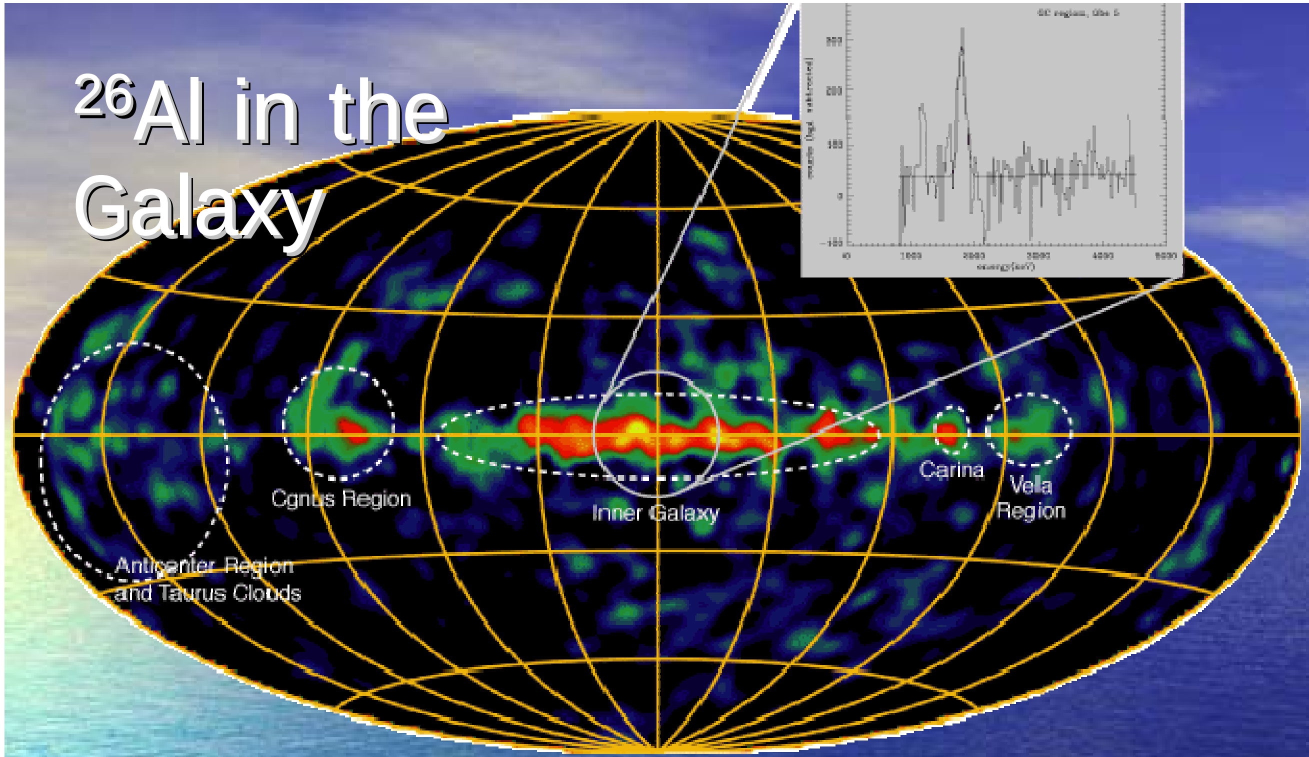
The $^{26g}Al(p,\gamma)^{27}Si$ Reaction in Novae

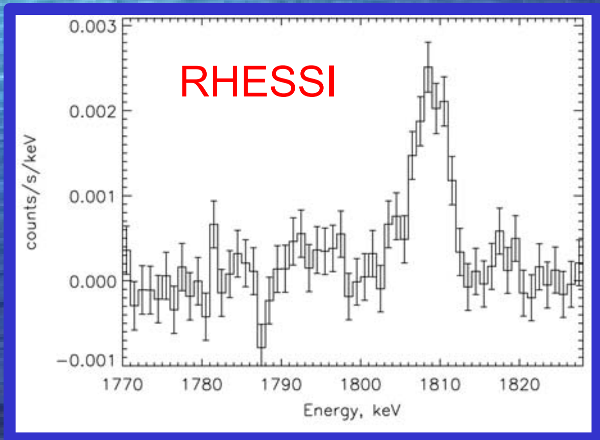
Chris Ruiz – TRIUMF/Simon Fraser University
For the DRAGON collaboration

