Study of unbound nuclei $^{33}\text{Ne}$ via $1p$ knock-out reactions

Hyunwoo Chae
Seoul National University
SAMURAI S027 Collaboration
- $N = 20$ shell gap is vanishing for Ne, Na, Mg isotopes.
- The $pf$ shell intrude into the $sd$ shell at $N = 20$, leading to vanishing of shell gap.
**Island of inversion of Ne**

- In case of even Ne isotopes, very low $E(2^+)$ at $N = 20, 22$ suggest that $^{30,32}$Ne belongs to the island of inversion.
- $^{30}$Ne $\otimes 2p_{3/2}$ configuration of $^{31}$Ne ground state is evidence of the island of inversion.
- Spectroscopic study of $^{33}$Ne is expected to broaden the understanding of island of inversion.

![Graph showing $E(2^+)$ in and Ne isotopes ($N = \text{even}$)](P. Doornenbal et al., PRL 103, 032501 (2009))

![Graph comparing $\sigma$ results of $^{31}$Ne compared with calculation](T. Nakamura et al., PRL 103, 262501 (2009))
- It is known that $^{33}$Ne is an unbound nucleus.
- The mass of $^{33}$Ne can be obtained by measurement of $S_n$.
- AME2012 predicts $S_n$ to be -0.9 MeV.
Experimental setup (BigRIPS)

- S027 experiment

Primary beam:
- $^{48}$Ca
- 345 MeV/u

Primary target:
- 20 mm Be

Secondary beam:
- F, Ne, Na…
Experimental setup (SAMURAI)

- S027 experiment
- Secondary beam: $^{34}\text{Na}$
- Secondary target: 12 mm C
- C($^{34}\text{Na}$, $^{33}\text{Ne}^*$)
- Proton knockout reaction
Procedure of analysis

1. Select the $^{34}$Na beam.
   - Beam PID using $B_\rho$-$\Delta E$-TOF method

2. Select the $^{32}$Ne & $n$ fragments.
   - Charged fragment PID using $B_\rho$-$\Delta E$-TOF method
   - Neutron selection with $1n$ coincidence

3. Reconstruct relative energy ($E_{rel}$) spectrum.
   - Invariant mass method from 4-momenta of fragments
   - Neutron detector efficiency & geometrical acceptance
Beam analysis

• Beam PID
  
  • F5 position for rigidity \((B\rho)\) of beam
  
  • Energy loss \((\Delta E)\) at ICB
  
  • Time of flight \((\text{TOF})\) from F7 to F13

• Beam Profile

• BDC analysis

\[
\frac{A}{Z} = \frac{B\rho}{\gamma m uc\beta}
\]

\[
Z = p_0 \sqrt{\frac{\Delta E}{f(\beta s)}} + p_1
\]
Beam PID results \((^{34}\text{Na})\)

<table>
<thead>
<tr>
<th></th>
<th>Secondary beam ((^{34}\text{Na}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number</td>
<td>(3.42598 \times 10^5)</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>(~7) pps</td>
</tr>
<tr>
<td>Energy</td>
<td>(~260) MeV/u</td>
</tr>
<tr>
<td>(\Delta Z/Z)</td>
<td>1.32% (in (\sigma))</td>
</tr>
<tr>
<td>(\Delta A/A)</td>
<td>0.14% (in (\sigma))</td>
</tr>
</tbody>
</table>
Fragments analysis

- Charged fragments PID
- $B_\rho$ reconstruction using FDC data with transfer matrix
- $\Delta E$ at Hodoscope
- TOF from target to Hodoscope
- Neutron
  - TOF from target to neutron detectors
- Position at neutron detectors

\[
\frac{A}{Z} = \frac{B_\rho}{\gamma m_u c \beta}
\]
\[
Z = p_0 \sqrt{\frac{\Delta E}{f(\beta_5)}} + p_1
\]
Fragment momentum

Direction of charged fragments

\[ \hat{p} = \frac{\vec{r}_{FDC1} - \vec{r}_r}{|\vec{r}_{FDC1} - \vec{r}_r|} \]

\( \hat{p} : \) (unit vector of \( \vec{p} \))

\( \vec{r}_{FDC1} : \) (position at FDC1)

\( \vec{r}_r : \) (reaction point)

Rigidity \( (B\rho) \) of charged fragments

\[ \frac{p}{Z} = B\rho = (B\rho)_0 (1 + \delta) \]

\[ \begin{bmatrix} x \\ \theta \\ \delta \end{bmatrix}_{FDC2} = \begin{bmatrix} (x|x) & (x|\theta) & (x|\delta) \\ (\theta|x) & (\theta|\theta) & (\theta|\delta) \\ (\delta|x) & (\delta|\theta) & (\delta|\delta) \end{bmatrix} \begin{bmatrix} x \\ \theta \\ \delta \end{bmatrix}_{FDC1} \]

