Destruction of ^{22}Na in Novae:
Surprising Results from an Absolute Measurement of ^{22}Na(p,γ) Resonance Strengths

CENPA
Center for Experimental Nuclear Physics and Astrophysics

TRIUMF

Anne L. Sallaska

C. Wrede, A. Garcia, D.W. Storm, T.A.D. Brown, K.A. Snover
University of Washington
C. Ruiz, D.F. Ottewell, L. Buchmann, D.A. Hutcheon, C. Vockenhuber, J.A. Caggiano
TRIUMF

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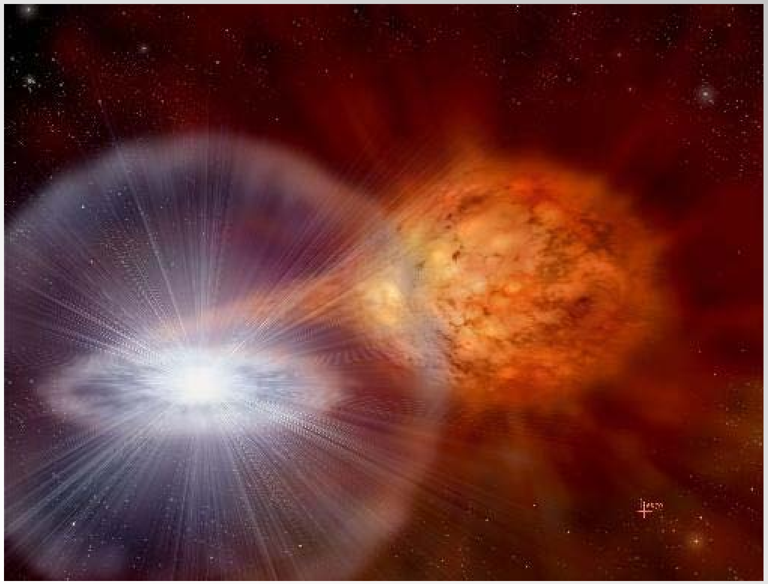
Outline

* panorama view

- ❑ Motivation for direct, absolute measurements
- ❑ Experimental strategy
- ❑ Apparatus, targets, measured parameters
- ❑ Final results and astrophysical implications

Motivation

- Classical nova: thermonuclear outburst on the surface of a white-dwarf star accreting H-rich material from a binary companion
  - Ideal sites for modeling of explosive nucleosynthesis: most of relevant thermonuclear reaction rates are based on experimental info



http://i.space.com/images/060719_ophiuchi_nova_02.jpg

  - Potential *sources* of γ-ray emitters
    - If detected, can provide more detailed info on underlying physical processes
    - ^{22}Na: $t_{1/2}$ ~ 2.6 y (E_γ =1.275 MeV): *short* $t_{1/2}$: remains *localized* near its progenitor
      - Novae could be the principal sites for ^{22}Na production

$^{22}Na(p,\gamma)^{23}Mg$

- Main destructive mechanism of ^{22}Na
- Reaction is dominated by narrow, isolated resonances at peak nova temps ($0.1 < T < 0.4$ GK)
  - Currently accepted rate based on two sets of direct measurements (only one was absolute)
- We have made direct, absolute measurements of resonance strengths for $E_p < 610$ keV
  - Including $E_p = 198, 232$ keV: never been observed
    - Has been suggested that a 198-keV resonance could dominate the rate[1]
  - Specially designed beamline using proton beams incident on implanted, radioactive ^{22}Na targets
  - Experimental strategy more robust than previous measurements

[1] Jenkins, PRL, **92**, 031101 (2004).

