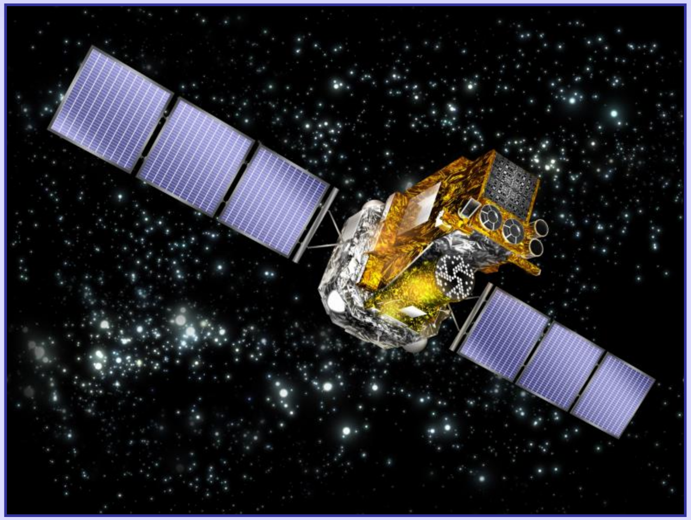
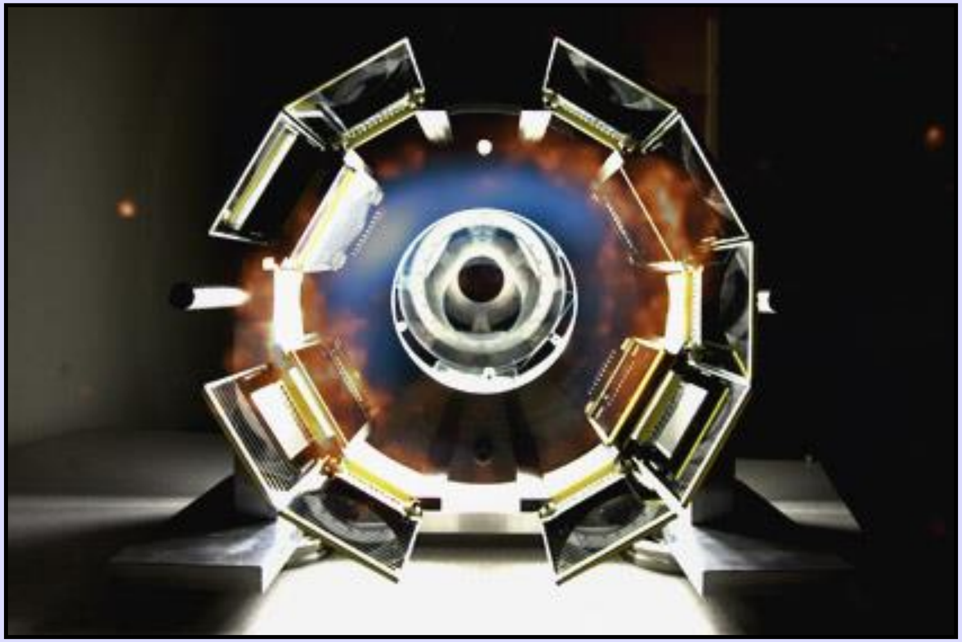
Measurement of the $^{26}Al(d,p)^{27}Si$ Reaction to constrain the $^{26}Al(p,\gamma)^{27}Si$ rate at stellar temperatures

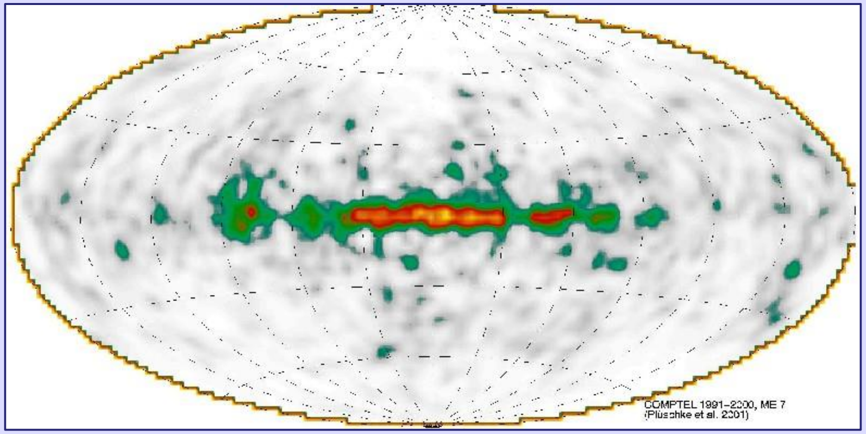
Steven D. Pain

Oak Ridge National Laboratory

- Astrophysical significance of ^{26}Al
- Previous constraints
- $^{26}Al(d,p)$ measurement
- Astrophysical implications

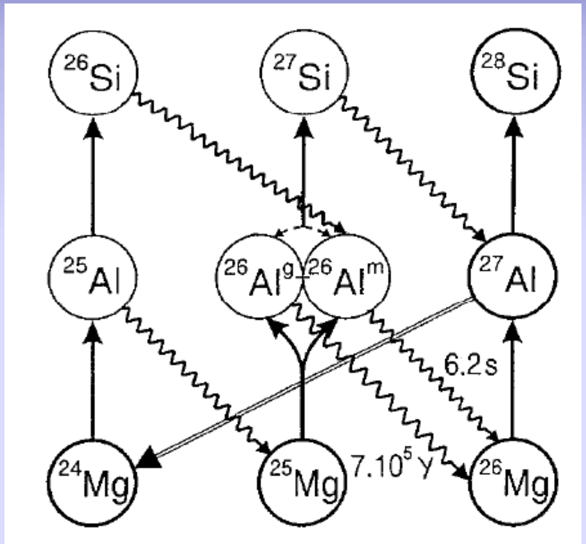






DREB 2016, Halifax

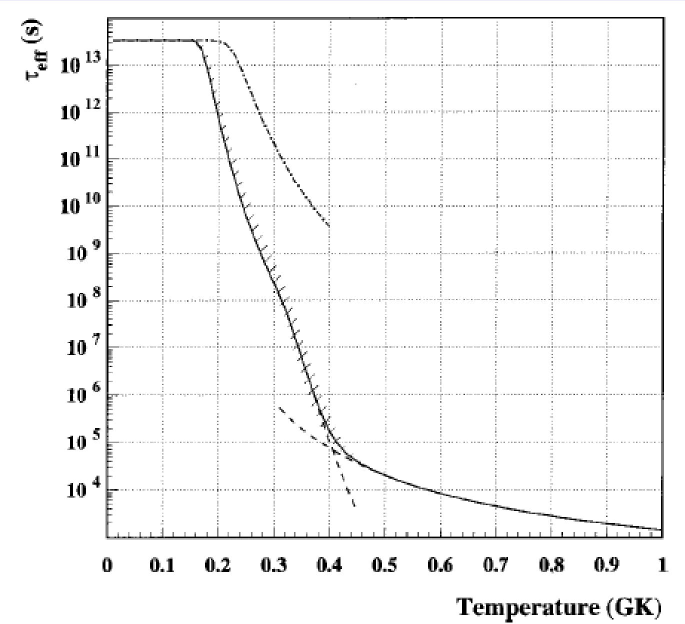
^{26}Al - Background



5^+ gs

0^+ isomeric state at 228 keV

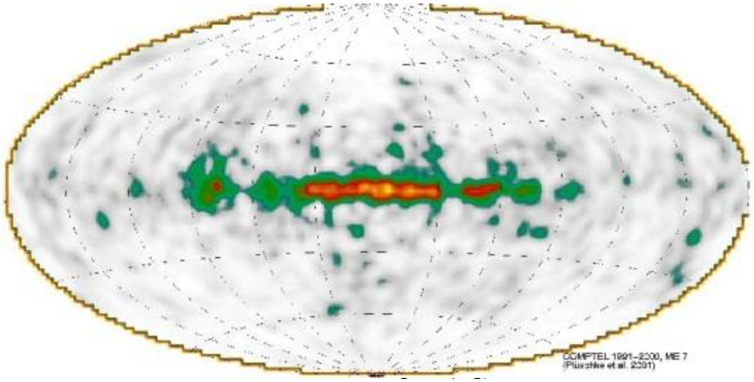
N. Prantzos, R. Diehl. **Physics Reports 267** 1-69 (1996)



Coc, Porquet and Nowacki **PRC 015801** (1999)

- ^{26}Al nucleus was the first radioisotope detected in the interstellar medium
- Half life of 7.2×10^5 years
- Observation of γ rays associated with its decay provides evidence of nucleosynthesis
- Temperatures 0.03 – 0.3 GK, the ^{26g}Al(p,γ)^{27}Si reaction is expected to contribute to the destruction of ^{26}Al

