Shapes, Coexistence, and Shell Closures
Towards the Limits: Exploring the Nature of Nucleon Interactions

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Physics Division – Oak Ridge National Laboratory
August 2, 2017

*The following slides represent a partial view of nuclear structure.
Opening Statements

• HRS will not be available on Day 1 and primary beam intensity will be < 3% ; this will limit our reach. Must degrade the beam energy for the S800 ( ≤ 50% loss ); furthest reach on Day 1 will be with fast beams + decay and, in some cases, knockout.
  ➢ Need versatile Decay Station on Day 1 and HRS + GRETA + FRIB expedited.

• Many of the interesting E(2⁺) values will have been measured by Day 1; there will be competition (e.g., RIKEN).
  ➢ In these cases, focus on where detailed spectroscopy can be done for first time but keep a lookout for unique circumstances/opportunities.

• Stopped and ReA beams offer an opportunity for the most detailed spectroscopy but the beams will be less exotic and many of the traditional decay and reaction methods require relatively pure beams.
  ➢ Need firm grasp on beam contamination; new techniques and detectors may need development if purity is nominally < 50%.

• There is only one GRET(IN)A, which must be shared between Fast and ReA beams.
  ➢ A second array may be needed for ReA at times (e.g., CLARION2 will be ready for campaigns).

• Many γ-ray transitions of interest (e.g., seniority isomers) and x-rays will be low energy.
  ➢ Need some HPGe with high efficiency at 20-200 keV (e.g., BEGe), particularly when expanding to heavier nuclei.
Regions of Interest (partial)

Many opportunities for both exploration and detailed spectroscopy towards the driplines

Explore N=Z interactions and shape coex.

Search for triaxial and oblate shapes

Explore shell closures, s.p. states, isomers, shape coexistence, emergence of collectivity, n skins, nucleon interactions, ....
Shapes, Coexistence, and Shell Closures Towards the Limits

In a Nutshell:
Study the most exotic nuclei in circles by fast beams (e.g., decay, knockout) and everything in-between with stopped and ReA beams (e.g., decay, Coulex, direct reactions).
Shapes, Coexistence, and Shell Closures Towards the Limits

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Recall that some of these exotic nuclei may be studied directly via isomer decay, e.g., 8+ seniority isomers 56,58,60Ca, 98Sn, 218-226Pb.
Example Storylines and Experiments For Day 1 FRIB

(FAST pps)
(ReA pps)
(Stopped pps)
N=20 and 28 Shell Closures

*calculated values with the SDPF-U-MIX interaction.

N=20 2p-2h Systematics

1p-2h + 2p-1h → 2p-2h Correlation

N=20
*same info is needed for N=28

33Mg 2p-1h:
1n ko with 34Mg (4E4)
Safe Coulex (2E4)
t,p) with 31Mg (8E5)
Decay with 33Na (1E3)
Decay-n with 34Na (1E2)

30Ne 0p-0h:
2n ko with 32Ne (3E1)

29Ne 1p-2h:
2n ko with 31Ne (3E2)
Fast Coulex (2E4)
Decay with 29F (5E1)

31Ne 2p-1h:
1n ko with 32Ne (3E1)
Fast Coulex (3E2)

Ca (Z=20) Isotopes
Ca (Z=20) Isotopes: Test of 3N Forces

*3N calculations to be updated

*J.D. Holt, Private Communication (2017).
Ca (Z=20) Isotopes

*E(2+) not sufficient indicator of subshell closure if J=1/2 is near Fermi Surface. G.S. may be depressed from strong mixing.
Ca Region: Ideal Day 1

**B(E2):**
- $^{54}\text{Ca}$ to $^{54}\text{Ca}$: 2.64E+2 Fast Coulex
- $^{55}\text{Sc}$ to $^{55}\text{Sc}$: 5.87E+3 1p knockout
- $^{56}\text{Ti}$ to $^{56}\text{Ti}$: 9.68E+4 2p knockout
- $^{52}\text{Ca}$ to $^{52}\text{Ca}$: 1.24E+4 Fast Coulex
- $^{53}\text{Sc}$ to $^{53}\text{Sc}$: 5.87E+3 1p knockout
- $^{54}\text{Ti}$ to $^{54}\text{Ti}$: 2.15E+6 2p knockout
- $^{36}\text{Ca}$ to $^{36}\text{Ca}$: 9.60E+3 Fast Coulex

