Direct Reactions for Nuclear Spectroscopy


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Focus is: using two recent examples

1. Determining/tracking single particle structure (level ordering and their spectroscopic strengths) at/near the N and Z Fermi surface(s)

   Reaction mechanisms:

2. Pickup (nucleon addition) from light-heavy-ion targets (e.g. C) – make use of reaction mismatch

3. Removal/breakup (nucleon removal) – make use of Coulomb and nuclear breakup selectivity

4. Interface to reactions is via shell model (or more microscopic 1N-overlaps – spectroscopic strengths

5. Spectroscopy and structure information enhanced by exploiting multiple, complementary reactions
Single-particle spectroscopy near Fermi-surfaces

Reactions using fast radioactive beams

addition

intruder strength (e.g. g_{9/2})

removal

deformation and highly-admixed g.s. configurations

Reaction mechanisms can (should) be chosen to selectively populate states of interest
Representative recent examples:

**Ground-states of weakly-bound neutron rich systems**

$^{29}\text{Ne}(-n) \ [^{31}\text{Ne}(-n), \ ^{37}\text{Mg}(-n)]$

T. Nakamura et al., Tokyo Institute of Technology:
  N. Kobayashi et al., PRC *93*, 014613 (2016)
  T. Nakamura et al., PRL *112*, 142501 (2014)
  N. Kobayashi et al., PRL *112*, 242501 (2014)

**Structure of N=29 systems near Z=20**

$^{47}\text{Ar} \ [^{48}\text{K}(-p), \ ^{46}\text{Ar}(+n)], \ ^{49}\text{Ca} \ [^{48}\text{Ca}(+n)],$

A. Gade et al., NSCL, Michigan State University:
  A. Gade et al., PRC *93*, 031601(R) (2016)
  A. Gade et al., PRC *93*, 054315 (2016)
Fast nucleon removal, \( \sim 100 \text{ MeV/u and greater} \)

Inclusive with respect to the target final states. Gamma spectroscopy of core final states - plus the momentum distributions of these residues.

Cross sections are large and (as they probe the wave function at the surface) are relatively insensitive to the separation energy and orbital angular momentum – and so populate all available (hole-like) final states.
Coulomb dissociation - 100 MeV/u and greater

\[
\frac{d\sigma}{dE} \rightarrow \frac{dB(E_1, j', \ell')}{dE} = \frac{\mu_k}{\hbar^2} \left( \hat{j}_2 \right)^2 \left| \langle k, j', \ell' || E_1 || j \rangle \right|^2 \int dr \ r \ u_{j', \ell'}(k, r) u_{j, \ell}(r)
\]

Mechanism is highly sensitive to ground states with small orbital angular momentum and weak binding – well suited for spectroscopy of halo-like ground-states.
Nuclear and Coulomb breakup sensitivities

\[ {^{19}}\text{C} \rightarrow {^{18}}\text{C} + \text{n} \]

Can exploit the different sensitivities of the Coulomb and nuclear (elastic and inelastic) breakup reaction mechanisms to separation energies (and orbital angular momenta) of the removed nucleon to deduce major spectroscopic strength of ground state configurations - especially halo-like configurations.

V. Maddalena et al. PHYSICAL REVIEW C, VOLUME 63, 024613 (2001)
Nucleon pickup – populating particle-like states

Inverse kinematics – exotic beam on a light target – $^{12}$C, $^{9}$Be

$(T-1)^*\ [l^s j] \ A$

Inclusive wrt final states of the target-like fragment $(T-1)$. $T=12$, the final state is 2-body. Mismatched at ~60 MeV per nucleon - is useful.

A. Gade et al., PRC 83, 057304 (2011)

State of pickup residue using gamma-ray spectroscopy

The highly absorptive nature of the high-energy ion-ion (60-70 MeV/u) projectile-target interactions localize reactions at the surface – where nucleon wave functions are probed
Exploit high-\(\ell\) transition selectivity

\[^{48}\text{Ca}+n, 67\text{MeV/u}\]

![Graph showing single particle cross section vs. orbital angular momentum with specific notation and labels for different energy levels and cross sections.]