Nuclei in the Cosmos IX – CERN, Geneva 2006

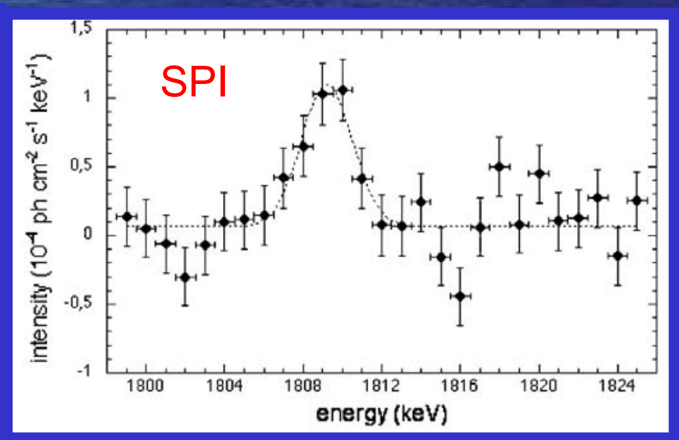
^{26}Al in the Galaxy



- $t_{1/2}$ = 7.2 x 10^5 yr
- E_γ = 1809 keV
  - COMPTEL → 2 $M_☉$
  - RHESSI, INTEGRAL → 2.8±0.8$M_☉$
  - Concentration in star forming regions: young massive progenitors
  - CCSN (O-Ne shell and H-shell)
  - Wolf-Rayet phases
  - AGB, Novae (O-Ne)?



Smith, D.M. ApJ 589, L55 (2003)



Knodlseder, J. New Astronomy Reviews 48 (2004)

^{60}Fe/^{26}Al ratio measured (RHESSI and SPI):

^{60}Fe/^{26}Al =0.11± 0.03

Harris, M.J. Astronomy & Astrophysics 433 (2005)

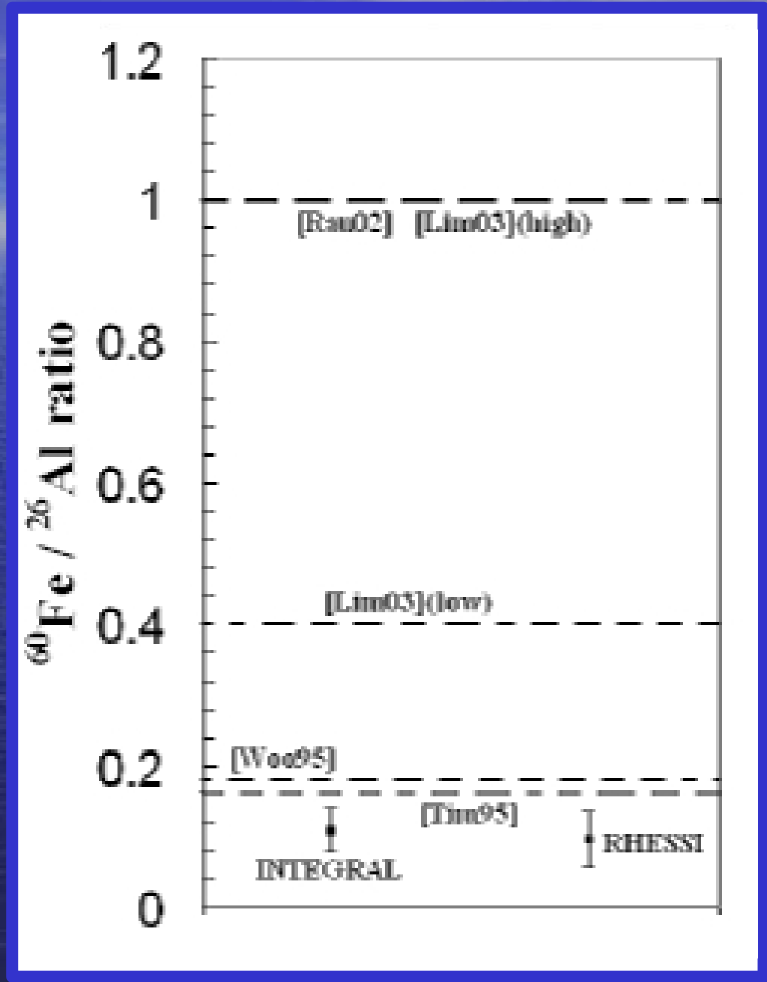
(SPI result)

1995 model (Woosley)

2002 model (Rauscher)

- Woosley and Weaver (1995)
  - 200 isotope network H to Ge
  - Neutrino induced nucleosynthesis
  - Large CCSN ^{26}Al yield
- Rauscher, Heger, Hoffman and Woosley (2002)
  - NON-SMOKER, similar to WW95 code
  - Improved stellar physics
  - Updated nuclear reaction rates (REACLIB)
- Limongi and Chieffi (2003)
  - REACLIB, no neutrino nucleosynthesis
  - Different treatment of explosion

In order to reproduce measured ^{60}Fe/^{26}Al, must integrate over Wolf-Rayet stars. However…yields uncertain.



N. Prantzos, Astronomy & Astrophysics 420, 1033-1037 (2004)

Nova contribution?

