Particle Spectroscopy of Unbound States for Nuclear Astrophysics

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- Reaction rates for novae, X-ray bursts & supernovae
- $\Gamma_p$: $(p,\gamma)$ & $(p,\alpha)$ rates via the $(d,n)$ and $(d,p)$ reactions
  - $^{18}\text{F}(p,\alpha)^{15}\text{O}$ (*Adekola et al.*)
  - $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ (*Pain et al.*)
  - N=Z: the future: $^{30}\text{P}$ (*Pain et al.*)
  - $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ (*Belarge et al.*)
  - $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ (*Kuvin et al.*)

- $\Gamma_{\alpha}$: $(\alpha,p)$ reaction rates
  - The SE-SPS
  - $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ and $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$
  - $^{14}\text{O}(\alpha,p)^{18}\text{Ne}$ and $^{18}\text{Ne}$: $^{18}\text{O}$ symmetry

- Concluding remarks
Explosions in proton-rich environments

- Cataclysmic binaries
  - Novae
  - X-ray bursts
- Certain nuclear reactions (on p-rich nuclei) influence observables

Model of GS1826-24

- Proton-rich ejecta of core-collapse supernovae may contribute to intermediate mass elements

Müller, Janka et al.
Reaction rates and resonances

- Hydrogen and helium induced reactions are dominated by resonances near threshold
- Direct measurements are challenging
- Easier: indirectly determine resonance properties
  - $E_r$, $J^\pi$, $\Gamma_p$, $\Gamma_\alpha$, $\Gamma_\gamma$
  - Reaction theory!

$\langle \sigma \nu \rangle = \sqrt{\frac{8}{\pi \mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE$

States near $p$ threshold are narrow
Branching ratios are observable!

$\Gamma_p > (\Gamma_\alpha$ or $\Gamma_\gamma$)

$\Gamma_\gamma > \Gamma_p$

$\theta_\alpha^2 << 1$


Some narrow states

$X+\alpha$ $\rightarrow$ $E1$

$Y+p$ $\rightarrow$ $Z$

Direct capture
$^{18}\text{F}(p,\alpha)^{15}\text{O}$ & Novae

- $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ and $^{18}\text{F}(p,\alpha)^{15}\text{O}$ determine 511 keV gamma production from novae that contribute to diffuse sources.

![Diagram showing nuclear reactions and energy levels.](image.png)
Use $^{18}\text{F}(d,n)^{19}\text{Ne}$ reaction to populate the states of interest in $^{19}\text{Ne}$

$^{18}\text{F}(d,p)^{19}\text{F}$ simultaneously measured

Do not detect the neutrons/protons!

Detect $^{15}\text{O}/^{15}\text{N}$ and $\alpha$ in coincidence from $^{19}\text{Ne}/^{19}\text{F}$ breakup

Kinematics of angle and excitation energy reconstructed

Six position sensitive silicon-strip detectors covering $\theta_{\text{lab}} \sim 2^\circ - 17^\circ$

716 $\mu$g/cm$^2$

CD$_2$

150 MeV

2x10$^6$ pps

$^{19}\text{Z}^*$

$^{15}\text{Z}$

$n,p$

Adekola et al., PRC 83, 84, 85 (2011-12).
$^{18}\text{F}(d,n)^{19}\text{Ne} \rightarrow ^{15}\text{O} + \alpha$ & $^{18}\text{F}(d,p)^{19}\text{F} \rightarrow ^{15}\text{N} + \alpha$

Simultaneous mirror measurements

<table>
<thead>
<tr>
<th>$^{19}\text{F}$</th>
<th>$^{19}\text{Ne}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ (keV)</td>
<td>$\ell$</td>
</tr>
<tr>
<td>----------------</td>
<td>--------</td>
</tr>
<tr>
<td>6331</td>
<td>2</td>
</tr>
<tr>
<td>6255/6497/6528</td>
<td>0</td>
</tr>
<tr>
<td>6787</td>
<td>1</td>
</tr>
<tr>
<td>7262/7364</td>
<td>0</td>
</tr>
</tbody>
</table>

Efficiency complicated

Definitive mirror assignments still often not clear

Reaction models to the continuum

Interference between levels
### $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ and Galactic $^{26}\text{Al}$

