Transfer and breakup of light weakly-bound nuclei

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Abstract. We investigate the origin of the effects observed in the fusion cross section of light weakly bound nuclei, through a review of the most recent experimental and theoretical works. In particular we focus on the well-documented fusion suppression at energies just above the potential barrier. We show that, besides the couplings to the breakup process, effects due to the couplings to transfer need be taken into account. The magnitude of the cross section for the direct process, breakup or transfer, is not a reliable indicator of the size of the effects induced on the elastic scattering and fusion.

Keywords: fusion, direct reactions, light nuclei, halo nuclei
PACS: 25.60.Pj,25.85.Ge

INTRODUCTION

In the reaction mechanism of light nuclei, anomalies in the behaviour of the elastic scattering at energies approaching the potential barrier have been first observed in the late '70s for ^{6,7}Li and ^{9}Be [1–4]. Such effects were interpreted as due to couplings to breakup [5–7]. Breakup has then been indicated as main responsible for the effects on the fusion cross section observed on the same nuclei [8–10]. However, there are strong indications that an important role could be played by the transfer process, especially when unstable and halo nuclei are considered. In this work we review the experimental results and calculations that support this conjecture.

COUPLING EFFECTS ON THE FUSION CROSS SECTION

The measurement of fusion cross section at energies around the Coulomb barrier is a difficult endeavour, and precise results have only been obtained with beam of stable nuclei. Dasgupta and collaborators [10] have observed a suppression of the *complete* fusion (CF) cross section at energies around and just above the Coulomb barrier for ^{6,7}Li and ^{9}Be on ^{209}Bi, when the experimental results were compared to a one-dimensional barrier penetration model calculation (1D-BPM). Most important, they were able to show that the amount of the "missing" cross section was similar to that of *incomplete* fusion (ICF).

In complete fusion, all the nucleons of the projectile fuse with those of the target. If breakup occurs instead, it is still possible that one or more fragments (but not all) fuse with the target: this is incomplete fusion. The results reported in ref. [10] meant that breakup would occur in place of fusion; this was corroborated by the observation that

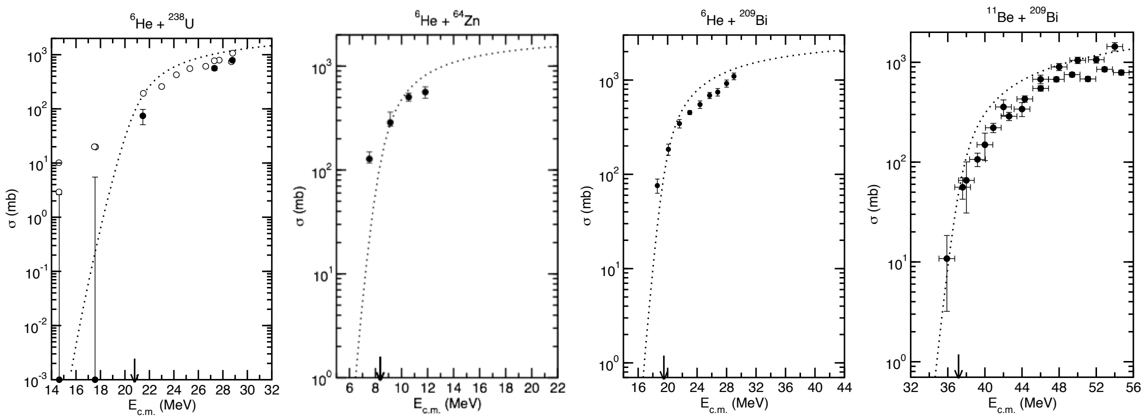

FIGURE 1. Experimental fusion cross sections for the halo nuclei ^{6}He and ^{11}Be [11–14]. The curves are 1D-BPM calculations. The arrows indicate the position of the calculated barriers (from[15]).

the amount of fusion suppression was more important for the projectile nuclei with a lower breakup threshold.

Studying such effects for unstable, and in particular halo nuclei, is interesting, since their weak binding and their peculiar structure could affect fusion even more. Measurements with such nuclei need to employ radioactive ion beams, thus are necessarily of a worse quality. However, the behaviour of the fusion cross section at energies just above the barrier has been determined in a rather accurate way. Results exist for ^{6}He on ^{238}U [11], ^{64}Zn [12] and ^{209}Bi [13], and for ^{11}Be on ^{209}Bi [14]. In order to draw conclusions from these different measurement, they were compared to consistent calculations in [15]. The results are shown in Fig. 1. Since there is no completely reliable way of including the breakup in the calculation of the fusion cross section (see further in the section dedicated to the breakup process), a simple 1D-BPM calculation was chosen, based on folding potentials built using the M3Y interaction as in ref. [2]. Compared to the model, a suppression of the fusion cross section is observed at energies above the barrier also for these halo nuclei, see Fig. 1. Essentially the same conclusions were drawn from a study that employed a more sophisticated model for the comparison, including the coupling to excited states but not to the breakup [16].