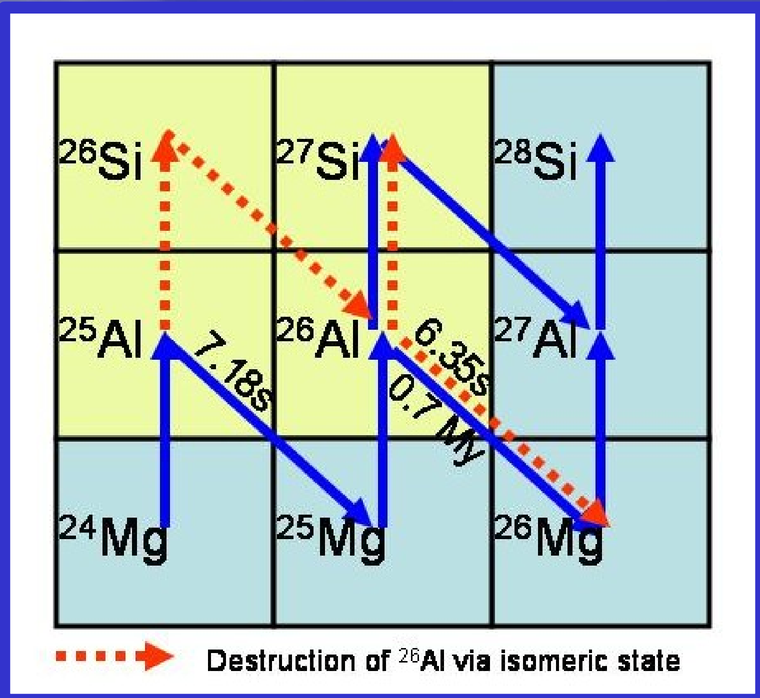
- $< 0.4\ M_{\odot}$ ^{26}Al from novae
  [J. José, M. Hernanz and A. Coc, Astrophys. J. Lett. 479 (1997)]

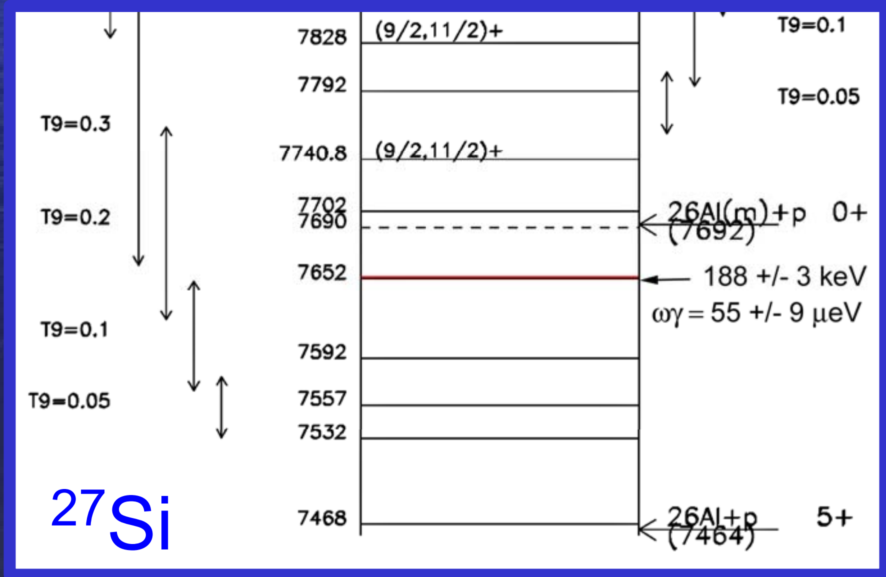
Novae: key NeNa-MgAl cycle reactions….

^{21}Na(p,γ)^{22}Mg	– DRAGON completed
^{25}Al(p,γ)^{26}Si	– DRAGON proposal
^{23}Na(p,γ)^{24}Mg	
^{22}Na(p,γ)^{23}Mg	– DRAGON/U. Wash.
^{26g}Al(p,γ)^{27}Si	– this work

Resonance at 188 keV dominates – measurement by R.B. Vogelaar, unpublished (1989).

Variation of factor 3 in strength yielded factor 2 in ^{26}Al yield for some O-Ne models [J. José, A. Coc and M. Hernanz, Astrophys. J. 520 (1999)]