**Q(2) and precise B(E2):**
- $^{50}\text{Ca}$: 4.69E+4 Coulex
- $^{38}\text{Ca}$: 9.19E+4 Coulex

**E&M g.s. Moments:**
- $^{53}\text{Ca}$: 5.13E+02 Laser / βNMR

**E(2) and B(E2) at N=40:**
- $^{62}\text{Ti}$: 4.25E+1 1p Knockout

**g9/2 Seniority Isomers?**
- $^{60}\text{Ca}$: 1.32E-3 Decay
- $^{58}\text{Ca}$: 6.52E-2 Decay
- $^{56}\text{Ca}$: 4.33E+0 Decay

**GT Strength Distributions:**
- $^{60}\text{Ca}$: 1.32E-3 Decay
- $^{54}\text{Ca}$: 6.83E+1 Decay
- $^{52}\text{Ca}$: 4.92E+3 Decay
Ca Region: Ideal Day 1

<table>
<thead>
<tr>
<th>E(0_2)?</th>
<th>54Ca</th>
<th>54K</th>
<th>1.04E+0</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>55K</td>
<td>1.18E-1</td>
<td>Decay-n</td>
<td></td>
<td></td>
</tr>
<tr>
<td>56Ti</td>
<td>9.68E+4</td>
<td>2p knockout</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2p-1h and 1p-2h:

<table>
<thead>
<tr>
<th>55Sc</th>
<th>56Sc</th>
<th>9.04E+2</th>
<th>1p knockout</th>
</tr>
</thead>
<tbody>
<tr>
<td>55Ca</td>
<td>3.46E+1</td>
<td>5.93E-1</td>
<td>Decay</td>
</tr>
<tr>
<td>56Ca</td>
<td>4.33E+0</td>
<td>4.80E-1</td>
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<tr>
<td>53K</td>
<td>5.87E+3</td>
<td>2p knockout</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>53Ar</th>
<th>2.64E-2</th>
<th>Decay</th>
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<tbody>
<tr>
<td>54Ar</td>
<td>3.07E-3</td>
<td>Decay-n</td>
</tr>
</tbody>
</table>

s.p. states:

<table>
<thead>
<tr>
<th>51Ca</th>
<th>56Ca</th>
<th>4.69E+4</th>
<th>(d,p), (α, 3He)</th>
</tr>
</thead>
<tbody>
<tr>
<td>52Ca</td>
<td>1.24E+4</td>
<td>1n knockout</td>
<td></td>
</tr>
<tr>
<td>51K</td>
<td>5.87E+2</td>
<td>2.14E+2</td>
<td>Decay</td>
</tr>
<tr>
<td>52K</td>
<td>7.50E+1</td>
<td>2.16E+1</td>
<td>Decay-n</td>
</tr>
<tr>
<td>53Ca</td>
<td>54Ca</td>
<td>2.64E+2</td>
<td>1n knockout</td>
</tr>
<tr>
<td>53K</td>
<td>8.99E+0</td>
<td>1.13E+0</td>
<td>Decay</td>
</tr>
<tr>
<td>54K</td>
<td>1.04E+0</td>
<td>1.30E-2</td>
<td>Decay-n</td>
</tr>
<tr>
<td>55Ca</td>
<td>56Ca</td>
<td>4.33E+0</td>
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<tr>
<td>55K</td>
<td>1.18E-1</td>
<td>Decay</td>
<td></td>
</tr>
<tr>
<td>56K</td>
<td>1.40E-2</td>
<td>Decay-n</td>
<td></td>
</tr>
</tbody>
</table>
N=49 1p-2h Systematics Near $^{78}$Ni

