barrier energies, it is hard to reach any conclusions owing to the large error bars. The results of Ref. [22] for $^6\mathrm{He}+^{209}$Bi fusion are shown on panel (b). In this case, the authors compare their data with the predictions of a single barrier penetration model (SBPM), represented by the red dashed line. They use the barrier parameters that fit their data at above-barrier energies. In this way, the theoretical curve has necessarily to reproduce the data in this energy region. Then, they compare the experimental and the theoretical cross sections at sub-barrier energies. They conclude that the experimental cross section is strongly enhanced. However, this conclusion results from the choice of the benchmark used in the comparison. To prove this point, we include in the figure the theoretical cross section obtained with the double-folding potential, as in panel (a). It is represented by the blue solid line. Now, there is an appreciable suppression above the Coulomb barrier and a weak enhancement at sub-barrier energies. Thus, using the same benchmark for the two systems, one reaches the same conclusions: suppression above the barrier and small effects at sub-barrier energies.

## 4 The Universal Fusion Function (UFF) Benchmark Curve and Systematics of the Dynamical Breakup Effect on Fusion Cross Sections

An alternative approach to investigate the influence of the breakup on the fusion cross section is the comparison of different systems in the same plot, containing data for both tightly and weakly bound nuclei. This requires a reduction method to eliminate the influence of trivial factors such as the different sizes and heights of the Coulomb barriers of the systems. Canto et al. [26,27] have shown that the traditional and widely used method of dividing the cross sections by $\pi R_\mathrm{B}^2$ and the collision energies by $V_\mathrm{B}$, where $R_\mathrm{B}$ and $V_\mathrm{B}$ 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 cross section, $F(x)$, called the Fusion Function, and a dimensionless energy variable $x$, defined as $F(x) = \left(2E/\hbar\omega\, R_\mathrm{B}^2\right)\sigma_\mathrm{F}$ and $x = \left(E - V_\mathrm{B}\right)/\hbar\omega$, respectively. In these expressions, $\hbar\omega$ is related to the curvature of the barrier, when it is approximated by a parabola.

The fusion function was inspired by Wong's formula [28],

$$\sigma = R_\mathrm{B}^2\, \frac{\hbar\omega}{2E} \ln\left[1 + \exp\left(2\pi\, \frac{E - V_\mathrm{B}}{\hbar\omega}\right)\right]. \tag{1}$$

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 becomes system independent. It becomes the Universal Fusion Function (UFF) with the form,

$$F_0(x) = \ln\left[1 + \exp\left(2\pi x\right)\right]. \tag{2}$$

The UFF can then be used as a benchmark for comparisons with reduced fusion data, $F_\mathrm{exp}(x)$.

However, in typical situations, this reduction method has two important shortcomings. The first is that the experimental fusion functions deviate from the UFF owing to channel coupling effects, which are not taken into account in the derivation of Wong's formula. It is well known that couplings to low lying collective channels may have a strong influence on the fusion cross sections, mainly at sub-barrier energies, and such effects can be important for both tightly bound and weakly bound systems. This is a serious drawback when one is investigating the influence of the breakup channel (or the breakup plus transfer channels) on the fusion cross sections. The second shortcoming is that the Wong model is inaccurate at energies well below the Coulomb barrier and/or for very light systems. This is the case of collisions of the main beams of stable and radioactive weakly bound projectiles with light targets. To handle such situations, Canto et al. [26] proposed to renormalize

