Understanding low energy reaction with exotic nuclei

F.M. Nunes, N.C. Summers*, A.M. Moro† and A.M. Mukhamedzhanov**

*NSCL and Department of Physics and Astronomy, MSU, East Lansing MI 48824, USA
†Departamento de FAMN, Universidad de Sevilla, Aptdo. 1065, 41080 Sevilla, Spain
**Cyclotron Institute, Texas A& M University, College Station TX 77843 USA

Abstract. Recent developments on the understanding of low energy reactions are highlighted. Emphasis is given to the CDCC framework where the breakup channels of the projectile are included explicitly. Properties of the breakup couplings are presented. Comments are given with regard to the separation between the nuclear and the Coulomb contributions to breakup cross sections as well as the dependence on the optical potentials. A discussion on the sensitivity of the CDCC basis is discussed, by comparing pure breakup results with transfer to the continuum calculations. Finally, some remaining controversies show the need to go beyond the single particle picture for the projectile.

INTRODUCTION

Light nuclei on the driplines can be studied through a variety of reactions. Models for nuclear reactions have been developed in recent years to incorporate the exotic features of these dripline nuclei [1]. They include the effects of the long tails of the wavefunctions, the correct asymptotics, and the proximity of the ground state to threshold. Whereas in the high energy regime many approximations are appropriate, the real challenge for reaction theory lies in the low energy regime where most approximations are not valid.

It is in the low energy region (5-50 MeV/A) that observables become much more sensitive to the detailed structure of the projectile and where more can be learnt. It is also at low energy where there is a larger sensitivity to the details of the interaction with the target and where more care needs to be taken in modelling the reaction.

We consider dripline nuclei of two body nature, meaning that the projectile can be decomposed into a core and a valence nucleon. Then, the study of the reaction consists of a three body scattering problem. Due to the loosely bound nature of the projectile, three body effects need to be carefully considered in the lower energy regime. The exact way to formulate this problem would be to use Integral Faddeev Equations. However, due to technical problems the Continuum Discretized Coupled Channel Method (CDCC) [2] is the best working alternative. In CDCC, the continuum couplings are included to all orders and nuclear and Coulomb are treated consistently.

The work here presented is based on the CDCC framework. We first present the properties of the couplings in breakup reactions, in particular continuum-continuum couplings. Second we emphasize the difficulty in separating nuclear from Coulomb contributions and finally we discuss the choice of the Jacobi coordinates to represent the CDCC basis. Finally we make some comments on lingering controversies calling for better description of the projectile.

COUPLINGS IN THE CONTINUUM

The proximity to the breakup threshold has been shown to have important effects in the reaction mechanism [3]. Continuum couplings are a way of looking into the effect of the final state interactions, an integral part of CDCC. They consist of the sum of the core-target interaction with the fragment-target interaction (both Coulomb and nuclear), averaged over an initial and a final bin wavefunction. A bin wavefunction is essentially a scattering wavefunction describing the two body continuum of the projectile, but averaged over a finite energy segment [3].

The properties of these continuum couplings and the influence they can have on breakup observables were addressed in detail [4]. The couplings considered are those involved in the breakup of ^{8}B into ^{7}Be+p when impinging on a ^{58}Ni target at 25.8 MeV [3]. Continuum couplings are most important when the initial and final state energies (E_i and

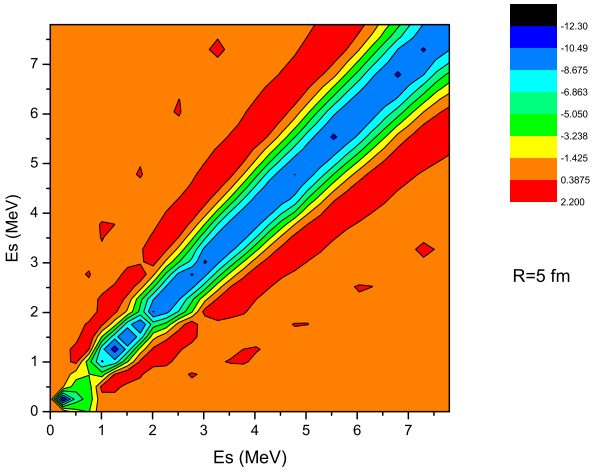

FIGURE 1. Contour plot of the continuum continuum potential couplings of an l=0 transition between two s-waves as a function of the initial and final energies.(color)

