Multistep Coulomb and Nuclear Breakup of One-nucleon Halo Nuclei

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We present the application of the coupled discretised continuum channel (CDCC) method for the Coulomb and nuclear breakup of one-nucleon halo projectiles. The method is tested for Coulomb breakup by comparison with adiabatic T -matrix and semiclassical calculations, and then used for ^8B , ^{11}Be and ^{17}F coincidence breakup cross sections.

1. Introduction

When an exotic nucleus contains a weakly-bound nucleon forming a halo, it will usually have only one bound state of those nucleon(s) and the remaining nucleons in the core. As a projectile in a high energy reaction with a target nucleus, therefore, the composite ‘halo nucleus’ will either scatter elastically, or it will break up. We show how to calculate specific breakup coincidence cross sections by means of the coupled discretised continuum channel (CDCC) method [1–3], which non-perturbatively includes Coulomb and nuclear breakup.

The CDCC approach can take into account (1) the recoil of the core within the halo nucleus, and the finite range of the core-halo interaction, (2) interference between different final state partial waves of halo-core relative motion, (3) multistep processes between breakup channels (continuum-continuum coupling), (4) final state interactions, after breakup, (a) between the halo nucleons and the core, and (b) between these fragments and the target nucleus, (5) Coulomb and nuclear excitation mechanisms, and their coherent combination, and (6) possible postacceleration of those breakup fragments with higher charge to mass ratios.

Usually experiments are designed to minimise certain of these contributions beyond first order. Coulomb breakup measurements, for example, are often performed at high energy and forward angles to minimise nuclear interference effects. However, in order to extract reliable spectroscopic information from any experiment, estimates need to be made of those contributions neglected in the initial analysis. All-order non-perturbative calculations allow the accuracies of the results to be assessed.

2. Coupled Discretised Continuum Channels (CDCC) Method

When a projectile is described as a single particle v outside a core c , its state can be disturbed by the interaction with the target nucleus T , as the tidal forces of the target act differentially on the particle and the core. If one separates the projectile-target interaction into V_{cT} , the interaction of the target nucleus with the core, and V_{vT} , the interaction of the target nucleus with the particle, then there is a mechanism for coupling ground and inelastic (continuum) states together. Nuclear and Coulomb components of V_{cT} and V_{vT} should be included on the same footing.

2.1. Continuum bins

In order to describe the breakup of a projectile such as ${}^8\text{B}$, we consider the inelastic excitations in the $p+{}^7\text{Be}$ system from the ground state $\phi_0(\boldsymbol{\rho})$ to excited states in the continuum $\phi_{\ell sj, \kappa}(\boldsymbol{\rho})$ for some momentum κ and partial wave ℓsj . We average these continuum states over a narrow range of energies, and obtain ‘bin’ states that are square integrable and real. For each $\alpha \equiv \ell sj, [\kappa_{i-1}, \kappa_i]$ the bin wave functions are

$$u_\alpha(\boldsymbol{\rho}) = \sqrt{\frac{2}{\pi N}} \int_{\kappa_{i-1}}^{\kappa_i} w(\kappa) e^{-i\delta_\kappa} \phi_{\ell sj, \kappa}(\boldsymbol{\rho}) d\kappa \quad (1)$$

with δ_κ the scattering phase shift for $\phi_{\ell sj, \kappa}(\boldsymbol{\rho})$, and with $N = \int_{\kappa_{i-1}}^{\kappa_i} |w(\kappa)|^2 d\kappa$ for some weight function $w(k)$ usually unity.

The couplings between the continuum bins, arising from $V_{cT} + V_{vT}$, are not given by the traditional collective form factors of $V_\lambda^N(r) = -\delta_\lambda dU(r)/dr$ for nuclear couplings, nor do they have the simple form $\propto 1/r^{\lambda+1}$ for the long-range part of the Coulomb couplings of multipole λ . Instead, the CDCC couplings are generated semi-microscopically from the ground state and bin wave functions. The first-order breakup coupling, for example, is

$$V_{\alpha:0}^{C+N}(r) = \langle u_\alpha(\boldsymbol{\rho}) | V_{cT}(\mathbf{r} - \gamma\boldsymbol{\rho}) + V_{vT}(\mathbf{r} + (1-\gamma)\boldsymbol{\rho}) | \phi_0(\boldsymbol{\rho}) \rangle$$

where both V_{cT} and V_{vT} may have both Coulomb and nuclear components. The nuclear couplings in $V_{\alpha:0}^{C+N}$ extend as far as the wave function $\phi_0(\rho)$ of the ground state, as do the deviations of the Coulomb couplings from $1/r^{\lambda+1}$, in both cases well beyond the bulk nuclear surfaces. The continuum-continuum couplings $V_{\alpha:\alpha'}^{C+N}$ have even longer range.