Tracing ^{26}Al sources

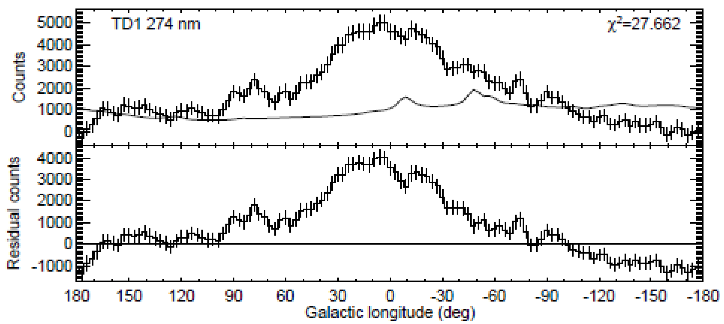


A multiwavelength comparison of COMPTEL 1.8 MeV ^{26}Al line data

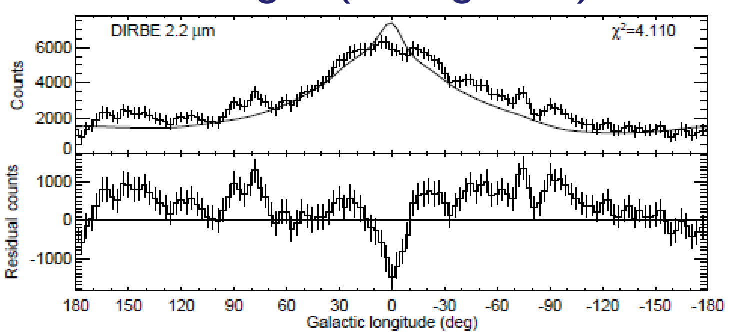
J. Knödlseder[1], K. Bennett[5], H. Bloemen[3], R. Diehl[2], W. Hermsen[3], U. Oberlack[6], J. Ryan[4], V. Schönfelder[2], and P. von Ballmoos[1]

Astron. Astrophys. 344, 68–82 (1999)

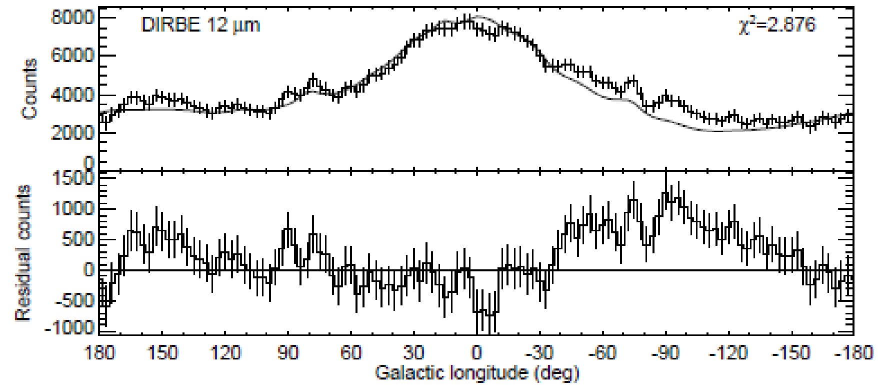
Starlight (nearby hot stars)



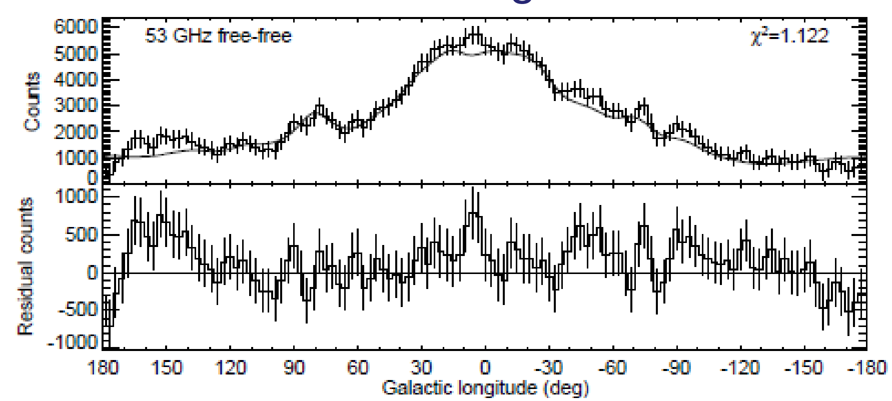
Starlight (K/M giants)



Thermal dust/AGB stars

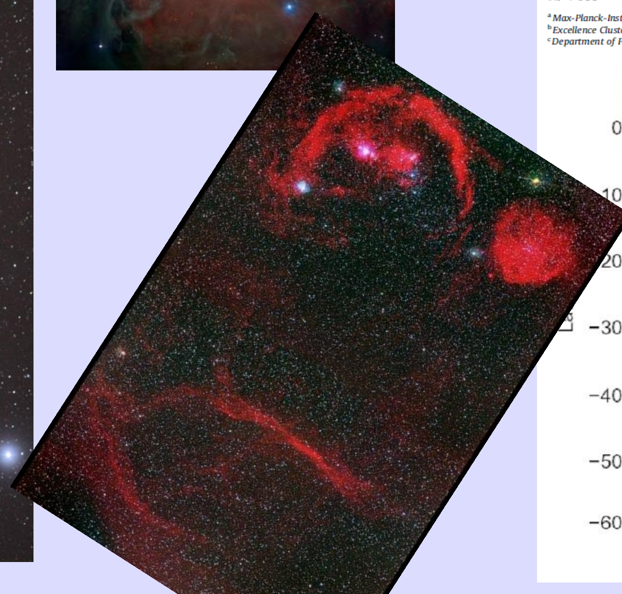


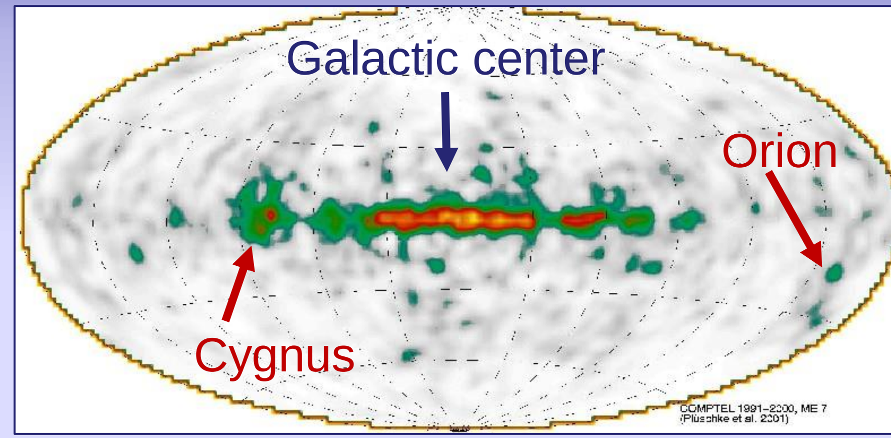
Ionized gas

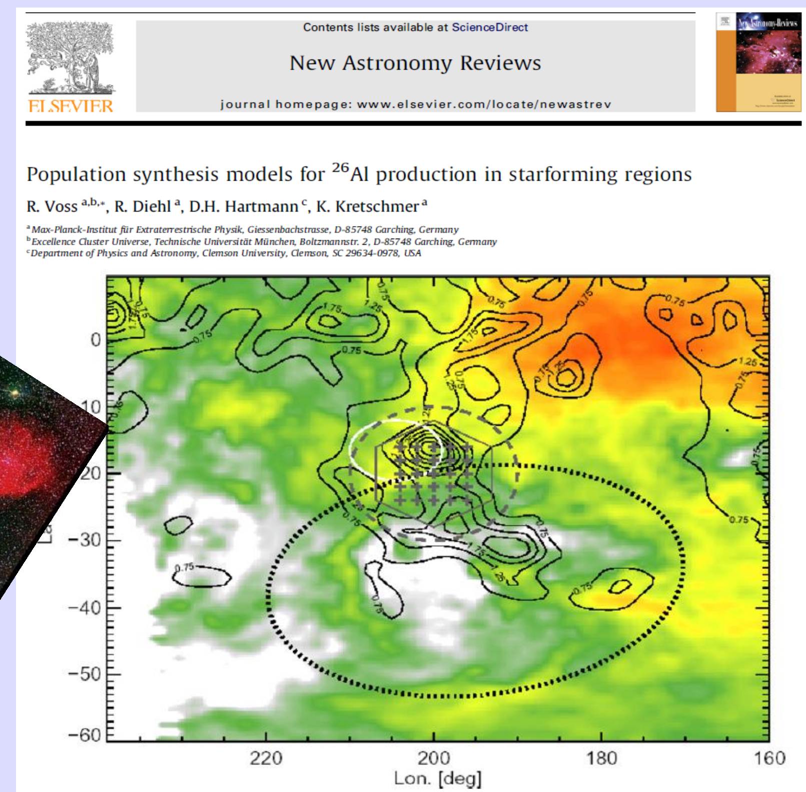


Orion region – tracing massive star ejecta

>30 M_{O} stars – develop strong stellar winds blowing material into space



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Population synthesis models for ^{26}Al production in starforming regions

