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Continuum-continuum coupling and polarization potentials for weakly bound systems

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We investigate the influence of couplings among continuum states in collisions of weakly bound nuclei. For this purpose, we compare cross sections for complete fusion, breakup, and elastic scattering evaluated by continuum discretized coupled channel (CDCC) calculations, including and not including these couplings. In our study, we discuss this influence in terms of the polarization potentials that reproduces the elastic wave function of the coupled channel method in single channel calculations. We find that the inclusion of couplings among continuum states renders the real part of the polarization potential more repulsive, whereas it leads to weaker absorption to the breakup channel. We show that the noninclusion of continuum-continuum couplings in CDCC calculations may lead to qualitative and quantitative wrong conclusions.

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After the elapse of almost two decades of extensive experimental and theoretical efforts, a full understanding of the way the coupling to the continuum influences the near-barrier fusion and other channels in collisions of weakly bound nuclei is still lacking [1–3]. Collisions of weakly bound projectiles can lead to different kinds of fusion. The first is the usual complete fusion (CF), when the whole projectile is absorbed by the target. The second type is incomplete fusion (ICF). This process corresponds to the situation where the projectile breaks up into fragments along the collision and some fragments are absorbed while at least one is not. In addition, the breakup process may end up as noncapture breakup (NCBU). In this case, none of the fragments is absorbed. An ideal theoretical description of the collision should take into account all these processes. In a rather detailed calculation within the continuum discretized coupled channel (CDCC) model [4–6], Diaz-Torres and Thompson [7] have managed to supply some very useful information about the aforementioned question. They found that the continuum coupling hinders the complete fusion cross section above and below the Coulomb barrier, with enhancement setting in only at deep sub-barrier energies. They further found that the inclusion of the continuum-continuum couplings (CCC) was of paramount importance in reaching the above conclusions about fusion. Their findings seem to concur with experimental data [8,9]. Increased fusion can arise from a lowering of the Coulomb barrier which results in a greater tunneling. On the other hand, decreased fusion can arise from an increase in the height of the barrier which results in a smaller tunneling. This latter effect would, in principle, be accompanied by an increase in the quasielastic scattering at backward angles.

This "common sense" argument about the effects on the noncapture, quasielastic, processes seems not be borne out by the explicit calculation which takes into account the CCC effects [10,11]. It is difficult to discern the physics behind all of the above. Clearly the inclusion or exclusion of the CCC dictates whether one is dealing with genuine breakup or merely a collection of inelastic channels. Further, there seems to be a need to invoke concepts such as irreversibility, and a doorway that funnels the flux to the continuum channel and hinders its return to the entrance channel. An attempt to develop a quantum transport theory for these reactions, that incorporates these concepts at the outset, has recently been made [12]. It becomes abundantly clear that more insight into the working of the CCC and the resulting irreversibility and doorway constriction is called for. This is an important issue which goes beyond the realm of nuclear physics. In fact, as far back as 1961, Fano [13] elaborated an elastic+breakup theory for the auto-ionization lines in atoms.

Our aim in this Brief Report is to further elucidate the physics of the CCC in the context of reactions involving weakly bound nuclei at near-barrier energies. For this purpose, we investigate the effects of the CCC on the cross sections for CF, NCBU, and elastic scattering. We find that the CCC lowers the CF and the NCBU cross sections, but enhances the elastic cross section at large angles. The calculated polarization potential clearly indicates a repulsive real part and a reduced imaginary part.

