Experiment e06006

Precise study of the diffractive components in two-proton knockout reactions
Two-proton knockout on neutron-rich nuclei

- Direct process
  - Path through sequential process energetically forbidden
  - See J. A. Tostevin et al., PRC 70, 064602 (2004)
- Spectroscopic information can be obtained from this type of reaction
  - Reaction drives towards more neutron-rich species

FIG. 2. Energy diagram of the neutron-rich $N=16$ isotones $^{28}$Mg, $^{27}$Na, and $^{26}$Ne, showing the single-neutron ($\nu$) and proton ($\pi$) separation energies for each nucleus. The diagram shows that nondirect population of the bound states of $^{26}$Ne, by one-proton removal to excited $^{27}$Na followed by proton evaporation, would involve states high above the (much lower) neutron evaporation threshold and so is expected to be negligible.
Knockout reactions

- Surface dominated collision with a light target
  - Stripping or inelastic breakup: removed nucleon absorbed - target is excited or even broken
  - Diffraction or elastic breakup: removed nucleon elastically scattered - target stays in its ground state
  - Heavy residue detected at forward angles
  - Residue final state measured from in-flight $\gamma$-ray decay

- Fast projectile
  - Momentum of residue directly related to momentum of removed nucleon
  - Longitudinal momentum free of Coulomb deflection and diffractive scattering, directly related to angular momentum of removed nucleon
  - Sudden/adiabatic approximation and eikonal model
Previous experiment: $^9$C and $^8$B

- Study of elastic and inelastic parts of cross section
  - One-proton knockout on $^9$C and $^8$B
  - HiRA array used in coincidence with S800
  - Clear kinematical differences between elastic and inelastic breakup
- Proportions calculated with eikonal model agrees with observations very well
- See D. Bazin et al., PRL 102, 232501 (2009)

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**Table 1**

<table>
<thead>
<tr>
<th>Proj.</th>
<th>$%_{\text{diff}}^a$</th>
<th>$%_{\text{diff}}^b$</th>
<th>$%_{\text{diff}}[9]$</th>
<th>$\sigma_{\text{th}}$ (mb)</th>
<th>$R_S^a$</th>
<th>$R_S[9]$</th>
<th>$R_S[11]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9$C</td>
<td>25(2)</td>
<td>26.8</td>
<td>26(10)</td>
<td>62.90</td>
<td>0.84(5)</td>
<td>0.82(6)</td>
<td>-</td>
</tr>
<tr>
<td>$^8$B</td>
<td>38(3)</td>
<td>37.1</td>
<td>28(14)</td>
<td>144.28</td>
<td>0.88(4)</td>
<td>0.86(7)</td>
<td>0.88(4)</td>
</tr>
</tbody>
</table>

$^a$This work
$^b$Calculated (from Table I)
Goal of experiment e06006

- Study proportions of elastic breakup in two-proton reaction
- 3 scenarios possible
  - Both protons removed inelastically
  - One proton elastically removed, the other not (times two)
  - Both protons elastically removed
- Eikonal model calculates cross sections for each scenario
  - Branching ratios already measured from experiment 01013 using S800+SeGA
  - Expected cross section for double diffraction channel: 0.1 mb

<table>
<thead>
<tr>
<th>$I^J$</th>
<th>$E$ (MeV)</th>
<th>$\sigma_{str}^{(f)}$</th>
<th>$\sigma_{str-diff}^{(f)}$</th>
<th>$\sigma_{diff}^{(f)}$</th>
<th>$\sigma_{diff}^{(f)}$</th>
<th>$\sigma_{expt}$ [4]</th>
<th>$R_{(2N)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}$Mg $\rightarrow ^{26}$Ne</td>
<td>83.2 MeV</td>
<td>0.00</td>
<td>0.63</td>
<td>0.47</td>
<td>0.09</td>
<td>1.19</td>
<td>0.70(15)</td>
</tr>
<tr>
<td>$2^+$</td>
<td>2.02</td>
<td>0.18</td>
<td>0.12</td>
<td>0.02</td>
<td>0.32</td>
<td>0.09(15)</td>
<td>0.28(47)</td>
</tr>
<tr>
<td>$4^+$</td>
<td>3.50</td>
<td>0.59</td>
<td>0.37</td>
<td>0.06</td>
<td>1.02</td>
<td>0.58(9)</td>
<td>0.57(9)</td>
</tr>
<tr>
<td>$2_1^+$</td>
<td>3.70</td>
<td>0.25</td>
<td>0.17</td>
<td>0.03</td>
<td>0.45</td>
<td>0.15(9)</td>
<td>0.33(20)</td>
</tr>
<tr>
<td>Incl.</td>
<td>2.98</td>
<td></td>
<td></td>
<td></td>
<td>2.98</td>
<td>1.50(10)</td>
<td>0.50(3)</td>
</tr>
<tr>
<td>$^{54}$Ti $\rightarrow ^{52}$Ca</td>
<td>72.0 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0^+$</td>
<td>0.00</td>
<td>0.21</td>
<td>0.58</td>
<td>0.03</td>
<td>0.38</td>
<td>0.21(3)</td>
<td>0.55(8)</td>
</tr>
</tbody>
</table>

