Direct reactions and nuclear spectroscopy; forward into the 21st century

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Introduction

• Direct Reactions, an essential spectroscopic tool:
  • Selectivity: single particle states; level energy and spin via matching
  • Access to **unbound** states and **nuclei** (driplines and beyond)

• Basic experimental information:
  • Spectra: level energies (and widths for unbound states)


• Angular distributions: transferred $\ell$, spectroscopic factors
  • via analysis; needs a **model** of the reaction …
Analysis Tools

- **Butler Theory** (S.T. Butler, Phys. Rev. **80** (1950) 1095)
  - Equivalent to plane wave Born approximation; gives transferred $\ell$

- **DWBA** (W. Tobocman, Phys. Rev. **115** (1959) 98)
  - Gives transferred $\ell$ and *spectroscopic factor* ($C^2S$)
  - Still useful in some cases: one-step reaction process, weak coupling
  - Important case where DWBA has known deficiencies: (d,p) stripping
  - Effect of deuteron breakup …

- **Coupled reaction channels**: strong transfer couplings
  - All couplings on same level; for multi-step paths and strong couplings
  - (Complex) redistributions of flux among channels:
Analysis Tools

  - Originally developed to describe deuteron breakup
  - More accurate treatment of breakup – discretisation of n-p continuum
  - Combine with CRC for (d,p), (p,d) reactions

- Can also be used for $^6\text{Li}$, $^7\text{Li}$, $^7\text{Be}$ – useful for e.g. $\alpha$-transfer reactions

- Coupling is a two-way process …
- Multi-step paths and strong couplings affect transfer cross sections
- Strong transfer couplings affect elastic (and inelastic) scattering …
Transfer coupling effects on elastic scattering

• First shown for (p,d,p): R.S. Mackintosh, Nucl. Phys. A209 (1973) 91
• Pickup: large spectroscopic factors: filled (sub) shells, sum rules
• $^8$He(p,d,p) particularly striking example: $Q = -0.36$ MeV; *well matched*
• Coupling scheme:
Transfer coupling effects on elastic scattering
An example with weaker coupling: $^{12}\text{C}(d,p)^{13}\text{C}$

- 12 MeV incident deuterons: Watanabe potential + CDCC
- Well-depth prescription for $n+^{12}\text{C}$ form factors
- Transfer couplings: CRC; remnant term + non-orthogonality correction
$^{12}\text{C}(d,p)^{13}\text{C}$

**Graphs and Data**

Graphs showing the angular distribution of the reaction $^{12}\text{C}(d,p)^{13}\text{C}$ for different states of $^{13}\text{C}$:

- $^{13}\text{C} 0.0 \text{ MeV} \ 1/2^-$
- $^{13}\text{C} 3.09 \text{ MeV} \ 1/2^-$
- $^{13}\text{C} 3.68 \text{ MeV} \ 3/2^-$
- $^{13}\text{C} 3.85 \text{ MeV} \ 5/2^-$

The graphs compare the results of CDCC + CRC calculations (solid line) with DWBA (dashed line). The data points are represented by circles.

**Equations**

- $\frac{d\sigma}{d\Omega}$
- $\theta_{\text{c.m.}}$ (deg)

**Energy Levels**

- $^{13}\text{C}$ at 0.0 MeV 1/2-
- $^{13}\text{C}$ at 3.09 MeV 1/2-
- $^{13}\text{C}$ at 3.68 MeV 3/2-
- $^{13}\text{C}$ at 3.85 MeV 5/2-
### Spectroscopic factors

<table>
<thead>
<tr>
<th>State</th>
<th>DWBA</th>
<th>CDCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2^-</td>
<td>0.80</td>
<td>0.88</td>
</tr>
<tr>
<td>1/2^+</td>
<td>1.06</td>
<td>0.91</td>
</tr>
<tr>
<td>3/2^-</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>5/2^+</td>
<td>0.70</td>
<td>0.83</td>
</tr>
</tbody>
</table>

\[ ^{12}\text{C(d,p)}^{13}\text{C} \]
Effect of reaction mechanism on structure information

- An extreme (?) example: $^8\text{He}(p,t)$
- We have seen that the $^8\text{He}(p,d)$ reaction is strong
- Two-step reaction path: $^8\text{He}(p,d)^7\text{He}(d,t)^6\text{He}$?

- 61.3 A.MeV: $^8\text{He}(p,t)$ to $^6\text{He}$ $0^+$ and $2^+$ similar magnitude

- DWBA $C^2S$ for $^8\text{He}(0^+)/^6\text{He}(0^+)$ and $^8\text{He}(0^+)/^6\text{He}(2^+)$?
- Korsheninnikov et al. – about equal
- 15.7 A.MeV data: about 2:1 in favour of $^8\text{He}(0^+)/^6\text{He}(0^+)$
- Supports supposition that reaction mechanism is not just direct transfer

- CRC calculation – coupling scheme:
Effect of reaction mechanism on structure information
Effect of reaction mechanism on structure information

\[ \frac{d\sigma}{d\Omega} \text{ (mb/sr)} \]

\[ \theta_{\text{c.m.}} \text{ (deg)} \]

Graph showing the variation of differential cross-section \( \frac{d\sigma}{d\Omega} \) with center-of-mass angle \( \theta_{\text{c.m.}} \) in degrees.
Effect of reaction mechanism on structure information

\[ \frac{d\sigma}{d\Omega} \text{ (mb/sr)} \]

\[ \theta_{\text{c.m.}} \text{ (deg)} \]

Plot showing the variation of cross-section with c.m. angle for different reaction mechanisms.
Effect of reaction mechanism on structure information

\[ \frac{d \sigma}{d\Omega} \text{ (mb/sr)} \]

\[ \theta_{\text{c.m.}} \text{ (deg)} \]

-10
-2
-1
0
10
100
101
102
103
104
105

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Effect of reaction mechanism on structure information

Spectroscopic factors for $^8\text{He}/^6\text{He}$ now **20:1** in favour of $^8\text{He}(0^+)/^6\text{He}(0^+)$ …

Good agreement with Korsheninnikov *et al.* data with *same* values

Reaction mechanism may be important …
Sources of uncertainty

- Perhaps the largest: bound state form factors
- Beyond the well-depth prescription? Use theoretical form factors?
- But, if they poorly describe e.g. binding energies?
- Distorting potentials in exit and entrance channels
- Constrain with measured elastic scattering where possible

- Non-locality effects: the “Perey effect”
- 10 – 20 % effect on spectroscopic factors
- Non-locality due to couplings included in CRC (to some extent)
- Non-locality due to exchange *not* included
- Should we correct for the effect in form factors?

- Reaction mechanism effects
- Require more structure information: too many parameters?
- need to be fixed by theory …
Processes not discussed …

- “Heavy particle stripping”: D. Robson, Nucl. Phys. 33 (1962) 594
- Only important for light “targets”: e.g. $^4\text{He}(d,p)^5\text{He}$ vs. $^4\text{He}(d,^5\text{He})p$

- Compound nucleus processes
  - Could be Important for lighter targets and in resonance regions
  - Will affect values extracted for spectroscopic factors …