In the CDCC method [4–6], the continuum states of the dissociated projectile are approximated by a discrete set of wave packets. In this way, the coupled-channel problem in the continuum can be handled analogously to the ones containing only bound channels. The scattering wave function is expanded in components with well defined values of total angular momentum and its z-projection. The full Schrödinger equation is then projected on each intrinsic state and one gets a set of differential equations. The difference between the CDCC and a coupled-channel problem restricted to bound channels is that the configuration space of the former is much larger. The computational problem is then considerably more complex. The calculation is greatly simplified if it takes into account only the couplings among the bound channels and the couplings between one bound channel and one channel in the continuum. In this way, continuum-continuum couplings are left out. This procedure was adopted in the first CDCC

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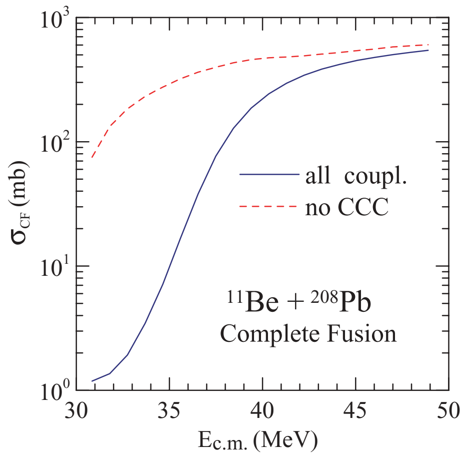

FIG. 1. (Color online) CF cross sections in the ^{11}Be + ^{208}Pb collision. The solid and the dashed lines correspond, respectively, to CDCC calculations with and without CCC [7].

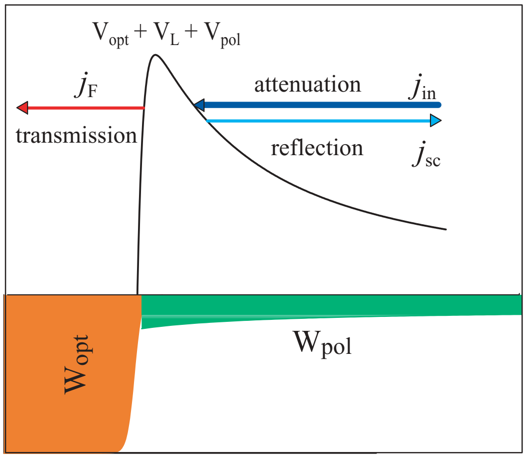

FIG. 2. (Color online) Effects of the real and imaginary parts of the optical and the polarization potential on the incident current.

calculation of the CF cross section for the ^{11}Be + ^{208}Pb system, performed by Hagino *et al.* [14]. The importance of CCC was investigated in a subsequent CDCC calculation for the same system, performed by Diaz-Torres and Thompson [7]. In this work, the CF cross sections evaluated with and without CCC were compared.

The results are shown in Fig. 1. The comparison indicates that CCC leads to a drastic reduction of the CF cross section at near- and sub-barrier energies. The reduction is of about two orders of magnitude.

Is there a simple and intuitive explanation for this result? To answer this question we use the language of polarization potentials. The elastic wave functions obtained from a set of coupled channel equations can always be obtained from a single-channel equation with an effective potential. This potential is the sum of the optical potential and polarization potentials. The former represents the diagonal part of the interaction in channel space and an average influence of channel coupling. The latter contains the detailed influence of the strongly coupled excited channels. In this way, the coupled channel problem can be handled as a problem of potential scattering. Following the approach of Ref. [15], we use this picture and resort to the schematic representation of Fig. 2. It shows the currents and the potentials (real and imaginary parts) involved in the collision, for some particular partial wave. The fusion barrier is the sum of the real parts of the optical and polarization potentials plus the centrifugal term. As the incident current, j_{in}, approaches the external turning point, it is attenuated by the long-range absorptive potential W_{pol}. The lost flux populates the channels that are responsible for this imaginary potential, that is, inelastic channels, transfer, and breakup. At large distances, W_{pol} is dominated by Coulomb breakup. The final destination of the fragments produced by the breakup process, namely NCBU, ICF is not relevant for our discussion. The situation would be different if all the fragments were absorbed sequentially, leading to CF. Since the contribution of this process to the CF cross section is not supposed to be large, it is neglected here. When the attenuated incident current reaches the barrier, it splits into two parts. The reflected component, j_{sc}, and the transmitted current, j_{CF}. The reflected current is attenuated as it moves away from the barrier, until it is out of the reach of W_{pol}. It is then responsible for the elastic scattering cross section. The transmitted current is fully absorbed by the short-range imaginary part of the optical potential inside the barrier giving rise to CF. The probabilities of elastic scattering, P_{sc}, and fusion P_{CF}, at that partial wave then given by are

$$P_{sc} = \frac{j_{sc}}{j_{in}} \quad \text{and} \quad P_{CF} = \frac{j_{CF}}{j_{in}}. \tag{1}$$