- Table I. Calculated and measured two-proton knockout reaction partial cross sections $\sigma^{(f)}$ from $^{28}$Mg and $^{54}$Ti on a $^9$Be target showing their stripping, $\sigma_{str}^{(f)}$, stripping-diffraction, $\sigma_{str-diff}^{(f)}$, and diffraction, $\sigma_{diff}^{(f)}$, components. All cross sections are in mb. $R_{(2N)} = \sigma_{expt}/\sigma^{(f)}$ is the ratio of the experimental and the theoretical total partial cross section $\sigma^{(f)}$. 

$0.84 \quad 0.58 \quad 0.1$
Experimental setup

- **S800**
  - Collect and identify $^{26}$Ne residues
  - Two rigidity settings necessary to cover full parallel momentum distribution

- **HiRA**
  - Detect high energy protons in coincidence
  - Use $\Delta E - E$ with DSSD + CsI to identify protons
  - Angular coverage between 10° and 50°, by moving target forward 15 cm (3 holes on table)
Rate estimation

- **Target thickness compromise**
  - Increase reaction rate - reduce energy broadening due to differential energy loss
  - Choice: $^9$Be 100 mg/cm$^2$
  - Differential energy loss between $^{28}$Mg and $^{26}$Ne: 22 MeV (similar to width obtained during the $^9$C experiment)

- **Expected rate**
  - Expected rate of $^{28}$Mg radioactive beam on target: $3.10^5$ pps
  - Expected rate for double diffraction channel (cross section of 0.1 mb): 0.2 pps
  - Solid angle efficiency of HiRA for two protons: $\sim 5\%$ (need real value for new geometry)
  - Rate for double diffraction events: 36 / hour
  - 72 hours give about 2,500 counts
Precise measurement on one-proton knockout

- Use thin $^9$Be target (9 mg/cm$^2$)
  - Reduce width of diffraction peak to $\sim$ 1 MeV
  - Eikonal calculation of one-proton knockout cross section to $^{27}$Na g.s. (remove valence proton from d$_{5/2}$ orbital)
    - Stripping (inelastic): 10.9 mb
    - Diffraction (elastic): 2.4 mb

- Rate estimation
  - Diffraction channel: 0.5 pps
  - HiRA solid angle efficiency: $\sim$ 20%
  - Estimated rate for diffraction events: 360 / hour
  - 12 hours give about 4,000 counts
## Experiment planning

<table>
<thead>
<tr>
<th>Goal</th>
<th>Beam</th>
<th>Target</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrate CsI</td>
<td>$^1$H</td>
<td>$^{197}$Au 20 mg/cm$^2$</td>
<td>6 hours</td>
</tr>
<tr>
<td>one-proton knockout</td>
<td>$^{28}$Mg</td>
<td>$^9$Be 9 mg/cm$^2$</td>
<td>12 hours</td>
</tr>
<tr>
<td>two-proton knockout</td>
<td>$^{28}$Mg</td>
<td>$^9$Be 100 mg/cm$^2$</td>
<td>72 hours</td>
</tr>
</tbody>
</table>
To-Do list

- Scattering chamber configuration
  - Remove MCP detectors and collimators
  - Move target drive downstream by 15 cm (3 holes on table)
  - Mount targets and target ladder
  - Position camera for new target location and check image
  - Check target drive control

- Trigger
  - Need OR from DSSD for coincidence (good timing)
  - Trigger in S800 trigger box (FPGA) sent back to HiRA electronics
To-Do list (continued)

• **Readout**
  • Same readout code as for previous experiments e07037 and e06035
  • HiRA readout with only DSSD + CsI
  • Install software on account e06006 (readout, SpecTcl, eLog)
  • Test it! (beware of recent upgrades from computer department)

• **Run organization**
  • Read and acknowledge experimenter responsibilities
  • Need one HiRA specialist and one S800 specialist per shift
  • Sign up for shifts in Data-U6