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, <u>or</u>
  - 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)
- **<u>Multistep Processes</u> (higher order effects)**

CDCC: Coupled Discretised Continuum Channels

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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 e.g. $d^3\sigma/dE_1 d\Omega_1 d\varphi_{12}$ and fold with detector apertures & efficiencies

CDCC Hamiltonian & model space

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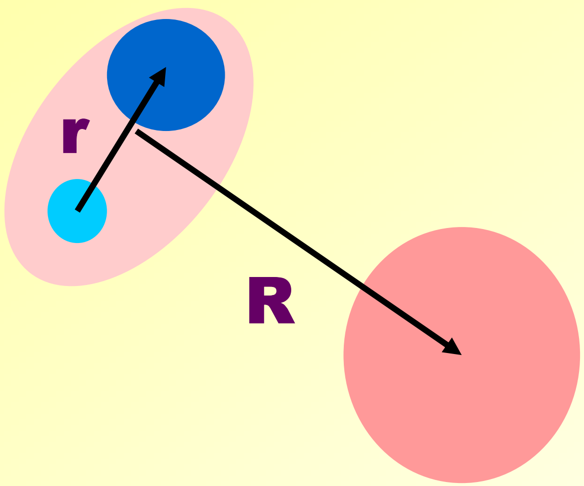
The Hamiltonian for the reaction of a projectile on a target

$$\mathbf{H} = \mathbf{h}_{\mathbf{proj}} + \mathbf{h}_{\mathbf{targ}} + \mathbf{T}_{\alpha} + \mathbf{V}_{\alpha}$$

$$\Rightarrow \mathbf{h}_{\mathbf{proj}} = \mathbf{h}_{\mathbf{core}} + \mathbf{h}_{\mathbf{frag}} + \mathbf{T}_{\mathbf{cf}} + \mathbf{V}_{\mathbf{cf}}$$

$$\Rightarrow \mathbf{V}_{\alpha} = \mathbf{V}_{\mathbf{core-targ}} + \mathbf{V}_{\mathbf{frag-targ}}$$



$$\psi^{\mathbf{CDCC}}_{\mathbf{JM}}(\mathbf{r},\mathbf{R}) = [\phi_0(\mathbf{r}) \otimes \mathbf{Y}_{\mathbf{L}}(\hat{\mathbf{R}})]_{\mathbf{JM}} \chi^{\mathbf{J}}_{0,\mathbf{L}}(\mathbf{R}) + \sum_{\mathbf{l}=0}^{\mathbf{l}\max} \sum_{\mathbf{L}} \sum_{\mathbf{i}=1}^{\mathbf{N}} [\phi_{\mathbf{i},\mathbf{l}}(\mathbf{r}) \otimes \mathbf{Y}_{\mathbf{L}}(\hat{\mathbf{R}})]_{\mathbf{JM}} \chi^{\mathbf{J}}_{\mathbf{i},\mathbf{l},\mathbf{L}}(\mathbf{R})$$

(neglect the internal structure of the target)

CDCC Formalism

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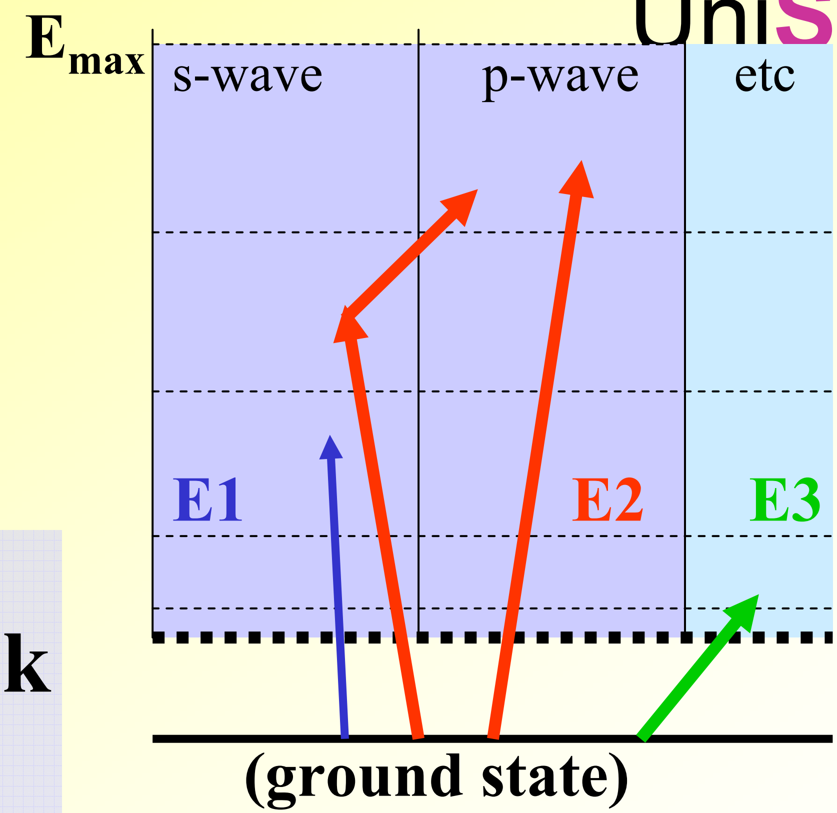
The CDCC basis consists of scattering wavefunctions averaged over an energy interval

$$\mathbf{h}_{\mathbf{proj}}\phi_{\mathbf{k}} = \varepsilon_{\mathbf{k}}\phi_{\mathbf{k}}$$

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



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

$$\mathbf{N_{bins}} = \frac{\mathbf{k_{max}}}{\Delta\mathbf{k}}$$

Coupling potentials

$$V^{CDCC}_{il,i'l'}(R) = <\phi_{il}(r)|V_\alpha(r,R)|\phi_{i'l'}(r)>$$

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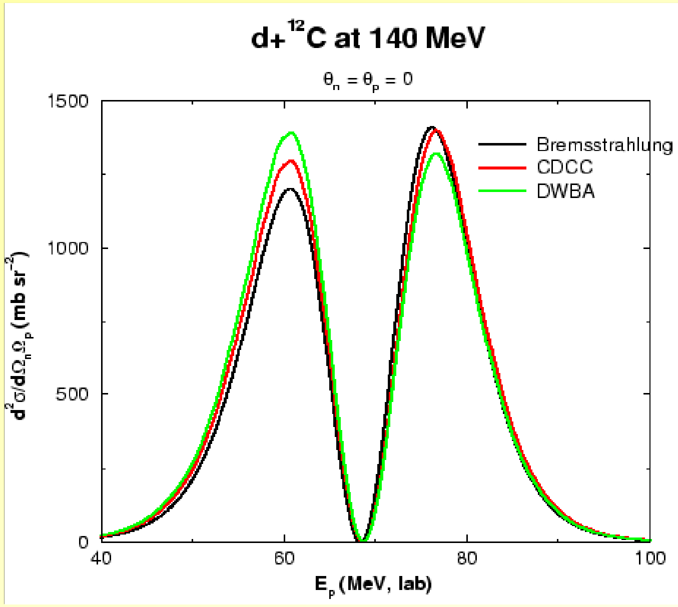
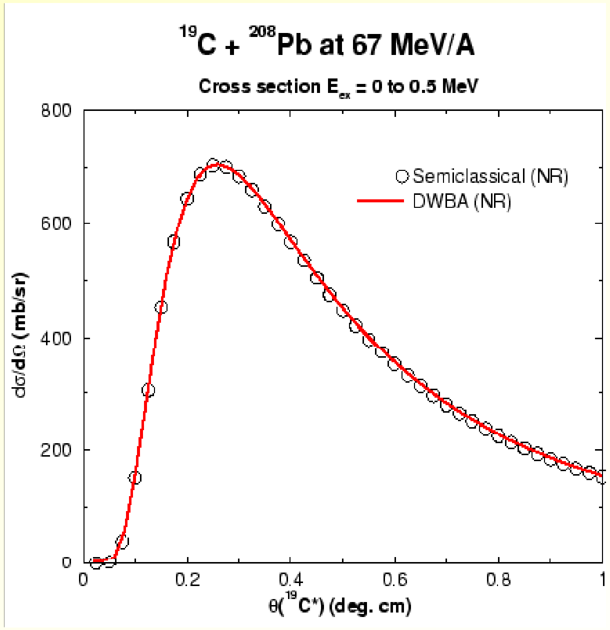
Testing CDCC Convergence

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





Note the 'post-acceleration'