2.2. Testing CDCC Convergence

Since we now include long range dipole and quadrupole Coulomb mechanisms in the CDCC framework, the convergence of the CDCC method has to be established. We can compare its results, for example, with the adiabatic T -matrix method of [4], which does not use either partial wave expansions or finite radial limits in its integrals. We can also compare with semiclassical methods where the latter are expected to be accurate. In Fig. 1a, we see good agreement of the CDCC results with the adiabatic T -matrix method for pure Coulomb breakup even at $\theta_p = \theta_n = 0^\circ$, and in Fig. 1b almost perfect agreement with semiclassical results.

2.3. Low energy ${}^8\text{B}$ breakup

Now looking at the low-energy breakup of ${}^8\text{B}$ on ${}^{58}\text{Ni}$ at 25.8 MeV (lab) as in the recent Notre-Dame experiments [5–7], we can investigate [8] the separate convergence of the

Figure 1. Comparisons of CDCC results with those of (a) the adiabatic T -matrix method, and (b) the semiclassical method.

Coulomb and Nuclear processes. Fig. 3 of [8] shows that there are Coulomb cancellations between E1 and E2 couplings, as discussed in [9], and Fig. 4 of [8] shows that the large nuclear DWBA (1-step) peak is almost entirely washed away when higher-order effects are included. We find that this reduction is largely caused by continuum-continuum couplings between breakup bins.

Recently [10] we have implemented methods for calculating the coincidence triple differential cross sections from the CDCC breakup calculations. We can thereby calculate specifically the laboratory-frame cross section of the ${}^7\text{Be}$ fragment, by integrating over the unobserved proton angles, and avoid any approximate treatment of three-body kinematics. We can then test the convergence of the CDCC amplitudes more stringently with respect to the maximum energy of the continuum bins, when both nuclear and Coulomb mechanisms operate. In the present case, of low-energy breakup of ${}^8\text{B}$ on ${}^{58}\text{Ni}$, we have a further question of convergence. We find (Fig. 2a) that bins up to at least 8 MeV are needed for convergence, while in Fig. 2b we compare the converged result with the experimental data of [6].

2.4. High energy breakup

The CDCC method has been applied to breakup at energies of $30 \sim 80$ MeV per nucleon for protons in ${}^8\text{B}$ and ${}^{17}\text{F}$, for neutrons in ${}^{11}\text{Be}$ and ${}^{19}\text{C}$. In each case the Coulomb transitions have been verified for purely Coulomb mechanisms by comparison with semiclassical theory, as in Fig. 1b. For ${}^8\text{B}$ breakup in the MSU experiment [11], we reproduce both the asymmetry in the momentum distributions of the ${}^7\text{Be}$ that comes from the interference between E1 and E2 transitions, and also the reduction in this interference that comes [9] from higher order effects. These techniques also give [12] the parallel momentum distribution of breakup fragments in the nuclear dissociation of ${}^{11}\text{Be}$.

Figure 2. The calculated laboratory frame ${}^7\text{Be}$ cross section angular distribution following the breakup of ${}^8\text{B}$ on ${}^{58}\text{Ni}$ at 25.8 MeV. From [10]: (a) convergence on the maximum p- ${}^7\text{Be}$ relative energy included in the calculation; (b) comparison with experimental data of [6] for two different ${}^8\text{B}$ structure models.

3. Conclusions

New non-perturbative theories reveal the cooperative effects of many aspects of breakup dynamics which we expect to be present, including finite-range and recoil, Coulomb and nuclear processes, as well as non-adiabatic multistep effects. This therefore allows the proper interpretation of coincident breakup experiments, for the one-nucleon halo projectiles considered here.

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