Breakup and the Spectroscopy of Continuum States

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Which Continuum?

• The continuum appears in several ways:
  – Part of expansion of bound states;
    • eg needed in RPA for weakly bound states
  – Dominated by resonances;
    • These ‘unbound states’ identified eg with shell model eigenstates above threshold
  – In non-resonant continuum;
    • eg in breakup reactions, or low-energy capture.

• ALL important parts of nuclear structure!!
‘Overlap’ Challenges

• Reaction models need few-body degrees of freedom in structure models.
  – Solve a few-body model directly, or
  – Extract few-particle dof from microscopic model
    • Difficult for: GFMC,
    • for HFB, QRPA and RMF structure models
    • Do we transfer quasi-particles, or particles?
What a good theory needs:

- Recoil & Finite Range of projectile vertex.
- Final-state (partial wave) interference
- Nuclear and Coulomb mechanisms
- Core excitation (initial and/or dynamic)
- **Final-state interactions:**
  - between halo fragments (needed if resonances)
  - between fragments and target (needed if close in)
- **Multistep Processes** (higher order effects)
CDCC: Coupled Discretised Continuum Channels

Try CDCC:
Coupled Discretised Continuum Channels
- Proposed by Rawitscher, developed by Kamimura group.
- Treat Coulomb and Nuclear mechanisms
  - Need to check convergence of long-range Coulomb process!
- All higher-order effects with a \((r,R,L)\) reaction volume
- Can calculate fragment coincident angular distributions: Predict \(d^3\sigma/dE_1d\Omega_1d\phi_{12}\) and fold with detector apertures & efficiencies
The Hamiltonian for the reaction of a projectile on a target

\[ H = h_{\text{proj}} + h_{\text{targ}} + T_\alpha + V_\alpha \]

\[ \Rightarrow h_{\text{proj}} = h_{\text{core}} + h_{\text{frag}} + T_{\text{cf}} + V_{\text{cf}} \]

\[ \Rightarrow V_\alpha = V_{\text{core-targ}} + V_{\text{frag-targ}} \]

\[ \psi_{\text{JM}}^{\text{CDCC}} (r, R) = [\phi_0 (r) \otimes Y_L (\hat{R})]_{\text{JM}} \chi_{0,L}^J (R) + \sum_{l=0}^{l_{\text{max}}} \sum_{L} \sum_{i=1}^{N} [\phi_{i,l} (r) \otimes Y_L (\hat{R})]_{\text{JM}} \chi_{i,l,L}^J (R) \]

(neglect the internal structure of the target)
CDCC Formalism

The CDCC basis consists of scattering wavefunctions averaged over an energy interval

\[ \hbar \phi_{\text{proj}} \phi_k = \varepsilon_k \phi_k \]

\[ \phi_{i,l} = \sqrt{\frac{2}{\pi N_i}} \int_{k_{i-1}}^{k_i} w_i(k) \phi_{lm}(k, r) \, dk \]

\[ N_i = \int_{k_{i-1}}^{k_i} |w_i(k)|^2 \, dk \]

\[ N_{\text{bins}} = \frac{k_{\text{max}}}{\Delta k} \]

Coupling potentials

\[ V_{il,l'}^{\text{CDCC}}(R) = \langle \phi_{il}(r) | V_\alpha(r, R) | \phi_{l'l'}(r) \rangle \]
Testing CDCC Convergence

- Compare, in Adiabatic Few-Body Model, with Bremstrahlung integral
- Compare, in first-order PWBA model, with semiclassical theory

Note the ‘post-acceleration’
Adiabatic CDCC: compare with Exact 3-body model

Absolute errors in CDCC for d+^{208}Pb at 50 MeV, Nuclear+Coulomb

d+^{208}Pb at 50 MeV, nuclear only
$^{15}\text{C} + 9\text{Be}$ breakup at 54 MeV/u

FIG. 4. Diagrammatic representation of the CDCC model space calculation for $^{15}\text{C}$. The left side shows the physical bound states and continuum and the right hand side the included continuum bins (16) in each $n + ^{14}\text{C}$ partial wave. The dashed arrows are representative of the one-way couplings included in the DWBA. The solid arrows show representative couplings for the full CDCC calculations which connect all bins, including diagonal bin couplings, with two-way couplings to all orders. Relative $h$ waves were found to make negligible contributions.