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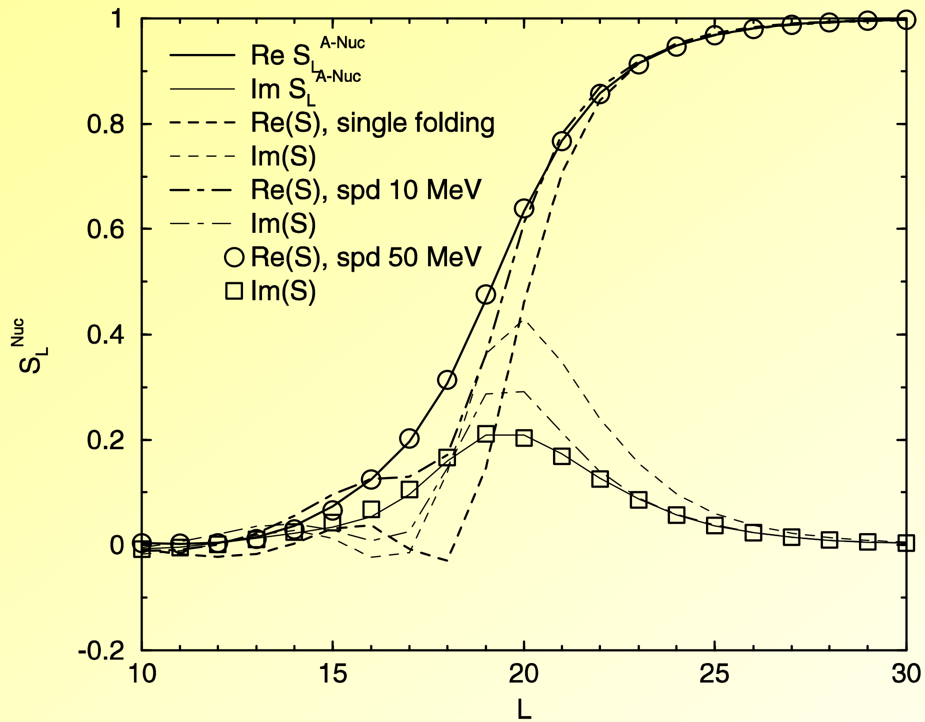
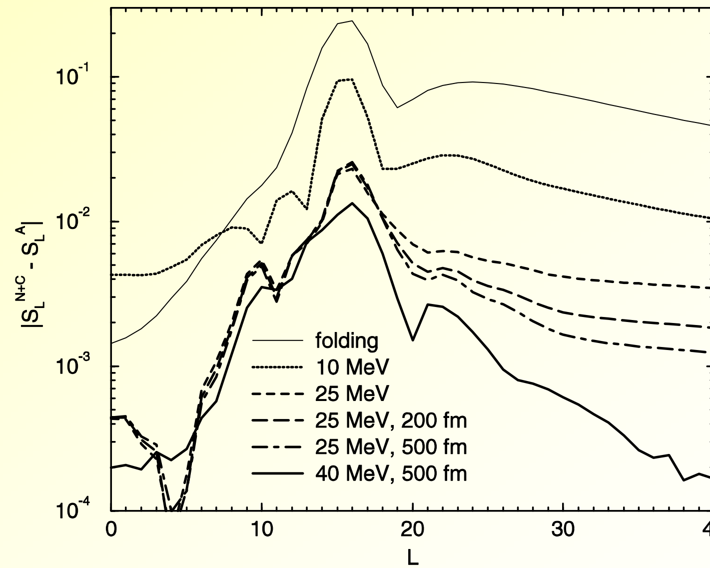
Adiabatic CDCC:
compare with Exact 3-body model



d+^{208}Pb at 50 MeV, nuclear only



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

^{15}C + 9Be breakup at 54 MeV/u

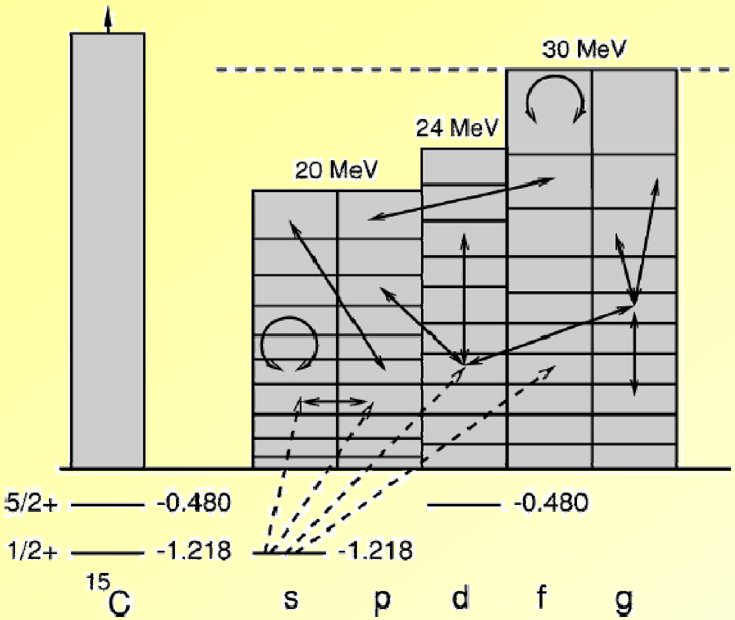


FIG. 4. Diagrammatic representation of the CDCC model space calculation for ^{15}C. The left side shows the physical bound states and continuum and the right hand side the included continuum bins (10) in each $n+{}^{14}$C partial wave. The dashed arrows are representative of the one-way couplings included 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.

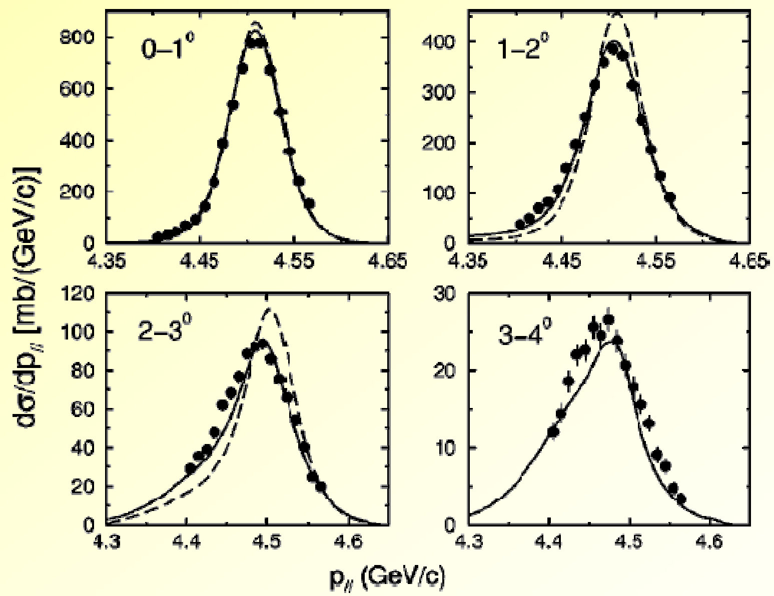
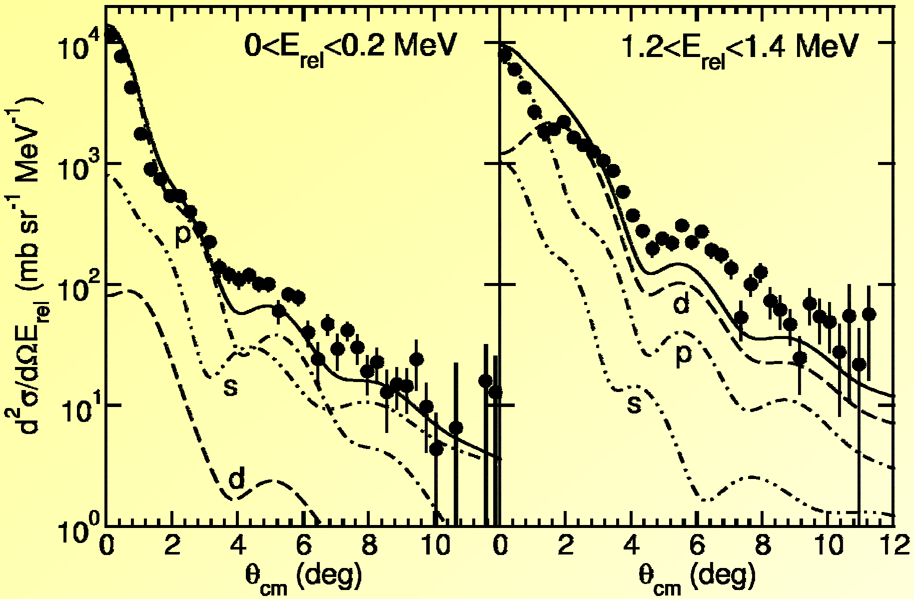


FIG. 11. The nucleon-removal parallel momentum distributions $d\sigma/dp_{\|}$, for the ^{15}C+^{9}Be reaction at 54 MeV/nucleon to the ^{14}C ground state, shown on a more familiar linear scale. The solid curves assume the stripping contributions have the same form as that calculated using the CDCC. The dashed curves assume the stripping contributions have a parallel momentum distribution at all angles of the residue given by the eikonal calculation shown in Fig. 2.