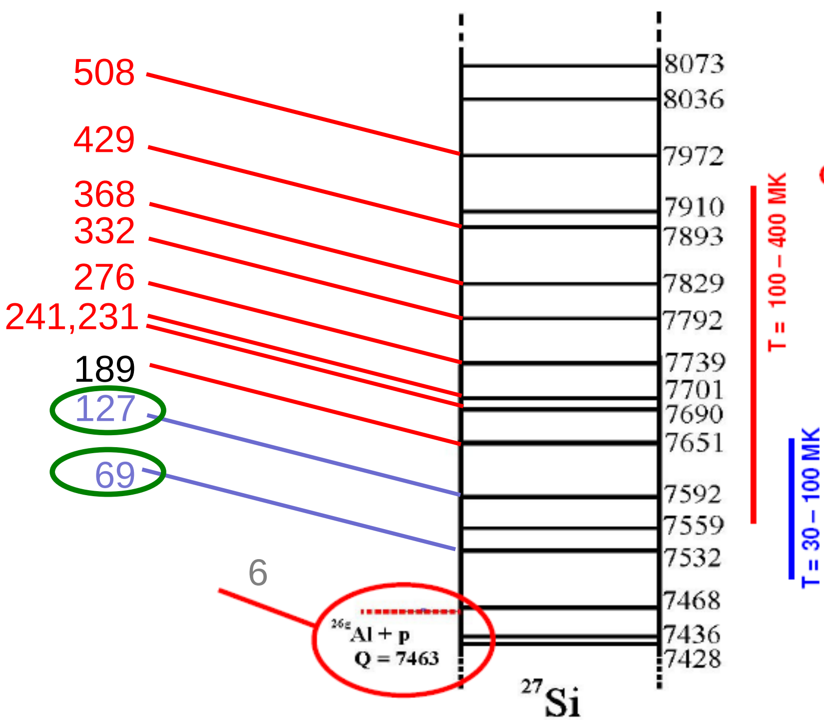
R. Voss [a,b,*], R. Diehl [a], D.H. Hartmann [c], K. Kretschmer [a]
[a] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany
[b] Excellence Cluster Universe, Technische Universität München, Boltzmannstr. 2, D-85748 Garching, Germany
[c] Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA

$^{26}Al(p,\gamma)^{27}Si$ – states and mirrors

E_x (keV)	E_{res} (keV)	J^π	$\omega\gamma$ (meV)	^{27}Al E_x (keV)
7469	6	$(1/2, 5/2)^+$	$< 2.3 \times 10^{-66}$ [2][a]	7676
(7491)	(28)	$(3/2^+)$	-	7799
7532	69	$5/2^+$	$< 2.3 \times 10^{-13}$ [2][a]	7790
(7557)[b]	(94)	$(3/2^+)$	$< 1.9 \times 10^{-10}$ [2][a]	7858
7590	127	$9/2^+$	$< 5.9 \times 10^{-6}$ [3][c]	7807
7652	189	$11/2^+$	0.055(9) [4], 0.035(7) [5]	7950
7694	231	$5/2^+$	≤ 0.010 [4]	7722
7704	241	$7/2^-$	0.010(5) [4]	7900
7739	276	$9/2^+$	3.8(10) [6], 2.9(3) [4]	7998

Unmeasured (7491–7590); ell=2 (7532); ell=0 (7590)

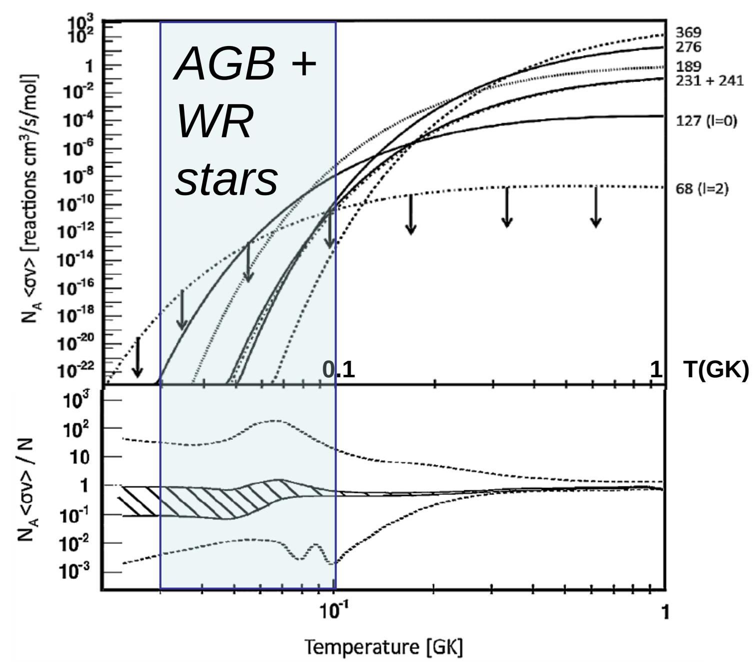
Measured (7652–7739)



ONe novae

Strengths of 69 and 127 keV resonances major uncertainty

AGB + WR stars



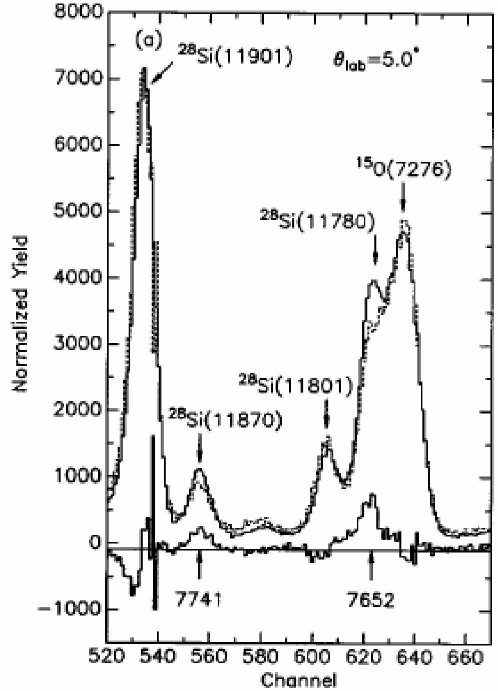
G. Lotay *et al*, **PRL 102** 162502 (2009)

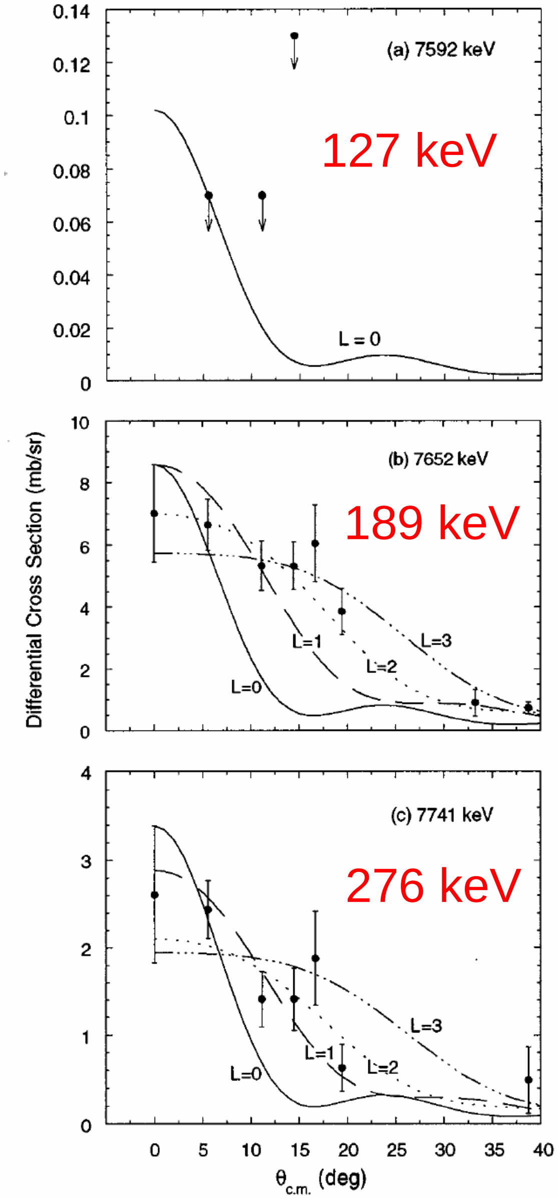
127 keV resonance strength from the $^{26}Al(^{3}He,d)^{27}Si$ reaction

