Transfer Coupling Effects on Elastic Scattering and Fusion for Weakly Bound Exotic Nuclei

N. Keeley[1,2]

[1] CEA Centre de Saclay, DSM/DAPNIA/SPhN, 91190 Gif-sur-Yvette Cedex, France
[2] Department of Nuclear Reactions, The Andrzej Sołtan Institute for Nuclear Studies, ul. Hoża 69, 00-681 Warsaw, Poland

Abstract. Studies of coupling effects in fusion and elastic scattering induced by beams of weakly bound exotic nuclei such as ^{6,8}He, ^{11}Be etc. have thus far focused on the influence of breakup. However, recent exclusive measurements for ^{6}He + ^{209}Bi found that at near-barrier energies the large total reaction cross sections observed for this system are dominated by one and two neutron stripping reactions. Although a large cross section is no guarantee of a significant effect, coupling to single neutron stripping reactions is found to have an important influence on the near-barrier total fusion and elastic scattering for those exotic nuclei classed as "halo" or "skin" systems, which appears to be unique to this type of nucleus. Examples are presented for several halo or skin nuclei plus the stable weakly bound nucleus ^{6}Li.

1 Introduction

The truly exotic light radioactive nuclei, i.e. those that exhibit new phenomena such as nucleon halos or skins, are weakly bound (a necessary condition for these phenomena): ^{15}C (S_n = 1.2 MeV), ^{11}Li (S_{2n} = 0.30 MeV), ^{11}Be (S_n = 0.50 MeV), ^{8}B (S_p = 0.14 MeV), ^{8}He (S_{2n} = 2.1 MeV), ^{6}He (S_{2n} = 0.97 MeV) etc. Attention has thus naturally focused on breakup and its coupling effects for these nuclei, both on fusion and elastic scattering. However, weak binding also implies extended valence particle wave functions, which should lead to enhanced transfer probability. Indeed, large 1n and 2n transfer cross sections — larger than the ^{6}He $\rightarrow \alpha$ + 2n breakup cross section at near-barrier energies — have been observed in the ^{6}He + ^{209}Bi system [1–3]. However, other factors also play an important rôle in the effect of transfer couplings, such as spectroscopic factors and Q-value and angular momentum matching. It is therefore interesting to compare the effect of transfer couplings for weakly bound exotic nuclei and their stable counterparts, ^{6,7}Li and ^{9}Be.

In this contribution we shall investigate the effect of single nucleon transfer couplings on near-barrier total fusion and elastic scattering for selected weakly-bound exotic nuclei by means of coupled reaction channels (CRC) calculations. For comparison, we shall also present similar calculations for the stable weakly-bound nucleus ^{6}Li. We limit our investigation to the effects of single nucleon transfers in order to avoid some of the problems associated with the calculation of, for example, the (^{6}He,^{4}He) 2n transfer reaction, not least of which being lack of basic spectroscopic information in the relevant excitation energy range for the target-like composite nucleus.

2 Breakup: Cross Section and Coupling Effect

Before considering transfer couplings we shall briefly discuss breakup and its coupling effect on near-barrier elastic scattering and fusion. It is often assumed that for weakly bound nuclei breakup is the main contribution to the total reaction cross section and has the largest coupling effect on other channels. However, there is a considerable body of data for stable weakly bound nuclei which shows that by any practical definition of the term breakup actually provides a small contribution to the total reaction cross section, see e.g. [4] and [5] and the discussion therein. This is also true for the ^{6}He + ^{209}Bi system, where for an incident ^{6}He energy just above the Coulomb barrier coincidence measurements found that the main contribution to the large total α cross section is actually 2n ($\sim$ 50 %) and 1n ($\sim$ 20 %) transfer, the remainder being due to breakup [1–3].

The relative importance of breakup will depend on threshold energy, target mass (or rather, charge) and incident energy — the fraction of breakup for ^{6}He + ^{209}Bi, while small, is still larger than for ^{6}Li + ^{208}Pb at similar incident energies relative to the Coulomb barrier. As a general rule, breakup only contributes significantly to the total reaction cross section for heavy targets such as Pb, low breakup threshold energies ($\sim$ 1 MeV or less) and low incident energies (at or below the Coulomb barrier), see [5] for supporting model calculations. Breakup should thus be more important for the exotic weakly bound nuclei, as they have lower breakup thresholds than their stable counterparts (in some cases much lower), but probably only for heavy targets where Coulomb breakup dominates.