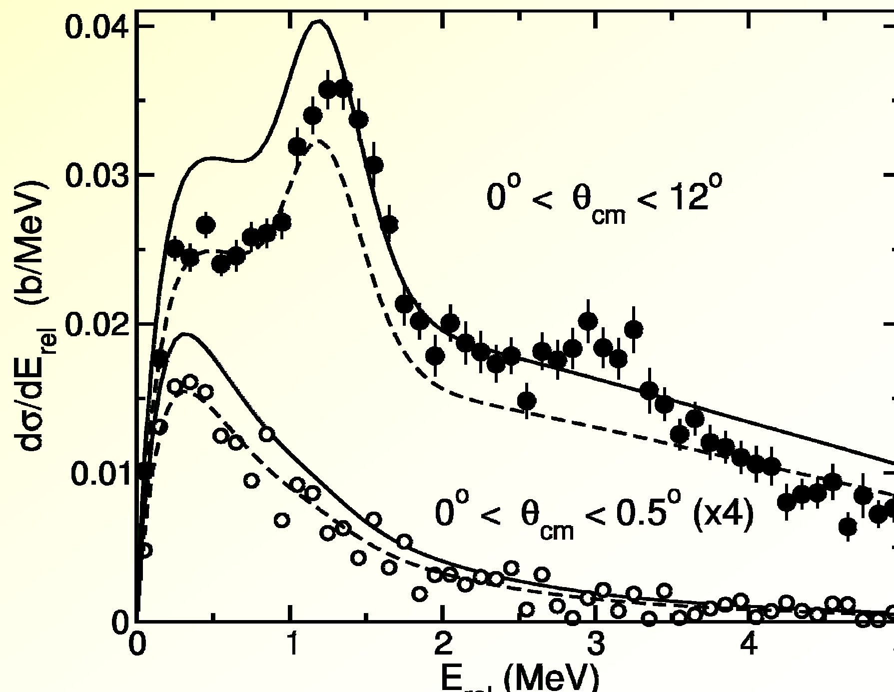
Tostevin et al, PRC **66**, 024607 (2002)

^{11}Be + ^{12}C breakup at 67 MeV/u



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

Energy excitation spectrum
dashed line: multiplied by 0.8



CDCC calculations of
Howell, Tostevin, Al-Khalili,
J. Phys. G **31** (2005) S1881

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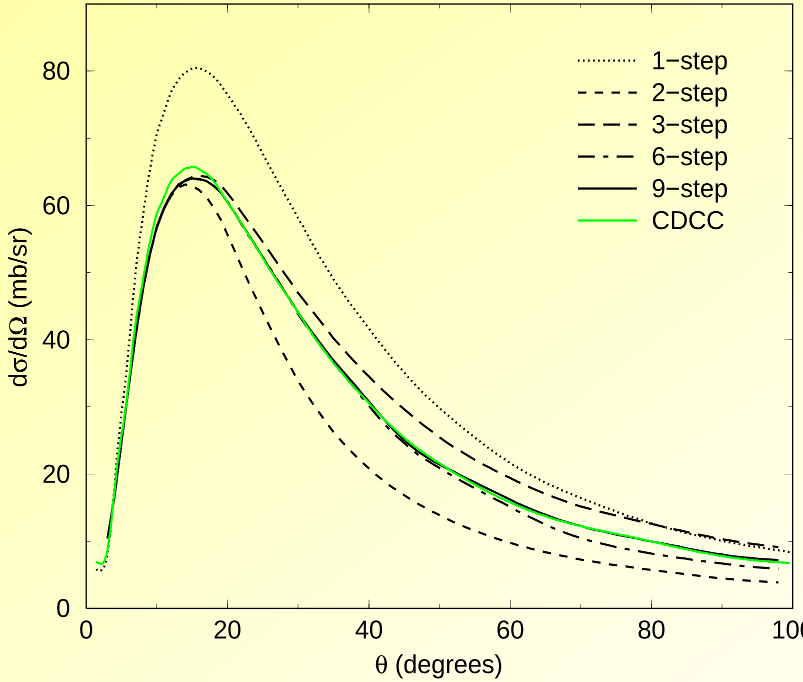
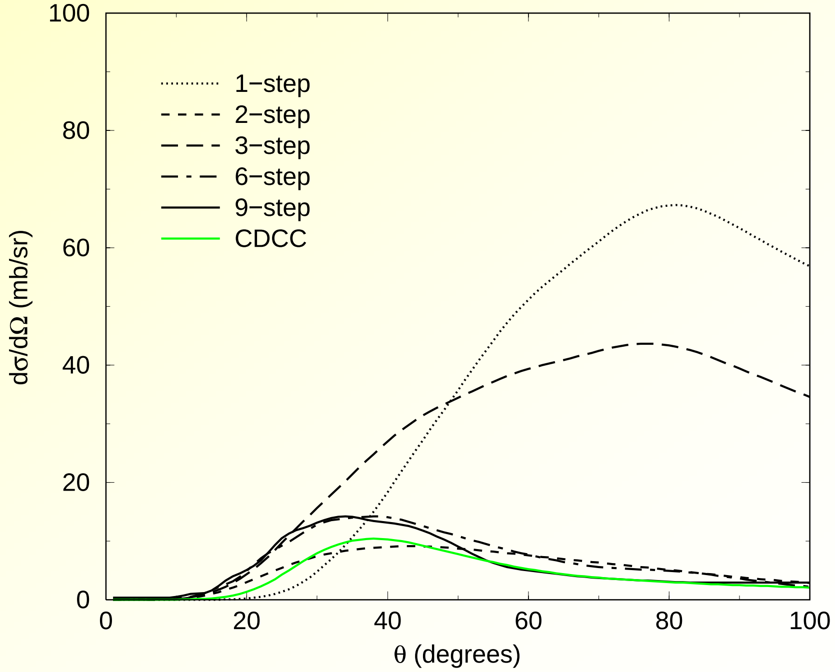
CDCC: sub-Coulomb $^{8}B+^{58}Ni$ (26 MeV)

- Multistep Coulomb only



- Multistep Nuclear Only



Coulomb+Nuclear Multistep

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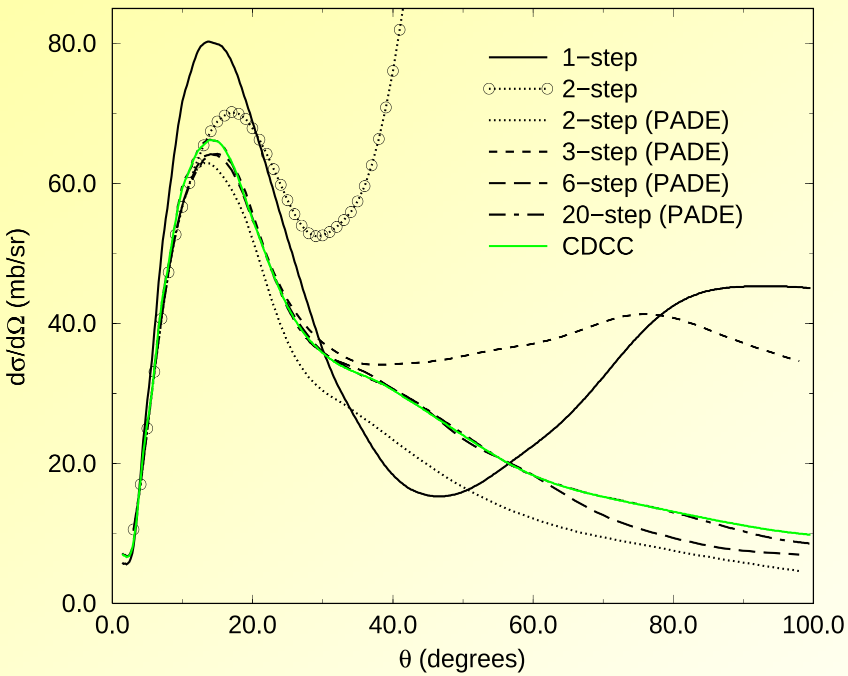
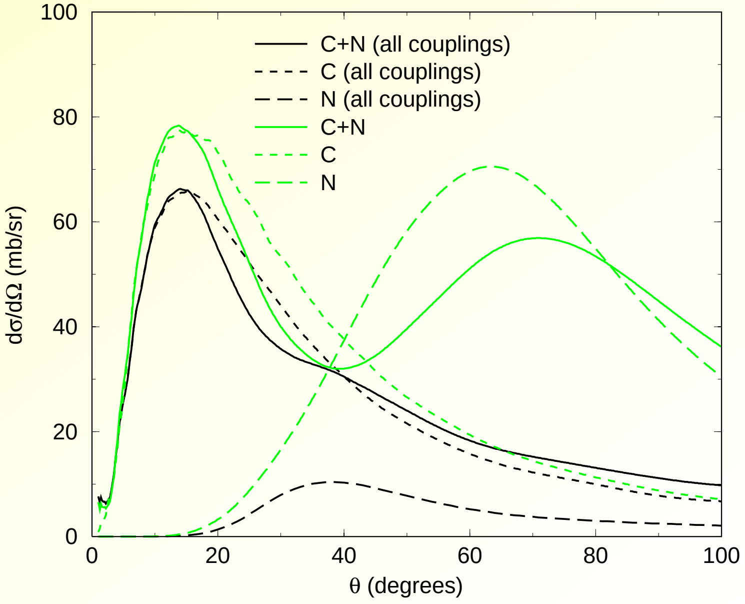
- Coulomb+nuclear