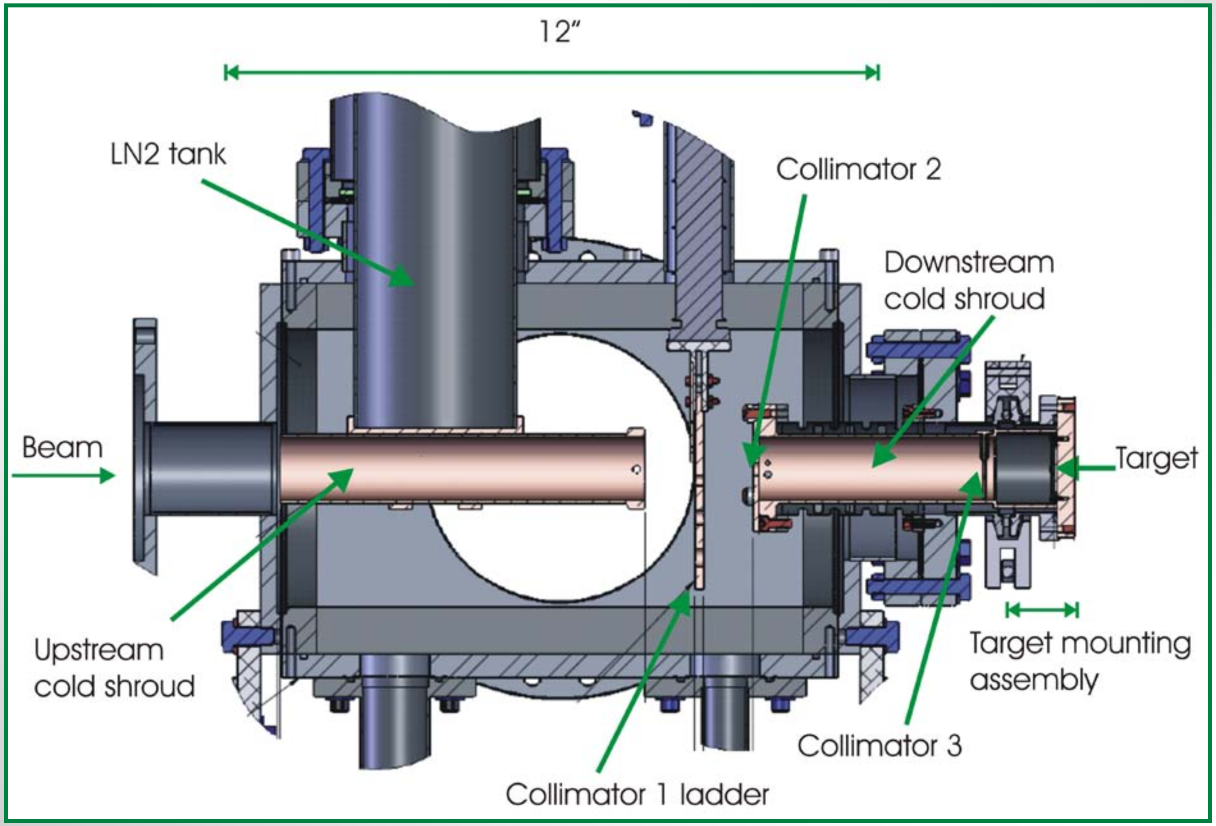
Strategy and Requirements: ωγ

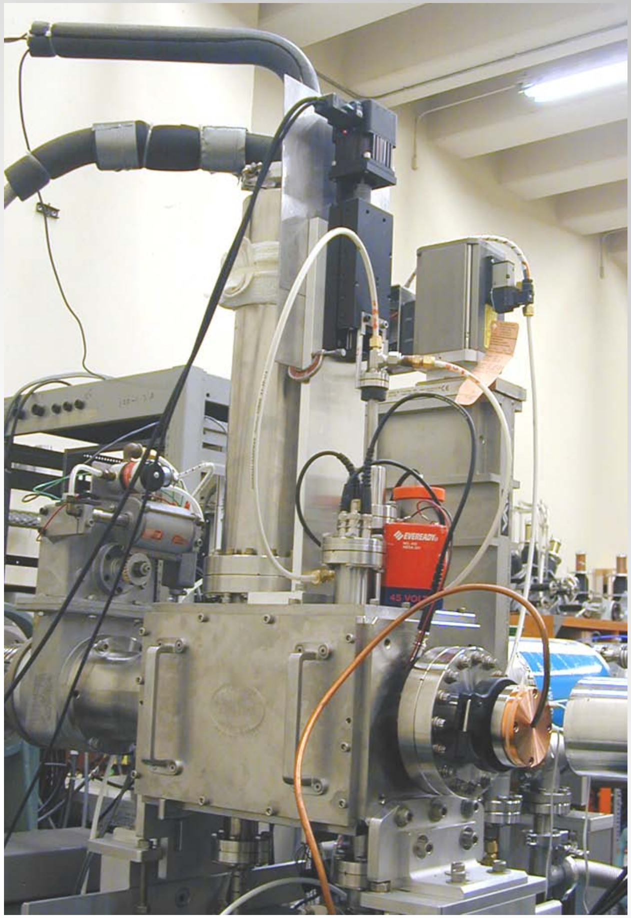
- Experimental strategy: reversed from the typical
  - *Small diameter target* illuminated with a *uniform beam*
    - Makes use of all ^{22}Na atoms
  - Insensitive to target:
    - Areal non-uniformity
    - Stoichiometry
  - Implanted targets allow use of *integrated*, not peak, yields
    - Insensitive to ^{22}Na distribution within the substrate

$$\int Y dE = 2\pi^2 \square^2 \frac{m+M}{M} N_{\text{Na}} \rho_{\text{beam}} \omega\gamma$$

