Correlations probed in direct two-nucleon knockout reactions

Sixth Asia-Pacific Conference on Few-body Problems in Physics
7th April 2014

Ed Simpson
The Australian National University
Outline

• Context and Motivation
• Two-nucleon removal
  – Overview
  – Structure and spatial correlations
  – Momentum distributions
• Recent results
  – Reactions mechanism and core recoil
• Summary
Context and Motivation
$N = 20$

$N = 28$

$N = 50$

$\Delta S_{2n}(A) = S_{2n}(A) - S_{2n}(A-1)$

Light Exotic Nuclei
Nucleon knockout reactions (~100 MeV/nucleon)

Current facilities
GANIL (France)
NSCL@MSU (USA)
RIBF@RIKEN (Japan)

Under construction
FAIR@GSI (2020, Germany)
FRIB@MSU (2020, USA)
RISP (2017, Korea)

Light particle?

Level energies
Orbital AM
Spectroscopic factors

In very exotic nuclei

(A-1)Z
Single-nucleon removal reactions

Knockout reactions

- Energy >80 MeV/nucleon on a light nuclear target (Be, C)
- Ideally 200 MeV/u or greater
- Cross section 5-200 mb

Absolute cross sections

- Cross section proportional to spectroscopic strength
- Suppression of spectroscopic strengths in asymmetric systems

$$\sigma_{-1n} = \sum_{\beta} C^2 \beta S_\beta \sigma_{sp}$$

$$\beta \equiv (n\ell j)$$

Beam directional momentum distributions

- Width $\rightarrow$ angular momentum (final state spins, evolution of shell ordering)

Two-nucleon removal
Cross sections, momentum distributions and spatial correlations
The island of inversion

Bazin et al., PRL 91, 012501 (2003)
Gade et al., PRL 99, 072502 (2007)
Santiago-Gonzalez et al., PRC 83, 061305(R) (2011)
Taekuchi et al., PRL 109, 182501 (2012)
Doornenbal et al., PRL 111, 212502 (2013)
$^9\text{Be}(^{28}\text{Mg},^{26}\text{Ne}^*)X$

**$^{28}\text{Mg thresholds}$**

- Proton evaporation
- Neutron evaporation
- $1p$ knockout

$^{28}\text{Mg}$

$\rightarrow$ $^{27}\text{Na}$

$\pi^+ + 13.300$

$\nu^+ + 6.750$

$\nu^+ + 16.73$

$^{26}\text{Ne}$

$\nu^+ + 5.583$

$\nu^+ + 30.03$

$^{26}\text{Ne} [0^+, 2^+, 4^+]$

$\rightarrow$ $^{28}\text{Mg}$

$\nu^- + 8.503$

---

Tostevin et al., PRC 70, 064602 (2004)

Tostevin and Brown, PRC 74, 064604 (2006)
Two-nucleon knockout schematic

Impact parameter plane

Assumptions:

• Eikonal (straight-line) reaction dynamics
• Spectator-core (core states not coupled)
• Sudden (internal coordinates frozen)
• No-recoil (massive core)

Two-nucleon stripping (pure inelastic)

Stripping-diffraction (elastic and inelastic)

Two-nucleon diffraction (pure elastic)
Two-nucleon stripping

Two-nucleon stripping cross section

\[ \sigma_{ss}^{(f)} = \int d\vec{b} \int d\vec{s}_1 \int d\vec{s}_2 \quad O_{ss}(b_c, \vec{s}_1, \vec{s}_2) \quad P_{if}(\vec{s}_1, \vec{s}_2) \]

\[ O_{ss} = |S_c|^2 (1 - |S_1|^2)(1 - |S_2|^2) \]

S-matrix in the tpp approximation (density-folding model)

\[ S_c(b) = \exp \left( -\int dZ \int dr_p^s \int dr_t^s \rho_p(r_p) \rho_t(r_t) \ t_{NN}(|\vec{b} + \vec{Z} + \vec{r}_p - \vec{r}_t|) \right) \]

Joint position probability

\[ P_{if}(\vec{s}_1, \vec{s}_2) = \frac{1}{f_i} \sum_{M_i M_f} \int dz_1 \int dz_2 \langle \Psi_{if} | \Psi_{if} \rangle_{sp} \]

Hartree-Fock calculations used to constrain the radial size of BOTH the density distributions and overlap function

Simpson et al., PRL 102, 132502 (2009); PRC 79, 064621 (2009)
Two-nucleon overlap function

\[ \Psi_{if}(1, 2) = \langle \Phi_{J_f M_f(A)} | \Psi_{J_i M_i(A+2)} \rangle \]

\[ = \sum_{I \mu \alpha} C^{ifI}_{\alpha} (I \mu J_f M_f | J_i M_i) \left[ \phi_{\beta_1(1)} \otimes \phi_{\beta_2(2)} \right] I_{\mu} \]