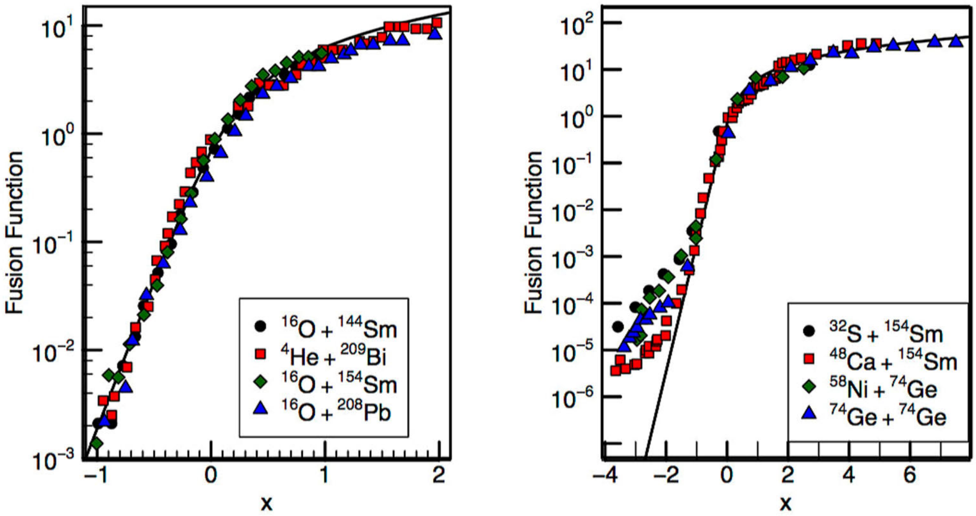

**Fig. 3** (Color online) left panel: Renormalized fusion functions for some tightly bound systems where inelastic couplings are well described by CC calculations and transfer channels are not relevant. The data are from Refs. [29–31]. *Right panel* a similar plot for systems where transfer channels have strong influence on fusion. The data are from Refs. [32–36]. In both plots the solid lines correspond to the UFF. The figure is adapted from [37]

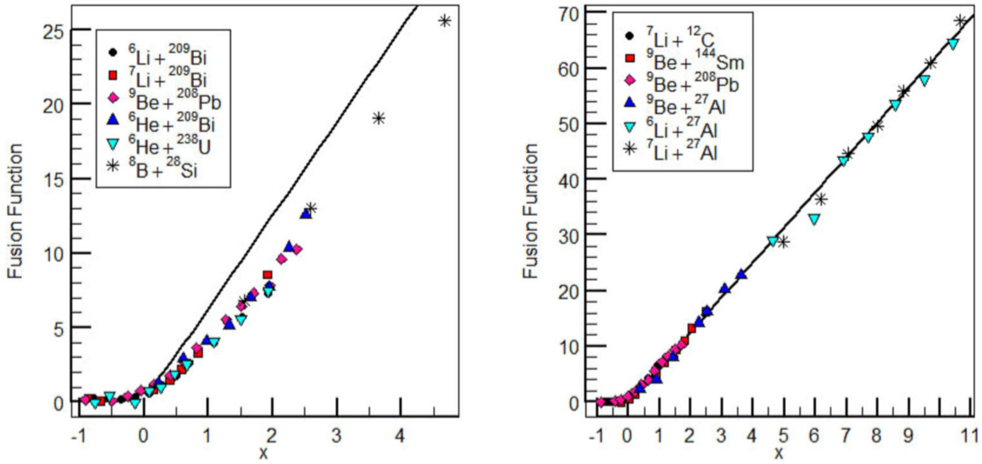

**Fig. 4** (Color online) Same as the previous figures but for weakly bound systems. The left panel shows renormalized experimental fusion functions corresponding to CF data of stable systems and TF of radioactive systems. The data are from Refs. [8,22,38–41]. The right panel shows fusion functions corresponding to TF data of stable weakly bound systems. The data are from Refs. [41–47]. For details, see the text

the experimental fusion functions, multiplying them by the ratio $\sigma_{\rm W}(E)/\sigma_{\rm CC}(E)$, where $\sigma_{\rm W}$ is the cross section of Eq. (1) and $\sigma_{\rm CC}$ is the fusion cross section obtained in a coupled channel calculation taking into account all the relevant inelastic channels. This procedure eliminates both shortcomings of the fusion function method, so that the differences between the renormalized experimental fusion functions and the UFF can be attributed to the couplings with the breakup and transfer channels.