The direct reaction probability, representing inelastic scattering + transfer + ICF + NCBU, is given by the current absorbed by W_{pol},

$$P_{DR} = 1 - \frac{j_{sc} + j_{CF}}{j_{in}}. \tag{2}$$

We can now speculate on the modifications of the polarization potential arising from the inclusion of CCC in the CDCC calculations. The strong suppression observed in Fig. 1 implies that the transmitted current is drastically reduced. In principle, it could be caused by three factors:

(i) The inclusion of CCC strengthens the absorptive imaginary potential W_{pol}. In this case the quasielastic cross section becomes larger, due to the increase of breakup.

(ii) The inclusion of CCC makes the real part of the polarization potential more repulsive, so that the incident current has to cross a higher barrier to produce fusion. If this case, j_{CF} is reduced and j_{sc} increases. Therefore, the suppression CF should be followed by an enhancement of the elastic scattering cross section.

(iii) A combination of possibilities (i) and (ii). In this case, both the breakup and the elastic cross sections could be enhanced.

To find out which of these possibilities is actually happening, one should check the cross section for other channels. We first consider possibility (i). In this case, the reduction of σ_{CF} would arise from some kind of *irreversibility* of the transition to

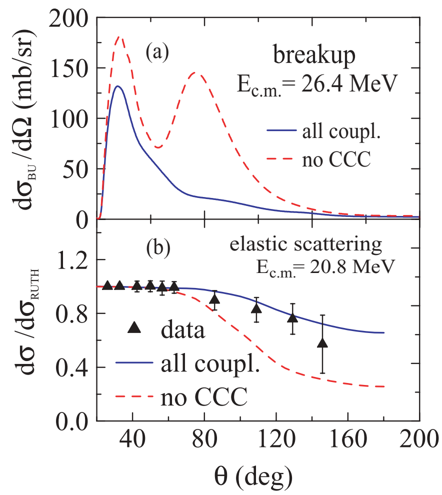

FIG. 3. (Color online) Angular distributions for different processes in the ^{8}B + ^{58}Ni collision calculated with (solid lines) and without CCC (dashed lines). In (a) and (b) we show, respectively, results for breakup [16] and elastic scattering [11]. For details, see the text.

the continuum. Of course, there is no irreversibility in quantum mechanics, as any transition can take place in two directions. However the elastic transition matrix is a superposition of a direct process with multistep processes of higher orders. To evaluate it, one should then perform sums over intermediate states. When CCC is taken into account, some of these sums become integrals. If these contributions have random phase, one could have destructive interference. Although this is a plausible hypothesis, there is no convincing arguments supporting it.

To settle the matter, we first look at results of CDCC calculations for the NCBU cross section, performed by Lubian and Nunes [16]. In (a) of Fig. 3, we show angular distributions of the center of mass of the ^{8}B projectile in its breakup in the ^{8}B + ^{58}Ni collision. The solid and the dashed lines correspond, respectively, to results of calculations with and without CCC. These curves are similar to the ones obtained in Ref. [10] for a different collision energy. The difference is that we only show the curves involved in our discussion, leaving out other details of their calculations. Comparing calculations with and without CCC, we conclude that CCC leads to a substantial suppression of the breakup cross section. Therefore, possibilities (i) and (iii) can be ruled out.