PHYSICAL REVIEW C 93, 031601(R) (2016)
Complementary mechanisms – $^{47}$Ar spectra

(a) $^{46}$Ar+1n
- 515\,(3)
- 1017\,(4)
- 1231\,(4)
- 1533\,(4)
- 1692\,(5)
- 1744\,(5)
- 3438\,(7)

(b) $^{48}$K-1p
- 1229\,(5)
- 516\,(5)
- 965\,(6)
- 1018\,(7)
- 1745\,(6)
- 2188\,(8)

Energy (keV)
Counts / 8 keV
Counts / 10 keV

Inset: coinc. with 1231 keV
Complementary mechanisms: $^{47}$Ar

PHYSICAL REVIEW C 93, 054315 (2016)
Shell-model interactions at N=29: Z=18
Positive-parity states of $^{49}$Ca (Utsuno)

- $9/2^+$ at 4.017 MeV
  - Spin-parity has been recently established (D. Montanari et al., Phys. Lett. B 697, 288 (2011)).
  - Probably the lowest positive-parity state
    - Low-spin states must be observed via the $b$ decay.
    - Without the sdg shell, $9/2^+$ is the highest among the multiplet.
    - A strong mixing with pf-to-sdg excitation associated only with $9/2^+$ accounts for the ordering.

<table>
<thead>
<tr>
<th>3/2$^+$</th>
<th>5/2$^+$</th>
<th>7/2$^+$</th>
<th>9/2$^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of sdg</td>
<td>% of sdg</td>
<td>% of sdg</td>
<td>% of sdg</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>7</td>
<td>51</td>
</tr>
</tbody>
</table>
Role of the g9/2 orbital at N=29 at Z=20
GRETTINA $\rightarrow ^{49}\text{Ca}$ spin-substate alignment

\[ \begin{align*} 
W(\theta_{\text{lab}})^{\text{iso}}_{\text{boosted}}/W(\theta_{\text{lab}})^{\text{iso}}_{\text{boosted}} 
\end{align*} \]

\[ \begin{align*} 
\theta_{\text{lab}} \text{ (deg)} 
\end{align*} \]

PHYSICAL REVIEW C 93, 031601(R) (2016)
Island of Inversion – the neutron-rich Ne isotopes

![Graph showing excitation energy and neutron number for Ne isotopes](image)
## Cross sections – ground- and excited-states

<table>
<thead>
<tr>
<th></th>
<th>$^{29}$Ne: $J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$3/2^+$</td>
</tr>
<tr>
<td>$\sigma_{-1n}(E1)$ (mb)</td>
<td></td>
</tr>
<tr>
<td>$^{28}$Ne($0^+_1$)</td>
<td>48.0</td>
</tr>
<tr>
<td>$^{28}$Ne*</td>
<td>92.4</td>
</tr>
<tr>
<td>Inclusive</td>
<td>140.3</td>
</tr>
<tr>
<td>g.s. fraction</td>
<td>34%</td>
</tr>
</tbody>
</table>

|                | $3/2^+$  | $3/2^-$  | $7/2^-$  | $1/2^+$  | Expt.      |
|----------------|---------------------|
| $\sigma_{-1n}^{th}$ (mb) |          |          |          |          |            |
| $^{28}$Ne($0^+_1$)       | 13.25    | 31.60    | 15.87    | 2.71     | 36(7)      |
| $^{28}$Ne*               | 49.82    | 37.41    | 32.24    | 52.41    | 38(7)      |
| Inclusive              | 63.07    | 69.01    | 48.11    | 55.13    | 74(2)      |
| g.s. fraction          | 21%      | 46%      | 33%      | 5%       | 49(9)%     |
Complementary – Coulomb/nuclear
Momentum distributions also add consistency

![Graph showing momentum distributions for different angular momenta](image)
Halo-components in heavier n-rich systems: $^{31}$Ne

