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

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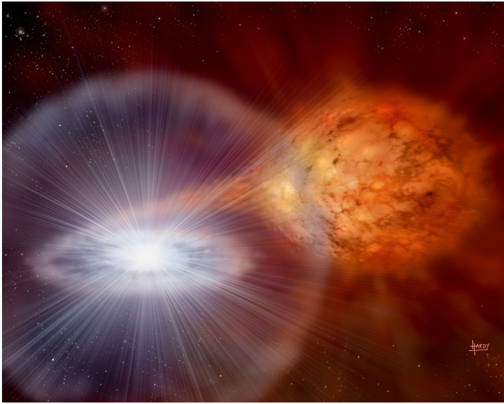
Outline

1. Role of $^{19}Ne(p,\gamma)^{20}Na$ 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 & ρ
  $\rightarrow$ explosive nuclear burning.
- Novae and X-ray bursts
  $\rightarrow$ thermonuclear runaway.
- Important contributors to galactic chemical evolution.



^{19}Ne(p,γ)^{20}Na in ONe Novae

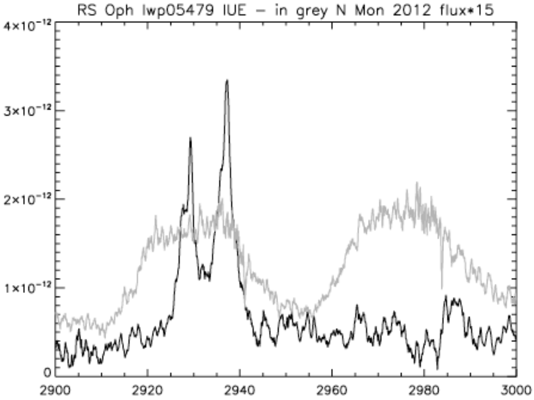
Constraining the Synthesis of ^{19}F

- ^{19}F is usually produced in novae via:

$$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}(\beta^{+})^{19}\mathrm{F}$$

- However, ^{19}F synthesis can be bypassed via:

$$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$$



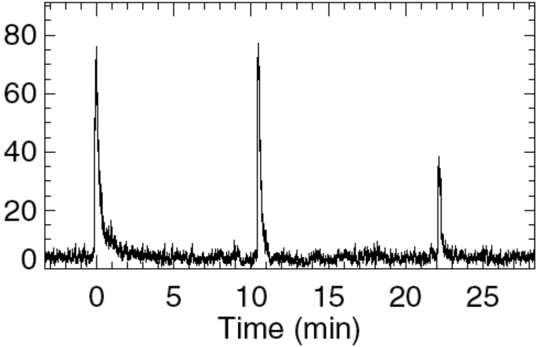
^{19}Ne(p,γ)^{20}Na in Type I X-ray Bursts

Understanding Breakout into the rp-process

- Between outbursts, Type I X-ray bursts generate energy through the β-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:

$$^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}(\mathrm{p},\gamma)^{20}\mathrm{Na}$$



Previous Studies I

1990-1995

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

L.O. Lamm *et al.*, Nucl. Phys. A **510**, 503 (1990)
M.S. Smith *et al.*, Nucl. Phys. A **536**, 333 (1992)
N.M. Clarke *et al*, J. Phys. G: Nucl. Part. Phys. **19**, 1411 (1993)

- 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.

R.D. Page *et al.*, Phys. Rev. Lett. **73**, 3066 (1994)

- 1995 - β-decay study of ^{20}Mg at GANIL. $J^\pi = 3^+$, but 1^+ could not be ruled out, due to high experimental background.

A. Piechaczek *et al.*, Nucl. Phys. A **584**, 509 (1995)

Previous Studies II

1998-2004

- 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 $J^{\pi} = 1^{+}$.

  G. Vancraeynest *et al.*, Phys. Rev. C **57**, 5 (1998)

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

  H.T. Fortune *et al.*, Phys. Rev. C **61**, 057303 (2000)

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

  M. Couder *et al.*, Phys. Rev. C **69**, 022801 (2004)

Previous Studies III

2010-2016

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

  C. Wrede *et al.*, Phys. Rev. C **82**, 035805 (2010)

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

  J.P. Wallace *et al.*, Phys. Lett. B. **712**, 59 (2012)

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

  J. Belarge *et al.*, Phys. Rev. Lett. **117**, 182701 (2016)

The Solution
Direct Measurement at DRAGON

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Main motivation:

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

Main aims:

Definitively measure the strength of the resonance.