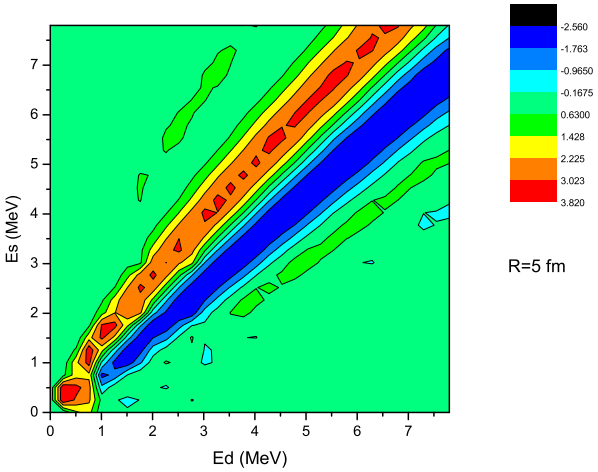

FIGURE 2. Contour plot of the continuum continuum potential couplings of an l=2 transition between an initial s-waves with energy E_i and a final d-wave with energy E_f.(color)

E_f) are close to each other. The energy here referred to are the relative energy of the projectile in the breakup state ^{7}Be+p. If the initial and final states have the same centrifugal barrier and the transition is a monopole transition, then the couplings are only non-zero when the initial and final energies match. This corresponds to the condition of orthonormality between bin states. The orthogonality condition is illustrated very clearly in Fig. 1 where a contour plot of the coupling potentials is shown for initial and final s-wave bins. As the difference in the centrifugal barrier and the order of the transition increases, one obtains a wider region $E_i - \Delta < E_f < E_i + \Delta$ where contributions are significant. In Fig. 2 we show a contour plot for an initial d-wave with energy E_d to a final s-wave with energy E_s (reverse coupling are equivalent). It is clear the formation of ridges parallel to the $E_i = E_f$ line. These couplings are

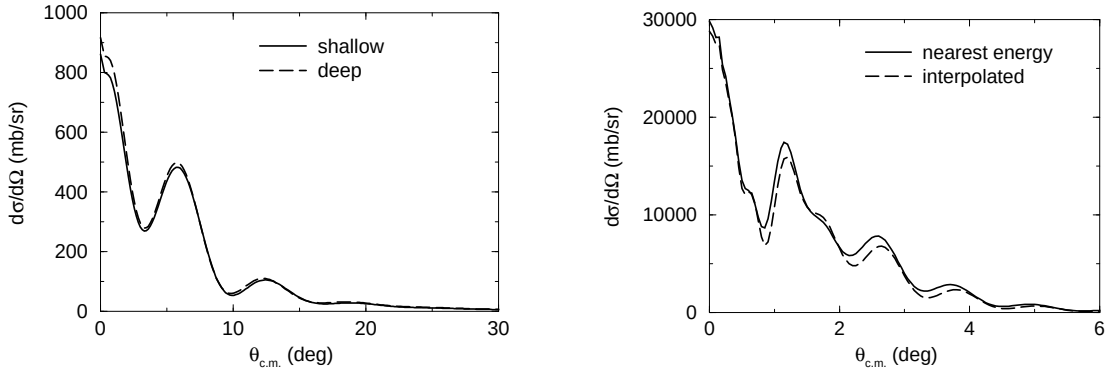

FIGURE 3. Sensitivity to optical potentials for the breakup of ^{7}Be on C (left) and Pb (right).

attractive for $E_d < E_s$ and repulsive for $E_d > E_s$.