We are then inclined to believe that the reduction of the CF cross section arises from an increase of the height of the potential barrier, when CCC is taken into account. This can be checked in an investigation of the elastic cross section. Such CDCC investigation of the elastic angular distributions, which also included the elastic breakup cross sections, was in fact performed in the past. In particular Sakuragi *et al.* [4] worked at length in calculating these observables for the systems ^{6}Li + ^{28}Si and ^{6}Li + ^{40}Ca at two laboratory energies of ^{6}Li: 99 MeV and 155 MeV. In the following we present our results for the elastic angular distribution of the proton halo nucleus ^{8}B on ^{56}Ni target at a much lower laboratory energy of 23.77 MeV, corresponding to $E_{c.m.}$ = 20.8 MeV.

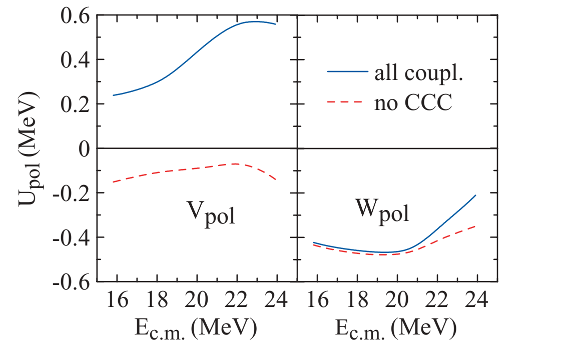

FIG. 4. (Color online) Real (left panels) and imaginary (right panels) parts of the polarization potential for the ^{8}B + ^{58}Ni system. Potentials based on CDCC calculations including and not including CCC are represented, respectively, by solid and dashed lines.

The results are shown in (b) of Fig. 3. The calculations are the same as in Ref. [11]. In this case the excitations of the target were not included explicitly. We do not show results for other collision energies because they are qualitatively similar. The figure shows clearly that the inclusion of CCC leads to a very strong enhancement of the cross section, as compared to the results without CCC. This confirms that possibility (ii) is the mechanism responsible for the suppression of complete fusion. That is, the main effect of CCC is making the polarization potential repulsive.

We now confront the conclusions of the previous section with the results of a direct analysis of the polarization potential. The calculation of an exact polarization potential presents some serious difficulties. This potential depends strongly on the angular momentum and has poles. However, there are approximate angular momentum independent polarization potentials which are free of poles and lead to reasonable predictions for cross sections. We derive here the approximate polarization potential following the prescription of Thompson *et al.* [17]. According to this prescription, the polarization potential is written as an average over angular momentum, involving radial wave functions and the S-matrix obtained from a coupled channel (in our case CDCC) calculation. We obtained polarization potentials based on CDCC calculations with and without CCC. The strengths of the real and imaginary parts of the polarization potential evaluated at the barrier radius are shown in Fig. 4 for the ^{8}B + ^{58}Ni system. First, we note that the imaginary part of the polarization potential is always negative, both in the calculations with and without CCC. This is not surprising since it represents the flux lost to the inelastic and breakup channels. The second relevant point is that the inclusion of CCC leads to a weaker imaginary potential, reducing the absorption associated with direct reactions. This is consistent with the reduction of the NCBU cross section found directly in our CDCC calculation with CCC. We now turn to the real part of the polarization potential. Again the effect of CCC on the polarization potential confirms our previous findings. In the absence of CCC, V_{pol} is attractive, reducing the barrier of the optical potential. The inclusion of CCC modifies V_{pol} qualitatively. It becomes repulsive. In this way, the fusion barrier becomes higher and the CF cross section lower. The higher barrier increases reflection and enhances the elastic elastic scattering cross section, as discussed in a previous paragraph.

Our conclusions above are in complete qualitative agreement with those of Ref. [4], where the dynamic polarization potential was also fully investigated within CDCC taken into account the reorientation part of the the continuum-continuum coupling effects. These authors calculated the DPP for each orbital angular momentum and summed all the contribution (Eqs. (7.4) and (7.5) of Ref. [4]). They obtained for the total, l-summed DPP for ^{6}Li + ^{28}Si at $E_{\rm lab} = 99$ MeV a rather strong repulsive real part and a small imaginary part in the surface region. This is in agreement with our results described above.