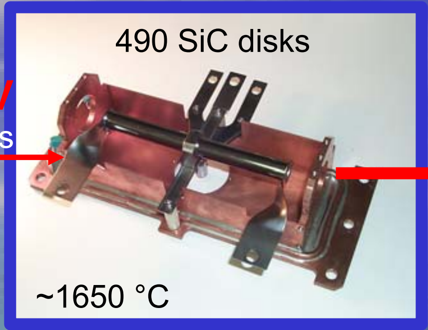


Resonance strength measurement at DRAGON

Beam production

500 MeV protons
70 μA

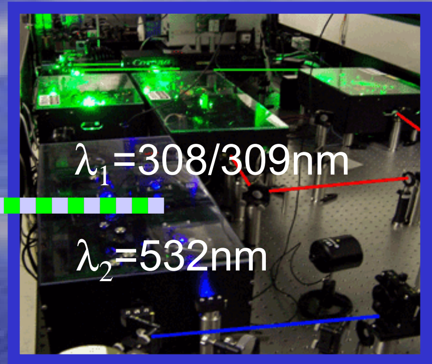
TRIUMF cyclotron



ISAC high-power SiC target

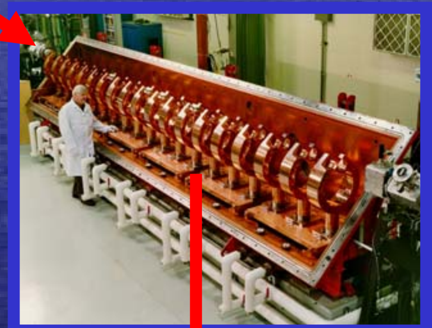
rhenium surface ion source

Laser Ion Source



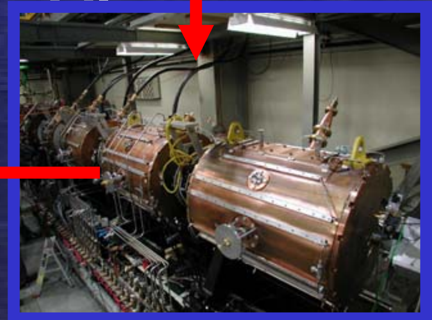
$^{26g}Al^{+}$

RFQ



$^{26g}Al^{6+}$ 0.15 MeV/u

DTL



< 1.8 MeV/u

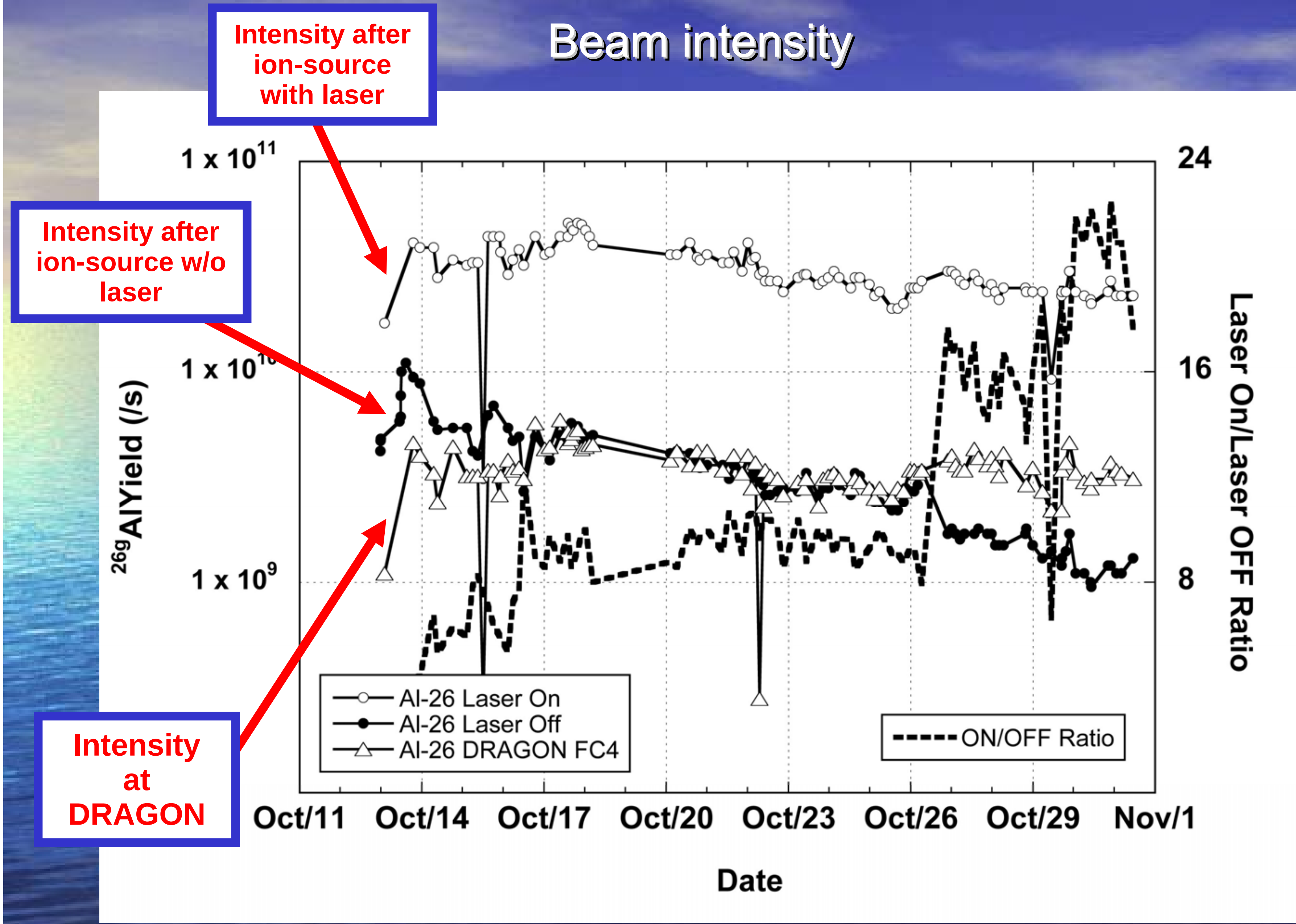
201 keV/u

197 keV/u

225 keV/u

- min. 1 x 10^9 ions/sec required > 100 counts
- beam purity: ^{26}Na (32ppm), ^{26m}Al (28ppm)
- beam size: 90% 4mm Ø collimator
- 85 ns bunched beam, ΔE ~ 0.3%
- achieved average 3.4 x 10^9 ions/sec
- peak 5 x 10^9 ions/sec