- Requirements:
  - Absolute detector efficiency
  - Total number of ^{22}Na atoms
  - Beam density

Chamber





- LN$_2$-cooled cold shroud assembly:
  - Serves to protect beamline by isolating the radioactivity and assures a clean vacuum
- Water-cooled target

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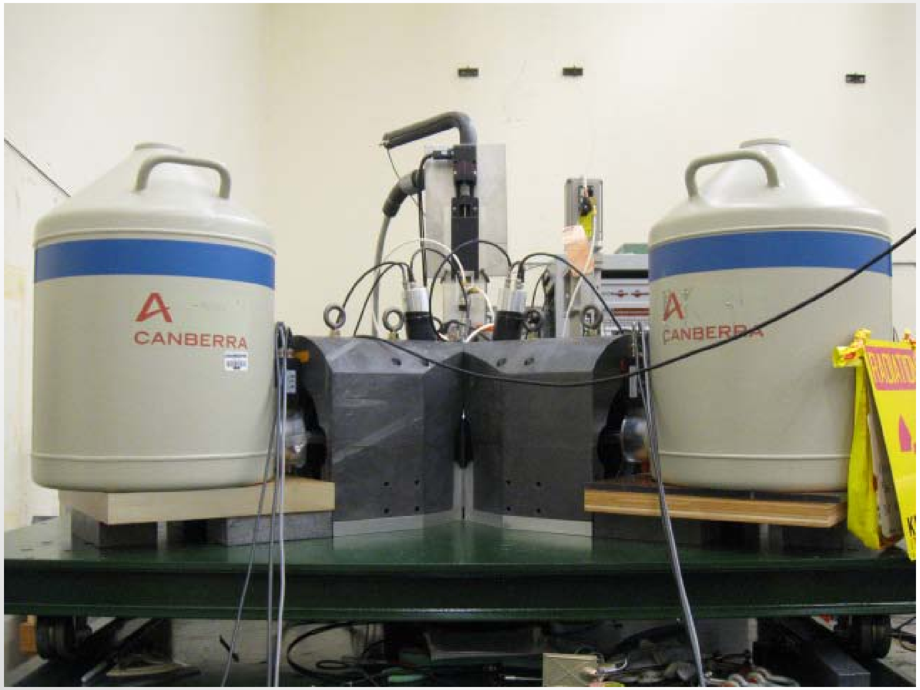
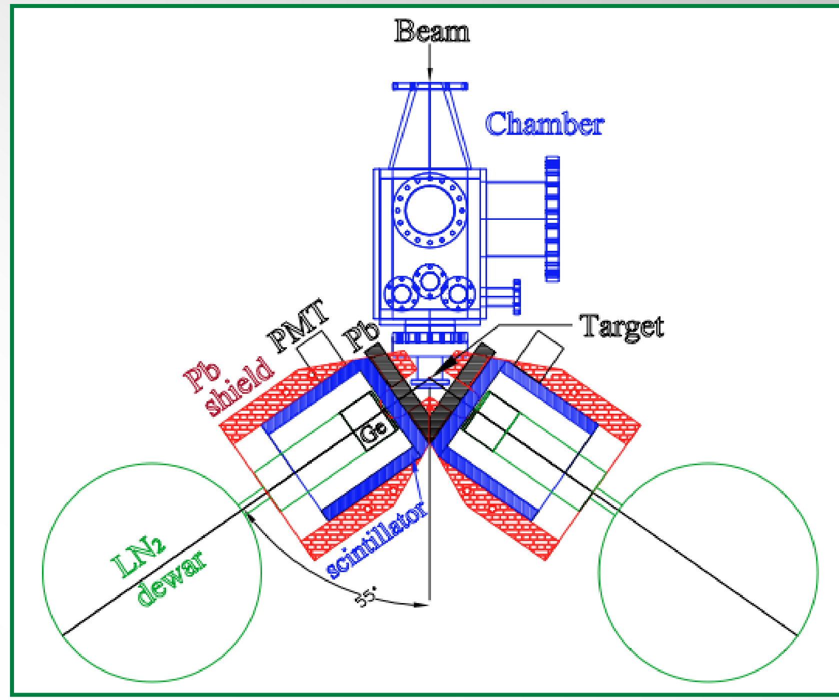
Detector Setup