(SM) Two-nucleon amplitudes (TNA)
Parentage amplitude for two-nucleon configuration \( \alpha \) and final state \( i \) in initial state \( i \)

\[ \alpha \equiv (\beta_1, \beta_2) \quad \beta \equiv (n \ell j) \]
**28Mg structure and cross sections**

**Shell model two-nucleon amplitudes**

Universal sd-shell (USD) **two-nucleon amplitudes** for different coherent **two-nucleon configurations** and **final states**

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$E^*$ (MeV)</th>
<th>$[0d_{3/2}]^2$</th>
<th>$[0d_{3/2}0d_{5/2}]$</th>
<th>$[0d_{5/2}]^2$</th>
<th>$[1s_{1/2}0d_{3/2}]$</th>
<th>$[1s_{1/2}0d_{5/2}]$</th>
<th>$[1s_{1/2}]^2$</th>
<th>$\Sigma TNA^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^+_1$</td>
<td>0.0</td>
<td>-0.30146</td>
<td>—</td>
<td>-1.04685</td>
<td>—</td>
<td>—</td>
<td>-0.30496</td>
<td>1.187</td>
</tr>
<tr>
<td>2$^+_1$</td>
<td>2.02</td>
<td>-0.05030</td>
<td>0.37358</td>
<td>-0.63652</td>
<td>-0.06084</td>
<td>-0.13916</td>
<td>—</td>
<td>0.570</td>
</tr>
<tr>
<td>4$^+_1$</td>
<td>3.50</td>
<td>—</td>
<td>0.33134</td>
<td>1.59639</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.658</td>
</tr>
<tr>
<td>2$^+_2$</td>
<td>3.70</td>
<td>0.04721</td>
<td>-0.07248</td>
<td>0.85297</td>
<td>0.16158</td>
<td>0.17590</td>
<td>—</td>
<td>0.792</td>
</tr>
</tbody>
</table>

**Measured** and **theoretical** cross sections for $^{28}$Mg(-2p), including suppression factor $R_s(2N)=0.5$.

Branching ratios very well reproduced

---

Tostevin *et al.*, PRC 70, 064602 (2004)
Spatial Correlations

$^{28}$Mg(-2p) using USD shell model TNA

Compared to uncorrelated calculations:
- $0^+$ enhanced by 70%
- $4^+$ suppressed by 23%

Pinkston, PRC 29, 1123 (1984); Insolia et al., J. Phys. G 15, 1249 (1989);
Momentum distributions

$^{28}\text{Mg}(-2p)$

$S_p = 16.8 \text{ MeV}$
$S_n = 8.5 \text{ MeV}$

Beam energy
$E = 82.3 \text{ A MeV}$

Broadening in thick reaction target
$^9\text{Be} 375 \text{ mg/cm}^2$
$\Delta K_A = 0.29 \text{ GeV/c}$

Counts

$^{0+}$
$K_A (\text{GeV/c})$

$^{4+}$
$K_A (\text{GeV/c})$

Bazin et al., PRL 91 012501 (2003); Simpson et al., PRL 102, 132502 (2009)
Recent results

Reaction mechanisms and core recoil
$^{28}\text{Mg}(-2\text{p})$: Reaction mechanisms in 2KO

**Missing mass spectrum for $^{26}\text{Ne}+2\text{p}$**

Peak at $M(^9\text{Be})$ is elastic breakup, the rest a mixture of inelastic and elastic mechanisms

<table>
<thead>
<tr>
<th></th>
<th>diff</th>
<th>diff-str</th>
<th>str</th>
<th>tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{obs}}$ (mb)</td>
<td>0.07(2)</td>
<td>0.27(14)</td>
<td>0.54(14)</td>
<td>0.88(2)</td>
</tr>
<tr>
<td>$\sigma_{\text{extr}}$ (mb)</td>
<td>0.11(3)</td>
<td>0.44(23)</td>
<td>0.87(23)</td>
<td>1.43(5)</td>
</tr>
<tr>
<td>fraction (%)</td>
<td>8(2)</td>
<td>31(16)</td>
<td>61(16)</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{inc}}$ (mb)</td>
<td></td>
<td></td>
<td></td>
<td>1.475(18)</td>
</tr>
<tr>
<td>$\sigma_{\text{theo incl.}}$ (mb)</td>
<td>0.19</td>
<td>1.13</td>
<td>1.70</td>
<td>3.02</td>
</tr>
<tr>
<td>$\sigma_{\text{theo } R_S(2\text{N})}$ (mb)</td>
<td>0.09</td>
<td>0.55</td>
<td>0.83</td>
<td>1.475</td>
</tr>
<tr>
<td>fraction$_{\text{theo}}$ (%)</td>
<td>6.3</td>
<td>37.4</td>
<td>56.3</td>
<td></td>
</tr>
</tbody>
</table>