Bands have been clearly established for Ge/Se but not others

$^{78}$Ni

<table>
<thead>
<tr>
<th>$^{77}$Ni</th>
<th>$^{77}$Co</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.34E-2</td>
<td>Decay</td>
</tr>
<tr>
<td>$^{78}$Co</td>
<td>5.56E-4</td>
<td>Decay-n</td>
</tr>
<tr>
<td>$^{78}$Cu</td>
<td>1.57E+2</td>
<td>1p knockout</td>
</tr>
<tr>
<td>$^{79}$Zn</td>
<td>3.56E+3</td>
<td>2p knockout</td>
</tr>
</tbody>
</table>

*E(0_2) < E(2_1) found recently in $^{80}$Ge

X. F. Yang et al., PRL 116, 182502 (2016)
Portal to the Fifth Island of Inversion

GT Strength:

<table>
<thead>
<tr>
<th></th>
<th>78Ni</th>
<th>78Co</th>
<th>76Fe</th>
<th>76Ni</th>
<th>76Co</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.39E-01</td>
<td>1.5E-01</td>
<td>3.81E-04</td>
<td>1.71E-4</td>
<td>5.56E-4</td>
</tr>
</tbody>
</table>

F. Nowacki et al., PRL 117, 272501 (2016)
Double-Magic N=Z

\[ \begin{array}{c|c|c}
9^+ & 11710 & 10^+ \\
10^+ & 11688 & 10^+ \\
8^+ & 9307 & 8^+ \\
7^+ & 8937 & 7^+ \\
5^+ & 7399 & 6^+ \\
6^+ & 6933 & 6^+ \\
4^+ & 6509 & 4^+ \\
3^+ & 6030 & 3^+ \\
2^+ & 5280 & 2^+ \\
1^+ & 5249 & 1^+ \\
0^+ & 5614 & 0^+ \\
5^+ & 4491 & 5^+ \\
4^+ & 3957 & 4^+ \\
3^+ & 3737 & 3^+ \\
2^+ & 3905 & 2^+ \\
1^+ & 3352 & 1^+ \\
0^+ & 3352 & 0^+ \\
\end{array} \]

\[ \begin{array}{c|c|c|c|c|c}
0^{+} & 0 & 0^{+} & 0 & 0^{+} & 0 \\
\end{array} \]

\[ \begin{array}{c|c|c}
^{40}\text{Ca} & ^{56}\text{Ni} & ^{100}\text{Sn} \\
\end{array} \]

\[^{100}\text{Sn} \quad 2.05E-1 \quad \text{Decay} \]
\[^{101}\text{Sn} \quad 8.60E+0 \quad 1\text{n knockout} \]
\[^{102}\text{Sn} \quad 3.80E+2 \quad 2\text{n knockout} \]

\[ ^{100}\text{Sn} \quad 0^+_2 \text{ near or below } 2^+_1 ? \]

\[ ^*E(0^+_2) < E(2^+_1) \text{ for } ^{16}\text{O}, ^{40}\text{Ca} \]

Standard feature for double-magic N=Z nuclei?

Soft $^{100}\text{Sn}$ Core?

E&M Moments and S.P. States

**E&M Moments:**

<table>
<thead>
<tr>
<th>Mass Number</th>
<th>B(E2; 0_1^+ → 2_1^+) (e^2b^2)</th>
</tr>
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<tbody>
<tr>
<td>$^{102}\text{Sn}$</td>
<td>3.80E+2</td>
</tr>
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<td>$^{104}\text{Sn}$</td>
<td>1.68E+4</td>
</tr>
<tr>
<td>$^{106}\text{Sn}$</td>
<td>5.78E+5</td>
</tr>
<tr>
<td>$^{108}\text{Sn}$</td>
<td>1.88E+6</td>
</tr>
<tr>
<td>$^{110}\text{Sn}$</td>
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1n knockout

(d,t), ($^3\text{He}$, $\alpha$)

(d,p), ($\alpha$, $^3\text{He}$)

(d,t), ($^3\text{He}$, $\alpha$)

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