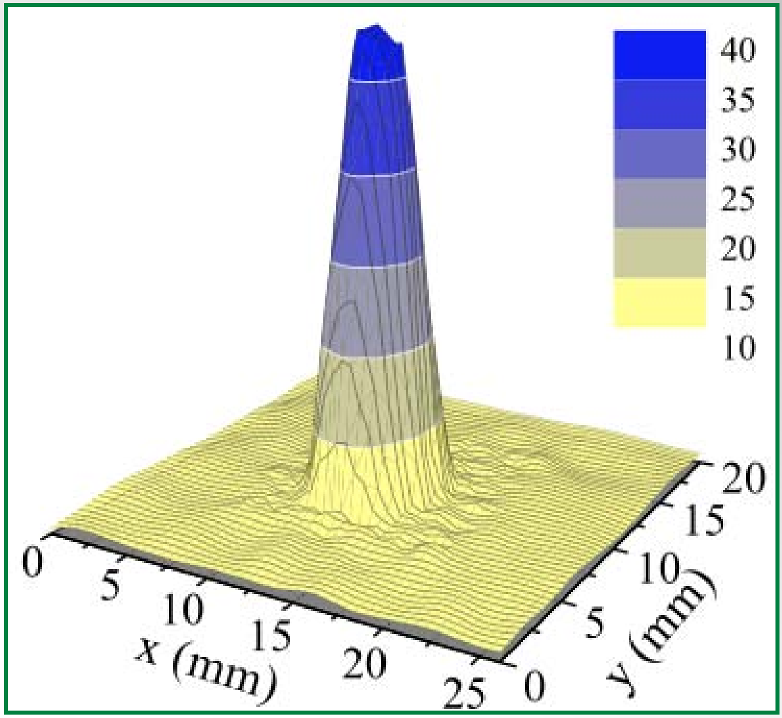




- Two HPGe at ±55° to the beam axis
- 26 mm of Pb to shield from radioactive target
- Cosmic ray shielding
  - Filter out excess background by rejecting 80% above 5 MeV

^{22}Na Targets

- Implanted at TRIUMF
  - 30 keV ion beam
  - 1/8” thk OFHC Cu substrate
  - Rastered over 5-mm diameter
  - 185, 300 μCi (2005)
    - Test targets
    - Extensive ^{23}Na tests revealed a Cr layer helped to stunt degradation during proton bombardment[1]
  - 2 300 μCi (2009)
    - Main targets
    - Cr layer