T. Nakamura et. al.

$\sigma_{1n}(E1; 0^+_1)/\sigma_{SP}(E1; n\ell j)$

PRL 112, 142501 (2014)
### 31Ne: configuration mixing – spherical basis

<table>
<thead>
<tr>
<th>Shell-model configuration</th>
<th>( \sigma_{-1n}(C) ) (mb)</th>
<th>SM(i)</th>
<th>WBMB</th>
<th>SM(ii)</th>
<th>SDPF-M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C^2 S )</td>
<td>( \sigma_{-1n}^{th}(C) ) (mb)</td>
<td>( C^2 S )</td>
<td>( \sigma_{-1n}^{th}(C) ) (mb)</td>
<td></td>
</tr>
<tr>
<td>( C^{(31}\text{Ne}(3/2^-),^{30}\text{Ne}) )</td>
<td>33(15)</td>
<td>0.080</td>
<td>9.2</td>
<td>0.21</td>
<td>24.3</td>
</tr>
<tr>
<td>( ^{30}\text{Ne}(0^+<em>1) \otimes 2p</em>{3/2} )</td>
<td></td>
<td>0.21</td>
<td>14.4</td>
<td>0.34</td>
<td>21.4</td>
</tr>
<tr>
<td>( ^{30}\text{Ne}^* \otimes 2p_{3/2} )</td>
<td></td>
<td>1.36</td>
<td>32.9</td>
<td>0.80</td>
<td>18.8</td>
</tr>
<tr>
<td>( ^{30}\text{Ne}^* \otimes 1f_{7/2} )</td>
<td></td>
<td>90(7)</td>
<td>58.3</td>
<td></td>
<td>93.3</td>
</tr>
<tr>
<td>Inclusive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C^{(31}\text{Ne}(1/2^+),^{30}\text{Ne}) )</td>
<td>33(15)</td>
<td>0.011</td>
<td>1.3</td>
<td>0.011</td>
<td>1.3</td>
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<tr>
<td>( ^{30}\text{Ne}(0^+<em>1) \otimes 2s</em>{1/2} )</td>
<td></td>
<td>0.76</td>
<td>16.2</td>
<td>0.55</td>
<td>12.8</td>
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<tr>
<td>( ^{30}\text{Ne}^* \otimes 1d_{3/2} )</td>
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<td>90(7)</td>
<td>18.1</td>
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<td>51.1</td>
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<tr>
<td>Inclusive</td>
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T. Nakamura et. al.  
*PRL 112, 142501 (2014)*
Halo-component in heavier n-rich system: $^{37}$Mg

N. Kobayashi et al.
PRL 112, 242501 (2014)

$$\sigma_{-1n}(E1; 0^+_1)/\sigma_{SP}(E1; n\ell j)$$

SDPF - M + $p_{1/2}$

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\sigma_{SP}$ (mb)</th>
<th>$C^2S$</th>
<th>$\sigma_{ln}^{th}$ (C) (mb)</th>
<th>$\sigma_{-1n}$ (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C[^{37}$Mg$(3/2^-), ^{36}$Mg]$</td>
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<td></td>
<td></td>
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<tr>
<td>$^{36}$Mg$(0^+<em>1) \otimes 2p</em>{3/2}$</td>
<td>89.4</td>
<td>0.31</td>
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<tr>
<td>$^{36}$Mg$^* \otimes 2p$</td>
<td></td>
<td>0.47</td>
<td>17.4</td>
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<tr>
<td>$^{36}$Mg$^* \otimes 1f$</td>
<td></td>
<td>1.35</td>
<td>23.0</td>
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</tr>
<tr>
<td>Inclusive</td>
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<tr>
<td>$C[^{37}$Mg$(1/2^-), ^{36}$Mg]$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$^{36}$Mg$(0^+<em>1) \otimes 2p</em>{1/2}$</td>
<td>88.1</td>
<td>0.20</td>
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<tr>
<td>$^{36}$Mg$^* \otimes 2p$</td>
<td></td>
<td>0.44</td>
<td>17.4</td>
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<tr>
<td>$^{36}$Mg$^* \otimes 1f$</td>
<td></td>
<td>1.80</td>
<td>28.4</td>
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<tr>
<td>Inclusive</td>
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<tr>
<td>$C[^{37}$Mg$(1/2^+), ^{36}$Mg]$</td>
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<tr>
<td>$^{36}$Mg$(0^+<em>1) \otimes 2s</em>{1/2}$</td>
<td>95.3</td>
<td>0.001</td>
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<td>$^{36}$Mg$^* \otimes 1d$</td>
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<td>0.85</td>
<td>15.7</td>
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<td>5.1</td>
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<tr>
<td>$^{36}$Mg$^* \otimes 1f$</td>
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<td>1.00</td>
<td>15.4</td>
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</tr>
<tr>
<td>Inclusive</td>
<td></td>
<td></td>
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<td>37.0</td>
</tr>
</tbody>
</table>

240 MeV/u
Summary

Tracking of single particle structure (level ordering and spectroscopic strengths) at and near the N and Z Fermi surface(s) can be advanced using:

- **Pickup** (nucleon addition) reactions from light-heavy-ion targets (C works well) – *exploiting mismatch*
- **Removal/breakup** (nucleon removal) – exploiting Coulomb/nuclear *breakup mechanism selectivity*
- Shell-model interface with reactions allows a detailed *assessment of calculations/interactions*
- Deduced spectroscopy and structure information is enhanced using multiple, *complementary* reactions