Reactions in Stellar Explosions
(T ~ 10^7-10^9 K, varying densities)

Studied at HRIBF:

\(^{17}\text{F}(p,\gamma)^{18}\text{Ne}\)

\(^{17}\text{O},^{18}\text{F}\) production

\(^{18}\text{F}(p,\alpha)^{15}\text{N}\) and \(^{18}\text{F}(p,\gamma)^{19}\text{Ne}\)

\(^{15}\text{N},^{18}\text{F}\) production

\(^{17}\text{O}/^{18}\text{O}\) ratios
The $^{17}\text{F}(p,g)^{18}\text{Ne}$ reaction rate

- Capture rate is comparable to the beta decay rate in novae.

- Two contributions to the rate:
  - Direct capture
  - $3^+$ resonance
The Holifield RIB Facility at Oak Ridge National Lab

- ORIC
- Hot, fibrous production target
- 25 MV tandem
- Ion source
- Mass analysis
- RIB (300 keV)

p, d, or a

To experiments
Energy and width of $3^+$ measured via $^{17}\text{F} + p$ scattering

- $\sim 8000$ $^{17}\text{F}$/s
- $48 \mu g/cm^2$ polypropylene ($\text{CH}_2$) target
- Protons detected in large SIicon Detector ARray (SIDAR)
- Heavy ions detected in coincidence by ionization counter

$E_r = 599.8 \pm 2.5$ keV
$\Gamma = 18.0 \pm 2.2$ keV
$E_x = 4523.7 \pm 2.9$ keV

- $3^+$ resonance is too high in energy to contribute significantly to the rate at nova temperatures.
- Direct capture dominates, but cross section is unmeasured. Estimates based on $^{18}\text{O}$.
- Direct capture cross section is too small to be measured at available $^{17}\text{F}$ intensities.
THE $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ DIRECT CAPTURE CROSS SECTION


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Direct capture cross section can be determined by measuring ANC’s (or spectroscopic factors) from proton transfer reactions

- Direct capture occurs via an electromagnetic transition at large radii.

- The cross section can be accurately calculated from the Asymptotic Normalization Coefficients (ANC’s) with little model dependence.

- The ANC’s can be determined by measuring the cross section for peripheral proton transfer reactions.
Some Remarks on the “ANC Method”

- The idea to use transfer reactions (via spectroscopic factors) to constrain direct capture (DC) has been around since at least the early 1970s.

- Mukhamedzhanov and collaborators contributed the important observation that both the DC and transfer cross section depend mostly asymptotic tail of the bound state (ANC).

- For transfer reactions, the choices of kinematics and reaction can be exploited to reduce theoretical uncertainties. Experimental realities may limit the choices.

- Error analysis must consider model parameters (e.g. optical potentials) as well the reaction mechanism (e.g. 2-step processes, compound-nuclear processes).
Proton transfer reactions are difficult in inverse kinematics (new experimental techniques are required)

- For stable targets the \(^3\text{He},d\) reaction can achieve \(~15\ \text{keV}\) resolution using a magnetic spectrograph.

- Inverse kinematics and low beam intensities (in the case of radioactive ion beams) produce several complications.

- \((d,n)\): gas target? CD\(_2\) target? Neutron detection?
- \(^3\text{He},d\): gas target? Poor kinematics for detecting the deuteron.
- \((^7\text{Li},^6\text{He})\) or \((^{14}\text{N},^{13}\text{C})\)

- The beam-like nucleus can be detected, but energy resolution tends to be poor.

- Gamma-ray tagging can be used for bound excited states.
$^{14}\text{N}(^{17}\text{F}, ^{18}\text{Ne}^\ast)^{13}\text{C}$ at the HRIBF

- The direct capture cross section is dominated by capture to excited states in $^{18}\text{Ne}$.
- Gamma rays were detected by the CLARION array in coincidence with $^{18}\text{Ne}$ to resolve the states of interest.
Charged-particle spectra

- $^{18}$Ne is the strongest neon group, but populated two ways:
  - Good Z separation, but (so far) poor isotopic separation in strip detector
  - Charged-particle energy resolution is not good enough (yet) to separate any of the states of interest in $^{18}$Ne.

Particle ID
Summed over whole detector

- $^{14}$N($^{17}$F, $^{18}$Ne*)$^{13}$C
- $^{12}$C($^{17}$F, $^{18}$Ne*)$^{11}$B

![Graph showing charged-particle spectra]
**Gammas needed to resolve states**

- data analysis in progress
- DWBA calculations with no free parameters
- S factor ~ 30% higher than shell model calculations
- Expect to accurately determine direct capture cross section within 10%.

\[ ^{14}\text{N}(^{17}\text{F}, ^{18}\text{Ne}_{4+})^{13}\text{C} \]
$^{14}\text{N}(^{17}\text{F},^{17}\text{F})^{14}\text{N}$ Measurement

- Silicon Detector Array $\theta_{\text{lab}}=7^\circ-18^\circ$
- Gas Ionization Counter