The fact that continuum couplings are only relevant around a certain region of the energy space offers a hint to optimize the calculations. We have performed tests for a couple of examples, namely the above mentioned example, the ^{8}B on Ni experiment from Notre Dame [5], and another case to be discussed in the next section, the ^{7}Be breakup on Pb experiment from Michigan State University [6]. In both cases we found up to 30% time gain for the calculations where only the lower l=0,1,2 projectile partial waves were included. For the larger calculations where l=3 is also included (necessary for complete convergence) the order of some transitions become too large to justify a truncation along the $E_i = E_f$ line. Unfortunately, in our typical calculations, it is exactly the larger partial waves (l>2) that make the calculations very large and increase running time dramatically. It is expected that this optimization will be more helpful when including core degrees of freedom as then even for the lower partial waves due to an order of magnitude increase in the number of channels [7].

SEPARATION BETWEEN NUCLEAR AND COULOMB

Historically, there has always been the underlying assumption that, by appropriately choosing the experimental conditions, Coulomb effects can be isolated from nuclear effects. Especially when breakup reactions are used to extract Astrophysical information, such as radiative capture rates, this separation is crucial [8]. In [6] breakup of ^{7}Be on a heavy and a light target is considered, motivated by recent experimental plans. The breakup reaction on Pb would be Coulomb dominated and would allow to extract information on the astrophysical factor S_{34}, whereas the experiment on the carbon target would be driven by nuclear effects and would provide an asymptotic normalization coefficient for the α+^{3}He system, again linking back to the astrophysical capture reaction at zero energy.

Results of CDCC calculations from [6], include the continuum of ^{7}Be to all orders. The most important conclusion of that work is that a simple angular selection of the so-called Coulomb Dissociation is not sufficient to guarantee that the data is nuclear free. Identically, for the lighter target, the data is always contaminated by a Coulomb contribution. Also, for the carbon case, coupling effects were in general non negligible for the center of mass forward angular region. The work in [6] shows that only careful massaging of the data, i.e. specific three-body kinematic selections, may recover the purity that is desired for Astrophysical problems.

It is common understanding that optical potentials can produce large uncertainties and there is a preoccupation in either keeping nuclear contributions small or choosing reaction regimes where there is less sensitivity to the details of the optical potentials. From the two cases studied in [6] one expects that the carbon case will show a larger dependence given that it has a larger nuclear component when compared to it Coulomb component. For illustration purposes we concentrate on the α-target interaction. We have compared the results when using a shallow [9] or a deep potential fit [10] for the $\alpha-^{12}$C and find a minor effect (see Fig.3 left). For the heavier target there is a weak dependence on the optical potential and the only issue arising has to do with the fact that optical potentials are not available at the correct energy. We show the sensitivity to the energy choice in Fig. 3. The differential cross section is plotted for the case where the α-^{208}Pb potential is taken directly from the literature [11] at the nearest available energy and compare to the results when an interpolation of the potentials is made to the correct energy. As can be seen the dependence is very small. These results suggest that, when the scattering of the fragments is well understood, the optical potentials

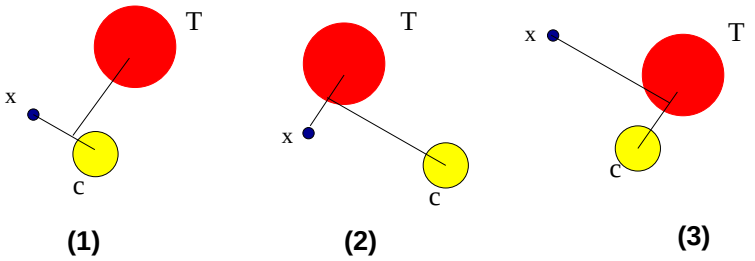

FIGURE 4. Each Faddeev component is written in its corresponding Jacobi coordinate system.

themselves do not introduce significant ambiguities in the analysis.