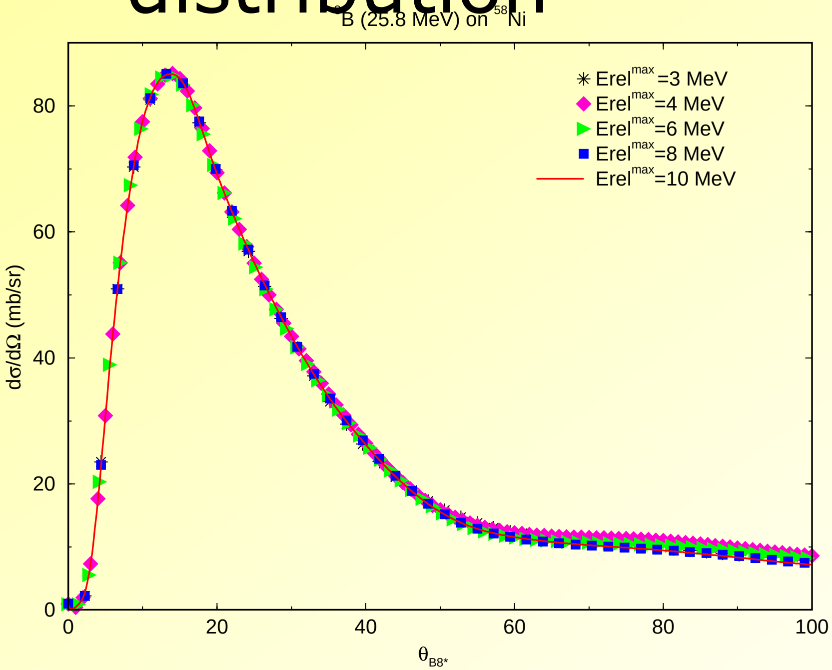
- Effect of continuum-continuum couplings

Green lines: no continuum-continuum couplings

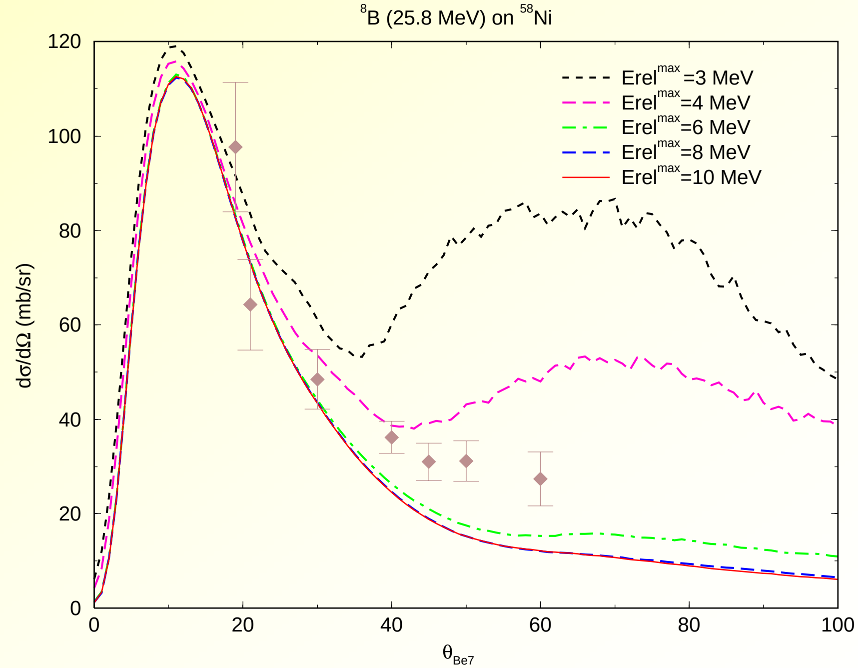


Convergence: max bin E_{rel}

- ^{8}B angular distribution



- ^{7}Be angular distributions



Elastic Breakup: $\sigma(\theta)$

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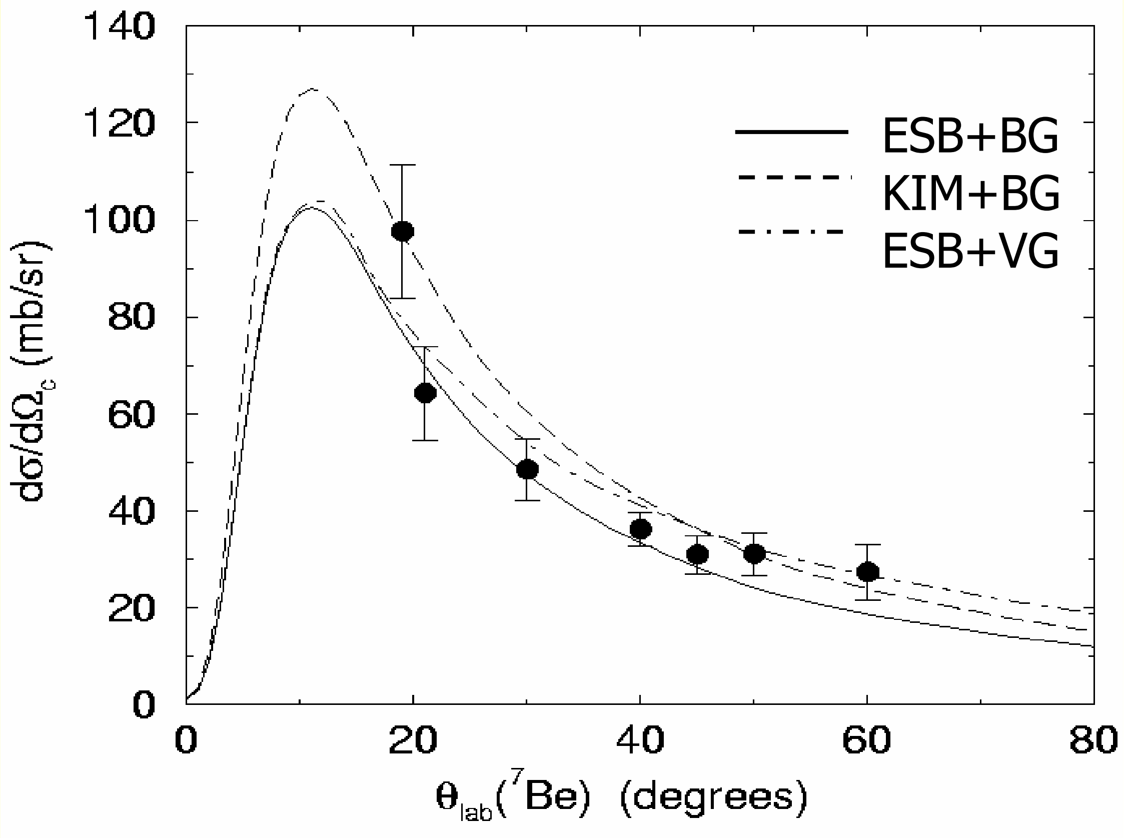
^{8}B breakup on ^{58}Ni
(E_{beam}=26 MeV)

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 $^{8}B + ^{58}Ni \rightarrow ^{7}Be+p + ^{58}Ni$ (E_b=26 MeV)