Tostevin et al, PRC 66, 024607 (2002)
$^{11}\text{Be} + ^{12}\text{C}$ breakup at 67 MeV/u

Energy excitation spectrum
dashed line: multiplied by 0.8

Angular distributions of $^{11}\text{Be}^*$
left: low-energy continuum
right: region of $d_{5/2}$ resonance

CDCC calculations of
Howell, Tostevin, Al-Khalili,

1 Nov 2005
CDCC: sub-Coulomb $^8B + ^{58}Ni$ (26 MeV)

- Multistep Coulomb only
- Multistep Nuclear Only
Coulomb+Nuclear Multistep

- Coulomb+nuclear

- Effect of continuum-continuum couplings

Green lines: no continuum-continuum couplings
Convergence: max bin $E_{\text{rel}}$

- $^8\text{B}$ angular distribution
- $^7\text{Be}$ angular distributions

![Graphs showing angular distributions for $^8\text{B}$ and $^7\text{Be}$ with different max $E_{\text{rel}}$.]
Elastic Breakup: $\sigma(\theta)$

$^8$B breakup on $^{58}$Ni ($E_{\text{beam}}=26$ MeV)

3-body observables
- sensitivity to $^8$B structure: overall normalisation
- sensitivity to p-target optical potential at larger angles

[Tostevin, Nunes and Thompson, PRC (2001) 024617]
Breakup reactions CDCC $^8\text{B} + ^{58}\text{Ni} \rightarrow ^7\text{Be}+p + ^{58}\text{Ni}$ ($E_b=26$ MeV)

Energy distributions: Excellent agreement with the data!
E1 & E2 breakup of $^8B$

- One-proton bound state known:
  - $^7\text{Be} \otimes (0p_{3/2} + 0p_{1/2})|_{2^+}$ at -0.137 MeV
- Need spectroscopy of non-resonant continuum!
  - $B(E1)$ & $B(E2)$ for transition $p \to s,d$ need to be accurately known
  - $E1$ and $E2$ amplitudes interfere in $p_{||}(^7\text{Be})$ momentum distribution
  - so measure relative $E2/E1$ amplitudes from asymmetries.
$^8\text{B} + ^{208}\text{Pb} \rightarrow ^7\text{Be}$ parallel momentum distributions

3.5 degrees

44 MeV/u

Dot-dashed: semiclassical Coul.
Solid: Coulomb+nuclear DWBA
Dashed: CDCC coupled channels
- reduced asymmetry

CDCC calculations with scaled E2 amplitudes
- need to increase asymmetry again!


1 Nov 2005
INT-05-3 Workshop
Extensions started

- Core excitation (static, dynamic)
  - Glauber: Batham et al
  - CDCC bins of particle+core coupled states, Summers & Nunes at MSU

- Three-cluster projectiles (e.g. two-neutron halo nuclei):
  - Gaussian expansions: Kamimura et al.
  - Transformed Harmonic Oscillator: Rodriguez-Gallardo et al
Wave functions of $^6$He

- Ground state wave function:
- Solution of coupled equations for $E \sim -0.97$ MeV.

Nuclei such as $^6$He have highly correlated cluster structures
1 Neutron stripping from three-body Borromean Nuclei

- Removal of a neutron from $^6\text{He}$, $^{11}\text{Li}$, $^{14}\text{Be}$, 
  - populates states of $^5\text{He}$, $^{10}\text{Li}$ or $^{13}\text{Be}$.
  - Experiments measure decay spectrum of $^5\text{He}$
    $= ^4\text{He} + \text{n}$, $^{13}\text{Be} = ^{12}\text{Be} + \text{n}$, etc

- Can we predict any energy and angular correlations by Glauber model?

- Can we relate these correlations to the structure of the A+1 or the A+2 nucleus?
1N stripping from $^6$He g.s.

- Calculate overlaps: $\langle ^5$He($E_{\alpha-n}$) | $^6$He(gs) $\rangle$ for a range of $^5$He($E_{\alpha-n}$) bin states,
- smooth histogram of Glauber bin cross sections.
- GSI data (H. Simon)

Promising technique!

Theory: $\sigma_{str}=137$ mb, $\sigma_{diff}=38$ mb
Expt: $\sigma_{str}=127\pm14$ mb, $\sigma_{diff}=30\pm5$ mb
from T. Tarutina thesis (Surrey)
1N stripping from $^{14}\text{Be}$ g.s.

- Calculate overlaps: $<^{13}\text{Be}(E_{\alpha-n}) |^{14}\text{Be}\text{(gs)}>$
- Inert-core $^{13,14}\text{Be}$ wfs.
- GSI data (H. Simon)
- See softer data, and not pronounced virtual-s and resonant-d peaks.
- New theory needed?

Theory: $\sigma_{\text{str}}=109\text{ mb}, \sigma_{\text{diff}}=109\text{ mb}$
Expt: $\sigma_{\text{str}}=125\pm19\text{ mb}, \sigma_{\text{diff}}=55\pm19\text{ mb}$
Elastic Breakup of 2N halo

- Elastic Breakup = Diffraction Dissociation:
  - all nuclear fragments survive along with the target in its ground state,
  - probes continuum excited states of nucleus.