<table>
<thead>
<tr>
<th>$E_x$ (keV)</th>
<th>$E_{res}$ (keV)</th>
<th>$J^\pi$</th>
<th>$\omega\gamma$ (meV)</th>
<th>$^{27}\text{Al} E_x$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7469</td>
<td>6</td>
<td>(1/2, 5/2)$^+$</td>
<td>$&lt; 2.3 \times 10^{-66}$</td>
<td>7676 (7799)</td>
</tr>
<tr>
<td>(7491)</td>
<td>(28)</td>
<td>(3/2)$^+$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7532</td>
<td>69</td>
<td>5/2$^+$</td>
<td>$&lt; 2.3 \times 10^{-13}$</td>
<td>7790 (7790)</td>
</tr>
<tr>
<td>(7557)$^b$</td>
<td>(94)</td>
<td>(3/2)$^+$</td>
<td>$&lt; 1.9 \times 10^{-10}$</td>
<td>7858 (7858)</td>
</tr>
<tr>
<td>7590</td>
<td>127</td>
<td>9/2$^+$</td>
<td>$&lt; 5.9 \times 10^{-6}$</td>
<td>7807 (7807)</td>
</tr>
<tr>
<td>7652</td>
<td>189</td>
<td>11/2$^+$</td>
<td>0.055(9) [4], 0.035(7) [5]</td>
<td>7950</td>
</tr>
<tr>
<td>7694</td>
<td>231</td>
<td>5/2$^+$</td>
<td>$\leq 0.010$ [4]</td>
<td>7722</td>
</tr>
<tr>
<td>7704</td>
<td>241</td>
<td>7/2$^-$</td>
<td>0.010(5) [4]</td>
<td>7900</td>
</tr>
<tr>
<td>7739</td>
<td>276</td>
<td>9/2$^+$</td>
<td>3.8(10) [6], 2.9(3) [4]</td>
<td>7998</td>
</tr>
</tbody>
</table>

- **Measured**
- **Unmeasured**

- **ell=2**
- **ell=0**

- **Strengths of 69 and 127 keV resonances major uncertainty in $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ rate**

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**Diagram:**
- ONe novae
- Orion
- Cygnus
- AGB + WR stars

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**Legend:**
- $^{26}\text{Al} + p$ Q = 7463
- $^{27}\text{Si}$
$^{26}\text{Al}(d,p)^{27}\text{Al}$ to Mirror States

- 117 MeV $^{26}\text{Al}$
- 5x10$^6$ pps
- 150 $\mu$g/cm$^2$ CD$_2$
- MCP normalization (200 kHz)
Neutron spectroscopic factors in $^{27}\text{Al}$

$7805(12)$ keV (127-keV mirror)

FWHM
72 keV (CoM)

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$E_x$ (keV)</th>
<th>$C^2 S_v^{\text{exp}}$</th>
<th>$C^2 S_v^{\text{th}}$</th>
<th>$C^2 S_{th}^{\text{th}}$</th>
<th>$C^2 S_{\pi}^{\text{th}}$</th>
<th>$\Gamma_{sp}$ (meV)</th>
<th>$\Gamma_{p}$ (meV)</th>
<th>$\omega \gamma$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9/2^+$</td>
<td>7807</td>
<td>$0.0102 \pm 0.0021$</td>
<td>$0.0112^{+0.0002}_{-0.0007}$</td>
<td>$0.0094^{+0.0002}_{-0.0004}$</td>
<td>$0.0085^{+0.0024}_{-0.0031}$</td>
<td>$6.70 \times 10^{-3}$</td>
<td>$5.7^{+1.6}_{-2.1} \times 10^{-5}$</td>
<td>$2.6^{+0.7}_{-0.9} \times 10^{-5}$</td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>7790</td>
<td>$\leq 0.061$</td>
<td>$0.0100^{+0.0006}_{-0.0002}$</td>
<td>$0.0088^{+0.0019}_{-0.0022}$</td>
<td>$\leq 0.054$</td>
<td>$2.06 \times 10^{-10}$</td>
<td>$\leq 1.1 \times 10^{-11}$</td>
<td>$\leq 3.0 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

$^a$From SMEC calculations using the USD-b effective interaction, using a continuum coupling constant of $-650$ MeV fm$^3$.

⇒ Quantifying uncertainties in reaction models and mirror symmetry?
$^{30}P(d,p\gamma)^{31}P$ with GODDESS

- $^{30}P(p,\gamma)^{31}S$: Most important reaction for understanding enrichment of $S$ and heavier elements in nova ejecta
- Large uncertainty but high level density and only a few resonances will likely contribute
- Proton singles and $p\gamma$ coincidences with $^{30}P(d,p\gamma)$ and GODDESS?
- Limitations from reaction model and mirror symmetry?

