Study of $\alpha$-cluster structure in $^{22}$Mg using radioactive ion beam

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OVERVIEW

• INTRODUCTION

• EXPERIMENT

• ANALYSIS

• SUMMARY
INTRODUCTION

Cluster structure in Nuclei

A=4N, A=Z nuclei (like $^{16}$O)

H. Yamaguchi, PLB 766, 11 (2017)
INTRODUCTION

Similarity of Mirror nucleus

M. Freer et al., PRC 85, 014304 (2012)

Fu et al., PRC 77, 064314 (2008)

HOW ABOUT $^{22}$Mg and $^{22}$Ne??!!!
INTRODUCTION

HOW ABOUT $^{22}$Mg and $^{22}$Ne??!!

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$E_x$ (MeV)</th>
<th>$\theta_\alpha^2$ (%)</th>
<th>$\Gamma$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-$^-$</td>
<td>12.14</td>
<td>11.5</td>
<td>63</td>
</tr>
<tr>
<td>1-$^-$</td>
<td>13.04</td>
<td>6.7</td>
<td>92</td>
</tr>
<tr>
<td>3-$^-$</td>
<td>12.46</td>
<td>11.6</td>
<td>18</td>
</tr>
<tr>
<td>3-$^-$</td>
<td>13.19</td>
<td>11.7</td>
<td>52</td>
</tr>
</tbody>
</table>

Dufour et al., NPA 726, 53 (2003)

• GCM calculation predicts $\alpha$-doublets.

But, missing!

Goldberg et al., PRC 69, 024602 (2004)
INTRODUCTION

We performed...

\(^{18}\text{Ne}(\alpha,\alpha)^{18}\text{Ne}\) scattering measurement!

GOAL OF THE EXPERIMENT?

- To search for the missing and unknown states of \(p\)-rich \(^{22}\text{Mg}\) nucleus in the \(E_x = 8.6-17\) MeV

- To extract \(\alpha\)-cluster structure information by extracting the \(\alpha\)-widths, spins, parities, ...
EXPERIMENT

WHERE?

At CRIB in RIKEN Nishina Center!
EXPERIMENT

HOW TO?

- Thick Target Method in Inverse Kinematics

\[ ^{18}\text{Ne beam} \]

\[ ^{4}\text{He gas (thick target)} \]

\[ ^{18}\text{Ne stopped} \]

\[ \alpha \]

Silicon Detectors
EXPERIMENT

HOW TO?

- Thick Target Method in Inverse Kinematics

\[ \frac{d\sigma}{d\Omega} \]

\[ E \]

\[ ^{4}\text{He gas} \]

\[ ^{18}\text{Ne beam} \]

Beam energy loss...
EXPERIMENT

$^{18}$Ne RI beam production at F0

Via $^{16}$O($^3$He,$n$)$^{18}$Ne
EXPERIMENT

$^{18}$Ne RI beam production at F0

- LN$_2$ cooling system (~90K) for enough target thickness
- 360 Torr of $^3$He gas → 1.54mg/cm$^2$
- $^{18}$Ne beam intensity increased than normal R.T.
### Primary beam

<table>
<thead>
<tr>
<th>Energy</th>
<th>Current</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O}^{6+}$</td>
<td>8.03 MeV/u</td>
<td>$\sim 260$ pnA</td>
</tr>
</tbody>
</table>

### Secondary beam

<table>
<thead>
<tr>
<th>Energy @ F3</th>
<th>Intensity @ F3</th>
<th>Purity @ F3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{Ne}^{10+}$</td>
<td>$\sim 2.75$ MeV/u</td>
<td>$\sim 3 \times 10^5$ pps</td>
</tr>
</tbody>
</table>
Beam ID at F2

- Parallel plate avalanche counter (PPAC) for timing information
- SSD (1500μm) for energy measurement
- Particle Identification by time-of-flight vs Energy
Beam ID at F2

Experiment

Calculation
EXPERIMENT

$^{18}\text{Ne}(\alpha,\alpha)^{18}\text{Ne}$ measurement at F3 focal plane

- Beam tracking by two delay-line type PPACs
  (Kumagai et al., NIM A 470, 562, 2001)
- Recoiling $\alpha$ particles measurement by silicon detectors
EXPERIMENTAL METHOD

F3 PPACs for beam tracking & beam ID

• Beam ID by Position vs time-of-flight
• Handling rate ~ 5x10^5 pps, Position resolution ~ 2mm
EXPERIMENT