It should however be noticed that the cross sections shown in Fig. 1 are those for the *total* fusion, including both CF and ICF. We can thus argue that either the breakup couplings are for these nuclei much stronger, and that the *direct breakup*, not follow by the fusion of any fragment, is the dominant process; or, invoke the effect of the couplings to other direct channels.

In the next section, we move on to investigate the importance of the breakup channel.

THE BREAKUP CROSS SECTION

Could the direct breakup really be responsible for all the missing cross section reported in the measurements with halo nuclei? To answer this question, it is interesting to look at the absolute magnitude of the breakup process with respect to the total reaction cross

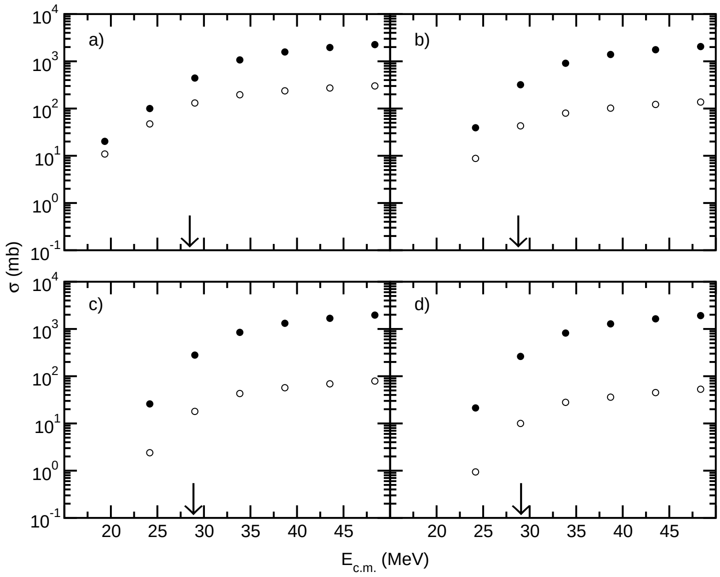

FIGURE 2. Results of model calculations for the direct breakup (open circles) compared to the total reaction cross section (filled circles) for a spinless ^{7}Li nucleus on a ^{208}Pb target. The breakup threshold is fixed respectively to (a) 1.0 MeV, (b) 1.5 MeV, (c) 2.0 MeV and (d) 2.5 MeV (from[15]).

section. In ref. [15] a number of model calculations for direct breakup were carried out employing an ideal system – a spinless ^{7}Li nucleus – and varying its breakup threshold from 1.0 MeV to 2.5 MeV. The Continuum-Discretised Coupled Channels (CDCC) method [5, 17, 18], which offers a satisfactory way of including breakup into a coupled-channel calculation for direct reactions, was used. Results are shown in Fig. 2 for a ^{208}Pb target. It appears that the direct breakup cross section is almost always negligible (notice the logarithmic scale), with the only exception at energies well below the barrier when the breakup threshold is very small (1.0 MeV). In similar calculations on light targets (^{58}Ni and ^{12}C), the direct breakup fraction of the total reaction cross section was even smaller.

The magnitude of the cross section alone may be misleading: in fact, the influence of the breakup on the elastic scattering is well documented [1–7, 19]. It would be desirable to explicitly evaluate the effect on fusion through calculations which took breakup into account; however such models are not available. While the CDCC method works well for direct reactions, there is at present no reliable way of including it into a calculation for fusion. Nevertheless, attempts have been made over the years using simplified models, and indications can be inferred from looking at those works.

In several cases, breakup has been taken into account by modifying the interaction potential used in the 1D-BPM, that is, by introducing a Dynamic Polarization Potential (DPP). In ref. [20] the authors reach a good agreement with the experimental data for the fusion of halo nuclei on several targets by decreasing the real part of the potential, in a way similar to the one used to describe the elastic scattering of stable weakly bound nuclei in [2]. The same procedure was adopted in [21] for ^{9}Be + ^{208}Pb, however in that work the modification of the potential was obtained from a fit of elastic scattering cross section angular distributions at various energies, and then use to predict the fusion cross section in a 1D-BPM calculation. The authors found that the calculated values reproduced well the experimental *total* fusion (CF + ICF), which left the the question open about the origin of the large amount of ICF events for this system.