\( \Diamond \) Transfer matrices were obtained from OPTRACE calculation
Neutron analysis

Schematic picture of neutron detector

- $x$ position: scintillator bar position
- $y$ position: $y = c_0 + c_1 \cdot (T_U - T_D)$

Neutron 4 - momentum calculation

$\text{TOF}_n = (T_U + T_D)/2 - T_{\text{target}}$

$\vec{v}_n = (\vec{r}_n - \vec{r}_r)/\text{TOF}_n$

$\vec{r}_n$: (neutron hit point)
$\vec{r}_r$: (reaction point)

$\vec{p}_n = \gamma m_n \vec{v}_n$

$E_n = \gamma m_n c^2$
Fragment PID

<table>
<thead>
<tr>
<th>Neutron Coincidence Status</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o $n$ coincidence</td>
<td>193</td>
</tr>
<tr>
<td>with $n$ coincidence</td>
<td>27</td>
</tr>
</tbody>
</table>

\[
\sigma = 1.53 \text{ mb}
\]
Acceptance correction

- Energy differential cross section
  \[
  \frac{d\sigma}{dE_{\text{rel}}} = \frac{n_{\text{scat}}}{n_{\text{beam}} \cdot n_{\text{target}} \cdot \epsilon_{\text{FDC}} \cdot \epsilon_{\text{neutron}} \cdot \epsilon(E_{\text{rel}}, k_F) \cdot \Delta E_{\text{rel}}} 1
  \]

- Acceptance map of NEBULA layer 1

- Efficiency correction

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<thead>
<tr>
<th></th>
<th></th>
<th>(\epsilon_{\text{FDC}})</th>
<th>(\epsilon_{\text{neutron}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_{\text{beam}})</td>
<td>(n_{\text{target}}) ((\text{mb}^{-1}))</td>
<td>975</td>
<td>488</td>
</tr>
<tr>
<td>342598</td>
<td>1.08\times10^{-4}</td>
<td>0.975</td>
<td>0.488</td>
</tr>
</tbody>
</table>

 Raw spectrum

 Relative energy spectrum for \(^{32}\text{Ne} + n\)

 Preliminary result
Relative energy spectrum

Preliminary result

Peak:

Breit-Wigner shape

\[ \Gamma_l(E) \sim \frac{(E - E_R + \Delta_l(E))^2 + \Gamma_l(E)^2/4}{(E - E_R + \Delta_l(E))^2 + \Gamma_l(E)^2/4} \]

Background:

Maxwell-Boltzmann

\[ a_0 \cdot \sqrt{E} \cdot \exp(-a_1 \cdot E) \]

<table>
<thead>
<tr>
<th>( E_{rel} ) (MeV)</th>
<th>( \Gamma ) (MeV)</th>
<th>( \sigma_{-1p} ) (mb)</th>
<th>AME2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st peak</td>
<td>0.5^{+0.06}_{-0.07}</td>
<td>&lt; 0.26</td>
<td>0.125^{+0.044}_{-0.048}</td>
</tr>
<tr>
<td>2nd peak</td>
<td>1.4^{+0.14}_{-0.13}</td>
<td>—</td>
<td>0.076^{+0.048}_{-0.051}</td>
</tr>
</tbody>
</table>

\( \chi^2 / \text{ndf} = 3.8 / 7 \)
Next plan

• Model calculations are necessary to understand the experimental results of $^{33}$Ne.

• Energy levels of $^{33}$Ne

• $1p$ knock-out cross section ($\sigma_{-1p}$)

  • Spectroscopic factor ($C^2S$)

  • Single particle cross section ($\sigma_{sp}$)

• Call for theoretical help!
• The unbound states of $^{33}\text{Ne}$, which has not been measured, are populated by $1p$ knock-out reaction performed at S027 experiment.

• Total 27 events of $^{32}\text{Ne}$ fragments with $1n$ coincidence are clearly identified from $^{34}\text{Na}$ beam with ~7 pps.

• The relative energy spectrum was reconstructed from the momenta of fragments by using invariant mass method.

• Measured $S_n = -0.5$ MeV is compatible with AME 2012 value of -0.9 MeV.

• Model calculations for energy levels and knock-out cross section of $^{33}\text{Ne}$ will help to interpret the experimental results.
Thank you!