A small cross section does not necessarily imply a small coupling effect on other channels; indeed, the effect of breakup coupling on elastic scattering for weakly bound stable nuclei has long been known to be important. This is also true for their exotic counterparts, see e.g. [6]. The coupling effect on the elastic scattering remains important even for light targets such as ^{12}C where the breakup cross section is negligible, see e.g. [5]. The effect of breakup coupling on fusion is still controversial [7] and we shall not consider it here. The problem is exacerbated by the lack of a universally agreed definition of "fusion" for weakly bound nuclei, nor is there any theoretical description that treats breakup and fusion equally realistically.

3 Transfer: Cross Section and Coupling Effect

We saw in the previous section how, despite a relatively small cross section, coupling to breakup has an important influence on elastic scattering (the nature of the effect on fusion is still *sub judice*, but is probably also important). With regard to transfer reactions, there are two questions of interest, viz. the importance of the transfer cross section itself, experimentally determined to be large for a single case, and the effect of coupling to transfer on the near-barrier elastic scattering and fusion (here the total fusion, as defined in [5]). To investigate these questions we shall employ a standard methodology that should enable us to probe reasonably realistically the effect of a given coupling in isolation.

Our standard procedure consists of building up the coupling effects step-by-step on the basis of a fixed "bare" optical potential. The real part of this bare potential was calculated using the double-folding model with the standard M3Y interaction, as used in [8] and (hopefully) realistic nucleon densities. The imaginary part consisted of an interior Woods-Saxon potential of fixed parameters, simulating the ingoing-wave boundary condition [9]. The necessary nuclear structure information, spin-parities, spectroscopic factors etc., was taken from the literature. All double folded potentials were calculated with DFPOT [10]; the CRC calculations were performed with FRESCO [11], and included the full complex remnant term and non-orthogonality correction.

As our first example, we take the ^{6}Li + ^{208}Pb system as a control, investigating the effect of both ^{208}Pb(^{6}Li,^{5}Li)^{209}Pb and ^{208}Pb(^{6}Li,^{5}He)^{209}Bi transfer couplings on the near-barrier elastic scattering and total fusion. The ^{6}Li, ^{5}Li and ^{5}He densities were taken from [12], [13] and [14], respectively, with the target densities calculated using the liquid drop model of [15]. Spectroscopic factors for the ^{6}Li:^{5}Li and ^{6}Li:^{5}He overlaps were taken from [16] while those for ^{208}Pb:^{209}Pb and ^{208}Pb:^{209}Bi were taken from [17] and [18], respectively. Transfers to both the $3/2^{-}$ ground and $1/2^{-}$ first excited resonant states of ^{5}Li and ^{5}He were included.

The results are compared with data in Fig. 1. The total fusion excitation function, taken from [19], is actually for the ^{6}Li + ^{209}Bi system with the shift in Coulomb barrier height compensated for by dividing the centre of mass energy scale by the nominal barrier height for ^{6}Li + ^{209}Bi then multiplying by that for ^{6}Li + ^{208}Pb. While crude, this compensation procedure should enable a reasonable comparison with the ^{6}Li + ^{208}Pb calculations (calculations for the ^{209}Bi(^{6}Li,^{5}Li)^{210}Bi transfer would be intractable due to the fragmentation of the single particle strength in ^{210}Bi). The ^{208}Pb(^{6}Li,^{5}Li)^{209}Pb cross section over predicts the data by a factor of about 2; this is due to insufficient absorption in the entrance channel (we are coupling to a single partition in this calculation) and good agreement may be obtained by CRC calculations using more conventional imaginary potentials in the entrance channel. The main point to note is that the single neutron stripping coupling has an entirely negligible effect on the total fusion cross section. Adding the ^{208}Pb(^{6}Li,^{5}He)^{209}Bi single proton stripping coupling has no visible effect. The coupling effect of single nucleon stripping on the near-barrier elastic scattering is also negligible.