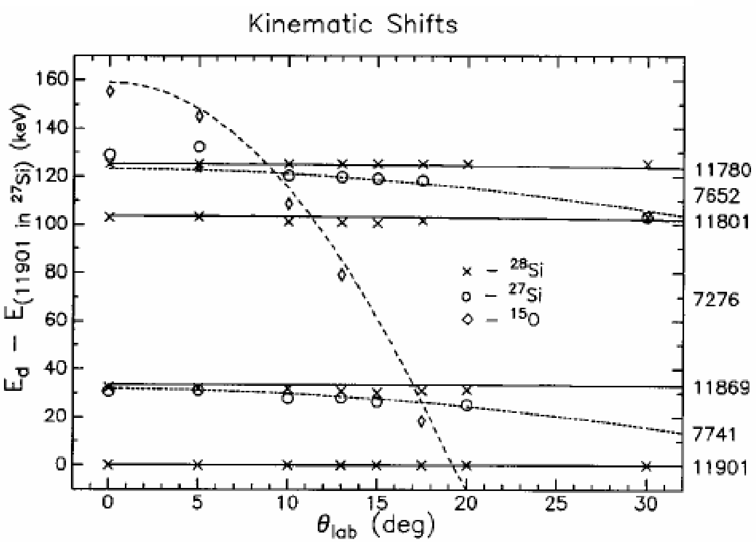
Vogelaar *et al*, **PRC 53** 1945 (1996)

$^{26}Al(^{3}He,d)^{27}Si$

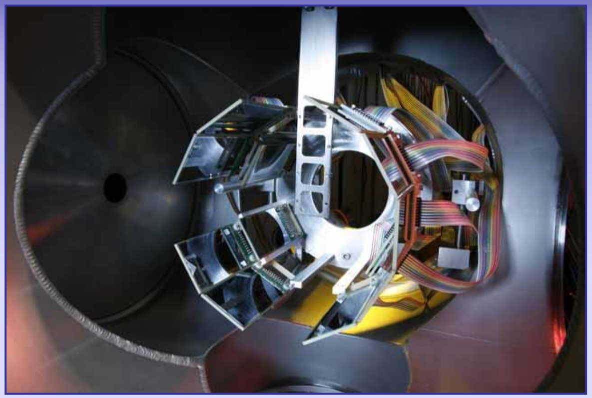
Isotopically enriched target (6.3% $^{26}Al/^{27}Al$)



