Investigation of High-Lying ($\alpha, \gamma$) Resonances in $^{22}$Ne via High-Resolution Gamma Ray Spectroscopy in Inverse Kinematics

Beau Greaves
CAP Congress 2019
SFU
Stellar Nucleosynthesis of $^{22}\text{Ne}$

$^{22}\text{Ne}$ produced in AGB stars from $^{18}\text{O}(\alpha, \gamma)$ out of CNO cycle

$^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$ competes with production of $^{19}\text{F}$, the abundance of which is poorly characterized in AGB stars
22Ne produced in AGB stars from $^{18}\text{O}(\alpha,\gamma)$ out of CNO cycle

Following $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ is main neutron source for heavy element s-process

Recent rate adjustments show drastic impact on abundances
- $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$
- $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$
Spectroscopy of $^{22}\text{Ne}$ resonances at ISAC-II

<table>
<thead>
<tr>
<th>$E_r$ (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$</th>
<th>$\omega\gamma_{(a,\gamma)}$ (µeV)</th>
<th>$\omega\gamma_{(a,n)}$ (µeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O} + \alpha$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.058.....</td>
<td>9.72</td>
<td>$3^-$</td>
<td>$4.1 \times 10^{-40}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(2^+)$</td>
<td>$1.5 \times 10^{-39}$</td>
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<td>$2^+$</td>
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<td></td>
<td>$0^+$</td>
<td>0.55</td>
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<td>0.566.....</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>$(2^+)$</td>
<td>1.95</td>
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<tr>
<td></td>
<td></td>
<td>$(3^-)$</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>0.662.....</td>
<td>10.21</td>
<td>$1^-$</td>
<td>$230 \pm 25^\circ$</td>
<td></td>
</tr>
</tbody>
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Diagram: $^{18}\text{O} (\alpha,\gamma)^{22}\text{Ne}$ cross-sections at various $E_R$ values, with data from Käppeler et al. 1994.
Spectroscopy of $^{22}\text{Ne}$ resonances at ISAC-II

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<tr>
<td>0.218</td>
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<td>$2^+$</td>
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<td>$(1^-)$</td>
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<td>0.470</td>
<td>10.05</td>
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<td>$(1^-)$</td>
<td>0.23</td>
<td></td>
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</table>

indirect: TUDA, TACTIC, TIGRESS, IRIS, EMMA

direct: DRAGON

Käppeler et al. 1994
ISAC-II at TRIUMF
Experimental Setup

- **Experiment S1855 – $^{21}\text{Ne}(d,p)^{22}\text{Ne}$**
  - Beam energy: 165 MeV (7.89 MeV/u)

- **Thin Target**
  - 120 $\mu$g/cm$^2$ self-supporting CD$_2$

- **SHARC**
  - Reduced noise to allow for measurement of high-lying excitation energies
  - Able to gate on excitation energies

- **TIGRESS**
  - Eight 90° detectors and four 135° detectors
Experiments in Inverse Kinematics

$^{21}\text{Ne} (E_x=0)$

$^{22}\text{Ne} (E_x=?)$

CD$_2$

silicon strip detector

Proton energy (MeV)

Proton angle ($\theta$)
Experiments in Inverse Kinematics

$^{21}\text{Ne} \ (E_x=0)$

$^{22}\text{Ne} \ (E_x=?)$

silicon strip detector

Proton energy (MeV)

Proton angle ($\theta$)

Ground State
First Excited State
Second Excited State
Experiments in Inverse Kinematics

Proton energy (MeV)

Proton angle ($\theta$)

$^{21}\text{Ne} (E_x=0)$

$^{22}\text{Ne} (E_x=?)$

CD$_2$

silicon strip detector

Ground State

First Excited State

Second Excited State

$\propto$
Experiments in Inverse Kinematics

$^{21}\text{Ne} \ (E_x=0)$

$^{22}\text{Ne} \ (E_x=?)$
Experiments in Inverse Kinematics

$^{21}\text{Ne} \ (E_x=0)$

CD$_2$

$^{22}\text{Ne} \ (E_x=?)$

Proton energy (MeV)

Proton angle ($\theta$)

Ground State

First Excited State

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Experiments in Inverse Kinematics

$^{21}\text{Ne} \quad (E_x = 0)$

$^{22}\text{Ne} \quad (E_x = ?)$

Proton energy (MeV)

Proton angle ($\theta$)

CD$_2$
Experiments in Inverse Kinematics

$^21\text{Ne} \ (E_x = 0)$

$\text{CD}_2$

$^22\text{Ne} \ (E_x = ?)$

Proton angle ($\theta$)

Excitation energy (MeV)