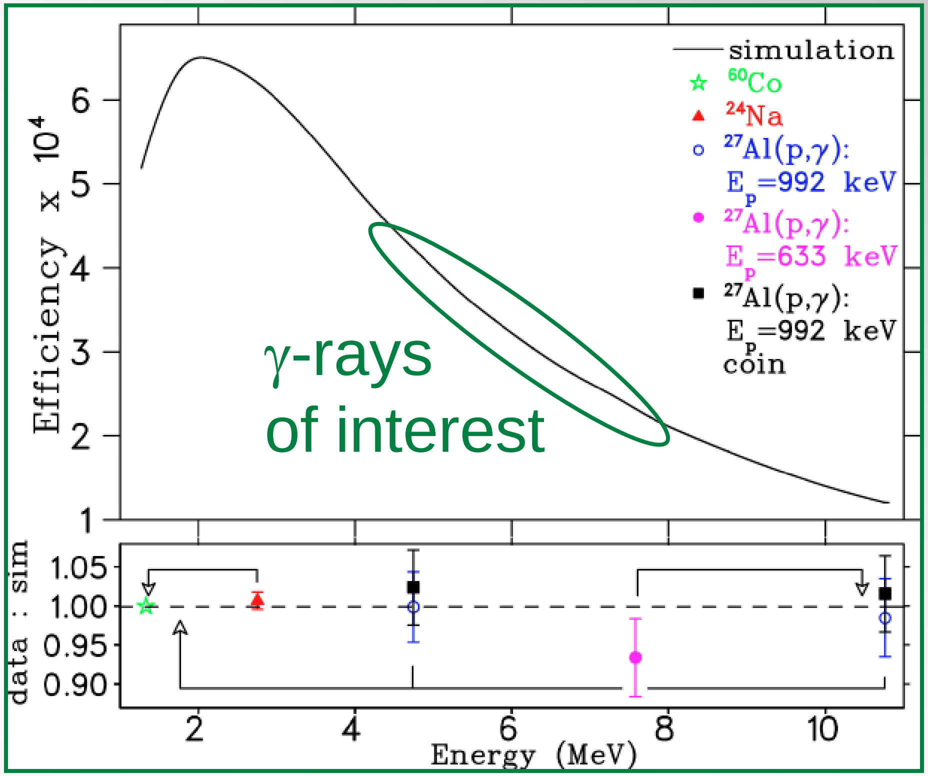


- Verified target: 5-mm diameter and centered on substrate:
  - Scan with a Geiger counter utilizing a 3-mm collimator

[1] Brown, NIM B **267**, 3302 (2009).

Absolute Detector Efficiency

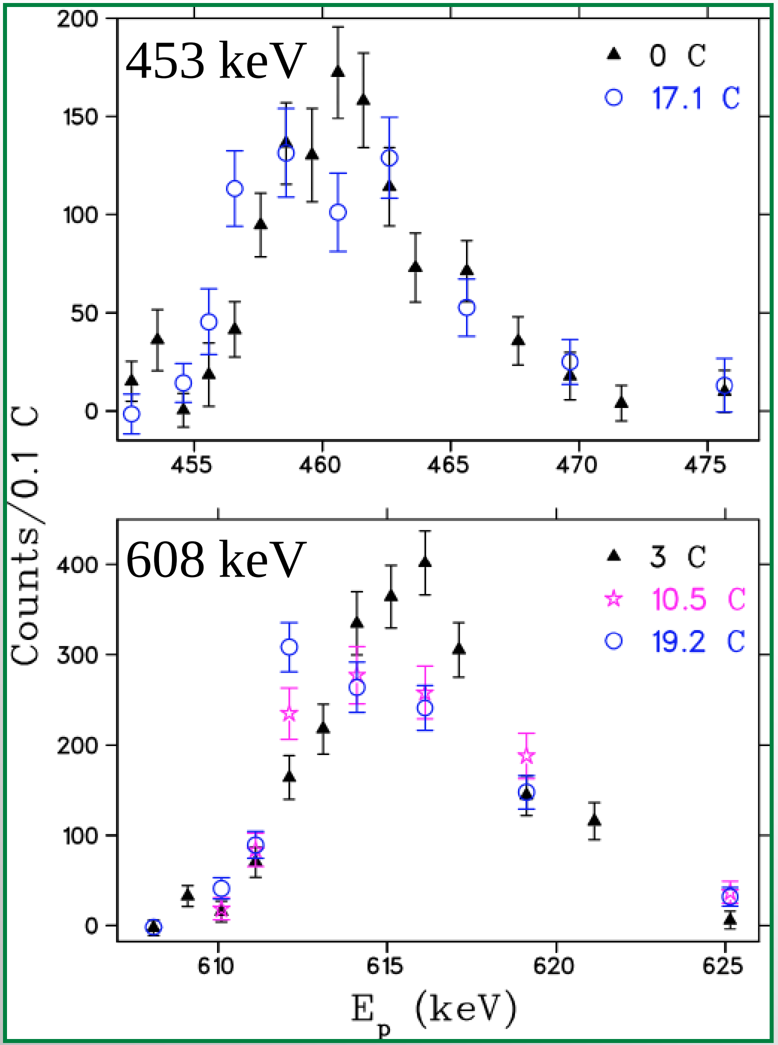
- Determined: measurement and simulation
  - Absolute measurement at E_γ= 1332 keV using calibrated ^{60}Co source (1.7%)
  - Relative measurements using:
    - ^{24}Na source: E_γ=1369, 2754 keV
    - ^{27}Al(p,γ) reaction branches: E_p= 633, 992 keV (γ-rays: 2-11 MeV)
  - PENELOPE simulations



- Assigned 6% systematic uncertainty
  - Includes estimated 3% from possible anisotropy

N_T and Target Degradation

- Initial N_T determined from activity measured *in-situ* using η of 1275 keV γ-ray

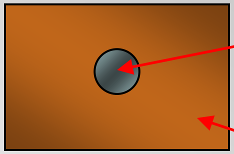


- Not sufficient due to possible target degradation from proton bombardment. Estimated from two methods:
  - *In-situ* activity measurements
  - Revisit strong, reference resonance periodically throughout bombardment because $N_T \propto \int YdE$