The use of the fusion function reduction method is illustrated in Fig. 3, in an application to tightly bound systems. On the left panel we show renormalized experimental fusion functions for a few selected systems, where the influence of inelastic channels is known to be well described by coupled channel calculations and transfer channels are not relevant. As bare potential, we used the double-folding São Paulo potential [24,25]. One can observe that the experimental points are all very close to UFF (solid line). On the other hand, a similar plot for systems where fusion is known to be influenced by transfer is shown on the right panel of Fig. 3. Now the experimental results deviate from the universal curve, showing strong enhancements at sub-barrier energies.

This method was applied to tens of tightly and weakly bound systems, for TF and CF cross sections. When the renormalized experimental fusion functions were compared with the benchmark UFF curve, systematic behaviors could be observed [26,27,48–50]. In Figs. 4a and 4b we show some examples of the systematics. The figures are drawn in a linear scale, since the effects that we want to comment are at energies above the barrier. Figure 4a shows the renormalized CF fusion functions for some stable weakly bound systems and the TF for neutron and proton halo systems. Comparing the data with the UFF (solid line) one concludes that the combined effect of breakup and transfer channels is to suppress fusion at above-barrier energies.

A systematic study involving tens of stable weakly bound systems, performed by Wang et al. [50], showed very clearly that the intensity of the suppression, measured by a suppression factor, does not depend on the target. Rather, it depends on the breakup threshold of the projectile, being stronger for the most weakly bound ones. We point out, however, that this study was restricted to targets with mass around 100 and larger, since there are no available CF data for light systems. Figure 4b shows the TF renormalized fusion functions for some stable weakly bound nuclei. Comparing the data with the UFF, we find that there is no suppression of TF at above-barrier energies. This behavior is analogous to the one observed for tightly bound systems. The conclusion is that the CF suppression is compensated by the ICF cross section. Plotting Fig.4a and 4b in logarithmic scales and comparing to the UFF, one observes that the data shows some enhancement at sub-barrier energies.

Only a few systems deviate from the systematics discussed above. The explanation for these anomalies is that either the system has some very unusual nuclear structure property, or that there is something wrong with the data or with the coupled channel calculation used to renormalize the fusion function. One example is the TF data of Refs. [42,51,52] for the $^{6,7}$Li $+^{64}$Zn systems, which are slightly suppressed at above-barrier energies. In this case there are indications that the data is not fully reliable, as the new data of Ref. [17] for the same systems follow the systematics. The TF data for the proton-halo $^{8}$B projectile on $^{58}$Ni [53] shows enhancement at above-barrier energies. However, the TF data for the same projectile on $^{28}$Si [38] shows suppression in the same energy range, following the systematics of neutron-halo systems. As there are only two measurements for proton-halo nuclei, no conclusion may be reached so far and new measurements involving proton-halo nuclei are required.

## 5 Special Characteristics of Scattering of Weakly Bound Systems

Another subject widely investigated in low-energy Nuclear Physics is the elastic scattering of weakly bound nuclei at near-barrier energies. For tightly bound systems, the energy dependence of the phenomenological optical potential has a behavior known as the *Threshold Anomaly* (TA) [54–56]. It corresponds to a rapid variation of its real and imaginary parts as the energy decreases, approaching the height of the Coulomb barrier. When it happens, there is a sharp decrease of the imaginary part of the potential, owing to the closure of non-elastic channels that drains the incident flux. This drop of the imaginary part of the potential is accompanied by an increase of it real part, showing a bell-shaped energy dependence around the Coulomb barrier. This behavior is explained by the dispersion relation connecting the real and imaginary parts of the potential [57], which is a consequence of causality. The real part of the potential can be written as $V = V_0 + \Delta V$, where $V_0$ is its high-energy limit and $\Delta V$ 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 reduces the height of the Coulomb barrier.