[Diagram showing the experimental setup with a $^{17}\text{F}$ beam of 170 MeV, $^{13}\text{C}_2\text{N}_6\text{H}_6$ target, and detection of $^{17}\text{F}$ with a silicon detector.]
These data constrain the Optical Model parameters for the transfer reaction.
\[ ^{17}\text{F}(p,\gamma)^{18}\text{Ne} \] resonant cross section

- Amplitude of \(3^+\) resonance is uncertain.
- Dominates the reaction rate at higher temperatures.
- We hope to measure the \( ^{17}\text{F}(p,g)^{18}\text{Ne} \) resonant cross section using a \( \text{H}_2 \) gas target and the DRS.

windowless \( \text{H}_2 \) gas target
10 mg/cm\(^2\)

\[ ^{17}\text{F} \] beam
10\(^7\) pps
10 MeV

\( ^{18}\text{Ne} \) from \( ^1\text{H}(^{17}\text{F},^{18}\text{Ne}) \) reaction detected by gas ionization counter.

The Daresbury Recoil Separator

ExB velocity filters

4 \( ^{18}\text{Ne} \)/day
$^{18}\text{F}(p,\alpha)^{15}\text{O}$ and $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$

- Several resonances may be important for nova temperatures
- $^{18}\text{F}(p,\alpha)$ can be measured directly, but not over the entire energy range needed for novae.
- Transfer reactions and mirror symmetry can also be used.
Experimental Approach

CH$_2$ target

$\sim 5 \times 10^5$ $^{18}$F/sec

Si Strip Detectors
Results
$^2\text{H}(^{18}\text{F},p)^{19}\text{F}$ at the HRIBF (6 MeV/u)

$^{18}\text{F}(d,p)^{18}\text{F}(6.6\text{ MeV})$

$\theta_{\text{lab}} \approx 116^\circ - 160^\circ$

$\theta_{\text{cm}} \approx 7^\circ - 29^\circ$

$\sim 3$ days of data with

$5 \times 10^5$ $^{18}\text{F}$/s on target.
$^{18}\text{F}(d,p)^{19}\text{F}$

proton spectrum

$\theta_{\text{lab}} = 147^\circ$
Proton Transfer on $^{18}$F

Appeared to be difficult…
but the $^{19}$Ne states of interest break up into
$^{15}$O+$\alpha$ which provides a unique signature.

Our new approach to (d,n) and (d,p):

$^{18}$F + $^2$H $\Rightarrow$ $^{19}$Ne* + n $\Rightarrow$ $^{15}$O + $\alpha$ + n

$\Rightarrow$ $^{19}$F* + p $\Rightarrow$ $^{15}$N + $\alpha$ + p

without detecting the n or p.

- The $^{15}$O and $\alpha$ are detected with position-sensitive Si strip detectors.
- The relative energy can thus be reconstructed.
- This approach is less sensitive to target thickness (720 $\mu$g/cm$^2$ was used).
- Work of my student: Remi Adekola
Reconstructing the Relative Energy

Reaction:

\[ ^{18}\text{F} + ^{2}\text{H} \rightarrow ^{19}\text{Ne}^* + \text{n} \rightarrow ^{15}\text{O} + \alpha + \text{n} \]

Relative energy of the state

\[ E_{rel} = \frac{1}{m_1 + m_2} \left[ m_1 E_2 + m_2 E_1 - 2 \cos \theta_{12} \sqrt{m_1 m_2 E_1 E_2} \right] \]

\[ E_x = E_{th} + E_{rel} \]

\[ Q = E_1 + E_2 + E_3 - E_A \]
- Each telescope is 5 cm x 5 cm and located ~45 cm downstream from the target.
- Inner $\Delta E$s are 65 $\mu$m; outers are 140 mm; E detectors are 1 mm.
Particles identification histogram
Outer Telescope
Energy resolution in c.m. system is $\sim$70 keV.
### Our Present Understanding

<table>
<thead>
<tr>
<th>$E_r$ (keV)</th>
<th>$J^\pi$</th>
<th>$\Gamma_p$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>$3/2^+$</td>
<td>$4 \times 10^{-37}$</td>
</tr>
<tr>
<td>26</td>
<td>$1/2^-$</td>
<td>$3 \times 10^{-20}$</td>
</tr>
<tr>
<td>38</td>
<td>$3/2^+$</td>
<td>$2 \times 10^{-14}$</td>
</tr>
<tr>
<td>287</td>
<td>$5/2^+$</td>
<td>$4 \times 10^{-5}$</td>
</tr>
<tr>
<td>330</td>
<td>$3/2^-$</td>
<td>$2.2(0.7) \times 10^{-3}$</td>
</tr>
<tr>
<td>665</td>
<td>$3/2^+$</td>
<td>$15.2(1.0)$</td>
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</tbody>
</table>

![Graph showing $^{16}\text{F}(\rho,\alpha)^{16}\text{O}$ reaction](image)
Reaction Rate

Note: SPI/INTEGRAL should be able to see 511-keV photons following a nova outburst provided it is with ~5kpc of earth.
Interfering $3/2^+$ Resonances
For the Future:

- Complete analysis of proton transfer data.

- Measure $^{18}\text{F}(p,\alpha)^{15}\text{O}$ at lower energies?

- Measure spectroscopy with $^{17}\text{O}{}^{3}\text{He,n}^{19}\text{Ne}$.