COMPARING CDCC BASES

A variety of breakup models are presently in use and, when two different models are applied to the same problem, there is often a disparity in the predictions. In this sense, a generalized effort to bridge the various approaches is very much needed. One of the important issues lies in the choice of the coordinate representation of the continuum wavefunctions. As mentioned in the introduction, the problem of a two-body projectile impinging on a target consists of a three-body problem of which an exact solution would be obtained by solving the Integral Faddeev Equations. Then, the wavefunction would contain components in the three Jacobi coordinates represented in Fig. 4. Due to the complexity of this task, the CDCC method was derived [12]. However, the CDCC method already imposes a preferential representation of the continuum, namely that of the projectile (coordinate set (1) in Fig. 4). If there are important resonant states in the target-fragment subsystem, the Jacobi coordinate set (2) in Fig. 4 would become more appropriate and the representation in terms of coordinates (1) would probably be very difficult.

The standard CDCC breakup uses coordinates (1) and the couplings are single particle excitations of the projectile into the continuum (referred to as BU). These are illustrated in Fig. 5 left. where the projectile A is excited into $A^* = c + x$ through the interaction with the target T. Alternatively, one can imagine that the projectile transfers its valence particle x into the continuum of the target (referred to as TR*). CDCC would be then applicable to the continuum of the T+x system and thus be associated with a final state interaction. In that situation the relevant coordinates would be (2) and the couplings would be transfer couplings such as those represented in Fig. 5(right).

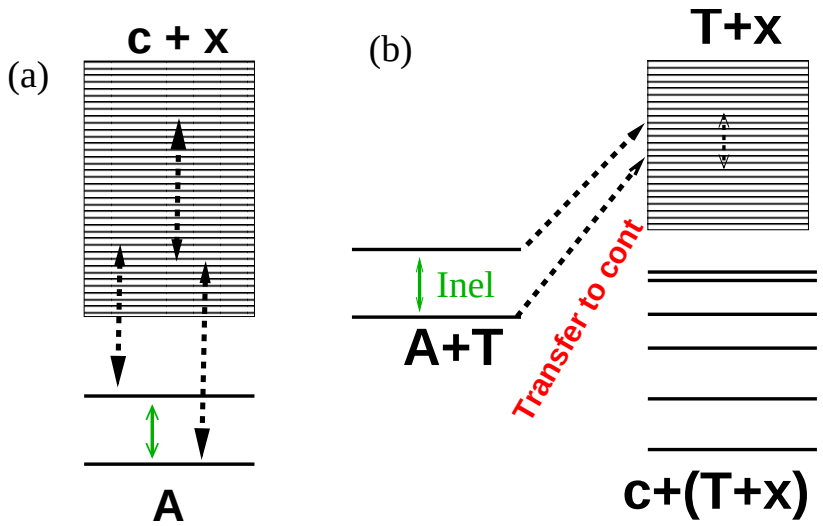

FIGURE 5. Breakup couplings for a two body projectile (c+x) impinging on a target T (on the left) and corresponding transfer to the continuum couplings (on the right).

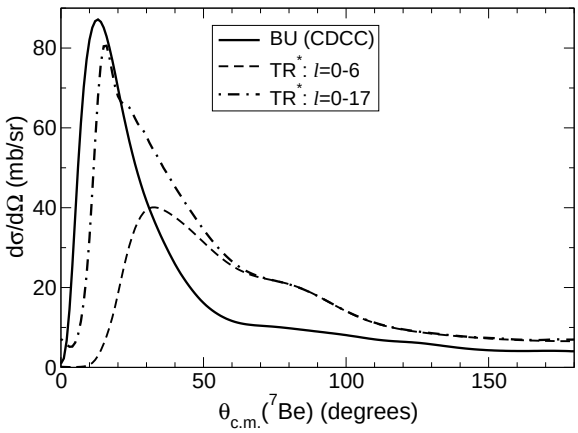

FIGURE 6. Angular distribution for the ^{7}Be after ^{8}B breakup: comparison between the standard breakup calculation and the transfer to the continuum.

