Decreased absorption cross sections in the case of strongly coupled channels with positive Q values

W. von Oertzen and I. Krouglov*
Hahn-Meitner-Institut Berlin and Fachbereich Physik, Freie Universität Berlin, Berlin, Germany
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The influence of the coupling of inelastic and transfer channels on the absorption cross section behind the barrier is discussed for reactions induced by weakly bound projectiles. It is shown that because of the prevailing positive Q values a decrease of the absorption cross section may occur. The result is demonstrated for a ^{11}Be+^{12}C system using the coupled reaction channel approach. The adiabatic potential energies of the asymptotic states which are subjected to strong coupling may give a natural explanation of this effect.

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A variety of discussions of reactions induced by weakly bound (exotic) nuclei have suggested that the fusion reaction may be enhanced at and below the Coulomb barrier for neutron-rich projectiles [1–4]. This work was often based on more schematic approaches and was influenced by the numerous studies on enhanced sub-barrier fusion reactions [5,6]. In these studies it was repeatedly suggested that transfer reactions should influence the fusion cross sections in a similar way as inelastic scattering channels. Using more elaborate coupled reaction channel methods (e.g., Refs. [7,8]) it was easy to show that inelastic and transfer coupling can give rise to an enhanced fusion cross section below the Coulomb barrier [5–7,9–11]. The effect of the transfer process is in principle not very different from that of inelastic coupling, even though its form factor is nonlocal as opposed to inelastic excitation. The main and, as we will see, crucial difference is the fact that inelastic excitations have only negative Q values and are generally more strongly coupled than transfer transitions; transfer reactions can have negative or positive Q values.

For neutron-rich (''exotic,'' radioactive) beams and stable targets the main transfer channels will have positive Q values and will give rise to strong coupling (comparable with the coupling of the inelastic transitions) due to the form factors with long tails. We will show in the following that this will lead to a decrease in the fusion cross section. The result is principally the same as that mentioned in Refs. [7,9], where inelastic excitations with *positive Q* value have been studied.

We will discuss inelastic and transfer reactions in the ^{11}Be+^{12}C system. This system allows strong inelastic transitions in ^{11}Be ($E1$ and $E2$) as well as strong n-transfer transitions—in particular, to the excited states of ^{13}C ($1/2^+$ at 3.09 MeV and $5/2^+$ at 3.59 MeV).

The ^{11}Be+^{12}C system has been studied in detail in a coupled reaction channel (CRC) approach using well known asymptotic eigenstates of ^{11}Be and ^{13}C [12]. These eigenstates and the coupling routes are shown in Fig. 1. The spectroscopic information for the 3 eigenstates in ^{11}Be and ^{13}C (with quantum number $1p_{1/2}$, $2s_{1/2}$, and $1d_{5/2}$) is well established and can be used in a quantitative study of the CRC effects; the system is studied in detail in a forthcoming paper [13]. The inelastic transition in ^{10}Be leading to the 2^+ state and the core excitation route for the $1/2^+$ ground state of ^{11}Be have been included. The 2^+ state of ^{12}C at 4.43 MeV was, however, omitted in view of its small influence for the energies studied here (due to its high excitation energy).

The information relevant for the asymptotic states of ^{11}Be and ^{13}C included in the CRC calculation is given in Table I. The unbound state of ^{11}Be is represented by an extremely weakly bound state; for the $d_{5/2}$ states, this is a good approximation because the tail of the wave functions is