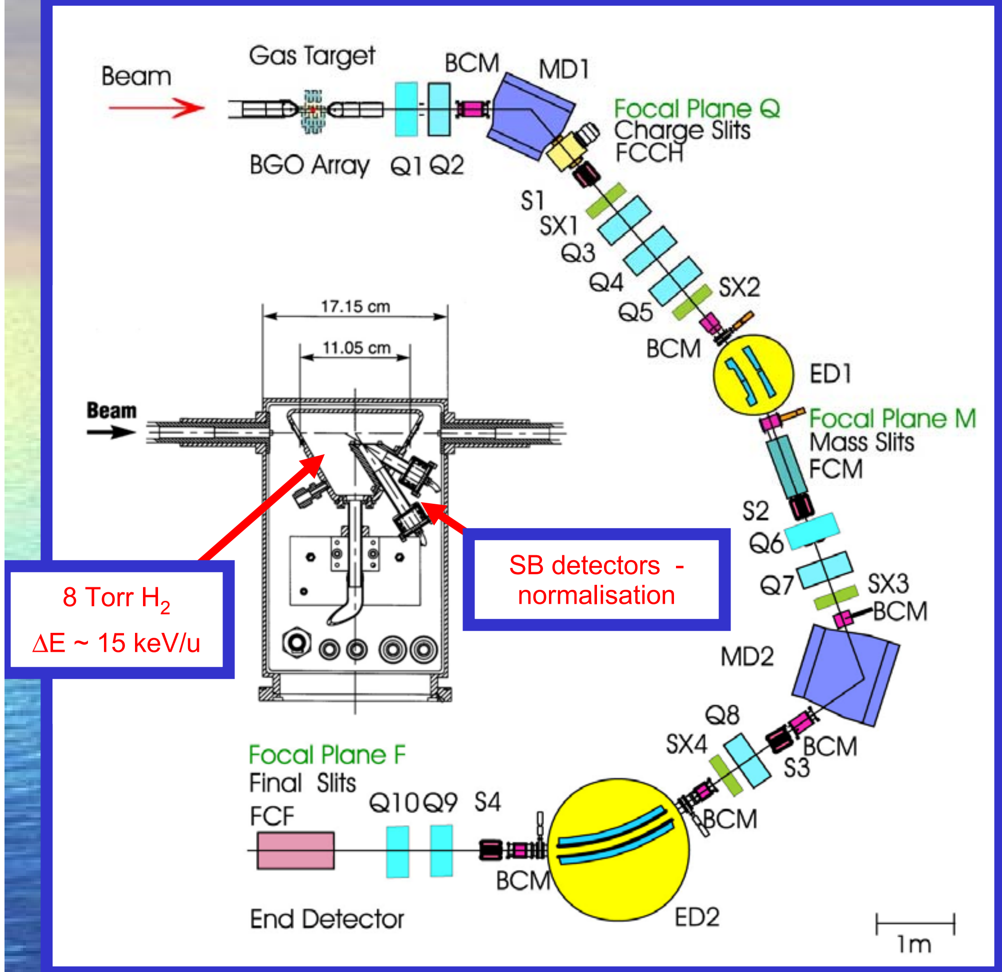
Beam intensity



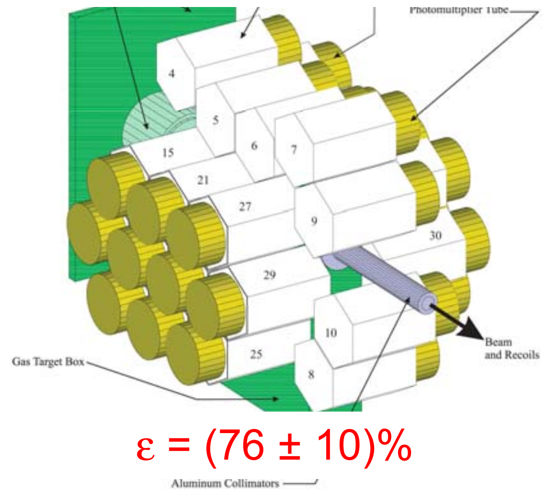
Measurement considerations

$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T_9)^{-3/2}\,\omega\gamma\exp\left(-11.605\frac{E_R}{T_9}\right)$$

$$Y = \frac{\lambda^2}{2}\frac{M+m}{m}\left(\frac{1}{\rho}\frac{dE}{dx}\right)^{-1}\omega\gamma$$