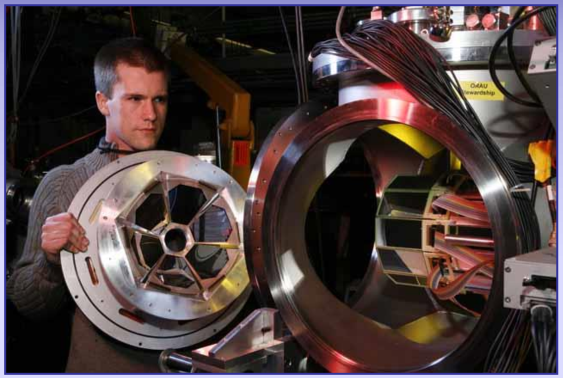


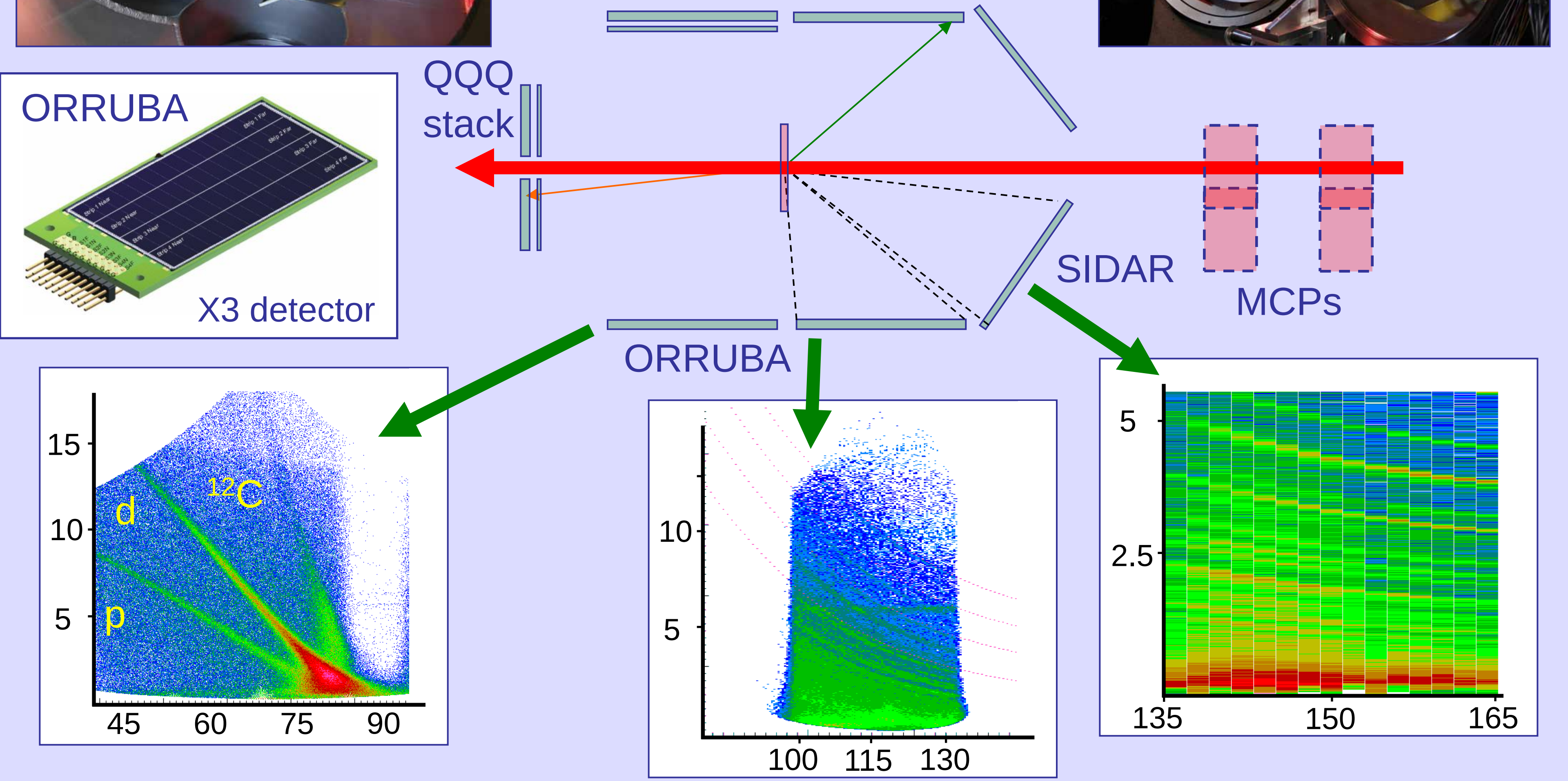


^{26}Al(d,p)^{27}Al Experimental Details

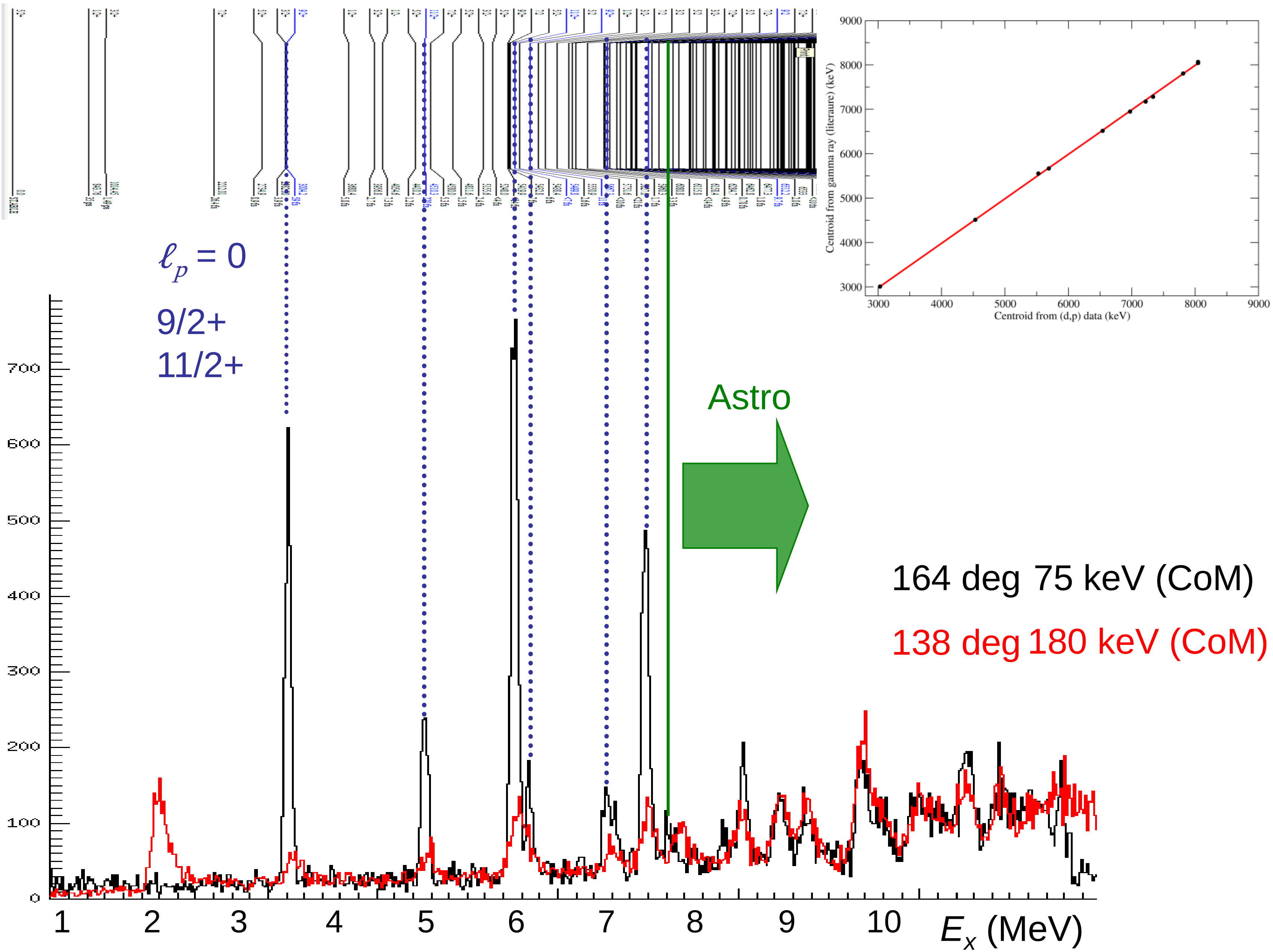


- 117 MeV ^{26}Al (Oak Ridge Tandem)
- 5×10^{6} pps
- 150 μg/cm^2 CD_2
- MCP normalization (200 kHz)

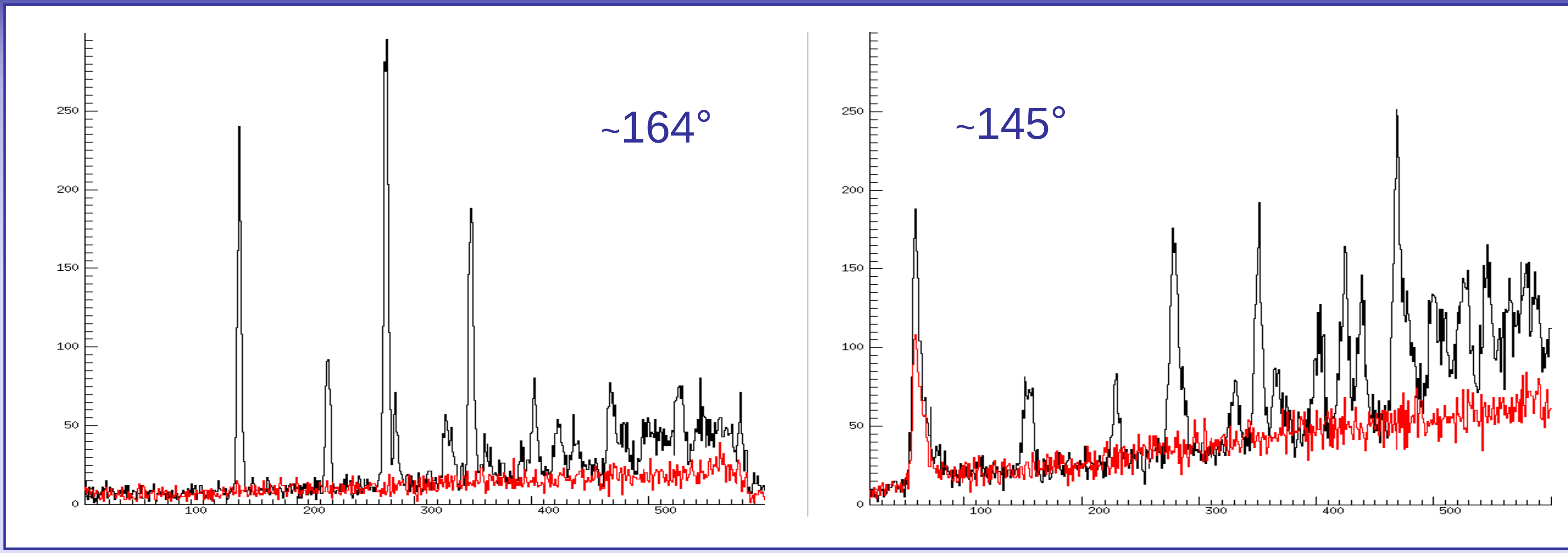




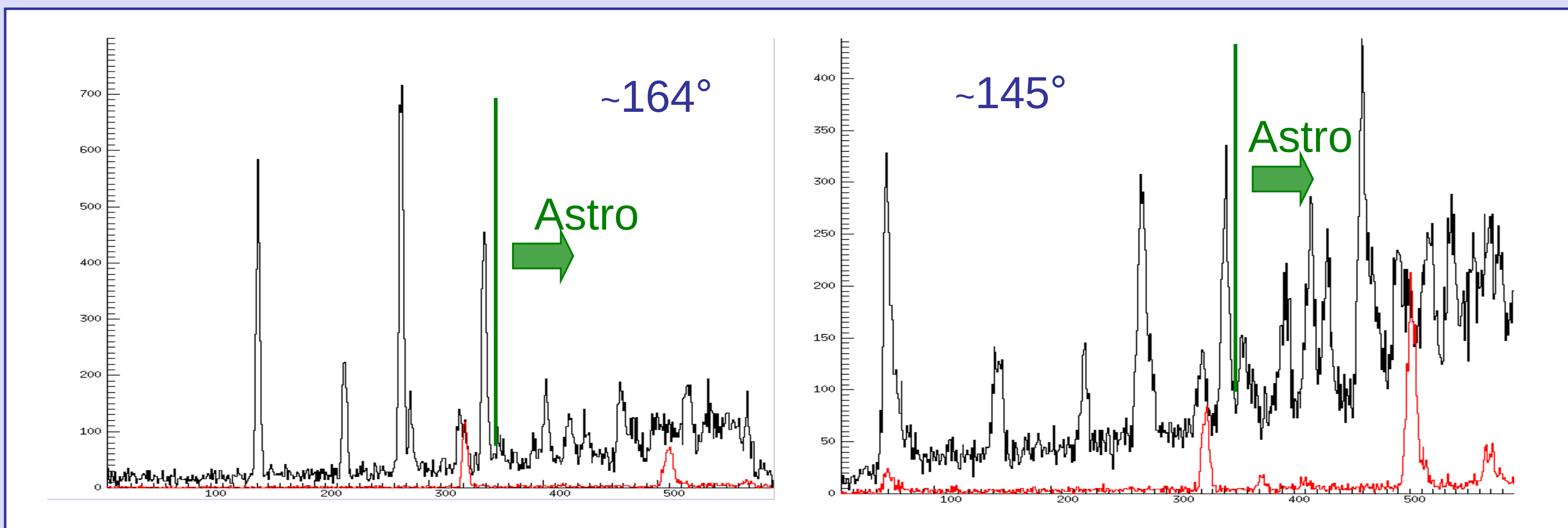
$^{26}Al(d,p)^{27}Al$ – Internal energy calibration



^{26}Al(d,p)^{27}Al – background runs



Run on carbon foil to determine form of background from reactions on carbon



Run with ^{26}Mg beam (5+) to determine background peaks from reactions ^{26}Mg(d,p)