Having seen that the coupling effect of single nucleon stripping on near-barrier total fusion and elastic scattering is negligible for the stable weakly bound nucleus ^{6}Li we now present calculations for the ^{6}He + ^{208}Pb system. The ^{6}He density was taken from [20] and the ^{6}He:^{5}He spectroscopic factors from [21]. All other details were as for the ^{6}Li + ^{208}Pb calculations. The results are compared with total fusion [22] and 1n transfer [3] data for the ^{6}He + ^{209}Bi system, again with the shift in Coulomb barrier height compensated for, in Fig. 2. In contrast to the ^{6}Li + ^{208}Pb case, we see that there is a significant coupling effect, a sub-barrier enhancement of the total fusion cross section and an above barrier *suppression*, the latter acting to improve the agreement with the data. An above barrier suppression of the ^{6}He fusion cross section compared to bare, no-coupling calculations using

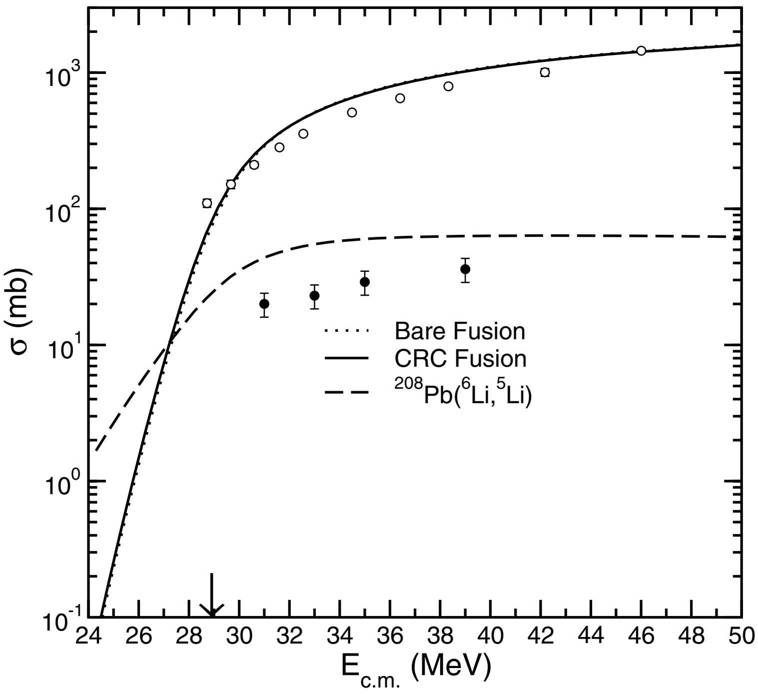

Figure 1. Total fusion cross sections with (full curve) and without (dotted curve) coupling to the ^{208}Pb(^{6}Li,^{5}Li)^{209}Pb stripping reaction. The dashed curve denotes the integrated stripping cross section. The filled circles denote the α + p coincidence cross sections of [4] and the open circles denote the ^{6}Li + ^{209}Bi total fusion data of [19] with the shift in Coulomb barrier height compensated for. The arrow indicates the position of the nominal Coulomb barrier.

the São Paulo double-folded potential has also recently been reported [23]. The ^{208}Pb(^{6}He,^{5}He)^{209}Pb cross section over predicts the single datum by a factor of about 2.5, again due to insufficient absorption in the entrance channel. However, even allowing for this over prediction, note the very large sub-barrier cross section for single neutron stripping, approximately two orders of magnitude larger than the total fusion cross section.

In Fig. 3 we compare the elastic scattering angular distribution at an incident ^{6}He energy of 27 MeV with the data of [24]. While we do not describe the data — we do not expect to, as the effect of breakup coupling, not included in the calculation, is known to be important here [6] — the effect of coupling to the single neutron stripping is seen to be important, unlike for ^{6}Li + ^{208}Pb. The effect of 2n transfer is difficult to quantify realistically, as we lack knowledge of the structure of ^{210}Pb in the relevant excitation energy region, $\sim$ 8 MeV. However, tests suggest that it acts in the same sense as the 1n transfer coupling and is possibly even more important.

