Constraining the $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ Reaction Rate Using Direct Measurements at DRAGON

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Outline

1. Role of $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ in Explosive Stellar Phenomena
2. Previous Experimental Measurements
3. S1560 Experiment at TRIUMF
4. Preliminary Results and Ongoing Analysis
Explosive Stellar Phenomena
Novae and X-ray Bursts

- Environments with large $T \& \rho$ → explosive nuclear burning.

- Novae and X-ray bursts → thermonuclear runaway.

- Important contributors to galactic chemical evolution.
$^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ in ONe Novae

Constraining the Synthesis of $^{19}\text{F}$

- $^{19}\text{F}$ is usually produced in novae via:
  \[^{17}\text{O}(p,\gamma)^{18}\text{F}(p,\gamma)^{19}\text{Ne}(\beta^+)^{19}\text{F}\]

- However, $^{19}\text{F}$ synthesis can be bypassed via:
  \[^{17}\text{O}(p,\gamma)^{18}\text{F}(p,\gamma)^{19}\text{Ne}(p,\gamma)^{20}\text{Na}\]
Between outbursts, Type I X-ray bursts generate energy through the \( \beta \)-limited hot CNO cycles.

During an outburst, it becomes possible to "breakout" from the hot CNO cycles into the rp-process, where the main reaction pathway linking these processes is:

\[ ^{15}\text{O}(\alpha, \gamma) ^{19}\text{Ne}(p, \gamma) ^{20}\text{Na} \]
Previous Studies I
1990-1995

- 1990 - 1993 - Indirect studies, using $^{20}\text{Ne}(^{3}\text{He},t)^{20}\text{Na}$ reactions. Single resonance at $E_R \sim 450$ keV dominates reaction rate. $J^{\pi} = 1^+$ or $3^+$. 
  

- 1994 - First direct study at Louvain-la-Neuve. $J^{\pi} = 1^+$, but $3^+$ could not be ruled out. Resonance strength upper limit of 18 meV.  
  

- 1995 - $\beta$-decay study of $^{20}\text{Mg}$ at GANIL. $J^{\pi} = 3^+$, but $1^+$ could not be ruled out, due to high experimental background.  
  
• 1998 - In-depth $^{19}$Ne(d,n) study in which the work by Page et al. was re-examined. The resonance strength upper limit was changed slightly to 21 meV, still assuming $J^\pi = 1^+$. 


• 2000 - Shell model study of $^{20}$Na. $J^\pi = 3^+$ for the resonant state, $1^+$ ruled out. Resonance strength lower limit of 16 meV. 


• 2004 - Another direct study using the ARES recoil separator. Updated resonance strength upper limit of 15 meV. $J^\pi = 1^+$ or $3^+$. 

Previous Studies III
2010-2016

- 2010 - A new \(^{3}\text{He},t\) measurement obtained a more precise Q value for the \(^{19}\text{Ne}(p,\gamma)^{20}\text{Na}\) reaction, implying previous measurements were 10 keV too low in energy.


- 2012 - \(\beta\)-delayed proton study at Texas A&M University, optimised to detect low energy protons. Non-detection of resonant state implies \(J\pi = 3^+\).


- 2016 - \(^{19}\text{Ne}(d,n)^{20}\text{Na}\) study at FSU, detecting protons from the decay of \(^{20}\text{Na}\). Finds \(J\pi = 3^+\) for the resonant state, but some inconsistencies with previous work.

Main motivation:

Direct measurement assuming new resonant energy of $\sim 457$ keV.

Main aims:

Definitively measure the strength of the resonance.

Bring all previous studies into agreement.

Solve a 20+ year old debate in nuclear astrophysics!
The DRAGON Recoil Separator
Detector of Recoils And Gammas Of Nuclear Reactions

• $^{19}$Ne beam from the ISAC facility.
• Windowless gas target filled with $H_2$ gas.
• $^{20}$Na recoil ions stopped in an ionisation chamber.
• Radiative capture $\gamma$-rays measured in BGO array.

$$\langle \sigma \nu \rangle = \left( \frac{2\pi}{\mu kT} \right)^{\frac{3}{2}} \hbar^2 (\omega \gamma) \exp \left(- \frac{E_r}{kT} \right)$$
Preliminary Results
The "Golden" Cut

- We seem to have seen $^{20}\text{Na}$ recoils!
Of the 15 events in the dual TOF spectrum, 9 are clustered together.
Preliminary Results
Resonance strength formula and Beam Normalisation

\[ \omega \gamma = \frac{2\epsilon}{\lambda^{2}_{cm}} \frac{N_{r}}{\eta_{r} N_{b}} \frac{m}{M + m} \]

S1560 - Beta Scaler Rate

<table>
<thead>
<tr>
<th>Proj</th>
<th>Entries</th>
<th>Mean</th>
<th>Mean y</th>
<th>RMS</th>
<th>RMS y</th>
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<tr>
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<td>684.1</td>
<td>1.114e+05</td>
<td>231.2</td>
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Run Time (s)
## Preliminary Results

### Table of Important Values

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<thead>
<tr>
<th>Physical quantity</th>
<th>Value</th>
<th>Error</th>
</tr>
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<tbody>
<tr>
<td>M (amu)</td>
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<td>3 $\times$ 10^{-7}</td>
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<td>m (amu)</td>
<td>1.007276466879</td>
<td>9.1 $\times$ 10^{-11}</td>
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<td>$\epsilon$ (eV cm$^2$ / 10$^{15}$ atoms)</td>
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<td>5.521</td>
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<td>$N_b$ (particles)</td>
<td>2.8449 $\times$ 10$^{12}$</td>
<td>6.2994 $\times$ 10$^{11}$</td>
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<td>CSF$_{Na}$</td>
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<tr>
<td>$\eta_{sep}$</td>
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<td>0.0210</td>
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<td>$\eta_{live}$</td>
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<td>$\eta_{MCP,t}$</td>
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<tr>
<td>$\eta_{end}$</td>
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<td>$\eta_{\gamma}$</td>
<td>0.462</td>
<td>0.026</td>
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Preliminary Results
BGO z-coordinate distribution

- Obviously not the ideal case, due to low statistics.
Despite issues with low statistics, a preliminary value for both the resonance strength and resonance energy could be determined.

\[ E_R \sim 458 \text{ keV} \quad \omega \gamma \sim 18 \text{ meV} \]
A log-likelihood analysis is being carried out to extract values of $E_R$ and $\omega\gamma$, by combining the low statistics data with suite of Geant simulations of DRAGON where $E_R$ is varied.
The $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ reaction rate plays an significant role in both nova and X-ray burst nucleosynthesis.

The reaction rate is dominated by a single narrow resonance at $E_R \sim 450$ keV, and has been a subject of debate for almost 25 years.

A direct measurement was made using the DRAGON recoil separator, at an energy $\sim 10$ keV higher than previous studies.

Experimental analysis is currently ongoing, but preliminary estimates show the resonance energy to be $\sim 458$ keV and the resonance strength to be $\sim 18$ meV.
This result seems to help reconcile previous experimental results:

- Previous direct measurements (Page et al. and Couder et al.) were optimised for the wrong resonance energy.

- Our strength is in line with the previous upper limits from (d,n) reactions of $\omega \gamma < 29$ meV (Vancraeynest et al.).

- Our strength is entirely consistent with a $3^+$ spin-parity assignment, in good agreement with beta-delayed proton studies at GANIL and TAMU (Piechaczek et al. and Wallace et al.).
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Thank you for your attention

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