$^{26}Al(d,p)^{27}Al$ – Astrophysically important states

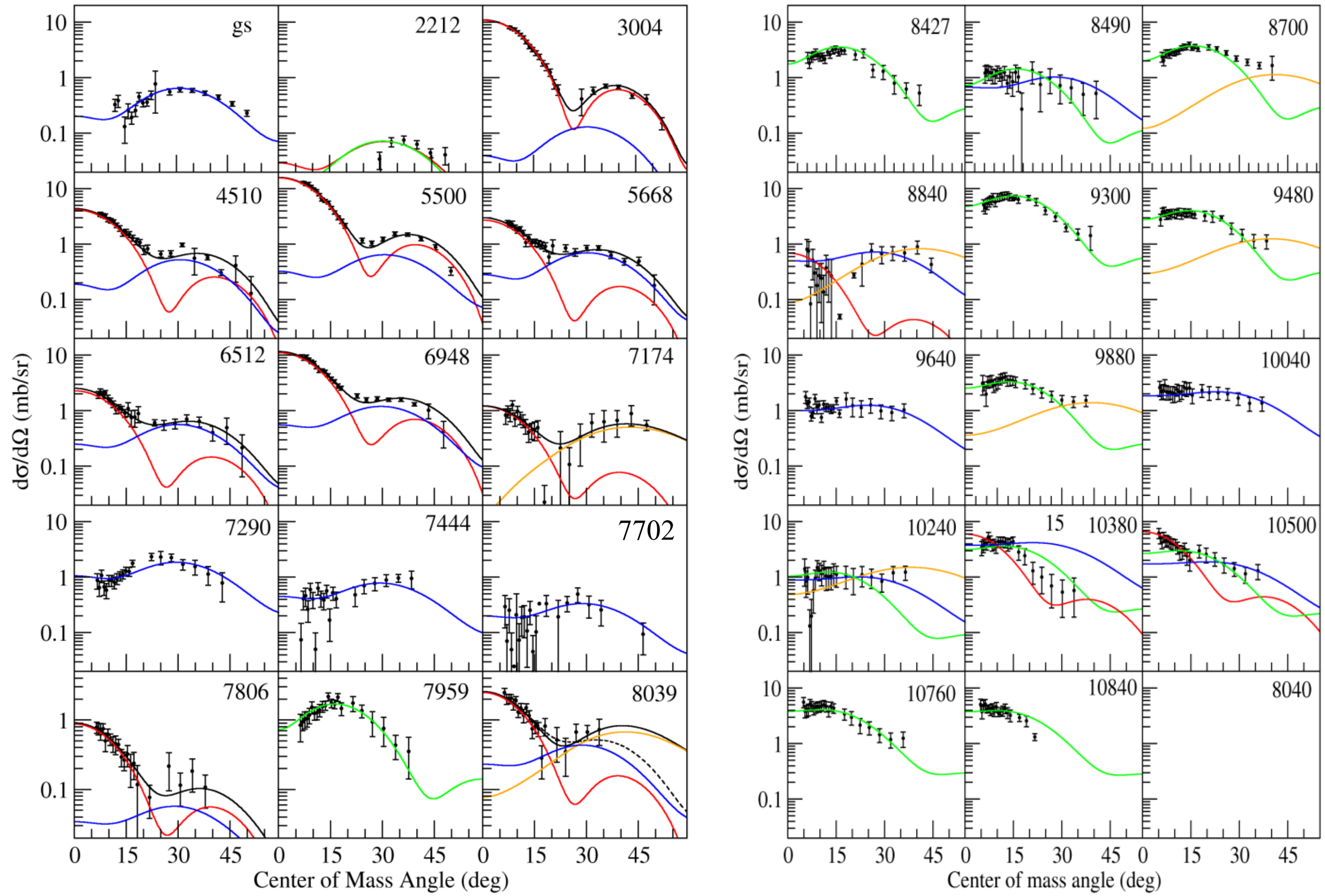
ADWA calculations

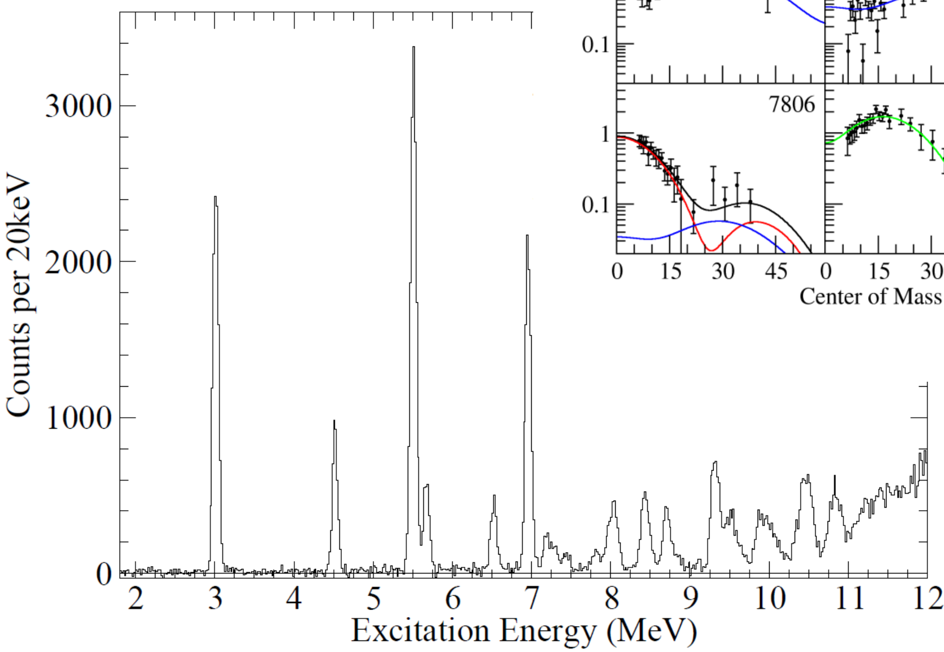
– ℓ = 0

– ℓ = 1

– ℓ = 2

– ℓ = 3



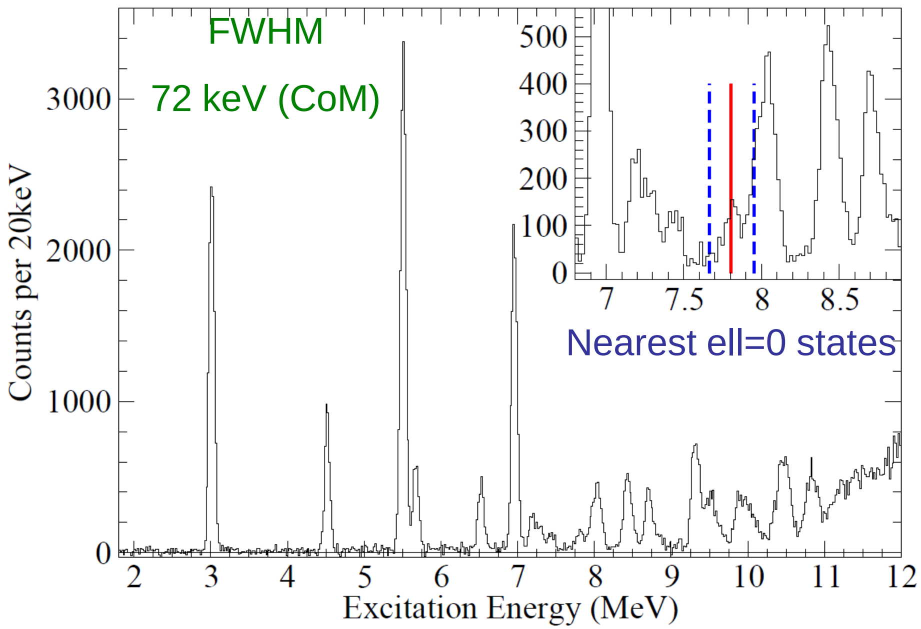


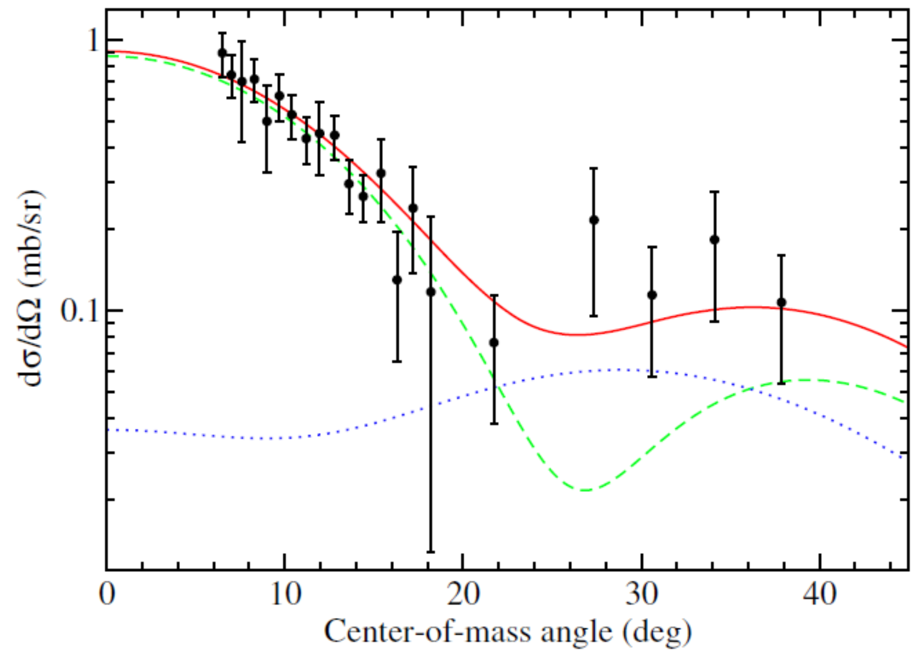
FWHM = 72 keV (CoM)