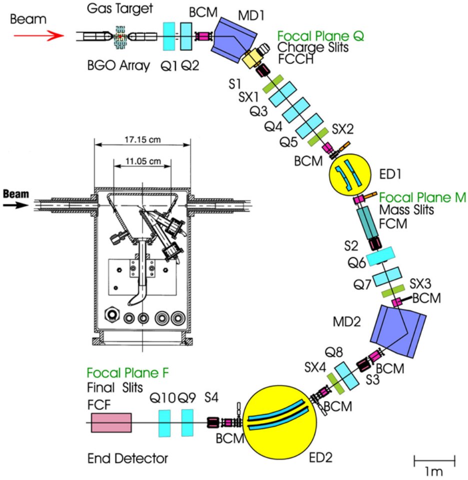
Bring all previous studies into agreement.

Solve a 20+ year old debate in nuclear astrophysics!

The DRAGON Recoil Separator

Detector of Recoils And Gammas Of Nuclear Reactions

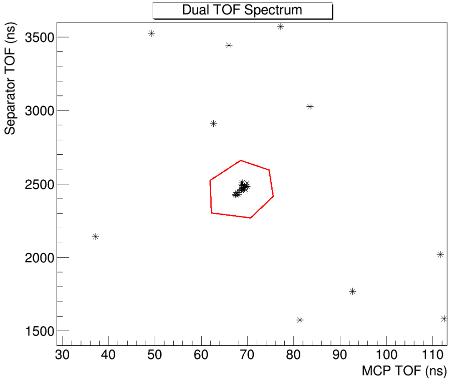
- ^{19}Ne beam from the ISAC facility.
- Windowless gas target filled with H_2 gas.
- ^{20}Na recoil ions stopped in an ionisation chamber.
- Radiative capture γ-rays measured in BGO array.

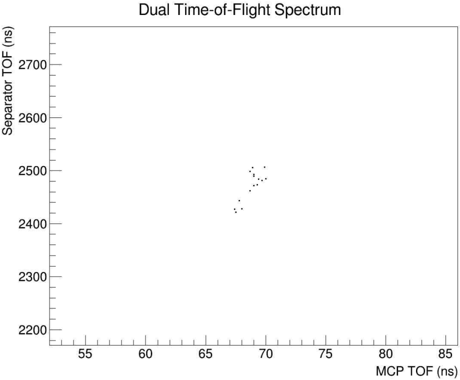


$$\langle\sigma\nu\rangle = \left(\frac{2\pi}{\mu kT}\right)^{\frac{3}{2}} \hbar^2 (\omega\gamma)\, exp\left(-\frac{E_r}{kT}\right)$$

Preliminary Results

The "Golden" Cut





- We seem to have seen ^{20}Na recoils!

Preliminary Results
Particle ID: Ionisation Chamber

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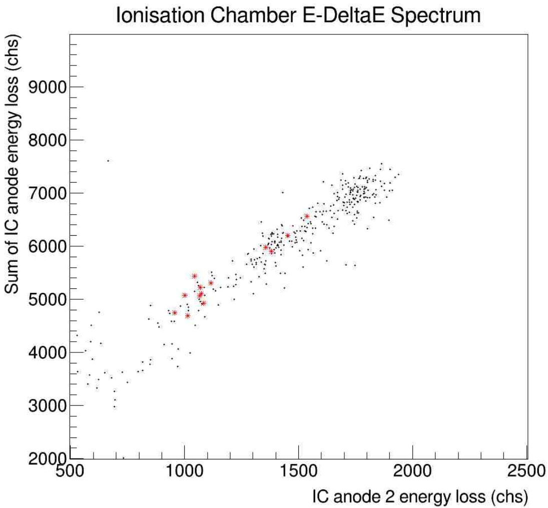
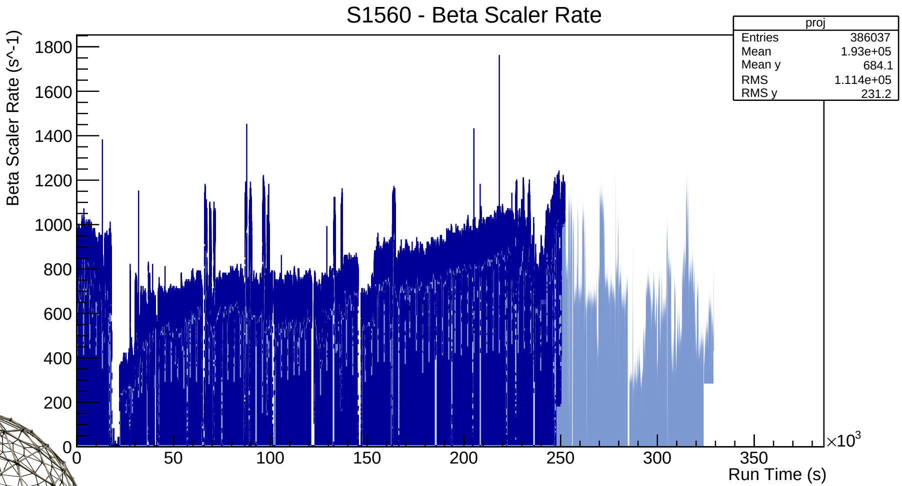