Similar calculations for the ^{8}He + ^{208}Pb and ^{11}Be + ^{208}Pb systems yield similar results, although the coupling effect on the total fusion for ^{11}Be + ^{208}Pb is always

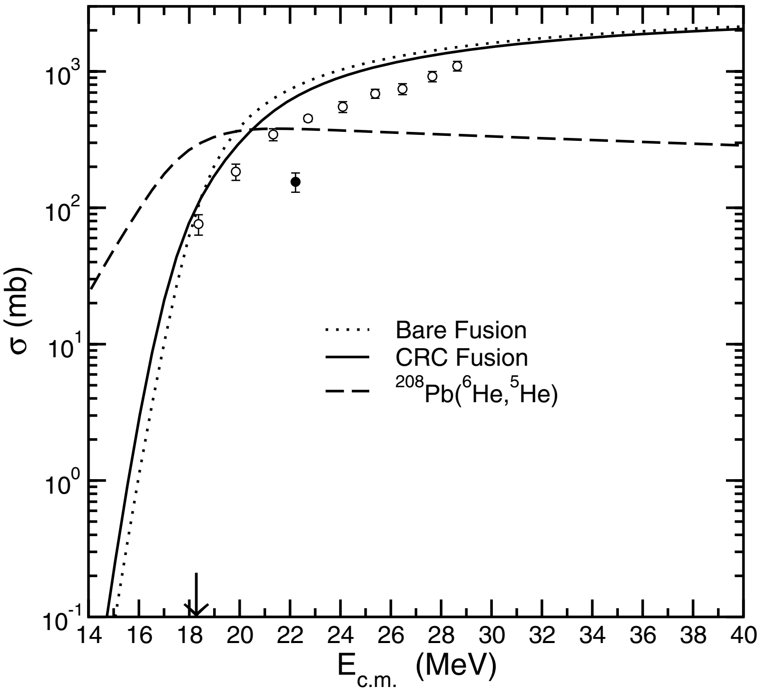

Figure 2. Total fusion cross sections with (full curve) and without (dotted curve) coupling to the ^{208}Pb(^{6}He,^{5}He)^{209}Pb stripping reaction. The dashed curve denotes the integrated stripping cross section. The filled circle denotes the 1n transfer cross section of [3] and the open circles denote the ^{6}He + ^{209}Bi total fusion data of [22], both with the shift in Coulomb barrier height compensated for. The arrow indicates the position of the nominal Coulomb barrier.

a suppression at the incident energies investigated here, see Fig. 4. The calculations for the ^{11}Be + ^{208}Pb system included transfers to the 0^+ ground and 2^+ first excited states of ^{10}Be but no coupling between these states. However, tests indicated that the effect of this coupling is small. It should be noted that very large sub-barrier single neutron stripping cross sections are a general feature of these systems involving neutron halo or skin nuclei as projectiles. These cross sections can be up to three orders of magnitude larger than the total fusion cross section, even allowing for the inevitable over prediction of the calculations.

We have so far dealt exclusively with *neutron* halo or skin nuclei, and we may pose the question whether proton halo nuclei also exhibit this strong coupling effect. As an example, we take ^{8}B which has a very low threshold against $^8\mathrm{B} \rightarrow {}^7$Be + p breakup ($S_p$ = 0.14 MeV). The ^{8}B and ^{7}Be densities were taken from [26] and the ^{8}B:^{7}Be form factors and spectroscopic factors from [27]. Transfers to both the $3/2^-$ ground and $1/2^-$ first excited states of ^{7}Be were included, but we did not include coupling between these states or ground state reorientation, as test calculations found that the effect of these couplings is small. The coupling effect of