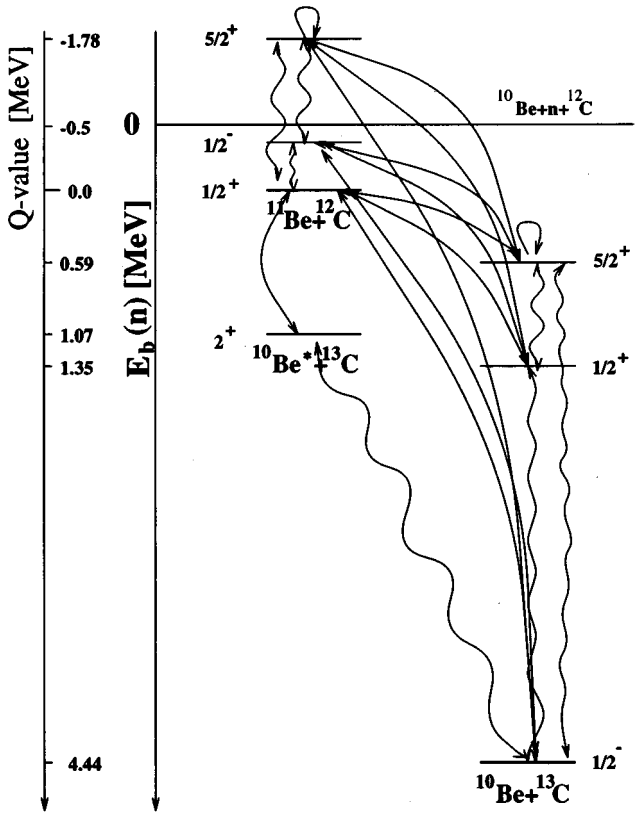

FIG. 1. Coupling scheme for the CRC calculations in the ^{11}Be+^{12}C↔^{10}Be+^{13}C reaction. The energy positions are scaled relative to the binding energy of the incident channel.

*Permanent address: Department of Nuclear Physics, University of St. Petersburg, St. Petersburg, Russia.

TABLE I. Properties of single particles states in ^{11}Be and ^{13}C.

Channel core+n	E_x (MeV)	nlj	CFP[a]	E_B (MeV)	Q value (MeV)
$^{11}\mathrm{Be}_{\frac{1}{2}^+}$	0.000	2 0 $\frac{1}{2}$	0.80	0.503	0.000
$^{11}\mathrm{Be}_{\frac{1}{2}^-}$	0.320	1 1 $\frac{1}{2}$	0.90	0.183	−0.320
$^{11}\mathrm{Be}_{\frac{5}{2}^+}$	1.778	1 2 $\frac{5}{2}$	0.70	0.03 (−1.275)[b]	−1.778
$^{13}\mathrm{C}_{\frac{1}{2}^-}$	0.000	1 1 $\frac{1}{2}$	0.77	4.946	4.443
$^{13}\mathrm{C}_{\frac{1}{2}^+}$	3.089	2 0 $\frac{1}{2}$	0.77	1.857	1.354
$^{13}\mathrm{C}_{\frac{5}{2}^+}$	3.854	1 2 $\frac{5}{2}$	0.77	1.092	0.589
			$\langle ^{10}\mathrm{Be}^*\otimes n \vert ^{11}\mathrm{Be}_{\frac{1}{2}^+}\rangle$		
$^{10}\mathrm{Be}_{2^+}$	3.368	1 1 $\frac{1}{2}$	0.6	1.578	1.075

[a]Coefficient of fractional parentage (from Ref. [12]).
[b]True value; see text.

dominated by the centrifugal barriers of the $l=2$ configurations. The binding energies used are also given in Table I, the excitation energies (Q values) are kept at their correct values. We have used the CRC code FRESCO by Thompson [8] for the calculations. As will be discussed in an independent paper [13] the finite range from factor has a very large width and has to be integrated up to distances of $R=45$ fm or more in order to obtain a correct result (i.e., differences between post and prior representations smaller than 10%). All single-particle routes for inelastic excitations (including reorientation) and transfer have been included. The nonorthogonality term and the full effective interaction (including remnant terms) were taken fully into account (see Ref. [8] for a discussion of these). The excitation of the $^{10}\mathrm{Be}_{2^+}$ state has been calculated in the collective model and the parameter for the deformation was $\beta_2=0.6$ (deformation length $\beta R=0.85$) (from Ref. [12]).

The complete calculations require more than 15 iterations and a sufficient computer size for finite range form factors with a width of 6 fm. We note that the ground-state transition to the channel $^{10}\mathrm{Be}_{0^+}+^{13}\mathrm{C}_{1/2^-}$ is strongly mismatched due to its *positive* Q value (see Ref. [14] for a discussion of this point) and therefore has a small cross section. The transitions to the states $^{13}\mathrm{C}^*_{1/2^+}$ state and $^{13}\mathrm{C}^*_{5/2^+}$ are strong and still have positive Q values (see Table I). The inelastic transition to the first excited $1/2^-$ state of ^{11}Be is very strong due to strong $E1$ coupling, but the CRC effects are not strong, especially at lower energies (it has a rather small negative Q value). The $5/2^+$ state in ^{11}Be is at much higher energy, it is coupled much more weakly; for this state one has problematic convergence behavior [for some smaller I^π values the iterative solution of the CRC equation shows very slow convergence because of the strong mismatch, as in the case of the $^{13}\mathrm{C}_{1/2^-}$ (ground state); the result oscillates around a few percent as function of iteration number, with small influence on the final cross section].