22 Ne (E_x = ?)
Spectroscopy of $^{22}$Ne resonances at ISAC-II
Analysis Status

- 20 states observed so far
- 28 corresponding γ rays have been found
  - 4 new, 3 of which correspond to resonances
- Angular distributions for key γ rays found, but detector efficiencies require refinement

<table>
<thead>
<tr>
<th>Ei</th>
<th>Si</th>
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<td>(4)+</td>
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<td>10.294</td>
<td>0+1-2+</td>
<td>5.329 0+</td>
<td>4.965</td>
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</tbody>
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Analysis Status

• 20 states observed so far
• 28 corresponding $\gamma$ rays have been found
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• Angular distributions for key $\gamma$ rays found, but detector efficiencies require refinement
Spin Investigation of 9.85 MeV Resonance

- 10.294 MeV (2⁺, 1⁺, 0⁺)
- 10.205 MeV (1⁺)
- 10.137 MeV (2⁺)
- 9.841 MeV (2⁺, 1⁺)
- 5.636 MeV (2⁺)
- 5.629 MeV (0⁺)
- 4.456 MeV (2⁺)
- 1.274 MeV (2⁺)
- 0 MeV (0⁺)
Spin Investigation of 9.85 MeV Resonance

10.294 MeV (2\(^+\),1\(^+\),0\(^+\))

10.205 MeV  1\(^+\)
10.137 MeV  2\(^+\)
9.841 MeV (2\(^+\),1\(^-\))

9.02 MeV M1
5.84 MeV M1
4.96 MeV ?
10.21 MeV E1
8.86 MeV M1
8.57 MeV ?
4.48 MeV ?

5.636 MeV  2\(^+\)
5.629 MeV  0\(^+\)
4.456 MeV  2\(^+\)
1.274 MeV  2\(^+\)
0 MeV  0\(^+\)
Spin Investigation of 9.85 MeV Resonance

- 9.85 MeV resonance decays to $2_1^+$ and $2_3^+$
  - Neutron transfer preferentially populates low J, positive parity states
  - Of states determined so far, eight are $2^+$, compared to two $1^-$
  - $2^+$ decay primarily via M1 to $2^+$
  - $1^-$ decay primarily via E1 to $0^+$

Propose 9.85 MeV as $2^+$, but currently investigating further

Käppeler et al. 1994
Next Steps

• Determining origin of unclassified states with $\gamma - \gamma$ coincidence

• Investigate particle angular distributions for spin confirmation on 9.85 MeV and several other unconfirmed spin levels via DWBA simulations

• Refine segment efficiencies to for gamma angular distributions
Acknowledgements

- **TRIUMF** – S. Gillespie, G. Hackman, A. Babu, F. Barrett, N. Bernier, S. Bhattacharjee, R. Caballero-Folch, A. Chester, A. Murphy B. Olaizola, Y. Saito, R. Umashankar

- **NSCL** – A. Spyrou
- **Surrey** – W. N. Catford, P. Siuryte
- **University of Toronto** – T. Drake

Thank you for listening!
Breit-Wigner Expression

\[
\langle \sigma \nu \rangle = \left( \frac{2\pi}{\mu k_B T} \right)^{\frac{3}{2}} \hbar^2 \sum_i \omega \gamma_i e^{-\frac{E_i}{kT}}
\]

\[
\omega \gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_x + 1)} \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma_\alpha + \Gamma_\gamma}
\]

\[
= g(1 - B_\alpha)B_\alpha \frac{\hbar}{\tau}
\]

\[
\langle \sigma \nu \rangle - \text{reaction rate}
\]

\[
E_i - \text{resonance energy}
\]

\[
J_{i/p/x} - \text{spins of resonance state/projectile/target}
\]

\[
\Gamma_\alpha/\gamma - \text{Partial width of } \alpha/\gamma \text{ decay}
\]

\[
\tau - \text{lifetime}
\]
Experiments in Inverse Kinematics

$^{21}\text{Ne} \ (E_x=0)$

$^{22}\text{Ne} \ (E_x=?)$

silicon strip detector

$^{130}\text{Sn}$ beam

$^{132}\text{Sn}$ beam

Proton

CD$_2$

Counts

$Q \ (\text{MeV})$

$2,005 \text{ keV}$

$1,561 \text{ keV}$

$1,393 \text{ keV}$

$854 \text{ keV}$

$0 \text{ keV}$
Intro: indirect approaches to nucleosynthesis studies
Intro: indirect approaches to nucleosynthesis studies
Example of particle angular distribution
Particle-gamma spectroscopy with TIGRESS

$^{21}\text{Ne}(d,p), \text{7.9 MeV/u}$

August 2017