However, it has been shown in several works that the TA is not observed in most collisions of weakly bound nuclei. In such cases, where the breakup cross section remains large even below the Coulomb barrier, the imaginary part of the potential does not decrease. It may even increase as the bombarding energy decreases. This increase of the imaginary part of the potential is followed by a decrease of its real part, which means that the polarization potential is repulsive [58–60]. This anomalous energy dependence of the potential was called the *Breakup Threshold Anomaly* (BTA) [61,62]. The BTA can be more clearly observed for neutron halo nuclei and for $^{6}$Li, than for $^{7}$Li. For the latter, there is a competition between the repulsive polarization potential associated with breakup and the attractive one arising from couplings with the bound inelastic state of $^{7}$Li. The net result of this competition (TA vs. BTA) depends on the target. It depends also on the theoretical analysis of the data, to the extent that they may lead to different conclusions in analyses of the same data, as in the case of the $^{138}$Ba target [61,63,64]. Of course, the imaginary potential must decrease and eventually vanish at low enough energies. So, what actually happens is that the Coulomb barrier is no longer the proper threshold energy for such reactions. This threshold is below the barrier. It is very difficult to find experimentally where

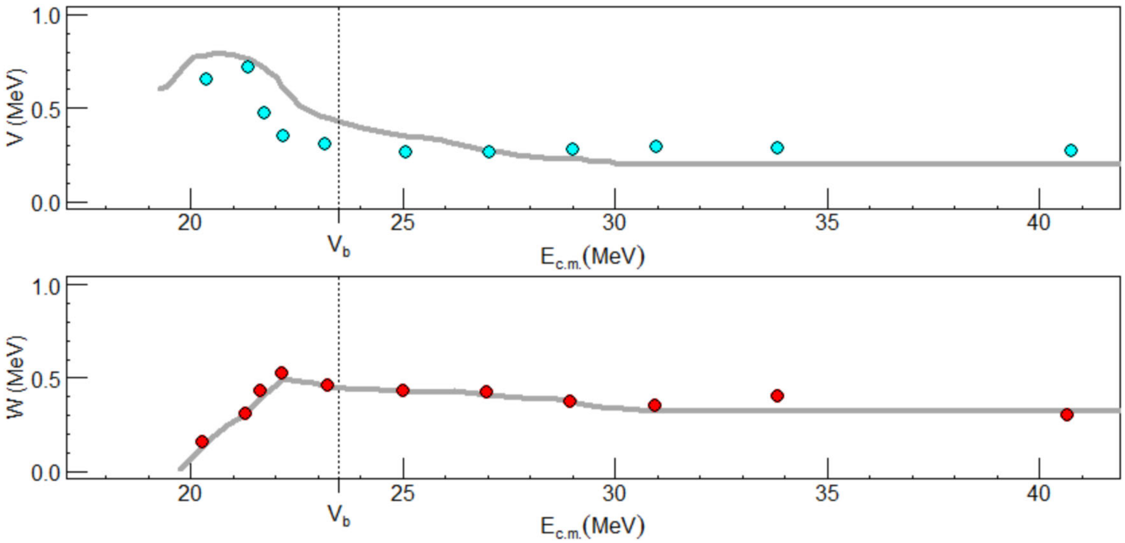

**Fig. 5** (Color online) Energy dependence of the real and imaginary parts of the optical potential in the scattering of $^6$Li on $^{144}$Sm. Data are from [65]. The figure is adapted from [65]. The *curves* obey the dispersion relation [57]. The BTA [62] can be clearly observed

the imaginary potential vanishes, since at sub-barrier energies the scattering is almost of fully Rutherford type. Thus, it is insensitive to the nuclear potential. However, in a few works it was possible to extrapolate the imaginary potential and find that it vanishes at energies around 85 % of the height of the Coulomb barrier. This is shown in Fig. 5 for the $^6\mathrm{Li} + ^{144}$ Sm system [65].