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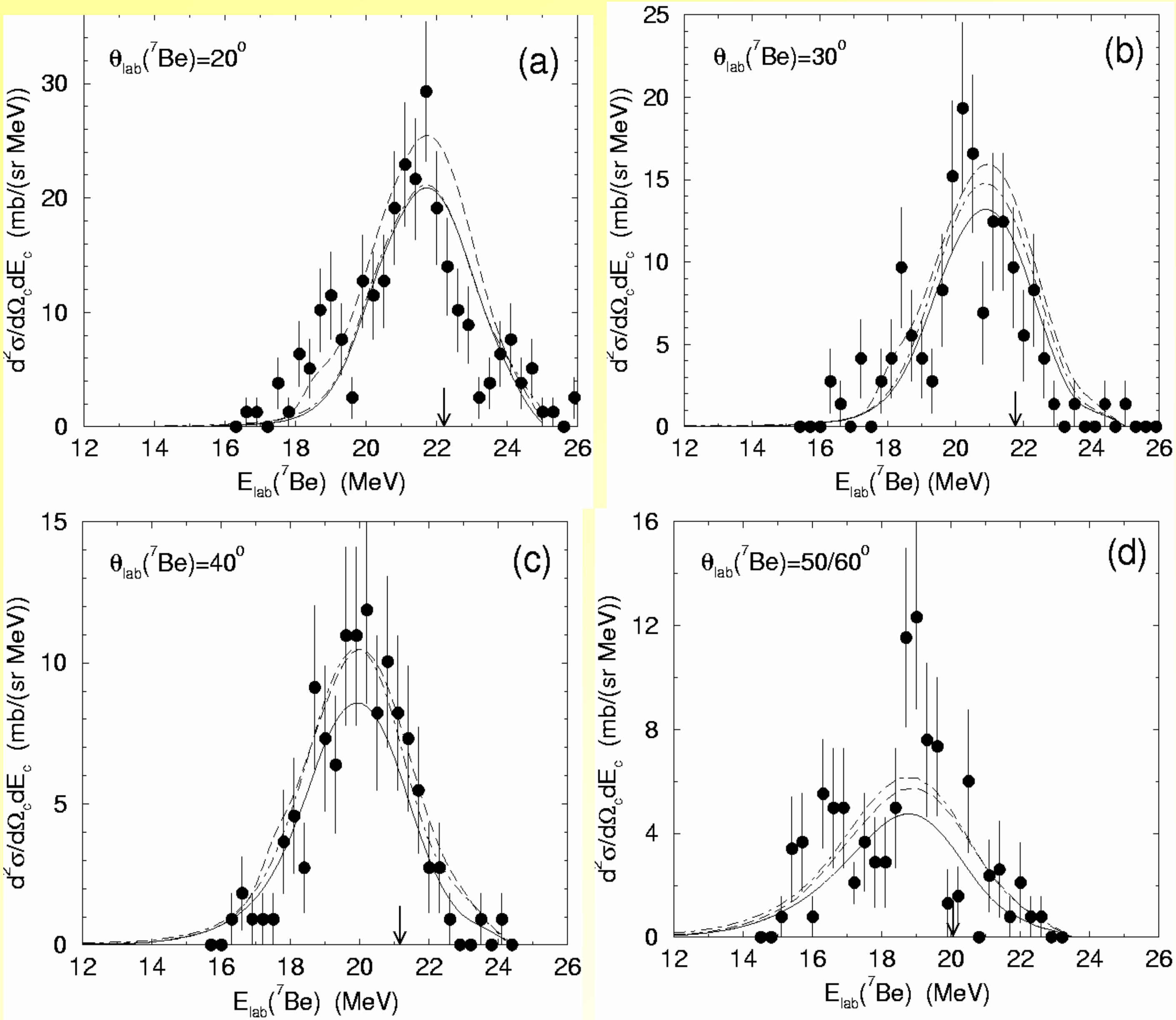

Energy distributions: Excellent agreement with the data!

ESB+BG
KIM+BG
ESB+VG
ND data

E1 & E2 breakup of ^{8}B

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

$^{8}B + ^{208}Pb \rightarrow ^{7}Be$ parallel momentum distributions

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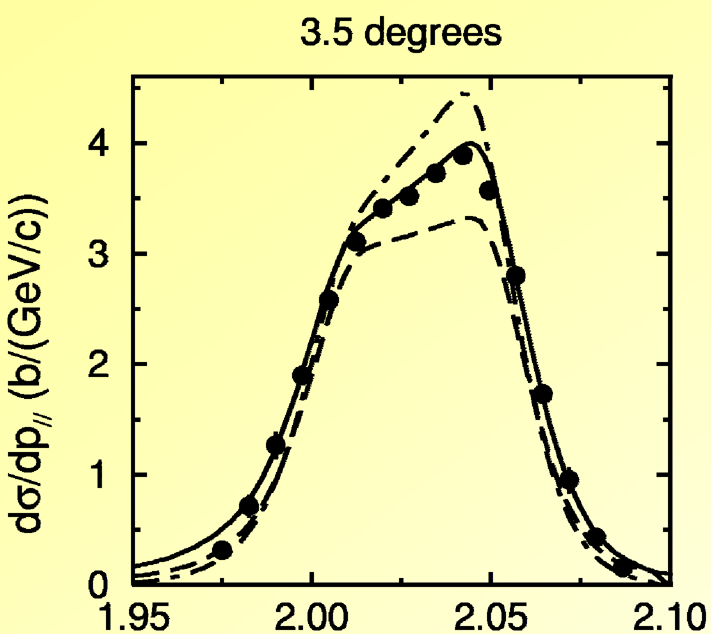
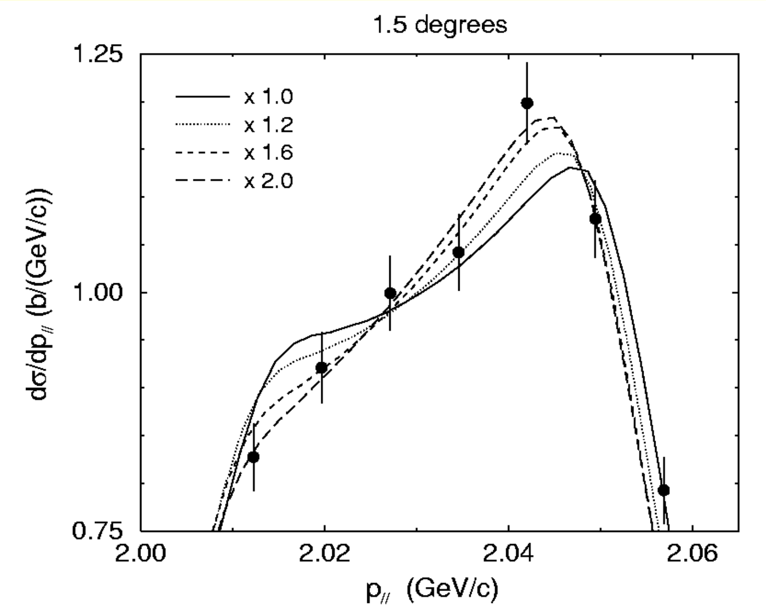
44 MeV/u





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!

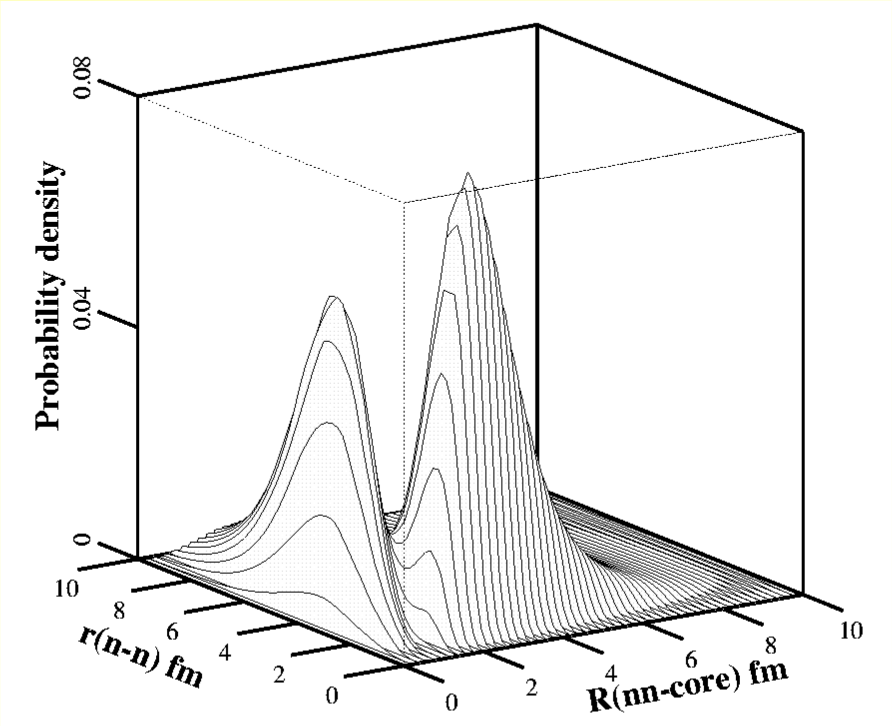
from Mortimer et al., Phys Rev C 65 (2002) 64619