How good is this picture?
\(^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}(p,\gamma)^{20}\text{Na}\)

- \(^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}\) reaction is a limiting reaction for CNO breakout
- \(^{19}\text{Ne}(p,\gamma)^{20}\text{Na}\) reaction should be much faster than \(^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}\)
- Spin assignments of states in \(^{20}\text{Na}\) are not clear
- Uncertainty in \(^{19}\text{Ne}(p,\gamma)^{20}\text{Na}\) rate is large

**Our approach:**

- Forget about the low energy neutron
- Detect \(^{19}\text{Ne}\) and \(p\) with high spatial and energy resolution

\[ ^{2}\text{H}(^{19}\text{Ne},n) \rightarrow ^{20}\text{Na}^* \]
$^{19}\text{Ne}(d,n)^{20}\text{Na} \rightarrow ^{19}\text{Ne} + p$ Approach

- Protons detected in silicon-strip array

- Beam and recoiling heavy ions detected in position-sensitive, gas ionization detector

Results from $^{12}\text{C}(p,p)$ test experiment

IC position gated on Si
$^{19}\text{Ne}(d,n)^{20}\text{Na} \rightarrow ^{19}\text{Ne} \pm p$ Results

- Reconstructed $E_{cm}$ spectrum and angular distributions
- 2.65 MeV state has equal decay branching to g.s. and $\frac{5}{2}^{+}$
- Thermal population of the first-excited $^{19}\text{Ne}$ state contributes to the $^{19}\text{Ne}(p,\gamma)$ reaction rate
$^{19}\text{Ne}(p, \gamma)^{20}\text{Na}$ Reaction Rate

- With $J^\pi$ established, it is hard to reconcile direct $(p, \gamma)$ limits with lifetime measurements in the mirror $^{20}\text{F}$.

Couder et al., PRC (2004): $\omega_{440} < 15$ meV

Lifetime measurements $\rightarrow \omega_{440} = 74$ meV

- Using $\Gamma_\gamma$ from mirror and reactions on the excited state increases the reaction rate significantly more than already expected.

Belarge et al., PRL 117 (2016)
$^{17}\text{F}(p,\gamma)^{18}\text{Ne}$

- Most important resonance directly measured
- Largest uncertainty is direct capture

Chipps et al., PRL (2009)

$\omega\gamma = 33 \pm 14_{\text{stat}} \text{ meV}$

- Need new approach for bound(ish) states
$^{17}\text{F}(d,n)$ using RESONEUT

$^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate
S. Kuvin et al.

ResoNeut = P-Terphenyl + Planacon PMT
$^{17}\text{F}(d,n)^{18}\text{Ne}$ data

- Good neutron TOF resolution
- Proton unbound states agree with HRIBF measurements
- Bound states are observed above background allowing ANC\(_s\) to be extracted
Asymptotic Normalization Coefficients (ANCs) allow accurate determination of the direct capture cross section.

We find the ANC to be in good agreement with those in the $^{18}\text{O}$ mirror.

Uncertainties in the reaction rate significantly reduced at nova and X-ray burst temperatures.

\[ F(p, \gamma)^{18}\text{Ne} \]
SE-SPS at FSU

- Former Yale large-acceptance Enge SPS now being installed at Fox Superconducting Accelerator Laboratory at FSU
- Experiments starting this year!
(α,p) reaction rates & X-ray bursts

- (α,p) reactions on $T_z=\pm 1$ nuclei are important reactions in X-ray bursts
- Uncertainties dominated by alpha widths of resonances
- We will measure alpha decay branching ratios with Enge+SABRE
- Mirror reactions on stable nuclei, e.g. ($^6\text{Li},d$) and (α,α) – but is it meaningful?
Alpha spectroscopic factors in $^{19}$F:$^{19}$Ne

- ~10x discrepancy in alpha spectroscopic factors for mirror states of astrophysical importance?

$^{19}$F wavefunctions?