Agreement within (large) experimental uncertainties

Wimmer et al., PRC 85, 051603(R) (2012)
Stripping-diffraction: core recoil

The no-recoil (heavy core) approximation:

\[ \bar{b}_1 = \bar{b} + \bar{s}_1 \]

No-recoil \[ \sigma_{2N-NR} > \sigma_{2N} \] Including core-recoil

Breakup through core-recoil
Reaction mechanisms: NR vs. FR in $^{28}\text{Mg}$(-2p)

Inclusive cross sections and mechanism-fractions

<table>
<thead>
<tr>
<th>$\sigma_{\text{exp}}$</th>
<th>$dd$</th>
<th>$ds$</th>
<th>$ss$</th>
<th>$\text{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.11(3)</td>
<td>0.44(23)</td>
<td>0.87 (23)</td>
<td>1.43(5)</td>
</tr>
<tr>
<td>$\sigma_{\text{th \ (NR)}}$</td>
<td>0.188</td>
<td>1.130</td>
<td>1.706</td>
<td>3.025</td>
</tr>
<tr>
<td>$\sigma_{\text{th \ (FR)}}$</td>
<td>0.135</td>
<td>0.958</td>
<td>1.706</td>
<td>2.798</td>
</tr>
<tr>
<td>$b_{\text{exp \ (%)}}$</td>
<td>8(2)</td>
<td>31(16)</td>
<td>61(16)</td>
<td></td>
</tr>
<tr>
<td>$b_{\text{th \ (NR \ (%))}}$</td>
<td>6.2</td>
<td>37.4</td>
<td>56.3</td>
<td></td>
</tr>
<tr>
<td>$b_{\text{th \ (FR \ (%))}}$</td>
<td>4.8</td>
<td>34.2</td>
<td>61.0</td>
<td></td>
</tr>
</tbody>
</table>

Improvement (modest) in the calculated ss and ds branches

- $ss$: $b_{\text{th \ (FR)}} - b_{\text{th \ (NR)}} = +4.7\%$
- $ds$: $b_{\text{th \ (FR)}} - b_{\text{th \ (NR)}} = -3.2\%$
- $dd$: $b_{\text{th \ (FR)}} - b_{\text{th \ (NR)}} = -1.4\%$

Wimmer et al., PRC 85, 051603(R) (2012)
Simpson (in preparation)
# $^{28}\text{Mg}(-2p)$ final-state-exclusive cross sections

<table>
<thead>
<tr>
<th>State</th>
<th>$\sigma_{ss}$</th>
<th>$\sigma_{ds}$</th>
<th>$\sigma_{dd}$</th>
<th>$\sigma_{tot}$</th>
<th>$\sigma_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_1$</td>
<td>0.633</td>
<td>0.465</td>
<td>0.085</td>
<td>1.183</td>
<td>0.70(15)</td>
</tr>
<tr>
<td>$2^+_1$</td>
<td>0.180</td>
<td>0.121</td>
<td>0.020</td>
<td>0.322</td>
<td>0.09(15)</td>
</tr>
<tr>
<td>$4^+_1$</td>
<td>0.586</td>
<td>0.374</td>
<td>0.060</td>
<td>1.020</td>
<td>0.58(9)</td>
</tr>
<tr>
<td>$2^+_2$</td>
<td>0.252</td>
<td>0.170</td>
<td>0.029</td>
<td>0.450</td>
<td>0.15(9)</td>
</tr>
<tr>
<td>Total</td>
<td>1.651</td>
<td>1.130</td>
<td>0.194</td>
<td>2.975</td>
<td>1.50(10)</td>
</tr>
</tbody>
</table>

Recoil effects depend on the state

- $0^+ = -21\%$
- $4^+ = -5\%$
- Total = -14\%

Total cross sections = -7\%

- $R_s(\text{NR})=0.50(3)$
- $R_s(\text{FR})=0.54(4)$
$[d_{5/2}]^2$ unit normalised overlaps

$$S_c A_s S_d \rightarrow S_c A_s S_d - S_c^{(1)} A_s^{(1)}$$

- Empty = 0
- Filled = 4

Cross section, $ds1$ (mb)

Projectile mass ($A_c+2$)
Conclusions
Two-nucleon removal

- Key tool for studying the structure of exotic nuclei
  - Efficient access to basic nuclear spectroscopy
  - Sensitive to structure and two-nucleon spatial correlations
  - In specific cases, structure (configuration mixing) effects evident in momentum distributions

Mechanisms and recoil

- New calculations in good agreement with observed reaction mechanism branches (within large errors)
- High precision tests (with $\gamma$s) required, with best test:
  - High J in light nuclei
  - Low J in heavier nuclei
Thanks for listening