Another very special and important characteristic of elastic scattering angular distributions involving halo nuclei is the strong damping of the Fresnel diffraction (or Coulomb rainbow) peak. At low energies, usually the Coulomb scattering is dominant and the elastic scattering amplitude is predominantly near-sided. The general characteristic of the angular distributions is that at at forward angles the cross section is essentially of Rutherford type, followed by a large bump (Fresnel diffraction), and then a gradual drop to small values at backward angles. In cases where another long-range potential is present, there is a damped Fresnel diffraction and the region where the ratio $\sigma_{\mathrm{Elast}}/\sigma_{\mathrm{Ruth}}$ is close to one is restricted to very forward angles. In collisions of halo nuclei, there is such effect, since the coupling interaction has a long range, owing both to the Coulomb dipole term and to the extended nuclear form factor resulting from the halo structure. So, the couplings with the breakup channel lead to a long-range complex polarization potential, which changes the Fresnel diffraction pattern. Some recent experiments with neutron halo nuclei show this property very clearly, like with $^{11}$Be on $^{64}$Zn [66,67] and $^{209}$Bi [68], $^6$He on $^{208}$Pb [13] and $^{11}$Li on $^{208}$Pb [69]. In Ref. [69] with the $^{11}$Li projectile, the results are particularly impressive. Comparing the cross section for the $^6$Li and $^{11}$Li isotopes, one observes a normal behavior for the $^6$Li scattering whereas for the $^{11}$Li the Fresnel peak is drastically suppressed, and the cross section is much smaller than the Rutherford one even at very small scattering angles and at energy below the Coulomb barrier. The theoretical predictions of a 4-body CDCC calculation are in very good agreement with the data.

New and interesting elements in the study of elastic scattering and breakup were reported by V. Soukeras et al. in Ref.[70]. They measured the $^6$Li + p elastic scattering angular distributions in inverse kinematics at the Lab. energies from 2.7 to 4.8 MeV/u. They showed the relevance of the coupling to the continuum states ($\alpha$ + d breakup channel). They succeeded in describing the angular distributions by performing CDCC calculations for this system at the low energies chosen. In a subsequent paper [71], Ch. Betsou et al. studied the $^6\mathrm{Li} + p \rightarrow\ ^3\mathrm{He} + ^4$ He reaction in inverse kinematics at the same energies as Ref. [70]. They found that while the backward part of the angular distributions are dominated by the the compound nucleus formation (85 %), at forward angles the cross sections are predominantly governed by direct reactions which are strongly dependent on the interaction potential. The same optical potentials which were determined through the CDCC calculation performed in Ref. [70] were used to accurately determine the total reaction cross section. The above two papers lend further support to the adequacy of the CDCC method used at low energies, as we do in our current paper.

Another subject extensively investigated, studied in about twenty papers over the last decade, is the contribution of breakup to increase the total reaction cross sections in collisions of weakly bound nuclei. As already mentioned in section 4 of this paper, if one wants to compare cross sections of different systems on a single plot, some reduction procedure has to be performed. Two of the most widely used methods are the one proposed by Gomes et al. [72], in 2005, and the one proposed by Shorto et al. [73], which is an extension of the fusion function method of Canto et al. [26,27]. However, it has been shown very recently [74] that none of those methods works satisfactorily. Thus, some conclusions reached through the use of those reduction procedure may be questionable. For this reason we will not explore this subject in the present review.

## 6 Trying to Solve some Puzzles and Apparent Contradictions

In this section we mention some apparent puzzles or apparent contradictions concerning the results that we have presented in the preceding sections, and we will try to explain them.