Constraint of the Astrophysical ^{26g}Al$(p,\gamma)^{27}$Si Destruction Rate at Stellar Temperatures

S. D. Pain,[1,*] D. W. Bardayan,[1,2] J. C. Blackmon,[3] S. M. Brown,[4] K. Y. Chae,[5,6] K. A. Chipps,[7] J. A. Cizewski,[7] K. L. Jones,[5] R. L. Kozub,[8] J. F. Liang,[1] C. Matei,[9] M. Matos,[3] B. H. Moazen,[5] C. D. Nesaraja,[1] J. Okołowicz,[10] P. D. O'Malley,[7] W. A. Peters,[9] S. T. Pittman,[5] M. Płoszajczak,[11] K. T. Schmitt,[5] J. F. Shriner, Jr.,[8] D. Shapira,[1] M. S. Smith,[1]

7805(12) keV (127-keV mirror)



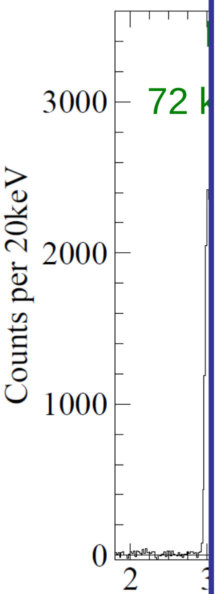


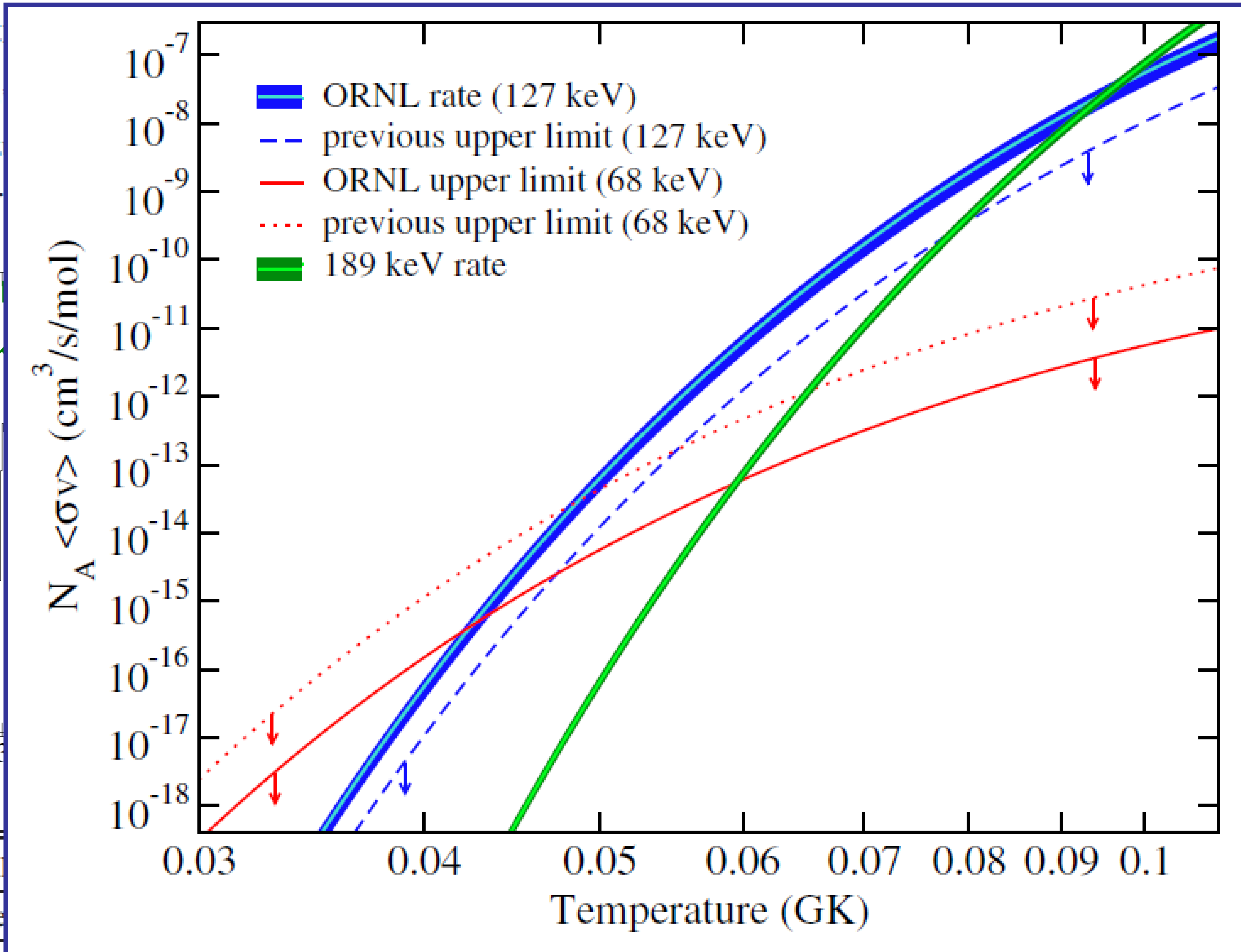
	^{27}Al	^{27}Al	^{27}Al[a]	^{27}Si[a]	^{27}Si	Γ_{sp}	Γ_p	$\omega\gamma$
J^π	E_x (keV)	$C^2S_\nu^{exp}$	$C^2S_\nu^{th}$	$C^2S_\pi^{th}$	C^2S_π	(meV)	(meV)	(meV)
$9/2^+$	7807	0.0102 ± 0.0021	$0.0112^{-0.0002}_{+0.0007}$	$0.0094^{+0.0016}_{-0.0024}$	$0.0085^{+0.0024}_{-0.0031}$	6.70×10^{-3}	$5.7^{+1.6}_{-2.1} \times 10^{-5}$	$2.6^{+0.7}_{-0.9} \times 10^{-5}$
$5/2^+$	7790	≤ 0.061	$0.0100^{+0.0006}_{-0.0002}$	$0.0088^{+0.0010}_{-0.0022}$	≤ 0.054	2.06×10^{-10}	$\leq 1.1 \times 10^{-11}$	$\leq 3.0 \times 10^{-12}$

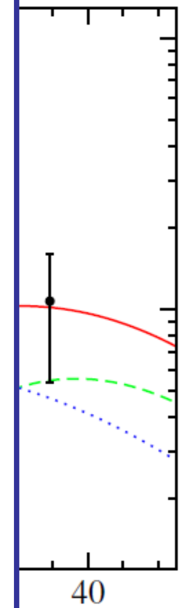
[a]From SMEC calculations using the USD-b effective interaction, using a continuum coupling constant of −650 MeV fm^3.

Const ... tures

S. D. Pain,[1,] ... K. L. Jones,[5]
R. L. Koz ... O'Malley,[7]
W. A. ... mith,[1]







^{27}Al ...							$\omega\gamma$
J^{π}	E_x (ke...						(meV)
$9/2^+$	7807	0.0102 ± 0.0021	$0.0112_{+0.0007}$	$0.0094_{-0.0024}$	$0.0085_{-0.0031}$	6.70×10 ...	$5.7_{-2.1} \times 10$ ...	$2.6^{+0.7}_{-0.9} \times 10^{-5}$
$5/2^+$	7790	≤ 0.061	$0.0100^{+0.0006}_{-0.0002}$	$0.0088^{+0.0010}_{-0.0022}$	≤ 0.054	2.06×10^{-10}	$\leq 1.1 \times 10^{-11}$	$\leq 3.0 \times 10^{-12}$

[a]From SMEC calculations using the USD-b effective interaction, using a continuum coupling constant of -650 MeV fm^3.