Previous work shows that both methods may hold different results. For example, the analysis of the ^{8}B breakup [3] was performed within the standard CDCC approach whereas the ^{8}Li data measured in the same energy regime could only be explained when using transfer to the continuum [13]. We have performed a comparative study between the standard CDCC breakup approach and the so called transfer to the continuum [15]. As a testing case we start with the ^{8}B breakup which is well understood within the standard approach. Detailed data exists for $^{8}\mathrm{B}\rightarrow{}^{7}\mathrm{Be}+p$ on ^{58}Ni at 25.6 MeV [5]. Calculations using the standard CDCC to breakup (BU) $^{8}\mathrm{B}+{}^{58}\mathrm{Ni}\rightarrow({}^{7}\mathrm{Be}+p)+{}^{58}\mathrm{Ni}$ have provided very good agreement with experiment [3, 14]. One can think of the alternative path to breakup, as transfer to the continuum (TR*) of the ^{59}Cu, i.e. $^{8}\mathrm{B}+{}^{58}\mathrm{Ni}\rightarrow{}^{7}\mathrm{Be}+(p+{}^{58}\mathrm{Ni})$. The results for the angular distributions of ^{7}Be are shown in Fig. 6. BU calculations are fully converged and provide a pronounced Coulomb peak around 10-20 degrees. This same peak is not well reproduced with the TR* approach. In fact, the convergence rate of the TR* calculation is very slow and the calculations are much larger than BU, due to the nature of the non-local transfer kernels. The breakup of ^{8}B on ^{58}Ni at 25.8 MeV is a good example where the BU configuration works much better than the TR* configuration.

General guidelines as to the conditions for choosing the standard breakup approach or the transfer to the continuum approach are under study. It seems clear that for the standard breakup approach to be valid, the average relative energy for c+x during the reaction should be small as well as the average relative angular momentum for c+x. Identically if the transfer to the continuum is to be applicable, the average excitation energy for t+x should be small as well as the average relative angular momentum for t+x. However the situation is not always clear. There are also issues on the choice of certain interactions that play a different role in the transfer process from the breakup process. A more detailed discussion on these and other issues will soon become available [15].

REMAINING CONTROVERSIES

As breakup states are an essential path in reactions with loosely bound projectiles, only reaction models that include the continuum have been successful in describing measurements for nuclei on the driplines.

There are some puzzling problems which can well correspond to cases where a single particle description is less appropriate. Note that, in the reaction models we have discussed, the ground state of the projectile is taken to be a single particle state of unit spectroscopic factor produced by a simple Woods-Saxon and spin-orbit interaction with standard geometries with a depth fitted to the correct binding energy of the $c+x$ system. The continuum is produced with that same interaction to ensure orthogonality. Below, we briefly discuss three different puzzles, the first related to breakup experiments of ^{8}B, the second related to inelastic process with ^{11}Be and the last associated with knock-out measurements for ^{16}C. They serve as an illustration of the need to go beyond the models so far developed.

There have been several ^{8}B breakup experiments performed at different facilities to provide the needed information for S_{17}. Using our best understanding of the reaction mechanism, and assuming the projectile can be represented by $^{7}\mathrm{Be(inert)}+p$, the Notre Dame data and the NSCL/MSU data show a 60% inconsistency in the quadrupole excitation

strength. This is an extremely severe problem from the point of few of the direct capture cross section [16]. In juxtaposition, accurate measurements have shown that ^{7}Be first excited state contributes to the ground state of ^{8}B [17].

GANIL data of ^{10,11}Be(p,p') inelastic scattering have remained unpublished for the last five years as we have been unable to understand the process [18]. Due to the proximity to the continuum, there is a large contribution of breakup ^{10}Be+n states to the inelastic cross section. Presently, this can only be modelled within an inert few-body model. It was not possible within this model to understand ^{10}Be data and the ^{11}Be simultaneously. Identical conclusions were found in MSU data [19]. It is well known that ^{10}Be first excited state contributes to the ^{11}Be ground state [20, 21]. A number of preliminary tests have been performed [22] and suggest that excitation of ^{10}Be is very important for ^{11}Be(p,p') in particular in the breakup channels. However, within the current model, a definite conclusion is yet to be drawn [22].