The calculations were made at energies in the vicinity of the Coulomb barrier, $E_L(^{11}\mathrm{Be})=5$ to 15 MeV. Parameters for the optical model (OM) were adopted from other light systems, however, the imaginary part was chosen to be rather strong but with a small radius in order to remove couplings from smaller distances (see Table II); absorption at the surface comes mainly from explicit couplings. This large imaginary part in the OM can be justified in view of the large number of open channels for a system with large neutron excess in the incident channel. It provides for absorption behind the barrier, which will be identified with the fusion cross section. For an illustration of the magnitudes of the cross sections Fig. 2 gives an example of calculated angular distributions of the elastic, inelastic, and transfer transitions.

The inelastic and transfer transitions, which are taken into account explicitly in the CRC calculation, contribute to the total reaction cross section σ_t. The latter is determined by the S matrix elements for elastic scattering obtained in the final calculations. The cross section defined by the difference

$$\Delta\sigma=\left(\sigma_t-\sum_i \sigma_i(\text{reaction})\right)=\sigma_{\text{fus}}$$

of the total cross section σ_t and the sum of all explicitly calculated transitions σ_i can thus be identified with the fusion cross section (see Refs. [2,6]), provided that the imaginary potential causes absorption only behind the barrier. The

TABLE II. Parameters for bound state calculations and for the optical model.

	V (MeV)	r_0 (fm)	a_0 (fm)	W (MeV)	r_i (fm)	a_i (fm)
$n+^{12}$C (g.s.)	47.39	1.20	0.72	–	–	–
$n+^{10}$Be (g.s.)	57.79	1.20	0.72	–	–	–
^{11}Be+^{12}C (^{10}Be+^{13}C)	17.0	1.43	0.50	20.0	1.11	0.350

