Mechanisms in knockout reactions

D. Bazin
National Superconducting Cyclotron Laboratory
Michigan State University
Motivation

- Knockout reactions have become a common tool to study the structure of nuclei far from stability
- Determination of spectroscopic factors relies on reaction theory to calculate single-particle cross sections
- It is essential to test the validity and accuracy of the reaction theory
Knockout reactions on fast beams

- Removal of one or two nucleons via nuclear interaction with a low-Z target (typically $^9$Be or $^{12}$C)
  - Direct (one-step) reaction
  - Measure probability of finding A-1 or A-2 residual nucleus in a given state
  - Composition of initial nucleus wave function
  - Spectroscopy of residual nucleus
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- **High sensitivity well adapted to radioactive beams**
  - Residual nucleus forward focused because of inverse kinematics
  - Final state of residual nucleus identified via $\gamma$-ray detection
  - Thick targets give high luminosity
Determination of spectroscopic factors

- Theoretical cross section between initial and final states directly related to spectroscopic factors

\[ \sigma_{if} = \sum_{|J_f - J_i| \leq j \leq J_f + J_i} S_{jf}^i \sigma_{sp} \]

- Experimental determination of cross sections
  - Angular momentum of removed nucleon(s) deduced from parallel momentum distribution of residual nucleus
  - Final state of residual nucleus deduced from its \( \gamma \)-decay in flight
  - Spectroscopic factors can be determined from the experimental cross sections and the calculated single-particle cross sections

Reaction mechanisms

- Experimentally only the residual nucleus is detected
  - Nothing is known on the whereabouts of the removed nucleon(s)
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- Elastic breakup also called Diffraction:
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  - the target stays in its ground state
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- **Inelastic breakup also called Stripping:**
  - the removed nucleon(s) interact inelastically with the target
  - the target is excited or broken up
  - the removed nucleon(s) can escape with much lower velocity and/or as different particle
Single-particle cross sections

\[ \sigma_{\text{str}} = \frac{1}{2j + 1} \int d\vec{b} \sum_m \langle \psi_{jm} | (1 - |S_n|^2) | S_c |^2 | \psi_{jm} \rangle \]

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- **Eikonal theory**
  - \( S_n \) and \( S_c \) \( S \)-matrices for the scattering of the nucleon and the core (residual nucleus) respectively
  - Calculated using Glauber theory, HF densities and effective NN interaction

Proposed experiment

- **Experiment aimed to measure stripping and diffraction parts of the cross section separately**
  - Detect removed nucleon with maximum solid angle to differentiate diffraction
  - One-proton knockout: easier to detect proton than neutron
  - Choose two cases with different binding energies and only one or two final states

<table>
<thead>
<tr>
<th>Initial state</th>
<th>Final state</th>
<th>$S_p$ (MeV)</th>
<th>$\sigma_{str}$ (mb)</th>
<th>$\sigma_{diff}$ (mb)</th>
<th>$S_{SM}$</th>
<th>$\sigma_{tot}$ (mb)</th>
<th>$%_{diff/str}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9C$ (3/2-)</td>
<td>$^8B$ (2+)</td>
<td>1.300</td>
<td>46.0</td>
<td>15.7</td>
<td>0.94</td>
<td>58</td>
<td>25.4</td>
</tr>
<tr>
<td>$^8B$ (2+)</td>
<td>$^7Be$ (3/2-)</td>
<td>0.137</td>
<td>61.5</td>
<td>30.5</td>
<td>1.036</td>
<td>111.8</td>
<td>32.7</td>
</tr>
<tr>
<td>$^8B$ (2+)</td>
<td>$^7Be$ (1/2-)</td>
<td>0.566</td>
<td>52.7</td>
<td>22.5</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental setup

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- Angles and energies of both residual nucleus and proton measured: full kinematics
S800 Spectrograph

Focal plane detectors
Particle identification
Scattering angle and energy
of residual nucleus

Scattering chamber
188 mg/cm² ⁹Be target
HiRA detector array

Incoming ⁹C cocktail beam

Acceptances
• 5% momentum
• 20 mrad solid angle
  (± 3.5° × ± 5°)
HiRA detector array

- 10 telescopes covering scattering angles between 10° and 60°
- Each telescope composed of $32 \times 32$ DSSD Silicon detectors, followed by 4 CsI crystals
- Digital electronics located inside the scattering chamber
Proton detection angular coverage

- Efficiency determined from Monte-Carlo simulation using a lookup table to take missing or bad channels into account.
Particle identification in HiRA

- Events in coincidence with a $^8$B residual nucleus observed in the S800 focal plane
- Standard E-$\Delta$E plot
Residual nucleus momentum distributions

- **Inclusive distributions compared to eikonal calculation**
  - Several settings necessary to cover whole distribution
  - Eikonal calculation reproduces data very well except for low momentum tail

![Graph showing inclusive and eikonal distributions for different isotopes and momentum settings.](image)
Proton - residual nucleus coincidences

- **Evidence for elastic breakup reaction mechanism**
  - Diagonal “band” corresponds to elastic process where energy is conserved
  - For other events proton interacts inelastically with target
Energy sum spectra

- **Hint of experimental distinction between diffraction and stripping reaction mechanisms**

- **Width of sharp peak due to target thickness and momentum width of incoming radioactive beam (1% \( \Delta P/P \))**
Deuteron - residual nucleus coincidences

- *Must come from stripping events*
  - Additional neutron in deuteron comes from \((p,d)\) on \(^9\)Be target
  - Diagonal “band” previously observed in proton coincidences has disappeared

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**Diagram:**

- \(^8\)B+d coincidences from \(^9\)C
- \(^7\)Be+d coincidences from \(^8\)B
Energy sum spectra

- Sharp peak corresponding to diffraction reaction mechanism is absent in residual nucleus + deuteron coincidences
Contributions from each reaction mechanism

- Take all particles in coincidence (not just protons)
- Assume sharp peak corresponds to diffraction
- Double Gaussian fit
Comparison to eikonal theory

- Eikonal prediction follows data both in trend and absolute value
  - Assumed angular distributions for stripping and diffraction are similar
  - Agrees with previous work by Enders et al., although error bars very large due to transmission method used

Comparison with Continuum Discretized Coupled Channel (CDCC) calculations in progress

- Study characteristics of diffraction reaction mechanism

Conclusions and prospects
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  - Interpretation of observed features require careful comparison with more refined theory such as CDCC calculations for diffraction
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- **Next step: test of two-proton knockout reaction theory**
  - Diffraction/Stripping combined channel can account for up to ~ 50% of cross section
  - Use same experimental setup: S800 + HiRA
  - Study well known case of two-proton knockout on $^{28}$Mg to populate final states in $^{26}$Ne for which branching ratios were already measured
Credits

- **S800 team**
  - D. Bazin, A. Gade, A. Obertelli, R. Terry, S. Mcdaniels

- **HiRA group**