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Progress on reactions with exotic nuclei

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Abstract. Modelling breakup reactions with exotic nuclei represents a challenge in several ways. The CDCC method (continuum discretized coupled channel) has been very successful in its various applications. Here, we briefly mention a few developments that have contributed to the progress in this field as well as some pertinent problems that remain to be answered.

PACS. 24.10.Ht Optical and diffraction models – 24.10.Eq Coupled-channel and distorted-wave models – 25.55.Hp Transfer reactions – 27.20.+n $6 \leq A \leq 19$

1 Introduction

Light nuclei on the drip lines can be studied through a variety of reactions. Models for nuclear reactions have been developed in recent years in order to incorporate the exotic features of these dripline nuclei. The real challenge for reaction theory lies in the low-energy regime where most approximations are not valid [1].

Three-body effects need to be carefully considered in the lower-energy regime. At energies close to the breakup threshold, Integral Faddeev Equations would be the appropriate choice. However, due to technical difficulties, the Continuum Discretized Coupled Channel Method (CDCC) [2] is the best working alternative. Here we consider specific features of breakup within CDCC, namely the continuum couplings in the usual breakup basis (sect. 2), and the alternative breakup mechanism consisting of transfer to the continuum of the target (sect. 3). Finally, in sect. 4, we briefly comment on remaining problems.

2 Continuum couplings

Measurements of ^{8}B breakup are of importance to nuclear astrophysics. There have been several experiments performed at different facilities to provide the needed information on the S_{17}. Using our best understanding of the reaction mechanism, we assume the projectile can be represented by ^{7}Be(inert) $+\, p$. Within CDCC, the scattering states are binned up in energy (or momentum) labelled by an index α. When the projectile breaks up through the interaction with the target it can rearrange itself within the continuum. The relevant couplings, connect two continuum bins and have the form

$$V_{\alpha;\alpha'}(\mathbf{R}) = \langle \phi_\alpha(\mathbf{r}) | V_{cT}(\mathbf{R}_c) + V_{fT}(\mathbf{R}_f) | \phi_{\alpha'}(\mathbf{r}) \rangle \,, \qquad (1)$$

where r is the projectile internal relative motion $(c + f)$, R is the relative motion between the projectile and the target and R_c (R_f) is the vector connecting the center of mass of the core (fragment) to the center of mass of the target.

The proximity to the breakup threshold has been shown to have important effects in the reaction mechanism. For instance, in the ^{8}B breakup around the Coulomb barrier [3] Coulomb multistep effects reduced the cross-section up to 20% but the most remarkable effect was related to the nuclear peak at larger angles which disappeared through continuum-continuum couplings. Continuum couplings are a way of looking into the effect of the final state interaction, integral part of CDCC.

The properties of these continuum couplings and the influence they can have on breakup observables have been the object of a recent study [4]. Their long range behaviour is preserved throughout the multipole expansion, which slows down convergence: these couplings are shown to behave as $1/R^2$ for dipole transitions and $1/R^3$ for all higher multipoles.

It was also found that continuum-continuum couplings have certain patterns with core-fragment relative energy and relative angular momentum. Monopole couplings are strongest when the initial and final relative energies are the same (represented in fig. 1 by the solid line), a simple consequence of the normalization of the bin wave function.

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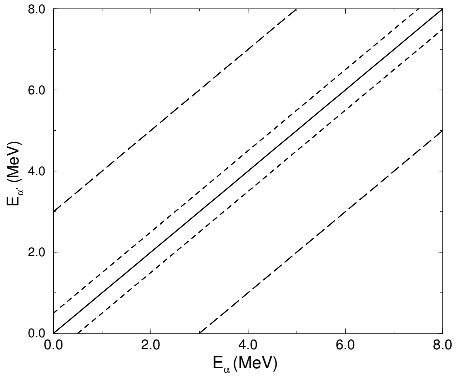

Fig. 1. Representation of the relevant bins that need to be considered in a CDCC calculation: for a monopole transitions (solid), dipole transitions (dashed) and hexadecapole transitions (long-dashed). More details can be found in the text.