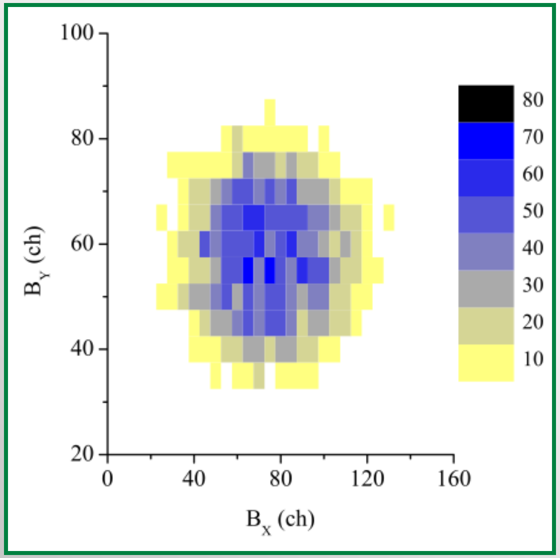
- Degradation < 12% for all resonances (except E_p = 232 keV)

Beam Density

- Measured yields from two thick targets: full and "coin" ^{27}Al
- Extracted using ratio of yields from: $\frac{Y_{\text{coin}}}{Y_{\text{full}}} = \rho_{beam} A_{\text{coin}}$



  - Measurements at E_p = 405, 992 keV in excellent agreement
- 9.7% systematic error determined by:
  - Physical measurements of beam spot via target coloration
  - Varied raster amplitudes/collimator diameters
  - Used Monte-Carlo simulation to model transport, applying constraints from various measurements



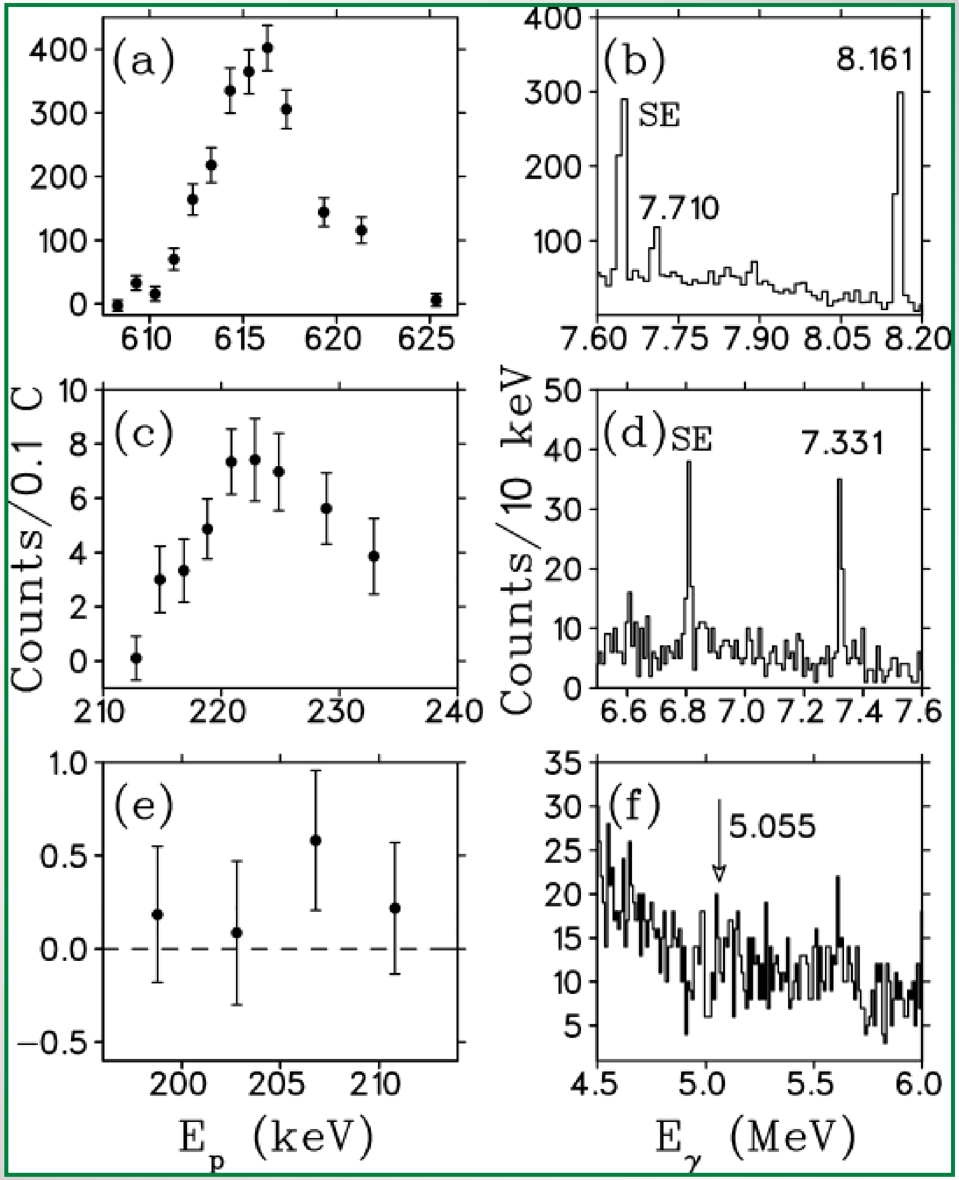
- DAQ system also registers raster amplitudes with every event
  - Used to detect possible errors