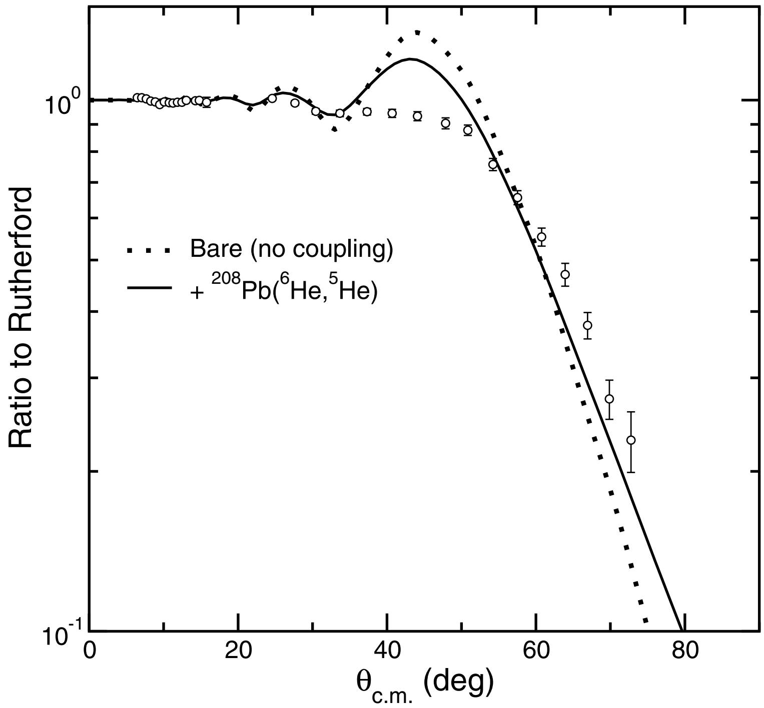

Figure 3. Elastic scattering angular distribution for 27 MeV ^{6}He + ^{208}Pb with (solid curve) and without (dotted curve) coupling to the ^{208}Pb(^{6}He,^{5}He)^{209}Pb stripping reaction. The data are taken from [24].

the ^{208}Pb(^{8}B,^{7}Be)^{209}Bi transfer is negligible for both near-barrier total fusion and elastic scattering. In addition, the integrated transfer cross section is negligible compared to the total fusion cross section at all the energies studied — the trend of the results suggests that it only becomes larger than the total fusion cross section at extreme sub-barrier energies.

The negligible coupling effect and transfer cross section for the single proton stripping reaction in the ^{8}B + ^{208}Pb system, despite the very small S_p value, may be explained by the fact that the proton has to traverse a Coulomb barrier in order to transfer from the ^{8}B to the ^{208}Pb, unlike the neutron in ^{6}He, for example. This Coulomb barrier effect will also play a rôle in the negligible effect of the proton stripping reaction in the ^{6}Li + ^{208}Pb system — the reaction Q-values for the ^{208}Pb(^{6}Li,^{5}Li) and ^{208}Pb(^{6}Li,^{5}He) reactions, -1.73 MeV and -0.79 MeV, respectively, are comparable — although other effects are more important as the neutron transfer also has a negligible effect in this system.

To test the influence of the Coulomb barrier effect, further calculations were performed for the ^{6}Li + ^{58}Ni and ^{8}B + ^{58}Ni systems. The ^{6}Li + ^{58}Ni calculations

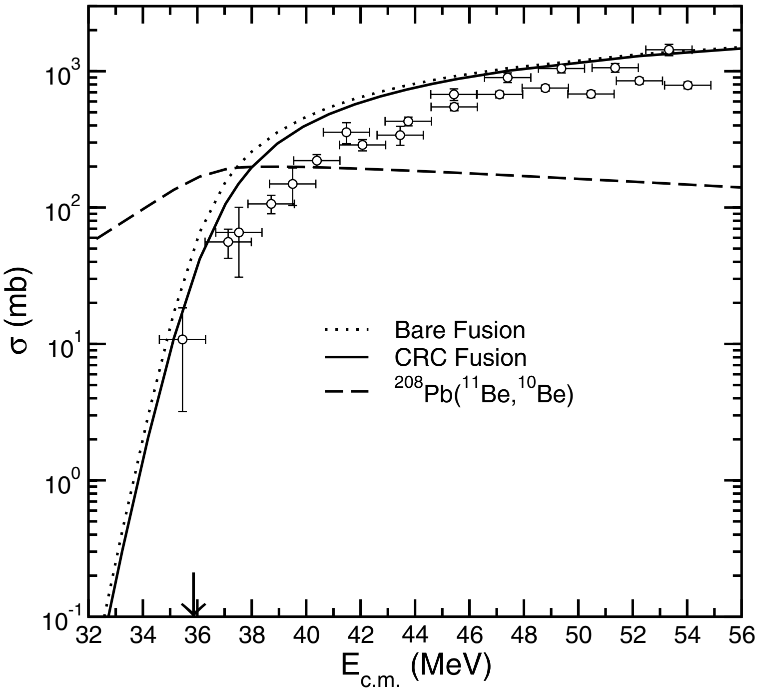

Figure 4. Total fusion cross sections with (full curve) and without (dotted curve) coupling to the ^{208}Pb(^{11}Be,^{10}Be)^{209}Pb stripping reaction. The dashed curve denotes the integrated stripping cross section. The open circles denote the ^{11}Be + ^{209}Bi total fusion data of [25], with the shift in Coulomb barrier height compensated for. The arrow indicates the position of the nominal Coulomb barrier.