- $^{12}$C $\otimes$ $^7$Li
- $^{11}$B $\otimes$ $^8$Be
- $^{14}$N $\otimes$ $^5$He
- $^{15}$N $\otimes$ $^4$He

“One can see that the disagreement exceeds one order of magnitude.”

de Oliveira et al., PRC 55 (1997)

<table>
<thead>
<tr>
<th>$E_x(^{19}$F) (MeV)</th>
<th>$E_x(^{19}$Ne) (MeV)</th>
<th>$J^\pi$</th>
<th>$\Gamma_\gamma$ (meV)</th>
<th>$B_\alpha(^{19}$Ne)$^b$ (meV)</th>
<th>$\Gamma_\alpha(^{19}$Ne) (meV)</th>
<th>$\theta_\alpha(^{19}$Ne)$^c$ ($\times 10^{-2}$)</th>
<th>$\theta_\alpha(^{19}$F)$^d$ ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.378</td>
<td>4.379</td>
<td>$(7/2)^+$</td>
<td>&gt; 60</td>
<td>0.044 ± 0.032</td>
<td>&gt; 2.8</td>
<td>&gt; 7.8</td>
<td>0.56</td>
</tr>
<tr>
<td>4.550</td>
<td>4.600</td>
<td>$(5/2)^+$</td>
<td>101 ± 55</td>
<td>0.25 ± 0.04</td>
<td>33 ± 18</td>
<td>3.2</td>
<td>4–8</td>
</tr>
<tr>
<td>4.556</td>
<td>4.549</td>
<td>$(3/2)^-$</td>
<td>38$^{+23}_{-19}$</td>
<td>0.07 ± 0.03</td>
<td>2.9$^{+1.7}_{-1.4}$</td>
<td>0.06</td>
<td>0.84</td>
</tr>
<tr>
<td>4.683</td>
<td>4.712</td>
<td>$(5/2)^-$</td>
<td>43 ± 8</td>
<td>0.82 ± 0.15</td>
<td>195 ± 36</td>
<td>0.67</td>
<td>1.5–2.4</td>
</tr>
<tr>
<td>5.107</td>
<td>5.092</td>
<td>$(5/2)^+$</td>
<td>&gt; 22</td>
<td>0.90 ± 0.09</td>
<td>&gt; 200</td>
<td>&gt; 0.19</td>
<td>0.033–0.33</td>
</tr>
</tbody>
</table>

$^1_2\sigma$
Maybe not as bad as it appears?

\[^{15}\text{N}(^{7}\text{Li},t)^{19}\text{F}\] \text{ de Oliveira et al., NPA 597 (1996)}

- 4.550 and 4.556 states not resolved
- Dominated by 4.550 strength – but to what degree?
- Only weak constraints on 4.556 level

\[E_x = 4.550 + 4.556\text{MeV}\]
\[S = 0.09\]
**α cluster states in $^{18}$O**

$^{14}$C($^6$Li,d)

Consolo et al., PRC 24 (2016).

$^{14}$C(α,α)

Avila et al., PRC 90 (2016).
α widths in $^{18}$Ne

$^{17}$F(p,α)$^{14}$O

Blackmon et al., NPA 688 (2001)
Harss et al., PRL 82 (1999)

$^{14}$O(α,p)$^{17}$F

Kim et al., PRC 92 (2015)

$^{16}$O(3He,n)$^{18}$Ne→$^{14}$O+α

Almaraz-Caldaron et al., PRC 86 (2012)
**18O:18Ne Comparison?**

14O(α,p)  

<table>
<thead>
<tr>
<th>Eₓ</th>
<th>Γα (keV)</th>
<th>17F(p,α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.35</td>
<td>1(-) 3.1 (2)</td>
<td>7.10 (1-) 0.30 (8)</td>
</tr>
<tr>
<td>7.60</td>
<td>0(+) 1.5 (5)</td>
<td>7.60 (1-, 2+, 3-) 0.5–1.2</td>
</tr>
<tr>
<td>7.72</td>
<td>2+, 3- 1.9 (3)</td>
<td></td>
</tr>
</tbody>
</table>

16O(3He,n)  

| 8.10 | 0(+) 40 (5) | 8.09 (3-) 6 (4) |

- Probably the only state with a clear mirror assignment is 6.20 ↔ 6.15 (1-) level
- Most important resonance for 14O(α,p)17F
  2 eV from 14C(7Li,t)
  8 eV from 17F(p,α)
- Limitation of mirror symmetry?
Concluding remarks

- Reactions on proton-rich nuclei are important
  - \((p, \gamma)\)
  - \((\alpha, p)\)
  - \((n, p)\)

- Direct measurements are very difficult
  - Small cross sections
  - Low radioactive ion beam intensities

- Indirect approaches are crucial

- Reliable reaction models into the continuum are important
  - Often narrow states near threshold

- Mirror reactions are much easier experimentally
  - But how reliable are any comparisons?