In other works, the interaction potential has been extracted directly from a CDCC calculation for the system of interest, thus including the breakup. This was for example the case in [22] for ^{6}He and ^{6}Li on ^{208}Pb, where the calculation managed to reproduce the total fusion cross section (experimental data for ^{6}He on ^{209}Bi were used for the comparison). A step further was made in refs. [23, 24] for ^{6,7}Li on ^{59}Co, where the CDCC method was used in combination with short-range imaginary potentials for each of the two fragments in the projectile (d and α for ^{6}Li, ^{3}H and α for ^{7}Li), simulating the ingoing-wave boundary condition. The resulting cross section predictions were still larger than the measured values for total fusion.

While a firm conclusion cannot be derived from the exampled above and other ones not cited here, we have indications that the breakup alone is not sufficient to explain the suppression of the complete fusion cross section above the potential barrier, observed for all weakly-bound nuclei. Other processes may play an important role: transfer is the main candidate, and we consider its features in the next section.

TRANSFER REACTIONS

The probability for a transfer reaction to occur for a given system depends on a number of factors. Matching conditions (Q-value and momentum), spectroscopic factors, the geometry of the potential and the bound-state wave functions are all playing a role. The magnitude of transfer cross sections cannot thus be easily predicted, since each projectile-target combination at a given collision energy is a unique system. Reliable methods for the calculation of the cross section exist in the case of one-nucleon transfer, and inclusion of transfer couplings into calculations for fusion is also possible. Still, uncertainties remain, which are related to the description of the structure of the interacting nuclei. The description of the transfer of two nucleons, on the other hand, is much more problematic: for one-step transfers the two nucleons are usually described as a cluster; for two-step transfers, very often assumptions need be made on the nature of the unknown intermediate states.

Effects of transfer couplings are present on the elastic scattering, as demonstrated in [25]. The authors considered the one-neutron transfer ^{208}Pb(^{9}Be,^{8}Be)^{209}Pb; in a series of calculations for elastic scattering, which included the coupling to transfer to various states in ^{209}Pb, they found that those couplings produced a DPP similar to the one due to the couplings to breakup. One such calculation, compared to experimental data from ref. [21], is shown in Fig. 3.

To evaluate the effects of such coupling on fusion, model calculations were carried out in [15, 26] for various light weakly bound nuclei. The authors used double-folded potentials for the real part and an interior Woods-Saxon potential for the imaginary part of the interaction, the latter to simulate the ingoing-wave boundary condition. Some of the results are shown in Fig. 4. We immediately observe that the magnitude of the transfer cross section may vary significantly among the different systems, as remarked

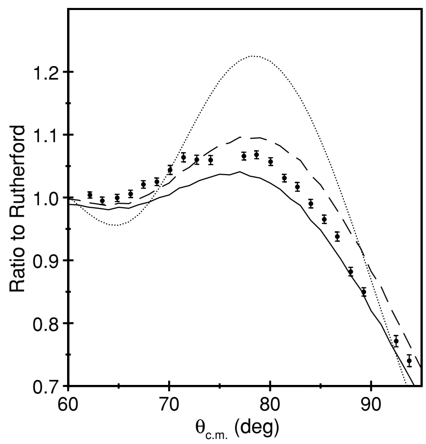

FIGURE 3. (from[25]) ^{9}Be + ^{208}Pb elastic scattering at $E_{\rm lab} = 44$ MeV. The dotted, dashed and solid curves are the results of calculations with no couplings, coupling to breakup only, and coupling to both breakup and single neutron stripping, respectively. Experimental data points are from [21].