included both ^{58}Ni(^{6}Li,^{5}Li)^{59}Ni and ^{58}Ni(^{6}Li,^{5}He)^{59}Cu transfers, while the ^{8}B + ^{58}Ni calculations included only single proton stripping. While the ^{6}Li + ^{58}Ni calculations do now show a coupling effect on both the near-barrier total fusion and elastic scattering similar to, but smaller than, that seen in the ^{6}He + ^{208}Pb system, it is the *proton* stripping coupling that is responsible for the bulk of the effect. This is despite the single neutron stripping reaction Q-value being positive, $+3.34$ MeV, compared to the negative Q-value, -1.17 MeV, for single proton stripping, demonstrating that reaction Q-value is not a reliable guide to the effect of a given coupling.

For the ^{8}B + ^{58}Ni system, we now find that the proton stripping coupling has an effect on the near-barrier total fusion and elastic scattering similar to that for neutron stripping in the ^{11}Be + ^{208}Pb system, see Figs. 5 and 6. The integrated proton stripping cross section is still much smaller than the single neutron stripping cross sections for neutron halo or skin nuclei, although considerably larger than for the ^{8}B + ^{208}Pb system.

It is interesting to note that the coupling effect on the elastic scattering is also very similar to that for the ^{208}Pb(^{11}Be,^{10}Be)^{209}Pb stripping reaction, i.e. the an-

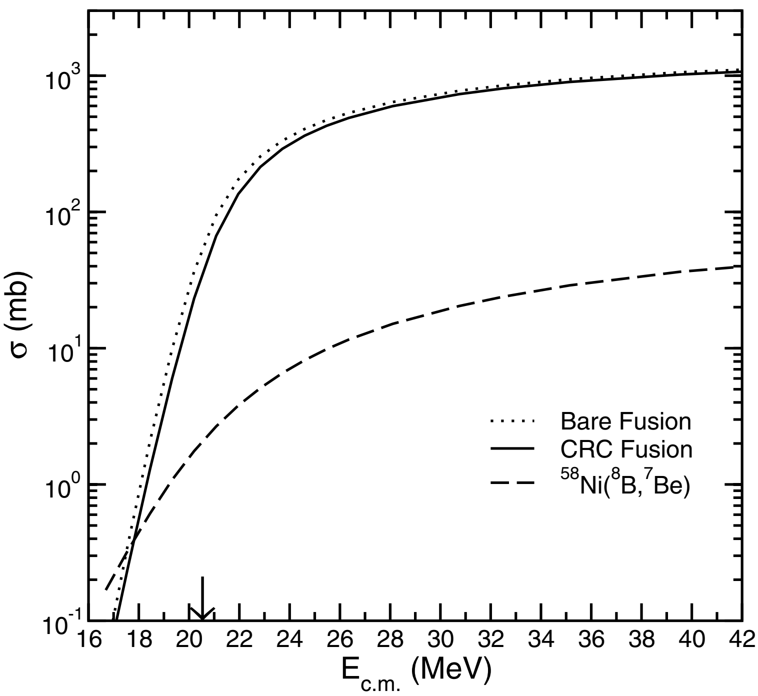

Figure 5. Total fusion cross sections with (full curve) and without (dotted curve) coupling to the ^{58}Ni(^{8}B,^{7}Be)^{59}Cu stripping reaction. The dashed curve denotes the integrated stripping cross section. The arrow indicates the position of the nominal Coulomb barrier.

gular distribution is mostly moved out to larger scattering angles with little or no reduction in the Coulomb rainbow. This is in contrast to the influence of single neutron stripping on near-barrier ^{6}He and ^{8}He + ^{208}Pb elastic scattering where the most striking effect is a considerable diminution of the Coulomb rainbow, see Fig. 3 (the ^{8}B incident energy in Fig. 6 has been chosen to give a similar $E_{\mathrm{c.m.}}/V_{\mathrm{B}}$ ratio). It is tempting to ascribe this similarity between ^{11}Be and ^{8}B (once the Coulomb barrier effect has been compensated for in the case of ^{8}B) to their very low single nucleon separation energies (S_{n} = 0.50 MeV for ^{11}Be and S_{p} = 0.14 MeV for ^{8}B, compared to S_{n} = 1.86 MeV and 2.58 MeV for ^{6}He and ^{8}He, respectively). However, a complete systematic study would be needed to test adequately this hypothesis.