BGO array



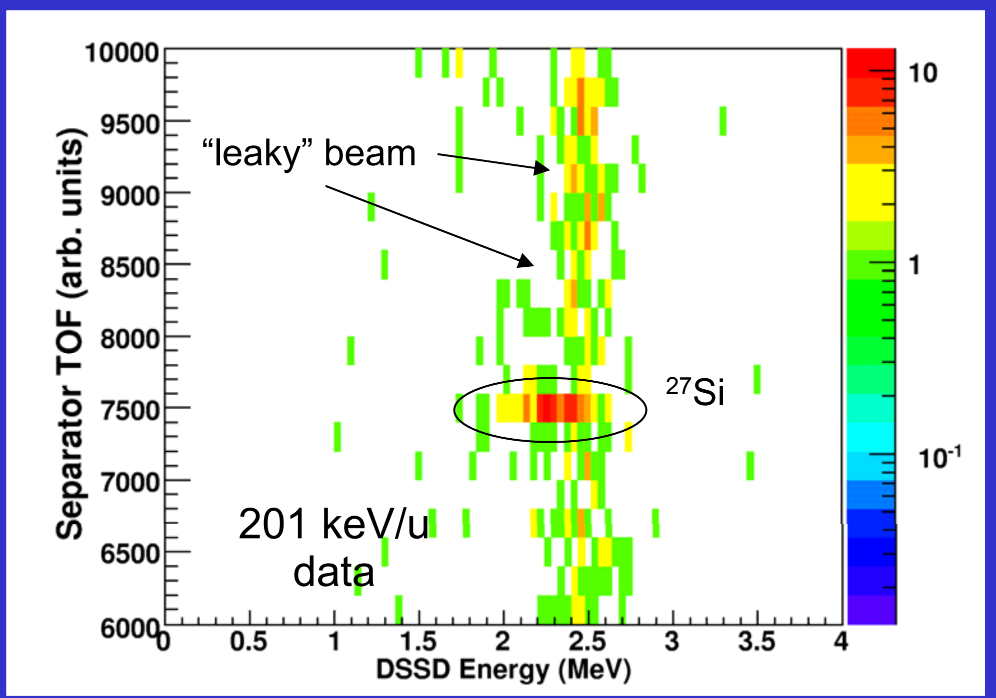
ε = (76 ± 10)%

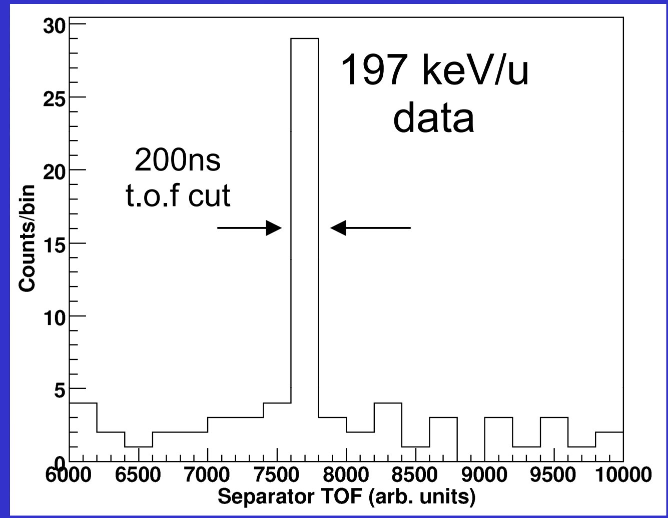
BGO detection efficiency (GEANT simulations compared to measurements)

- Separator transmission (GEANT) ~ 98%
- DSSD efficiency ~ 97%
- Si^{4+} charge-state fraction → (42 ± 2)% measured with Si beam

Analysis - Yield

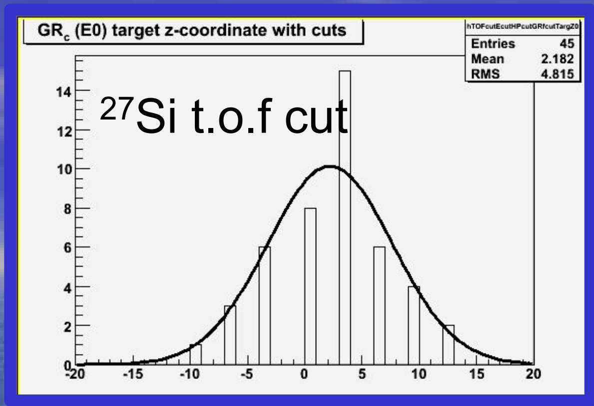
- Primary cut on 21m separator time-of-flight
- 200ns t.o.f window
- Background subtraction from large (~ 5 μs) cut – checked with fit to "leaky" energy distribution
- Modest energy cuts
- 201 keV/u → 119 ± 14
- 197 keV/u → 28 ± 6
- 225 keV/u → < 3.72(90%)