- Need correlations in the three-body continuum of Borromean nuclei.
Continuum **Spatial** Correlations

from B. Danilin, I. Thompson, PRC 69, 024609 (2004)

- Now average scattering wave functions over angles of $k_x$ and $k_y$, to see spatial correlations in continuum states in $^6\text{He}$:
  
  **T-basis 2+ plane wave**
  
  **T-basis 2+ resonance**
‘True’ 3-body resonances?

- Expect continuum wave functions like:

\[
\psi(\rho, \Omega_5^{\rho}, E, \Omega_5^{\kappa}) \\
\propto \frac{1}{(\kappa \rho)^{5/2}} \sum_{K, \gamma} C_{K\gamma}(E) \psi_{K\gamma}^{R}(\rho) Y_{K\gamma}(\Omega_5^{\rho}) Y_{K\gamma}(\Omega_5^{\kappa})
\]

with

\[
|C_{K\gamma}(E)|^2 = \frac{\Gamma_{K\gamma}}{(E - E_0)^2 + \Gamma^2 / 4}
\]
Continuum Energy Correlations

- Now average scattering wave functions over angles of $k_x$ and $k_y$, for fixed three-body energy $E$.
- Obtain similar plots for continuum energies.

- (Continuum momentum and angular correlations for later)
Continuum three-body wave functions

- Three-body scattering at energy $E$:

  \[ \kappa = \sqrt{k_x^2 + k_y^2} = \sqrt{2mE/\hbar^2}, \]
  \[ \alpha_\kappa = \tan(\frac{k_x}{k_y}) \]

- Plane wave 3-3 scattering states:

  \[ \frac{(2\pi)^{-3}}{\sqrt{(\kappa \rho)^2}} \sum_{KLM L' L''} i^K J_{K+2}(\kappa \rho) Y^l_{KLM L} (\Omega_5^\rho) Y^l_{K'L'M' L} (\Omega_5^{\kappa})^* \]

- Dynamical solutions for scattering states:

  \[ \Psi_{KJM}^T (x, y, \vec{k}_x, \vec{k}_y, \alpha_\kappa) = (\kappa \rho)^{-5/2} \sum_{K\gamma, K'\gamma'} \psi^J_{K, K' \gamma} (\kappa \rho) \gamma_{JM} (\Omega_5^\rho) \]
  \[ \sum_{M_L M_S} \langle L' M_L' S' M_S' | J M \rangle Y^l_{L' M_L' L} (\Omega_5^{\kappa}) X_T \]
Virtual states & Resonances

from B. Danilin, I. Thompson, et al

 Virtual n-n pole

Effect of n-n 'resonance' in $E(c-n)$, $E(cn-n)$ coordinates
$^6$He excitations & resonances

Pronounced $2^+$ resonance

No pronounced $1^-$ resonance
Four-body dynamics

• High Energies (first order & all order):
  – T-matrix multiple scattering (Crespo)
  – Eikonal+Adiabatic (Tostevin, Al-Khalili)
  – Eikonal (Exact fragment) (Brooke, Tostevin, Al-Khalili)
  – Adiabatic (Johnson, Christley et al)

• All Energies (all orders), new challenges:
  – 4-body pseudo-state CDCC (Kamimura)
  – 4-body bin-states CDCC
  – “Two-nucleon states in deformed nuclei”
T-matrix expansions for breakup

$^{11}\text{Li}$ on protons at 68 MeV/A

- Preliminary Method:
  - First-order expansion on fragment-target T-matrices
  - Pseudo-state continuum, smoothed.

- Strong sensitivity on the structure models for $^{11}\text{Li}$: S, P0, P2

Crespo et al., PRC66 (2002) 021002
Data: RIKEN.
σ(θ) for $^{11}$Li(p,p′) at 68 MeV/u

- (a) Comparison of the theoretical calculations with experimental data
- Solid, dashed and dotted lines show the total, monopole and dipole angular distributions, respectively.
- In (b) and (c), solid lines show angular distributions for the monopole and dipole excitations, respectively.
- Dashed and dotted lines are contributions from the halo neutrons and the core nucleons.
Conclusions

- **CDCC method good for 2-cluster halo nuclei:**
  - Finite-range & recoil included
  - **Coulomb and nuclear** both approach convergence
    - Large radii and partial-wave limits needed, but feasible now
    - **Non-adiabatic treatment of Coulomb breakup**
    - Multistep effects manifest from all final-state interactions

- **Extensions:**
  - Deformed cluster models: Summers & Nunes at MSU
  - Three-cluster projectiles (e.g. two neutron halo nuclei): Kamimura et al.