4 Conclusions

Coupling to single neutron stripping has an important effect on both near-barrier total fusion and elastic scattering for neutron halo and skin nuclei, see [5, 28] for further examples. The effect of coupling to single proton stripping for the proton halo nucleus ^{8}B is damped as the transferred proton has to traverse a Coulomb

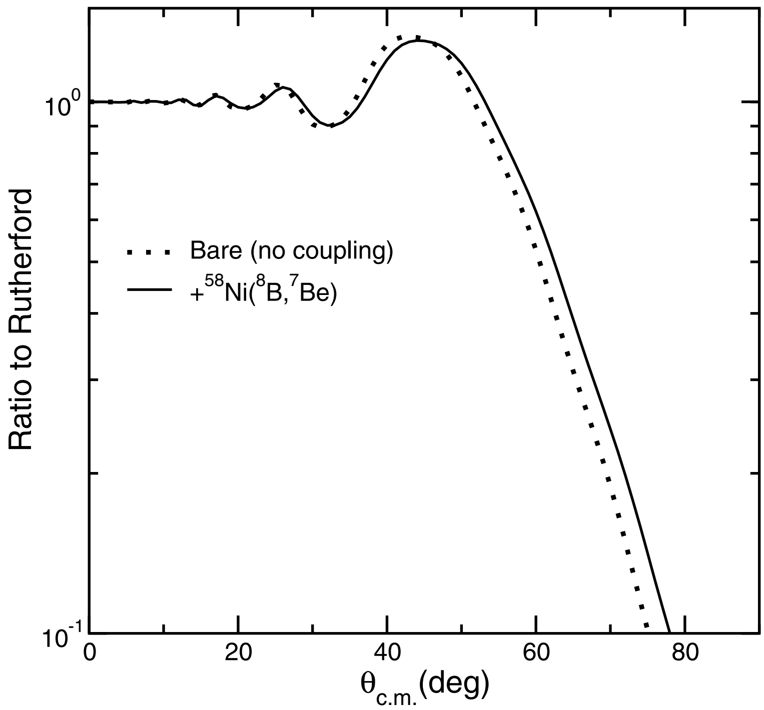

Figure 6. Elastic scattering angular distribution for 33.5 MeV ^{8}B + ^{58}Ni with (solid curve) and without (dotted curve) coupling to the ^{58}Ni(^{8}B,^{7}Be)^{59}Cu stripping reaction.

barrier; it is only significant for lighter targets with smaller Z. Similar couplings for the stable weakly bound nucleus ^{6}Li have a small or negligible effect, depending on the target mass; paradoxically, for a medium mass target the proton stripping coupling was responsible for most of the effect. A feature that seems to be unique to *neutron* halo or skin nuclei is a very large sub-barrier stripping cross section, up to three orders of magnitude greater than the corresponding total fusion cross section.

We have not considered 2n or d transfer for nuclei where this is relevant, ^{6}He and ^{6}Li. As the 2n stripping cross section for ^{6}He is known to be stronger than the 1n, it is reasonable to suppose that the coupling effect could be even stronger. However, a realistic calculation is not currently possible as we lack spectroscopic information in the required excitation energy range for the target-like composite nuclei formed by 2n transfer (the Q-values for these reactions are large and positive). Deuteron transfer is more problematic, as except for target nuclei where $N \approx Z$ direct d transfer should only be important for high-lying states where the neutron and proton levels are close, which may be unbound.

Several questions remain to be investigated: how sensitive are the results to the densities used in the folding model? Tests found the choice of density to affect only the details; the calculations are most sensitive to the choice of projectile density in the entrance channel. Choice of interaction: we used the standard M3Y, but for halo nuclei density dependence of the effective interaction may be important. Finally, is ^{6}Li a fair control? Would not d stripping provide a more suitable comparison in this case? This may be true, but perhaps only for nuclei where N $\approx$ Z; ^{9}Be (S_n = 1.67 MeV) may provide a more suitable comparison for single neutron stripping [29].

Acknowledgments

The author would like to thank Drs. A. Antonov, L. Giot and V. Lapoux for supplying listings of densities and Drs. N. Alamanos, K. Kemper, R. Raabe, K. Rusek and J.-L. Sida for many interesting discussions on this subject. This work was supported by the European Commission through the award of a Marie Curie Intra-European Fellowship, Contract No. MEIF-CT-2005-010158.

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