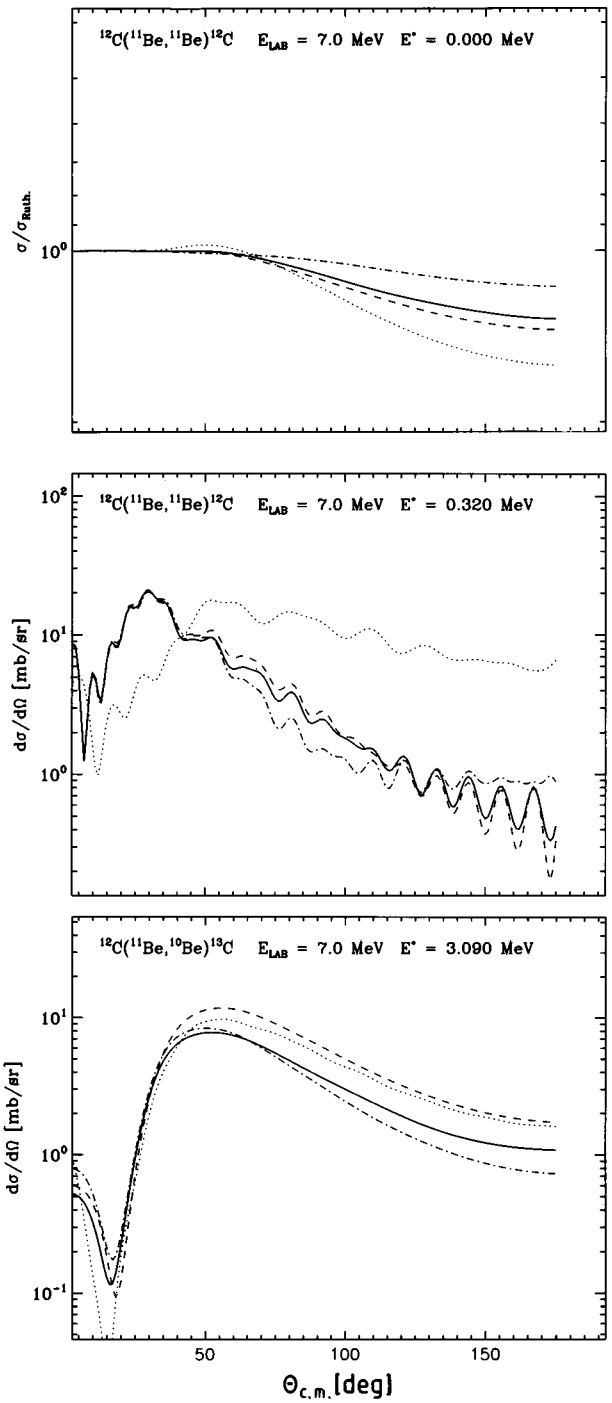

FIG. 2. Angular distributions of the dominant reaction channels for the ^{11}Be+^{12}C system. The full curve is the complete CRC result (see Fig. 1 and text). The dotted curve is the result of a first-order calculation. The second- (dashed) and third- (dot-dashed) order iterations are shown as well.

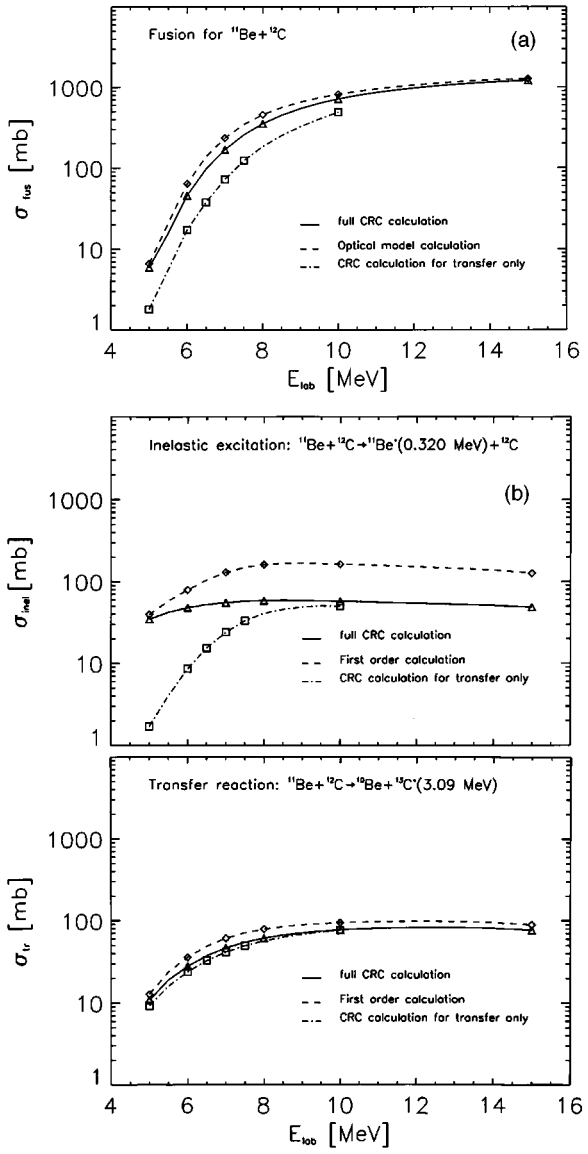

FIG. 3. (a) Absorption cross sections (due to imaginary potential) as function of energy for the system ^{11}Be+^{12}C. The full CRC result (full curve) is compared with the optical model result and the result for transfer coupling alone. (b) The cross sections for the dominant reaction channels for the ^{11}Be+^{12}C system as function of incident energy. The full CRC result (full curve) is compared to the first order result and to the result of CRC with transfer interactions only.

present calculations were performed for energies from below the barrier up to energies of 50% above. The results are shown in Fig. 3.

Figure 3 shows the result of the OM calculation (identical to the result with one iteration) and the result of the full CRC calculation. The most conspicuous result is the decrease of the cross sections, in particular, a decrease of the absorption cross section once the full coupling is included. The cross sections of the reaction channels, of course, strongly violate unitary for many spins and parity values in the first-order calculation at the lowest energies. Introducing the couplings in higher order reduces all cross sections. The coupling of the transfer alone shows a strong effect, i.e., a decrease of the absorption cross section. This is partially compensated by the inelastic couplings (negative Q value); couplings to the inelastic excitations have the tendency to increase the absorption cross section, as discussed previously [5].