F3 Telescopes

- Calibrated by an $\alpha$-emitting source, $\alpha$-beams (13-, 15-, 20-, 25MeV)

2017.11.17 International Conference on Accelerators and Beam Utilization 2017 HICO, Gyeongju
F3 Telescopes

- $\Delta E$ (20µm, X strip) + $E_1$ (496µm, Y strip) + $E_2$ (485µm)
- $\Delta E$ (20µm, X strip) + $E$ (1500µm, Y strip)
**EXPERIMENT**

F3 target: $^4\text{He}$, 470Torr // Ar, 87 Torr

- $^4\text{He}$ gas run for main measurement (~100 hours)
- Ar gas run for the background subtraction (~35 hours)
\( ^{18}\text{Ne}(\alpha,\alpha) :\) PID

- **Standard Energy Loss Technique for Particle ID**
- **No significant contaminations from other particles**
$^{18}\text{Ne} (\alpha, \alpha)$: comparing two spectra

Yields

$^4\text{He}$ gas measurement

$\text{Ar}$ gas measurement

Energy of alpha particles
$^{18}\text{Ne}(\alpha,\alpha) :$ comparing two spectra

Yields

4He gas measurement
Ar gas measurement

Energy of alpha particles

originated from production target...
ANALYSIS

$^{18}\text{Ne}(\alpha,\alpha)$: Energy reconstruction

• Converting $E_\alpha$ to $E_{\text{c.m.}}$ of the $^{18}\text{Ne} + \alpha$ system

$$E_{\text{c.m.}} = \frac{M_{\text{Ne}} + M_\alpha}{4M_{\text{Ne}} \cos^2 \theta_{\text{lab}}} E_\alpha$$

• Needs detailed calibration b/w two measurement
$^{18}\text{Ne}(\alpha,\alpha)$: alpha spectrum

- Resonance-like peaks
- Detailed analysis is ongoing!
- Hope to see missing states in the previous works
$^{18}\text{Ne}(\alpha,\alpha)$ : Further analysis

- Extract excitation function

$$\frac{d\sigma}{d\Omega_{\text{c.m.}}}(E_{\text{c.m.}}, \theta_{\text{c.m.}}) = \frac{1}{4\cos\theta_{\text{lab}}} \frac{\text{Yields}}{I\cdot N\cdot \Delta\Omega_{\text{lab}}}$$

- Comparing with theoretical R-matrix calculation
- Energy level properties (spin, parity, $\alpha$ reduced width..)
- The $\alpha$-cluster study in $^{22}\text{Mg}$ will be investigated!
SUMMARY

• The $^{18}\text{Ne}(\alpha,\alpha)^{18}\text{Ne}$ scattering was measured at CRIB in inverse kinematics in order to study the $\alpha$-cluster structure in proton-rich $^{22}\text{Mg}$ nuclide.

• By adopting the thick target method, a wide range of excitation energy of $^{22}\text{Mg}$ ($E_x = 9.9 - 16.5$ MeV) was investigated.

• Scattered $\alpha$ particles were measured by silicon detector telescopes.

• Measured energy of $\alpha$ particle was converted to center-of-mass energy of $^{18}\text{Ne}+\alpha$ system.

• The contribution from the background $\alpha$ particle was considered by measuring with argon gas target.

• By comparing the empirical excitation function with the theoretical R-matrix calculation, the energy level properties of $^{22}\text{Mg}$ will be extracted.

• The $\alpha$-cluster structure in proton-rich $^{22}\text{Mg}$ nuclide will be investigated as well.
THANK YOU!

2017.11.17
International Conference on Accelerators and Beam Utilization 2017
HICO, Gyeongju
EXPERIMENTAL METHOD

Inelastic ??

- Time difference
  - A. Kim et al., PRC 92, 035801 (2015)

- Peak shift method
  - J.J He et al., PRC 76, 055802 (2007)
  - (120-, 160keV at $\theta_{lab}=0^\circ$, 30°)
EXPERIMENT

$^{18}$Ne Beam ID at F2 & F3 focal planes

- Energy (SSD) & Timing (PPAC) measurement at F2
- Position & Timing measurement (PPACs) at F3
Reaction vertex?