Dipole couplings are strongest when these energies differ by an amount comparable to the energy width of the bin, (represented in fig. 1 by the area in between the dashed lines). The higher the order of the couplings, the larger the region that needs to be taken into account. Tests on using this property for optimizing the large CDCC calculations have been performed. Optimization of lower partial waves is of little interest since the number of bins involved are typically small. It is for the larger partial waves ($l > 2$) that calculations become heavy. Our tests show that couplings with initial and final energies differing by several energy steps need to be considered in order to get convergence. This does not allow for significant improvement of the size and the time of the calculations.

3 Transfer to the continuum

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 wave functions.

We present results of a comparative study between the standard CDCC breakup approach and the so-called transfer to the continuum [5]. In the standard breakup approach, a projectile fragment is excited into the continuum, whilst keeping the correlation to the projectile core. There are cases where the correlation of the fragment with the target is more important, and then an expansion in terms of the standard breakup basis does not enable convergence within practical limits. Such was the case for the breakup studies of ^{6}He [6] and ^{8}Li [7] at energies around the Coulomb barrier. In fig. 2 we show the coordinate representation for the breakup of ^{8}Li on ^{208}Pb in the standard approach (a) and in the transfer to the continuum of the target approach (b). The differences between the two approaches are over-emphasized when resonances (in any particular channel) play a role in the dissociation process.

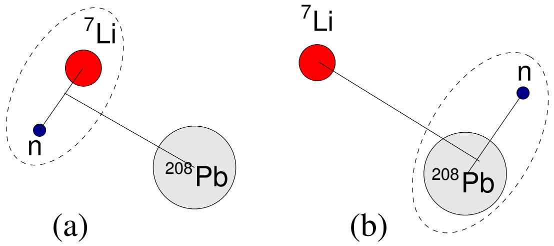

Fig. 2. Schematic diagram for the breakup of ^{8}Li on ^{208}Pb: (a) the standard breakup and (b) the transfer to the continuum of the target.

Typically, with an option of using an expansion based on the continuum of the projectile or the continuum of the target, one chooses the continuum of the more loosely bound nucleus, since it will be more prone to breaking up. However, there are some cases where this choice is not clear. For example, in the ^{7}Be(d,n)^{8}B reaction [8] one can immediately expect the ^{8}B continuum to be very important given the binding energy 0.137 MeV. However, the deuteron breakup is often very strong too. The inclusion of both continua, in the entrance channel and the exit channel raise some orthogonality issues that need to be addressed soon.

4 Remaining problems

Even though the ^{8}B breakup application of CDCC has been extremely successful [9], low-energy Notre Dame data and high-energy NSCL/MSU data show a 60% inconsistency in the quadrupole excitation strength. This is an extremely severe problem from the point of view of direct capture [10]. Independently, accurate measurements have shown that ^{7}Be first excited state contributes to the ground state of ^{8}B [11]. It is possible that core excitation will help solve the puzzle.

Major advances have been performed on microscopic approaches to reactions which include the treatment of one and two particle continuum (*e.g.*, the Shell model embedded in the continuum model [12]). Although the variety of reactions that can be addressed through these microscopic models is rather limited, core excitation is much better treated than within the CDCC few-body approach.

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References

1. J. Al-Khalili, F. Nunes, J. Phys. G **29**, R89 (2003).
2. M. Yahiro, N. Nakano, Y. Iseri, M. Kamimura, Prog. Theor. Phys. **67**, 1464 (1982); Prog. Theor. Phys. Suppl. **89**, 32 (1986).

3. F.M. Nunes, I.J. Thompson, Phys. Rev. C **59**, 2652 (1999).
4. F.M. Nunes, *et al.*, Nucl. Phys. A **736**, 255 (2004).
5. A.M. Moro, F.M. Nunes, resubmitted to Phys. Rev. C.
6. E. F. Aguilera *et al.*, Phys. Rev. Lett. **84**, 5058 (2000).
7. A.M. Moro *et al.*, Phys. Rev. C **68**, 034614 (2003).
8. Kazuyuki Ogata *et al.*, Phys. Rev. C **67**, 011602R (2003).
9. J.A. Tostevin, F.M. Nunes, I.J. Thompson, Phys. Rev. C **63**, 024617 (2001).
10. N.C. Summers, F.M. Nunes, arXiv:nucl-th/0410109v3.
11. D. Cortina-Gil *et al.*, Phys. Lett. B **529**, 36 (2002).
12. J. Okolowicz *et al.*, Phys. Rep. **374**, 271 (2003).