Excitation Functions and Spectra

E_p = 608 keV

E_p = 211 keV

E_p = 198 keV



Results

Systematic Error Budget

Error	453/608 keV	211/608 keV	287 keV	232 keV
η	6%	6%	6%	6%
ρ_b	10%	10%	10%	10%
N_T	2.6%	+5.6%, -2.6%	+7%, -14%	40%
Total	11.7%	+12.7%, -11.7%	+13.4%, -18.1%	42%

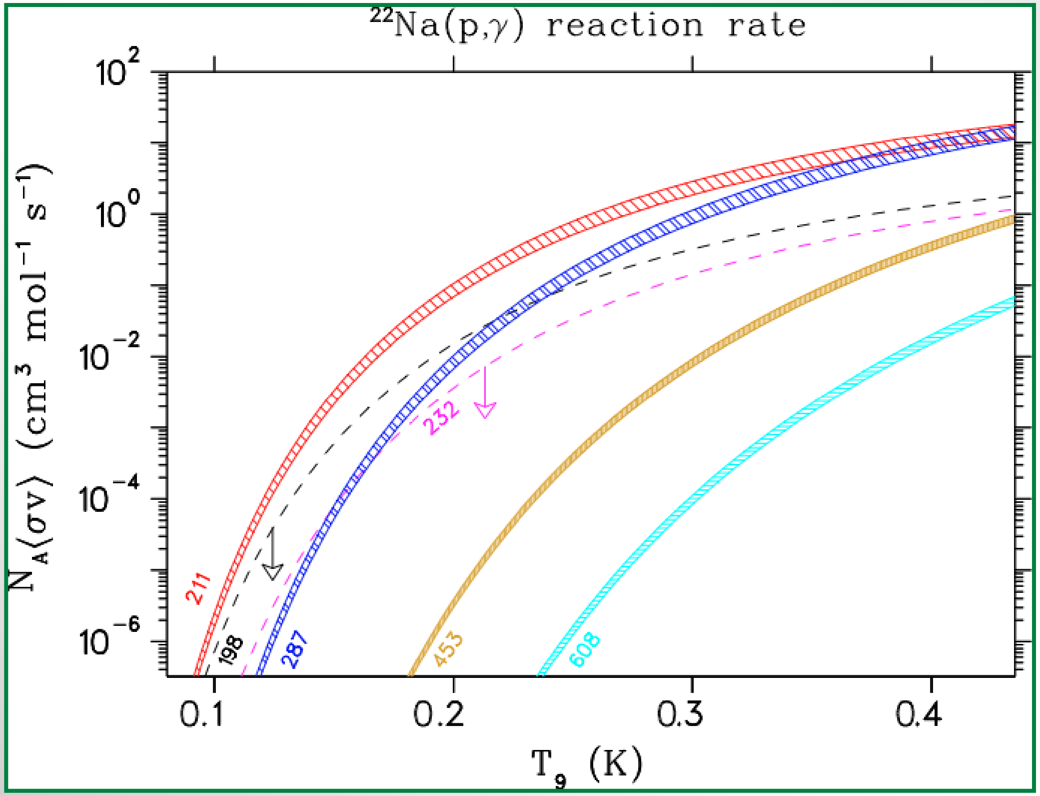
Results for $\omega\gamma$

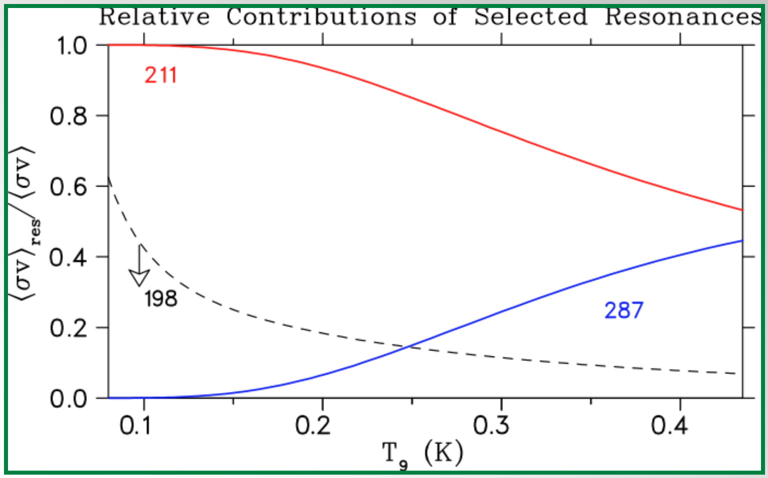
E_R (keV)	$\omega\gamma_{previous}$ (meV)	$\omega\gamma_{present}$ (meV)	Ratio present : previous
198	≤ 4*	≤ 0.50	0.1
211	1.8 ± 0.7 1	$5.5^{+1.6}_{-0.9}$	3.1
232	2.2 ± 1.0*	≤ 0.65	0.3
287	15.8 ± 3.4 1	38 ± 8	2.4
453	68 ± 20 2	161 ± 21	2.4
608	235 ± 33 2	573^{+100}_{-72}	2.4

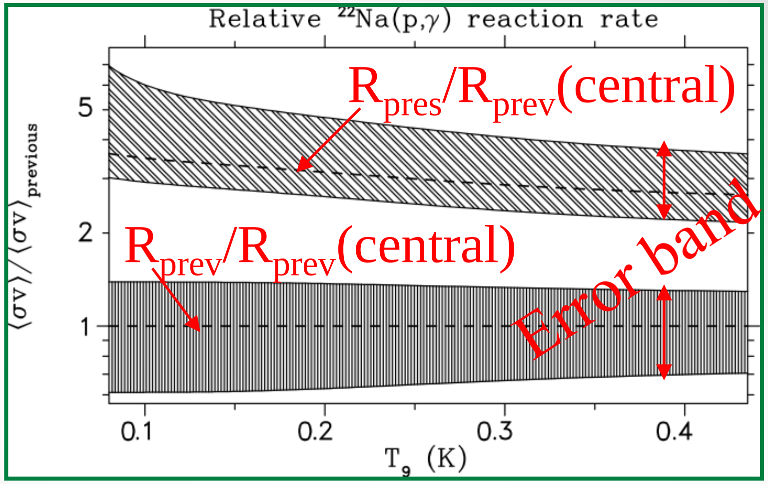
* indirect determination

[1] F. Stegmuller *et al.*, Nucl. Phys., A601, 168 (1996). [2] S. Seuthe *et al.*, Nucl. Phys., A514, 471 (1990).

Reaction Rate and Astrophysical Implications







- 198-keV resonance does not dominate
  - 211-keV supercedes at all temps
- Based on post-processing network calculations[1,2], we estimated ^{22}Na consumption increases by factors of 2 to 3

[1] C. Iliadis *et al*,, Astrophys. J. Suppl. Ser., 142, 105 (2002).
[2] Hix *et al.*, Nucl. Phys., A718, 620c (2003).

Summary

- We performed direct, absolute measurements of ^{22}Na(p,γ) resonance strengths
  - Radioactive targets: minimal degradation
  - Robust experimental method
    - Insensitive to target distributions within the substrate
    - Only N_T needed to be determined, not target density
- Surprisingly found resonance strengths to be higher by 2.4x to 3.1x!
  - Directly affects the consumption of ^{22}Na in novae

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University of Washington

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D.W. Storm

A. Garcia

C. Wrede

K. Snover

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G. Harper

D.I. Will

D. Zumwalt

S. Stattel

B.M. Freeman

TRIUMF

C. Ruiz

D.A. Hutcheon

L. Buchmann

D.F Ottewell

C. Vockenhuber

C. Holmberg

J.A. Caggiano

Publications:

- short paper submitted to Phys. Rev. Lett.
- long paper in preparation for Phys. Rev. C