Extensions started

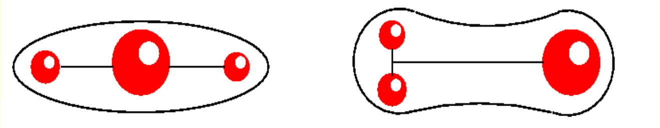
- Core excitation (static, dynamic)
  - Glauber: Batham et al
  - CDCC bins of particle+core coupled states, Summers & Nunes at MSU
- Three-cluster projectiles (e.g. two-neutron halo nuclei):
  - Gaussian expansions: Kamimura et al.
  - Transformed Harmonic Oscillator: Rodriguez-Gallardo et al

Wave functions of ^6He

- Ground state wave function:
- Solution of coupled equations for E ~ –0.97 MeV.



Nuclei such as ^6He have highly correlated cluster structures



1 Neutron stripping from three-body Borromean Nuclei

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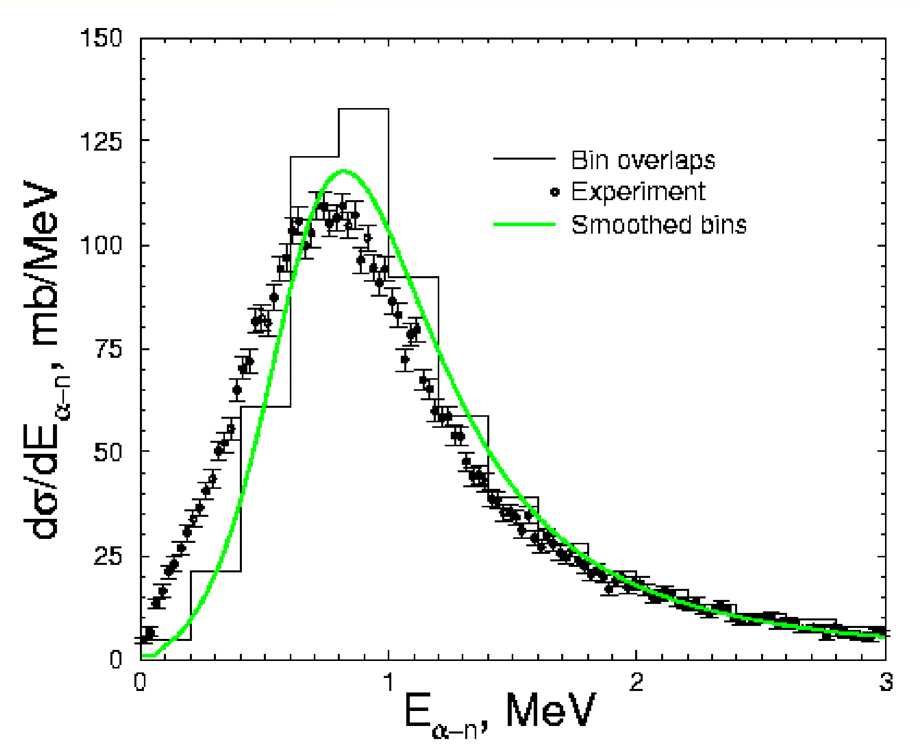
- Removal of a neutron from ^{6}He, ^{11}Li, ^{14}Be,
  - populates states of ^{5}He, ^{10}Li or ^{13}Be.
  - Experiments measure decay spectrum of $^{5}He = {}^{4}He + n$, $^{13}Be = {}^{12}Be + n$, etc
- Can we predict any energy and angular correlations by Glauber model?
- Can we relate these correlations to the structure of the A+1 or the A+2 nucleus?

1N stripping from ^{6}He g.s.

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

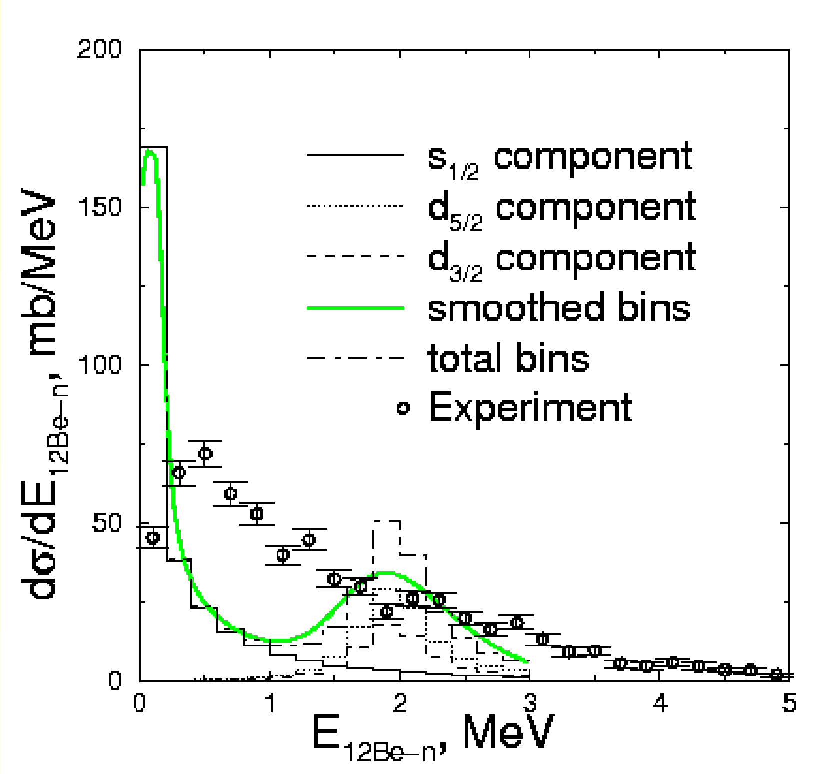


Theory: σ_{str}=137 mb, σ_{diff}=38 mb
Expt: σ_{str}=127±14 mb, σ_{diff}=30±5 mb
from T. Tarutina thesis (Surrey)

Promising technique!

1N stripping from ^{14}Be g.s.

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



Theory: σ_{str}=109 mb, σ_{diff}=109 mb
Expt: σ_{str}=125±19 mb, σ_{diff}=55±19 mb

Elastic Breakup of 2N halo

- Elastic Breakup = <u>Diffraction Dissociation:</u>
  - 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.

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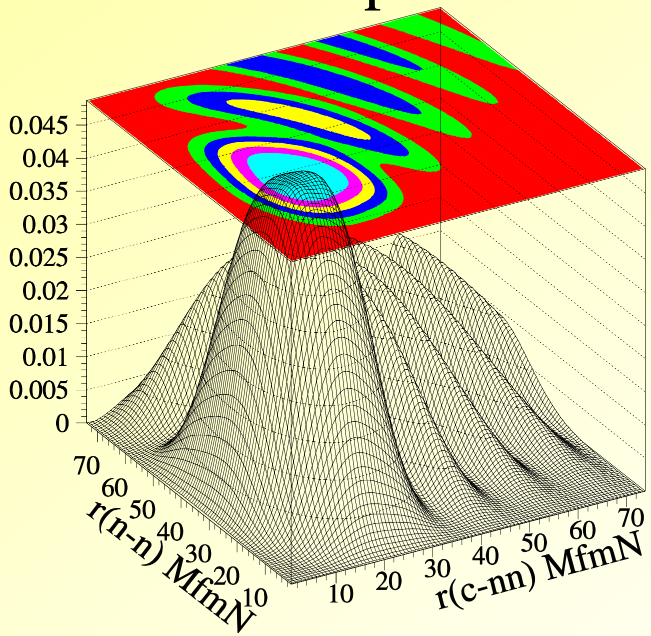
Continuum Spatial Correlations

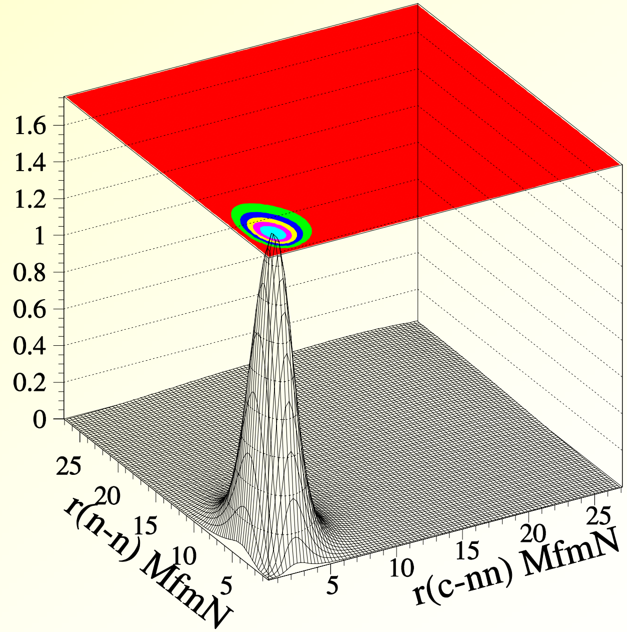
from B. Danilin, I. Thompson, PRC 69, 024609 (2004)

- Now average scattering wave functions over angles of $\mathbf{k}_x$ and $\mathbf{k}_y$, to see spatial correlations in continuum states in ^{6}He:

T-basis 2+ plane wave



T-basis 2+ resonance



'True' 3-body resonances?