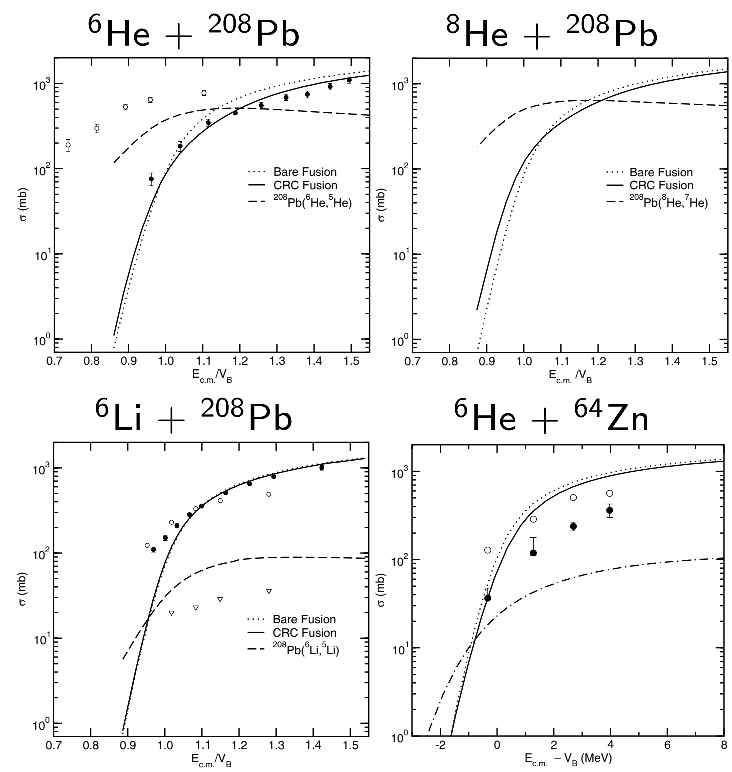

FIGURE 4. Results of the calculation for the fusion cross section (dotted curves: bare potential; solid curves: with the inclusion of one-neutron transfer couplings) and the one-neutron transfer excitation function for the systems ^{6}He + ^{208}Pb, ^{8}He + ^{208}Pb and ^{6}Li + ^{208}Pb (from [15]) and ^{6}He + ^{64}Zn (from [26]). Experimental data are: for ^{6}He + ^{208}Pb the total fusion cross section (filled circles, from [13]) and the total α-particle production (open circles [27]); for ^{6}Li + ^{208}Pb the total fusion (filled circles, from [10], the total α-particle production (open circles [28]) and the α-p coincidences (open triangles [28]); for ^{6}He + ^{64}Zn the complete fusion (filled circles [12]) and the total fusion (open circles [12]).

above. In particular, poor matching in the ^{6}He + ^{64}Zn system results in a very small cross section. Secondly, the effect of transfer couplings on the fusion cross section (solid curves) is similar to that of breakup, suppressing the fusion probability at energies above the potential barrier with respect to the prediction of the bare-potential calculations (dotted curves). And finally, we see that for the ^{6}He halo nucleus, the calculations cannot fully reproduce the experimental fusion cross section, in particular the *complete* fusion cross section for ^{6}He + ^{64}Zn.

From these observations we can conclude that transfer couplings induce effects on the elastic scattering and on the fusion of light weakly bound nuclei, similar to those of breakup. The magnitude of such effects may depend strongly on the particular system, but it could certainly be comparable to that of breakup couplings. Also, it is clear that transfer *alone* cannot explain the suppression of the fusion cross section at energies above the barrier observed in halo nuclei, and that other couplings are necessary. Besides breakup, one should not forget two-nucleon transfer, which is however difficult to calculate.

CONCLUSIONS

We have investigated the origin of the effects observed on the behaviour of the fusion cross section of light weakly bound nuclei, in particular the suppression of the fusion probability at energies just above the potential barrier.

Besides the couplings to breakup, which have been advocated in most cases, couplings to the transfer process may also play an important role, with effects on the elastic scattering and the fusion cross sections similar to those of the breakup. The magnitude of the transfer effects may vary, and quantitative predictions are difficult at present – especially considering that the importance of the cross section for the process in question (breakup or transfer) can hardly be taken as an indicator of the size of the effects on fusion. For sure, both these processes should be taken into account when evaluating the cross sections for elastic scattering and fusion.

In the present work we did not examine the debated question of sub-barrier fusion enhancement for halo nuclei. Results reported for the ^{6}He + ^{206}Pb system [29] seem to indicate a strong enhancement, explained through a mechanism of "sequential fusion" [30] favoured by one-neutron transfer channels with positive Q-values. These observations are somehow at variance with previous results (see Fig. 1), however the uncertainties still present in this sort of measurements leave both possibilities open. New measurements performed very recently with improved beam intensities and detection setup will probably help clarifying the situation.

Finally, we would like to underline that the study of reactions at energies around the barrier has eventually started to bring valuable information on the structure of the nuclei involved, in particular of the very interesting halo nuclei. This is due to the recent advances both in the theoretical description of the reaction mechanism, in particular with the introduction of the four-body CDCC method [31]; and in experimental techniques, with the improvements in beam intensity (for example at the SPIRAL facility at GANIL) and detection methods (coincidence detection of γ, neutron and particle radiation [32]).

ACKNOWLEDGMENTS

The ideas presented in the present paper stem from discussions with Dr. N. Keeley and Dr. K. Rusek (Andrzej Sołtan Institute, Warsaw), Dr. J. L. Sida (CEA-IRFU, France) Prof. N. Alamanos (CEA Saclay) and Dr. A. Navin (GANIL).

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