- Of the 15 events in the dual TOF spectrum, 9 are clustered together.

Preliminary Results

Resonance strength formula and Beam Normalisation

$$\omega\gamma = \frac{2\epsilon}{\lambda_{cm}^2} \frac{N_r}{\eta_r N_b} \frac{m}{M+m}$$



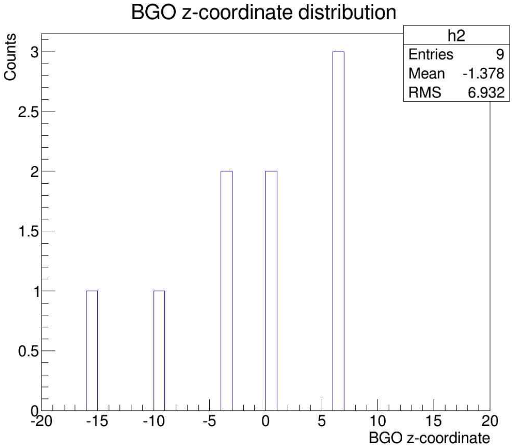
Preliminary Results

Table of Important Values

Physical quantity	Value	Error
M (amu)	19.0018802	3 xx 10^{-7}
m (amu)	1.007276466879	9.1 x 10^-11
ϵ (eVcm^2/10^{15} atoms)	84.275	5.521
N_b (particles)	2.8449 x 10^{12}	6.2994 x 10^{11}
CSF$_{Na}$	0.4386	0.0003
η_{sep}	0.9926	0.0210
η_{live}	0.884638	4.4 x 10^-5
$\eta_{MCP,t}$	0.769	0.006
η_{end}	00.589222	0.084294
η_{γ}	0.462	0.026

Preliminary Results

BGO z-coordinate distribution



- Obviously not the ideal case, due to low statistics.

Preliminary Results

Preliminary E_R and $\omega\gamma$

- Despite issues with low statistics, a preliminary value for both the resonance strength and resonance energy could be determined.

$$E_R \sim 458 \text{ keV} \qquad \omega\gamma \sim 18 \text{ meV}$$

Ongoing analysis

What still needs to be done?

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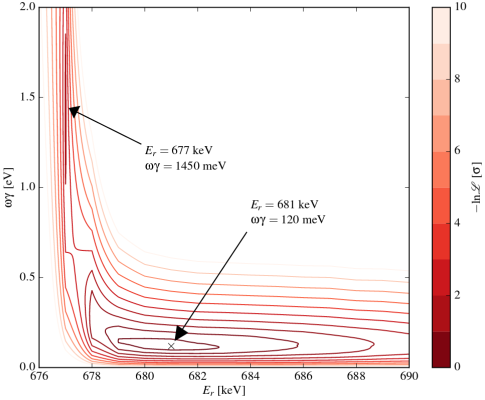
- A log-likelihood analysis is being carried out to extract values of E_R and $\omega\gamma$, by combining the low statistics data with suite of Geant simulations of DRAGON where E_R is varied.



Summary

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- The ^{19}Ne(p,γ)^{20}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 ~ 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.

Summary

Reconciling previous measurements

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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