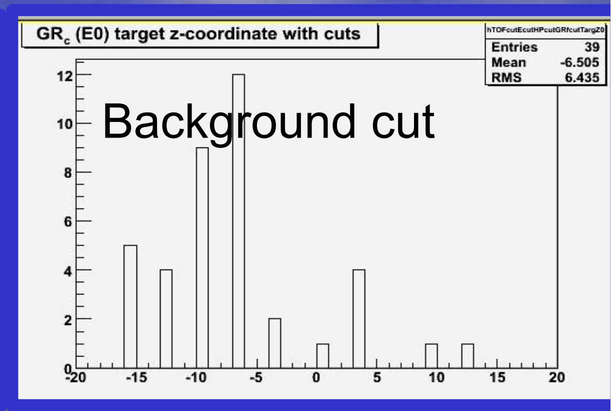




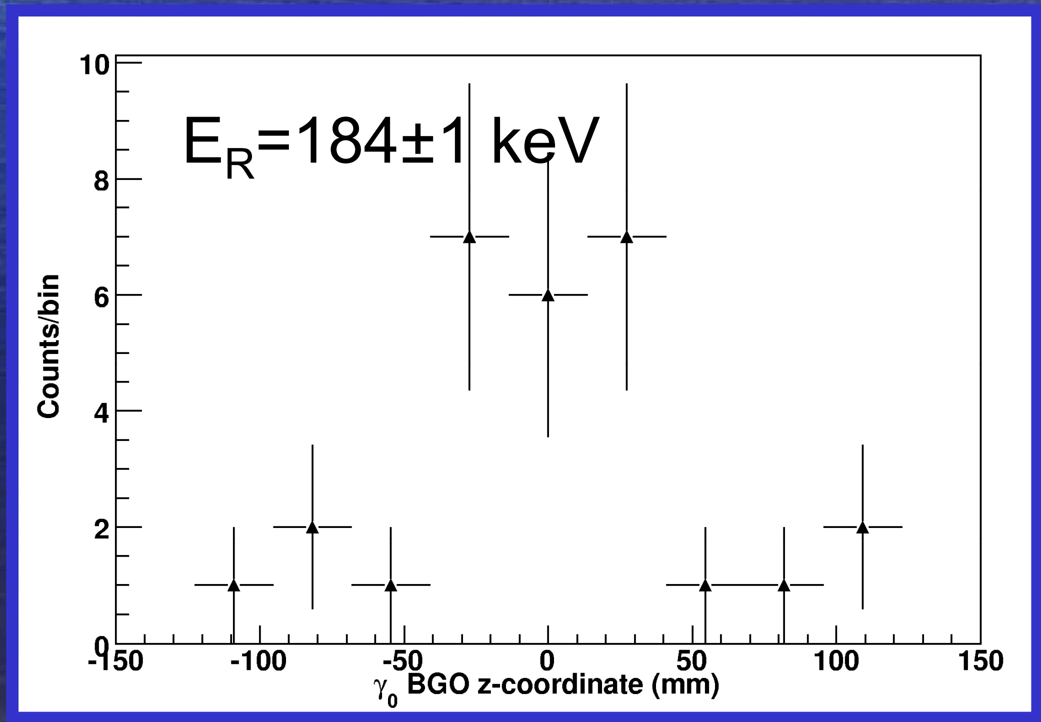
Analysis – resonance energy

- Centroid of z-distribution of primary gamma hits gives resonance position to ~1cm accuracy
- Translates to error of 1 keV
- Distribution modeled with GEANT, compared with other strong, narrow resonance reactions
- 4σ deviation from previous measurement – leads to ~ 15% change in exponential





Z-distribution (along beam-axis) of BGO hits



Error budget

E_{beam} (keV/u)	$\Delta\varepsilon$	$\Delta\eta_{DSSD}$	$\Delta\eta_{BGO}$	$\Delta\eta_{sep}$	$\Delta\eta_{Si4+}$	ΔN	Tot sys. error	Stat. error
201	5%	1%	13%	2%	5%	3%	15%	12%
197	5%	1%	13%	2%	5%	8%	17%	22%

- Systematic error dominated by BGO efficiency
- Total uncertainty (in 201 keV/u measurement) 20% c.f. 16%

Results and Implications

- Resonance strength $35 \pm 5_{sys} \pm 4_{stat}$ µeV - (c.f Vogelaar 55 ± 9 µeV)
- Combined with new resonance energy, up to 20% reduction of reaction rate over Gamow window for typical O-Ne nova
- Representative case – 1.25 $M_{\odot}$ accreting O-Ne white-dwarf: onset to explosion & ejection, spherically symmetric, implicit, Lagrangian hydro- code (J. José, UPC-IEEC)
- Net reduction of $^{26g}Al(p,\gamma)^{27}Si$ rate favours ^{26}Al synthesis – mean ejecta yield 0.074% by mass
- Supports paradigm of secondary nova contribution to Galactic ^{26}Al distribution
- Exact contribution uncertain because (mostly) of $^{25}Al(p,\gamma)^{26}Si$ rate