Concluding, in this Brief Report we investigated the role of the continuum-continuum coupling in CDCC calculation of low-energy observables in heavy-ion reactions involving weakly bound nuclei. We have found that this coupling reduces the value of the nonelastic cross sections, which includes fusion, noncapture breakup, etc., in full agreement with previous works [7,10], while it increases the purely elastic scattering cross section ratio to Rutherford at back angles. We have traced this effect to the rather peculiar behavior of the breakup dynamic polarization potential which we found to have a repulsive real part and a weaker absorptive part when the CCC is included. Without the CCC, the real part was found to be attractive with a stronger absorption. The latter case is a common feature of coupling to inelastic channels, which leads us to conclude that a discretized continuum can only be a loyal representative of a breakup channel if the continuum-continuum coupling is fully accounted for in a CDCC calculation.

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[1] L. F. Canto, P. R. S. Gomes, R. Donangelo, and M. S. Hussein, Phys. Rep. **424**, 1 (2006).
[2] J. F. Liang and C. Signorini, Int. J. Mod. Phys. E **14**, 1121 (2005).
[3] N. Keeley, R. Raabe, N. Alamanos, and J. L. Sida, Prog. Part. Nucl. Phys. **59**, 579 (2007).
[4] Y. Sakuragi, M. Yahiro, and M. Kamimura, Prog. Theor. Phys. **70**, 1047 (1983).
[5] Y. Sakuragi, M. Yahiro, and M. Kamimura, Prog. Theor. Phys. Suppl. **89**, 136 (1986).
[6] N. Austern, Y. Iseri, M. Kamimura, M. Kawai, G. Rawitscher, and M. Yashiro, Phys. Rep. **154**, 125 (1987).
[7] A. Diaz-Torres and I. J. Thompson, Phys. Rev. C **65**, 024606 (2002).
[8] M. Dasgupta, D. J. Hinde, R. D. Butt, R. M. Anjos, A. C. Berriman, N. Carlin, P. R. S. Gomes, C. R. Morton, J. O. Newton, A. Szanto de Toledo *et al.*, Phys. Rev. Lett. **82**, 1395 (1999).
[9] M. Dasgupta, P. R. S. Gomes, D. J. Hinde, S. B. Moraes, R. M. Anjos, A. C. Berriman, R. D. Butt, N. Carlin, J. Lubian, C. R. Morton *et al.*, Phys. Rev. C **70**, 024606 (2004).
[10] F. M. Nunes and I. J. Thompson, Phys. Rev. C **59**, 2652 (1999).
[11] J. Lubian, T. Correa, E. F. Aguilera, L. F. Canto, A. Gomez-Camacho, E. M. Quiroz, and P. R. S. Gomes, Phys. Rev. C **79**, 064605 (2009).
[12] A. Diaz-Torres, D. J. Hinde, M. Dasgupta, G. J. Milburn, and J. A. Tostevin, Phys. Rev. C **78**, 064604 (2008).
[13] U. Fano, Phys. Rev. **124**, 1866 (1961).
[14] K. Hagino, A. Vitturi, C. H. Dasso, and S. M. Lenzi, Phys. Rev. C **61**, 037602 (2000).
[15] W. H. Z. Cardenas, L. F. Canto, R. Donangelo, M. S. Hussein, J. Lubian, and A. Romanelli, Nucl. Phys. **A703**, 633 (2002).
[16] J. Lubian and F. M. Nunes, J. Phys. G: Nucl. Part. Phys. **34**, 513 (2007).
[17] I. J. Thompson, M. A. Nagarajan, J. S. Lilley, and M. J. Smithson, Nucl. Phys. **A505**, 84 (1989).