- Expect continuum wave functions like:

$$\psi(\rho\ \Omega_5^\rho, E\ \Omega_5^\kappa)$$

$$\propto \frac{1}{(\kappa\rho)^{5/2}} \sum_{K,\gamma} C_{K\gamma}(E) \quad \psi^R_{K\gamma}(\rho)\ Y_{K\gamma}(\Omega_5^\rho)\ Y_{K\gamma}(\Omega_5^\kappa)$$

with

$$|C_{K\gamma}(E)|^2 = \frac{\Gamma_{K\gamma}}{(E-E_0)^2+\Gamma^2/4}$$

Continuum <u>Energy</u> Correlations

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- Now average scattering wave functions over angles of $\mathbf{k}_x$ and $\mathbf{k}_y$, for fixed three-body energy E.
- Obtain similar plots for continuum energies.

- (Continuum <u>momentum</u> and <u>angular</u> correlations for later)

Continuum three-body wave functions

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- Three-body scattering at energy E:

hypermomentum $\kappa = \sqrt{k_x^2 + k_y^2} = \sqrt{2mE/\hbar^2}$,
hyperangle $\alpha_\kappa = \mathrm{atan}(k_x/k_y)$

- Plane wave 3-3 scattering states:

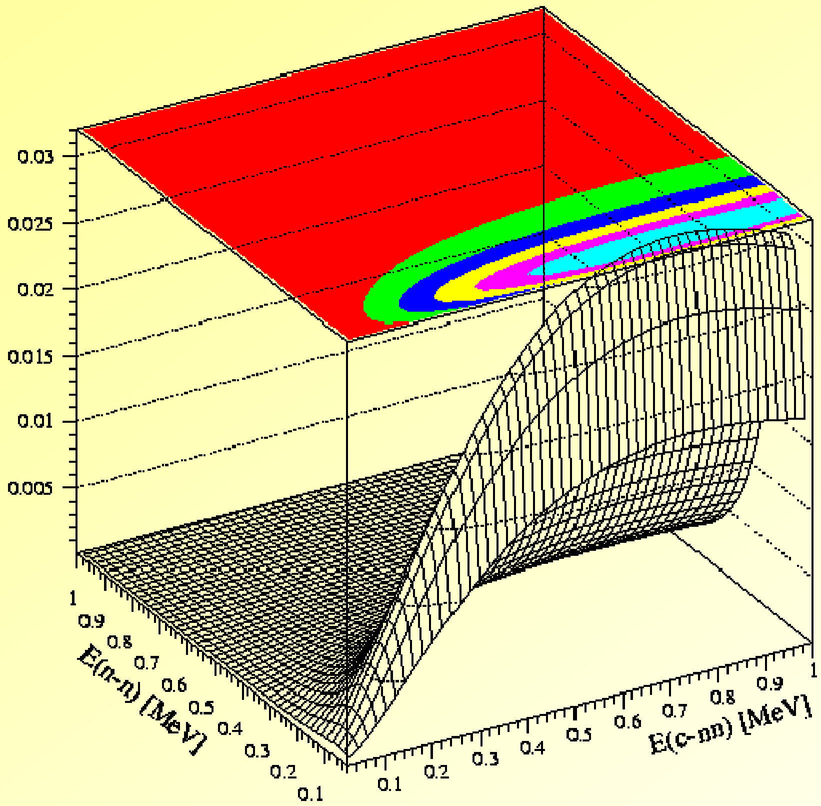
$$\begin{aligned} & (2\pi)^{-3} \exp[i(\mathbf{k_x}\cdot\mathbf{x} + \mathbf{k_y}\cdot\mathbf{y})] \\ = \; & (\kappa\rho)^{-2} \sum_{KLM_L l_x l_y} i^K J_{K+2}(\kappa\rho) \mathcal{Y}^{l_x l_y}_{KLM_L}(\Omega_5^\rho)\ \mathcal{Y}^{l_x l_y}_{KLM_L}(\Omega_5^\kappa)^* \end{aligned}$$

- Dynamical solutions for scattering states:

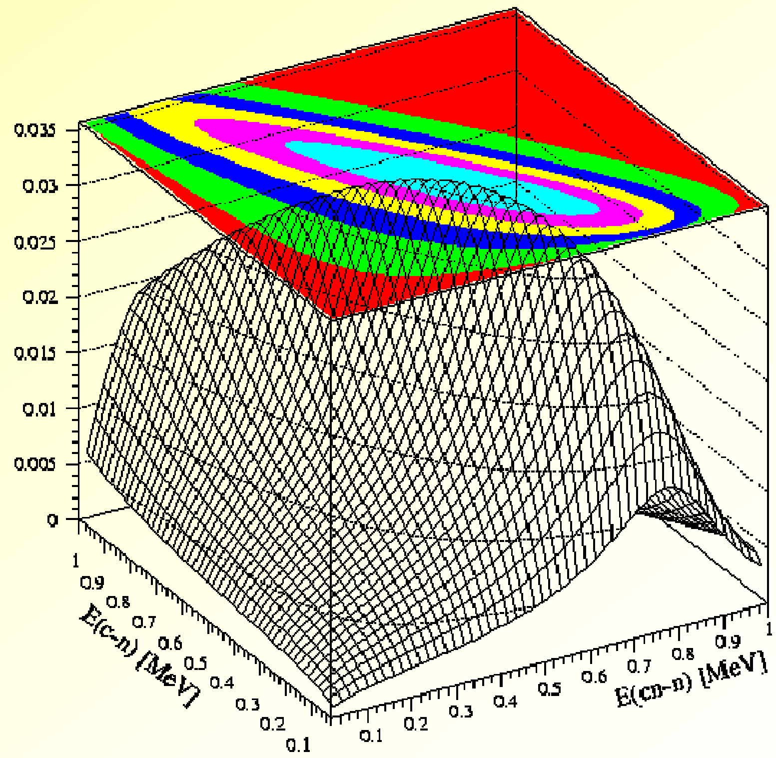
$$\Psi^T_{\kappa JM}(\mathbf{x}, \mathbf{y}, \widehat{\mathbf{k}}_x, \widehat{\mathbf{k}}_y, \alpha_\kappa) = (\kappa\rho)^{-5/2} \sum_{K\gamma, K'\gamma'} \psi^J_{K\gamma, K'\gamma'}(\kappa\rho) \Upsilon^{K\gamma}_{JM}(\Omega_5^\rho)$$
$$\sum_{M'_L M'_S} \langle L' M'_L S' M'_S \mid JM\rangle \mathcal{Y}^{l'_x l'_y}_{K'L'M'_L}(\Omega_5^\kappa)\ X_T$$