We note that the effect of coupling is strongly reduced at the highest energies, where the asymptotic (geometric) cross section is reached. This is understood since couplings become weaker at higher energy and the overall effect is averaged out. The observation that the coupling effects disappear

at the smallest energies may be explained by the decrease of the couplings with larger distances; at lower energies the turning points of the scattering waves move to larger and larger distances. The maximum effect is observed just below the barrier. The same result is observed for more asymmetric systems like ^{11}Be+^{16}O and ^{11}Be+^{88}Sr [13].

Calculations for the system ^{11}Be+^{12}C using the approach of orthogonalized channels (OCRC) [15] essentially gave the same result as the CRC calculations (a complete account will be given later); the absorption cross section is decreased for the case of the full calculation. Here the ^{10}Be$_{2^+}$ core excitation routes were omitted. This difference is not essential for the present discussion.

The framework of the OCRC approach is discussed in Refs. [15] and [16]. There it is possible (due to approximations leading to local form factors) to calculate the adiabatic energy for each channel which is connected to one of the asymptotic channels defined in the conventional CRC approach (also called correlation diagram). The energies of these states obtained by diagonalization of all interactions (transfer, inelastic, rotational coupling) except for the radial coupling represent a ''correlation diagram'' for adiabatic energies. The interactions among the different levels act coherently so as to push down the lowest state giving rise to a lowered total potential energy curve for this state. This is usually the case when the incident channel is the lowest state in energy and also happens in the system ^{16}O+^{13}C$\rightarrow$^{17}O+^{12}C (with negative Q values studied previously [11]) and for the ^{11}Be+^{10}Be system [17], where also only negative Q values occur.

In the correlation diagram we can choose as incident channel any asymptotic channel. *The lowest channel* (which usually is pushed downwards) thus becomes a reaction channel with positive Q value. If *the incident channel is positioned between many other states* to whom it is coupled, *it often will show an adiabatic potential energy curve which is pushed up* at smaller distance (it is repelled by the states with more positive Q values). Thus absorption behind the barrier from this channel will be decreased in these cases (this may not be the case as a general rule and a more explicit discussion of the adiabatic energy curves and the transition mechanisms is needed and will be given in future work).

It is very tempting to discuss this effect also in terms of density distributions of valence particles in the neck region as done in Ref. [2], where an antinecking is suggested. We also find that the *strongest effect in enhanced fusion* is made by configuration mixing (hybridization)—all with negative Q values, which in fact increases the neutron density between the two centers (see Refs. [15–17]).

In conclusion the present study shows that fusion with neutron-rich (weakly bound) nuclei may be strongly reduced due to the dominance of strongly coupled transfer channels with positive Q values. This is a purely quantal effect, which is, however, related to the general picture of ''chemical binding.'' The positive Q values virtually represent the case of *ionic binding*, but with neutral valence particles (the neutrons), where the valence particles are *not shared* by the two centers, as in the covalent case with $Q\approx 0$. The positive Q value of the reaction channel implies that the energetically lowest state is formed by transfer of one or more neutrons. Via its interaction with the incident channel this channel may repel the incident channel and may hinder the absorption from the incident channel (the ingoing flux is primarily there). This is opposed to the case of the ''covalent binding'' with hybridization [15–17], where the valence particle is shared by the two nuclei, with Q values $Q\leqslant 0$ leading always to a lowering of the effective fusion barrier. Such cases are typically ^{13}C+^{12}C, ^{16}O+^{13}C, and ^{11}Be+^{10}Be [11,15–17]. However, as shown in Ref. [15] the latter effect depends strongly on the possibility of hybridization.

The present discussion of a few cases is based on a purely microscopic picture of the coupling of transfer and fusion at low energies. The transition mechanism in the two-center correlation diagram has to be studied in order to fully understand the observed effect. Other features connected with macroscopic deformations related to the extra push in fusion have to be considered with heavier systems. It can be expected that the fusion cross section at energies below and at the Coulomb barrier will be a very interesting subject in nuclear reaction studies with exotic beams.

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