The analysis [23] of knockout data to extract spectroscopic factors for ^{16}C proved to be extremely difficult. The same reaction model that had been so successful in a number of cases did not provide very good agreement with the data. Efforts to check the relevance of core excitation in reaction models [24, 25], by treating it statically were also unfruitful. In those models the core excited component is kept constant throughout the reaction process. This approximation does not seem adequate, especially in cases where the couplings to core excited states are strong.

Although much progress has been made in the last decade concerning scattering and breakup reaction theory, core degrees of freedom in the continuum has not been studied. The significance of the structure dynamics on reaction observables can be very large (see for instance [26]) and it is fundamental to address this problem as soon as possible. Given that there are large core excited configurations in many dripline nuclei, one can expect an impact on many of the reaction observables. Work on the dynamic treatment of core excitation in the continuum is underway [7].

ACKNOWLEDGMENTS

This work was supported by the National Superconducting Cyclotron Laboratory, Fundação para a Ciência e a Tecnologia (F.C.T.) of Portugal, under the grant POCTIC/36282/99, by the Department of Energy under Grant No. DE-FG03-93ER40773 and the U. S. National Science Foundation under Grant No. PHY-0140343. One of the authors (A.M.M.) acknowledges a F.C.T. post-doctoral grant.

REFERENCES

1. Jim Al-Khalili and Filomena Nunes, J. Phys. G: Nucl. Part. Phys. 29 (2003) R89.
2. M. Yahiro, N. Nakano, Y. Iseri and M. Kamimura, Prog. Theo. Phys. **67** (1982) 1464; Prog. Theo. Phys. Suppl. **89** (1986) 32.
3. F.M. Nunes and I.J. Thompson, Phys. Rev. **C 59** (1999) 2652.
4. F.M. Nunes, A.M. Mukhamedzhanov, C.C. Rosa, B. Irgaziev, Nucl. Phys. A 736 (2004) 255.
5. J. J. Kolata *et al.*, Phys. Rev. C 63 (2001) 024616.
6. N.C. Summers and F.M. Nunes, Phys. Rev. **C 70** (2004) 011602.
7. N.C. Summers, F.M. Nunes and I.J. Thompson, *in preparation*
8. B. Davids *et al.*, Phys. Rev. Lett. **81**(1998) 2209.
9. G. Hauser *et al.*, Nucl. Phys. A 128 (1969) 81.
10. S. M. Smith, W. Reichart and N.S. Wall, Nucl. Phys. A 207 (1973) 273.
11. B. Boonin *et al.*, Nucl. Phys. A 445 (1985) 381.
12. N. Austern, M. Kawai and M. Yahiro, Phys. Rev. C 53 (1996) 314; Phys. Rev. Lett. 63 (1989) 2649.
13. A.M. Moro *et al.*, Phys. Rev. C 68 (2003) 034614.
14. J. A. Tostevin, F. M. Nunes, and I. J. Thompson, Phys. Rev. C 63 (2001) 024617.
15. A.M. Moro and F.M. Nunes, Phys. Rev. C (2004) *to be resubmitted.*
16. N.C. Summers and F.M. Nunes, Phys. Rev. C (2004) *submitted.*
17. D. Cortina-Gil *et al.*, Phys. Lett. B 529 (2002) 36.
18. V. Lapoux, *private communication* 1999.
19. A. Shrivastava *et al.*, Phys. Letts. B 596 (2004) 54.
20. J. S. Winfield *et al.*, Nucl. Phys. A 683 (2001) 48.
21. T. Aumann *et al.*, Phys. Rev. Lett. 84 (2000) 35.
22. A.M. Moro, *private communication*, Lisbon 2003.
23. V. Maddalena *et al.*, Phys. Rev. C 63 (2001) 024613.
24. V. Maddalena and R. Shyam, Phys. Rev. C 63 (2001) 051601(R).
25. R. Shyam and P. Danielewicz, Phys. Rev. C 63 (2001) 054608.
26. J. Al-Khalili and J.A. Tostevin, Phys. Rev. Lett. 76 (1996) 3903.