The first puzzle is to explain why breakup suppresses the complete fusion of weakly bound systems at energies above the barrier and enhances it at sub-barrier energies. Gomes et al. [75] gave a possible explanation in terms of polarization potentials. The calculations of polarization potentials for weakly bound systems available in the literature use the CDCC method to take into account all couplings among the bound and the continuum discretized states of the weakly bound projectile. They find that the real part of the polarization potential is repulsive [59,60,76,77]. As consequence, the barrier height increases, and the fusion cross section is suppressed. The increase in the barrier height for the quasi-elastic scattering of $^8$B $+^{58}$ Ni, when breakup couplings are taken into account, was clearly shown for the quasi-elastic barrier distribution of this system [59]. On the other hand, it is well accepted that transfer and inelastic channels produce attractive polarization potentials, lowering the barrier and consequently enhancing the fusion cross section. Gomes et al. [75] suggested that at energies above the barrier, direct breakup is the main channel coupling effect and this gives rise to a repulsive polarization potential. Therefore, it leads to a reduction of the CF cross section in this energy range. On the other hand, at sub-barrier energies, breakup following transfer has been shown experimentally to predominate over the direct breakup [6,7]. In this case, the coupling with the transfer channel produces an attractive polarization potential. Indeed, coupled channel Born approximation (CCBA) and CDCC calculations were performed to evaluate separately the polarization potentials produced by transfer and breakup, and the attractive nature of the former and the repulsive nature of the latter were confirmed [75,78]. If the transfer contribution dominates the overall polarization potential at sub-barrier energies, the fusion barrier is reduced and the CF cross section is enhanced. We remark that the suppression of CF at energies above the barrier is compatible with the presence of the BTA behavior in the elastic scattering optical potential already mentioned.

Now we address the apparent contradiction between two observed facts: (1) the breakup cross section increases with the target mass (or charge); (2) the effect of the breakup on the suppression of CF does not depend on the target mass (or charge), as shown in the systematic study of Ref. [50]. One might expect that larger cross section in collisions with heavy targets would imply stronger CF suppression effects. However, this apparent contradiction can easily be explained. The large breakup cross section for heavy targets is a consequence of the long range of the Coulomb field, which plays a major role in collisions with heavy targets. In this case, there is Coulomb breakup even at distant collisions, which corresponds to very high angular momenta. On the other hand, fusion is phenomenon limited to low and grazing partial-waves, where the $l$-dependent effective potential has a 'pocket' and the fusion barrier can be surpassed more easily. Therefore, the large breakup cross sections observed for heavy targets comes from partial-waves that do not contribute to the CF. Furthermore, there may be an additional factor contributing to the different behaviors of the breakup and CF cross sections. As mentioned in Sect. 2, the breakup cross section is the sum of contributions from prompt and delayed processes, whereas only prompt breakup affects CF. If the prompt breakup is the dominant contribution and it does not have a strong dependence on the target mass, the opposed trends of the breakup and the fusion cross sections would be explained. So far there are no theoretical tools available to check this hypothesis. Another explanation might be that, indeed, the CF suppression due to the breakup varies with the target mass/charge, but there are no available CF data for light systems, only TF. Since the available systematic studies are restricted to targets with masses larger than 100, it is possible that this trend is not confirmed for lighter systems. That is, the effects of the breakup channel on CF may be weaker for lighter targets. Indeed, very recently [79] it was found that the suppression of CF for the $^6$Li $+^{96}$ Zr system is only 25 %, which is much smaller than the 40 % suppression found by Wang et al. [50] for heavier systems. So, we believe that this is still an open subject.

## 7 Conclusions and Perspectives

In conclusion, we hope to have shown that the physics of weakly bound nuclei is a very alive fascinating topic, with several interesting results coming out frequently. Many questions have already been answered, a lot has been learned, but there is still much to be learned, both from the experimental and the theoretical points of view.

From the experimental side there is much to be done: get additional data in the sub-barrier energy regime, which is of great importance for nucleosynthesis and for the production of super heavy elements; perform new studies of nuclear reactions with radioactive beams, with smaller error bars; perform new measurements of fusion cross section for proton-halo nuclei (presently only two experiments have been performed - with conflicting results); carry out new measurements of individual CF and ICF cross sections, especially for light and medium mass systems; distinguish ICF and transfer reactions leading to the same nucleus; perform a systematic study of the dependence of the suppression with the mass of the target; perform new and reliable measurements of non-capture breakup cross sections (for several projectiles and targets in different mass ranges, below and above the barrier), to determine the corresponding time scale of prompt and delayed breakup.

From the theoretical side, great advances are required, like: improve the CDCC calculations to include also transfer and excitations of the target; develop theoretical methods to give individual CF and ICF cross sections for any weakly bound systems; perform more four-body CDCC calculations, etc.

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