Virtual states & Resonances

from B. Danilin, I. Thompson, et al

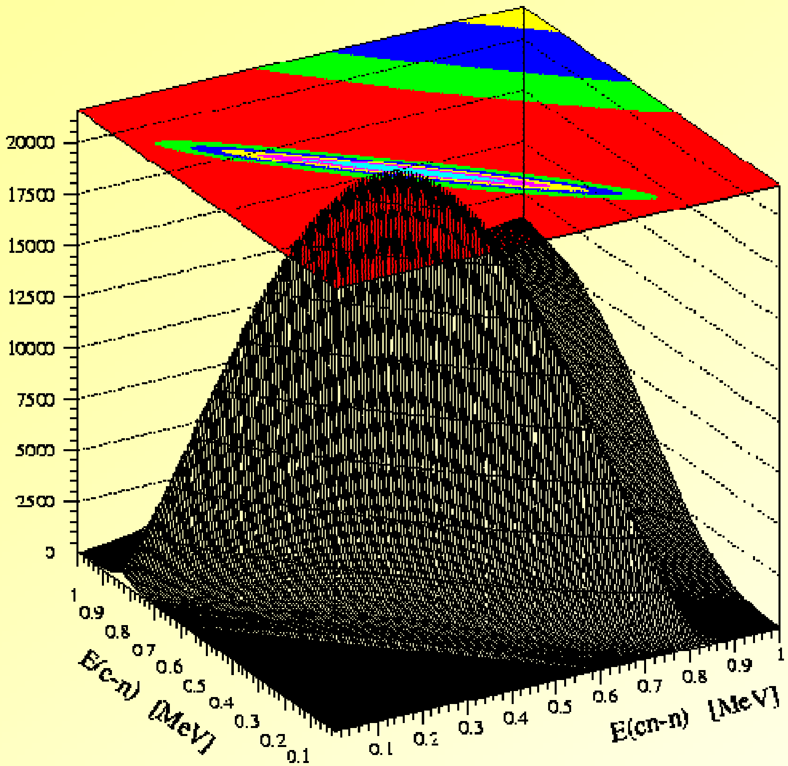


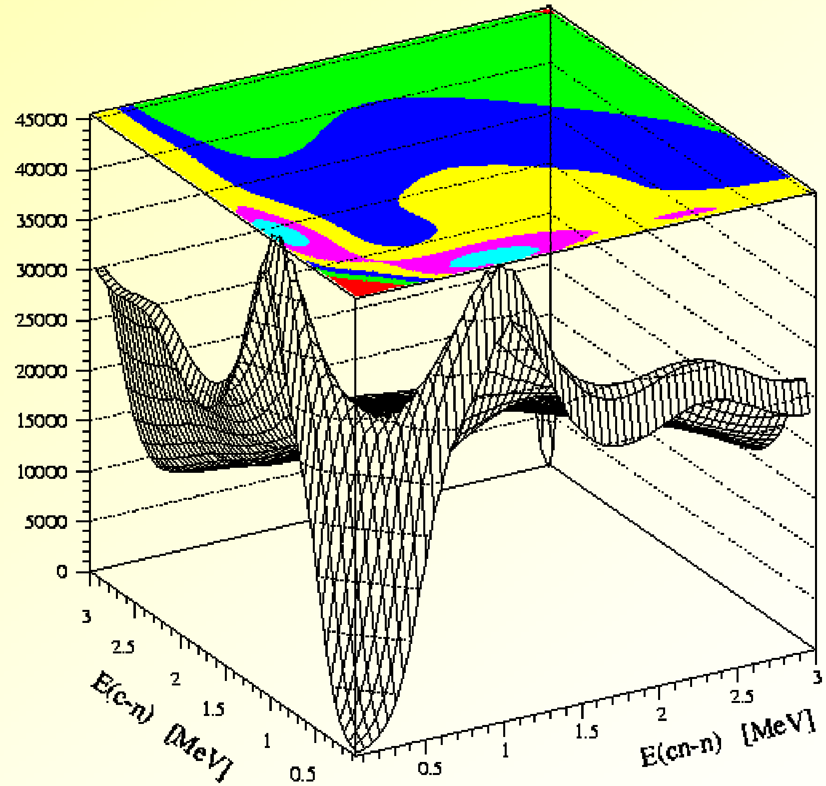
Virtual n-n pole



Effect of n-n 'resonance' in E(c-n), E(cn-n) coordinates

^{6}He excitations & resonances





Pronounced 2^+ resonance

No pronounced 1^- resonance

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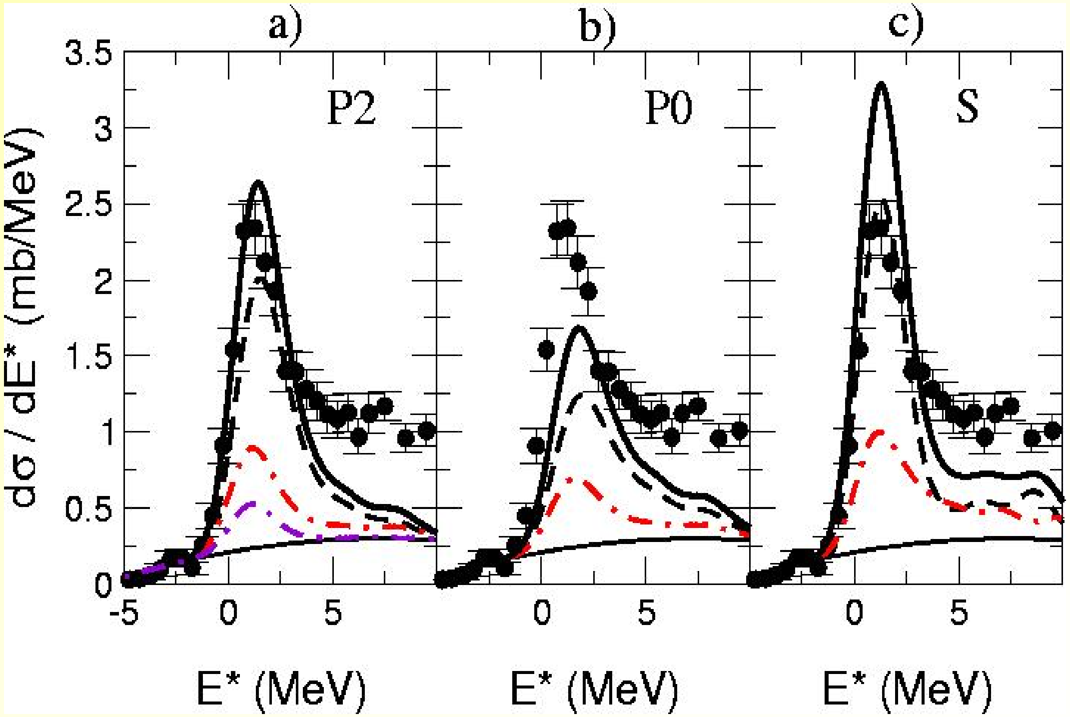
Four-body dynamics

- 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
  - "<u>Two</u>-nucleon states in deformed nuclei"

T-matrix expansions for breakup

^{11}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}Li: S, P0, P2



Crespo et al., PRC66 (2002) 021002
Data: **RIKEN**.

$\sigma(\theta)$ for $^{11}Li(p,p')$ at 68 MeV/u

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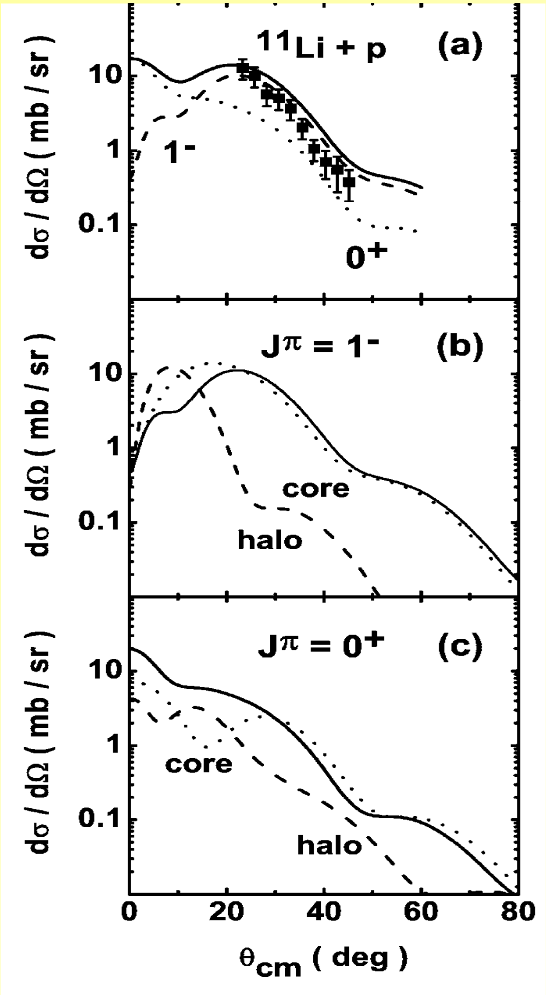

- (a) Comparison of the theoretical calculations with experimental data
- Solid, dashed and dotted lines show the total, monopole and dipole angular distributions, respectively.
- In (b) and (c), solid lines show angular distributions for the monopole and dipole excitations, respectively.
- Dashed and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