Summary

- Independent inverse-kinematics measurent of $^{26g}Al(p,\gamma)^{27}Si$ 184 keV resonance – sources of error well controlled
- Challenging experiment requiring large beam-development effort – very high intensity radioactive beam from ISOL method achieved
- Nova ^{26}Al constrained by $^{26g}Al(p,\gamma)^{27}Si$ and pinned-down by future $^{25}Al(p,\gamma)^{26}Si$ reaction

The Usual Suspects

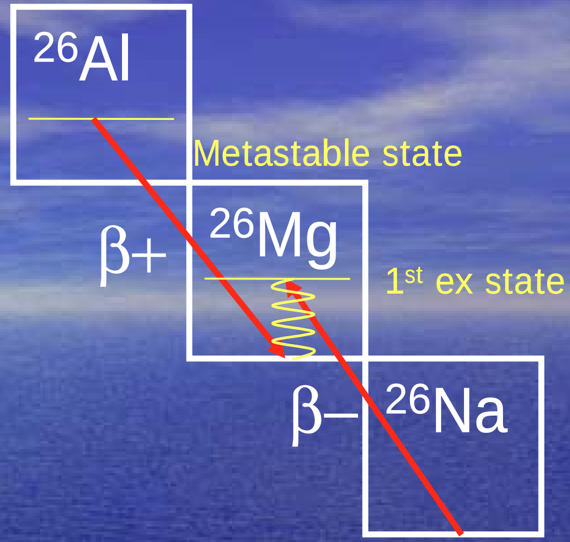
TRIUMF: C. Ruiz, L. Buchmann, J.A. Caggiano, B. Davids, J.M. D'Auria (SFU), C. Davis, D. A. Hutcheon, A. Olin, D.F. Ottewell, J. Pearson (McMaster), G. Ruprecht, M. Trinczek, C. Vockenhuber
Yale : A. Parikh, J.A. Clark, C. Deibel, R. Lewis, P. Parker. C. Wrede
UPC Barcelona: J. José
McMaster University: A.A. Chen, C.V. Ouellet
Simon Fraser University: H. Crawford
University of Northern British Columbia: A. Hussein
Colorado School of Mines: L. Erikson, U. Greife, C. Jewett
National University of Ireland: L. Fogarty
WWU Münster: D. Frekers
KUL Leuven: M. Huyse
University of York: A.M. Laird, P. Mumby-Croft

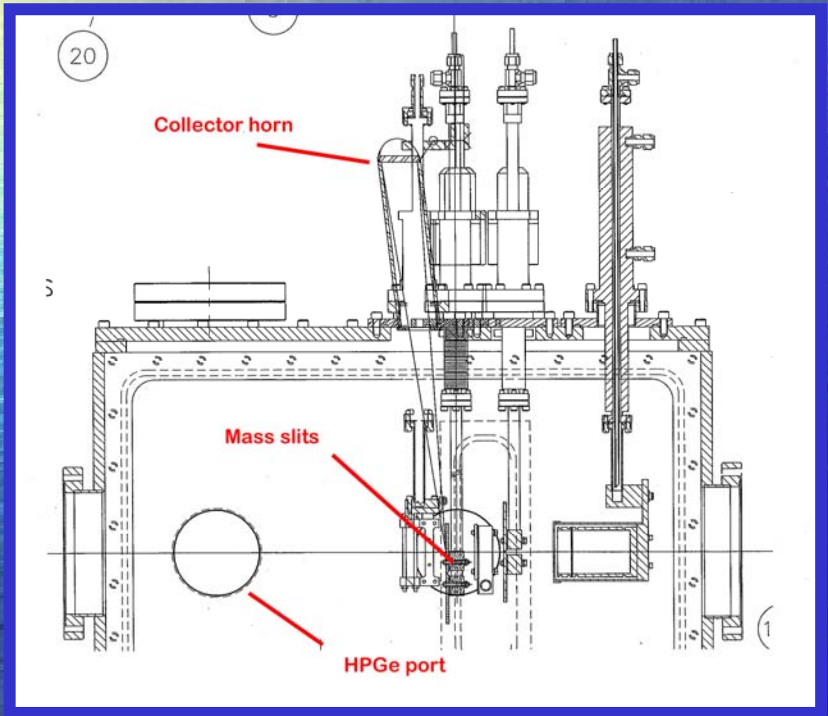
Post-Docs
Graduate students
Undergraduates

Beam development: P. Bricault, M. Dombsky, A.C. Morton, J. Lassen & team

Acceleration: R.E. Laxdal and M. Marchetto

- Measuring contaminants





- ^{26m}Al, ^{26}Na contaminants.
- ^{26m}Al β+ decays to ground state ^{26}Mg – positrons captured in 'horn' – annihilate – detect 511 keV γ-rays in coincidence with NaI detectors.
- ^{26}Na β- decays to 1st ex state of ^{26}Mg – get 1.8 MeV γ-ray – HPGe detector.
- ^{26}Na 32 ppm -> 0.9 ppm