- Comparing the calculated $E_\alpha$ and the measured $E_\alpha$

- Energy loss calculation by SRIM code  
  J. Ziegler et al.
**EXPERIMENT**

**F3 PPACs for beam tracking**

- **Delay-line type** (Kumagai *et al.*, NIM A 470, 562, 2001)

- **Handling rate** ~ $5 \times 10^5$ pps, **Position resolution** ~ 2 mm
INTRODUCTION

$^{22}\text{Ne} - \text{GCM calculation}$

- $0_2^-$ band: Clustering!
- Predicts $1^-, 3^-, 5^-$ states
  
  $(11.47, 12.58, 14.77\text{-MeV})$
- Consistent with experimental data
  
  $(11.47, 12.88\text{-MeV})$

```
<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$E_{\text{exp}}^\pi$</th>
<th>$E_{\text{GCM}}^\pi$</th>
<th>$E_{\text{GCM}}^{\text{c.m.}}$</th>
<th>$\theta_0^\pi$</th>
<th>$\theta_2^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1^-</td>
<td>7.05</td>
<td>-2.36</td>
<td>7.31</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>2^-</td>
<td>7.66</td>
<td>-1.85</td>
<td>8.05</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>3^-</td>
<td>7.72</td>
<td>-1.62</td>
<td>7.82</td>
<td>0.02</td>
<td>0.13</td>
</tr>
<tr>
<td>4^-</td>
<td>9.07</td>
<td>-0.31</td>
<td>9.36</td>
<td></td>
<td>0.18</td>
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<tr>
<td>5^-</td>
<td>10.61</td>
<td>0.31</td>
<td>10.08</td>
<td>0.01</td>
<td>0.21</td>
</tr>
<tr>
<td>6^-</td>
<td>11.11</td>
<td>2.50</td>
<td>12.17</td>
<td></td>
<td>0.27</td>
</tr>
<tr>
<td>7^-</td>
<td>11.48</td>
<td>3.36</td>
<td>13.13</td>
<td>9.7 x 10^{-4}</td>
<td>0.54</td>
</tr>
<tr>
<td>8^-</td>
<td>6.53</td>
<td>16.20</td>
<td></td>
<td></td>
<td>0.64</td>
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P. Descouvemont, PRC 38, 2397 (1988)```
### INTRODUCTION

#### $^{22}$Ne – ETCM calculation

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<td>3$^-$</td>
<td>12.92</td>
</tr>
<tr>
<td>3$^-$</td>
<td>13.69</td>
</tr>
<tr>
<td>5$^-$</td>
<td>13.68</td>
</tr>
<tr>
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<td>14.69</td>
</tr>
<tr>
<td>7$^-$</td>
<td>18.79</td>
</tr>
<tr>
<td>7$^-$</td>
<td>19.56</td>
</tr>
<tr>
<td>9$^-$</td>
<td>20.85</td>
</tr>
<tr>
<td>9$^-$</td>
<td>21.84</td>
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- Observed the splitting of $\alpha$-clustering states
  
  Rogachev et al., PRC 64, 051302 (2001)

- ETCM results predict doublet states ($1^-, 3^-, 5^-, 7^-$)
  
  Dufour et al., NPA 726, 53 (2003)

- Experimental & Theoretical studies were consistent.
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**22Ne – ETCM calculation**

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- Observed the splitting of $\alpha$-clustering states  
  Rogachev et al., PRC 64, 051302 (2001)

- ETCM results predict doublet states (1-,3-,5-,7-)  
  Dufour et al., NPA 726, 53 (2003)

- Experimental & Theoretical studies were consistent.
INTRODUCTION

\( ^{22}\text{Ne} \) – Hybrid GCM calculation

\[ \begin{array}{c|c|c} \hline J^\pi & E_x \text{ (MeV)} & \theta_\alpha^2 \text{ (%)} \\ \hline 1^- & 14.8 & 8.7 \\ 3^- & 15.2 & 9.1 \\ 5^- & 16.8 & 9.0 \\ 7^- & 18.9 & 10.3 \\ 9^- & 22.5 & 11.7 \\ \hline \end{array} \]

\[ \begin{array}{c|c|c} \hline J^\pi & E_x \text{ (MeV)} & \theta_\alpha^2 \text{ (%)} \\ \hline 1^- & 12.58 & 13 \\ 1^- & 13.53 & 8 \\ 3^- & 12.92 & 13 \\ 3^- & 13.69 & 11 \\ 5^- & 13.68 & 23 \\ 5^- & 14.69 & 100 \\ 7^- & 18.79 & 52 \\ 7^- & 19.56 & 81 \\ \hline \end{array} \]

- \( ^{18}\text{O} + \alpha \) cluster model?
- Predicts new singlet states with negative parities \((14 < E_x < 23 \text{ MeV})\)
- No experimental data is available for \( ^{22}\text{Mg} \) case!

M. Kimura, PRC 75, 034312 (2007)