^{26}Al(d,p)^{27}Al Experiment at TRUIMF

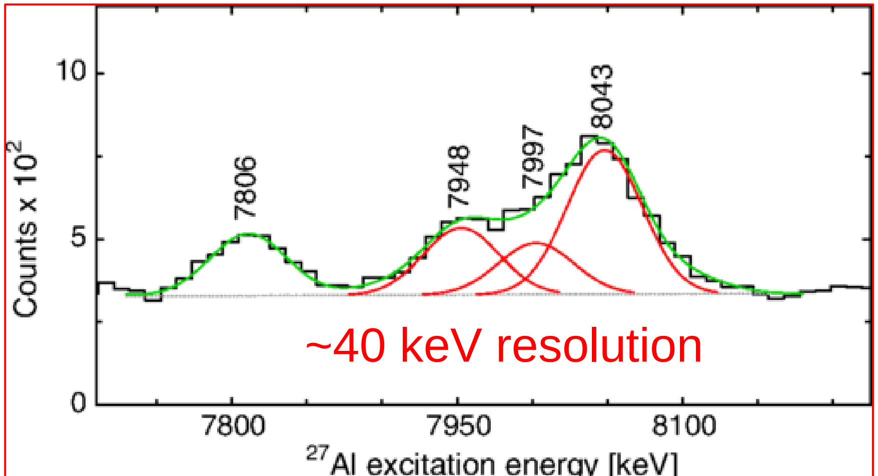
PRL **115**, 062701 (2015) PHYSICAL REVIEW LETTERS week ending 7 AUGUST 2015

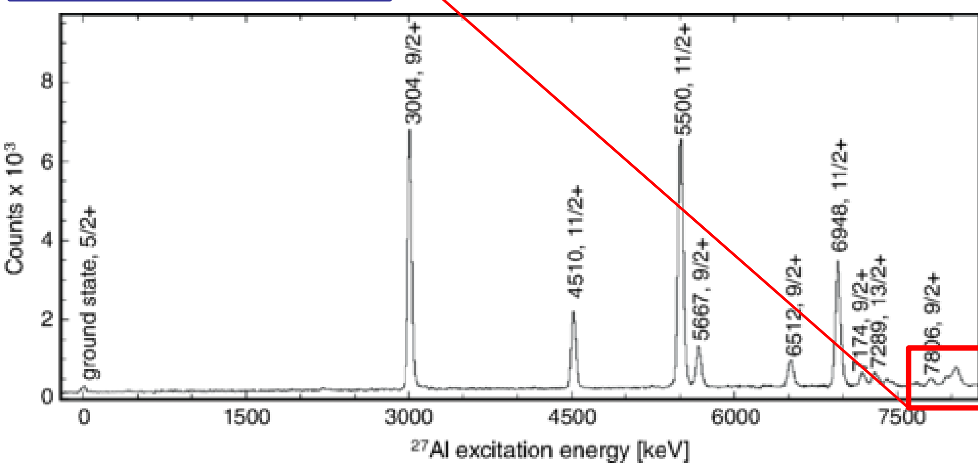
Inverse Kinematic Study of the ^{26g}Al$(d,p)^{27}$Al Reaction and Implications for Destruction of ^{26}Al in Wolf-Rayet and Asymptotic Giant Branch Stars

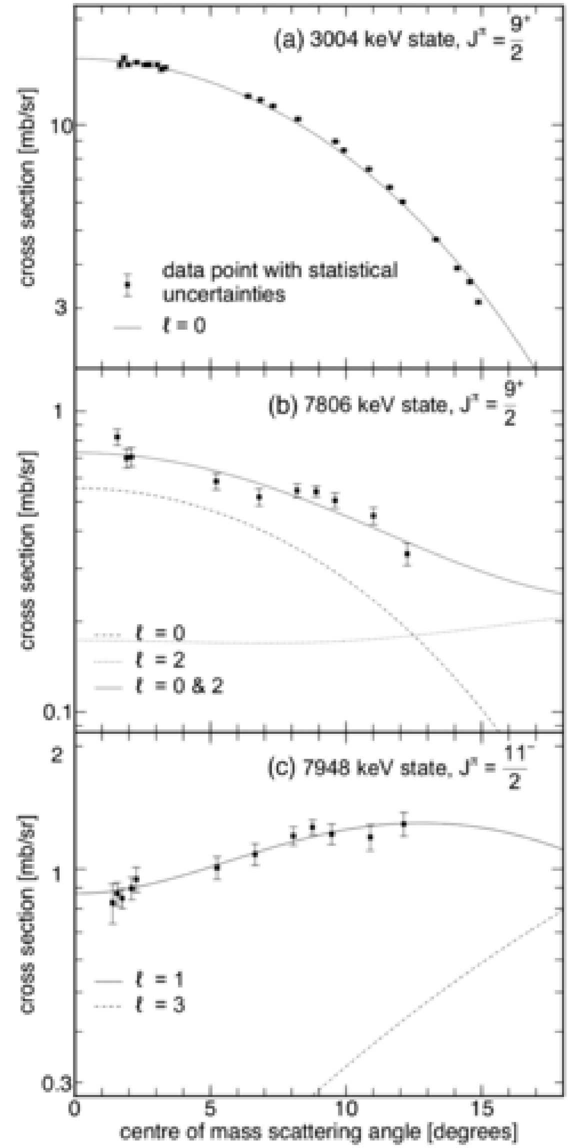
V. Margerin,[1] G. Lotay,[1,2,3,*] P. J. Woods,[1] M. Aliotta,[1] G. Christian,[4] B. Davids,[4] T. Davinson,[1] D. T. Doherty,[1,†] J. Fallis,[4] D. Howell,[4] O. S. Kirsebom,[4,‡] D. J. Mountford,[1] A. Rojas,[4] C. Ruiz,[4] and J. A. Tostevin[2]

Smaller angular range

- 1 pnA ^{26}Al
- 6 MeV/u
- ~50 μg CD_2
- Detectors 21 and 75 cm upstream







Comparison of HRIBF and TRIUMF results

PRL 114, 212501 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

Constraint of the Astrophysical $^{26g}Al(p,\gamma)^{27}Si$ Destruction Rate at Stellar Temperatures

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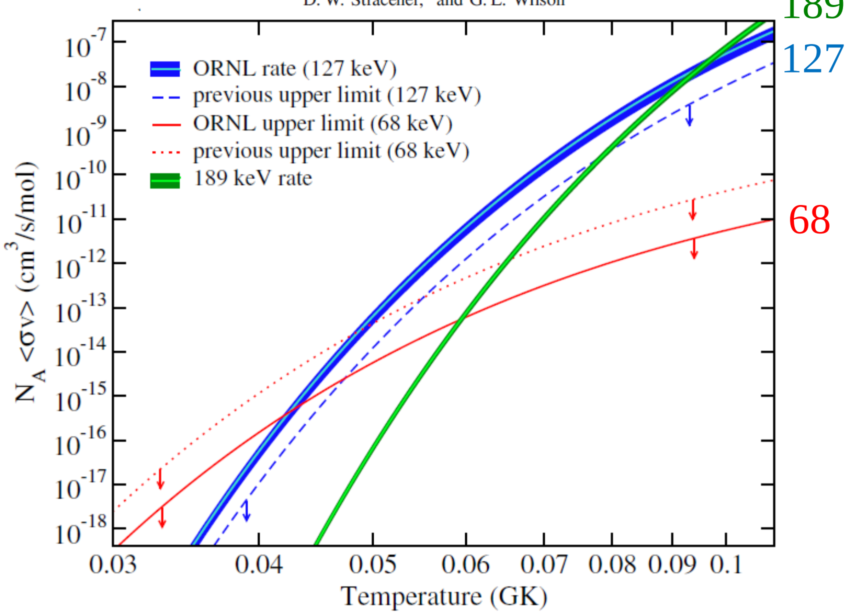

PRL 115, 062701 (2015) PHYSICAL REVIEW LETTERS week ending 7 AUGUST 2015

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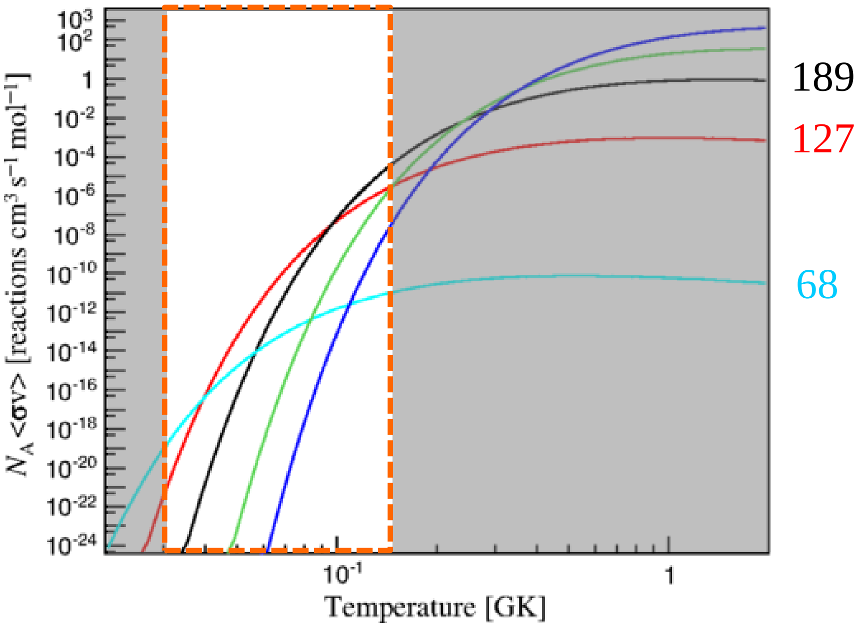
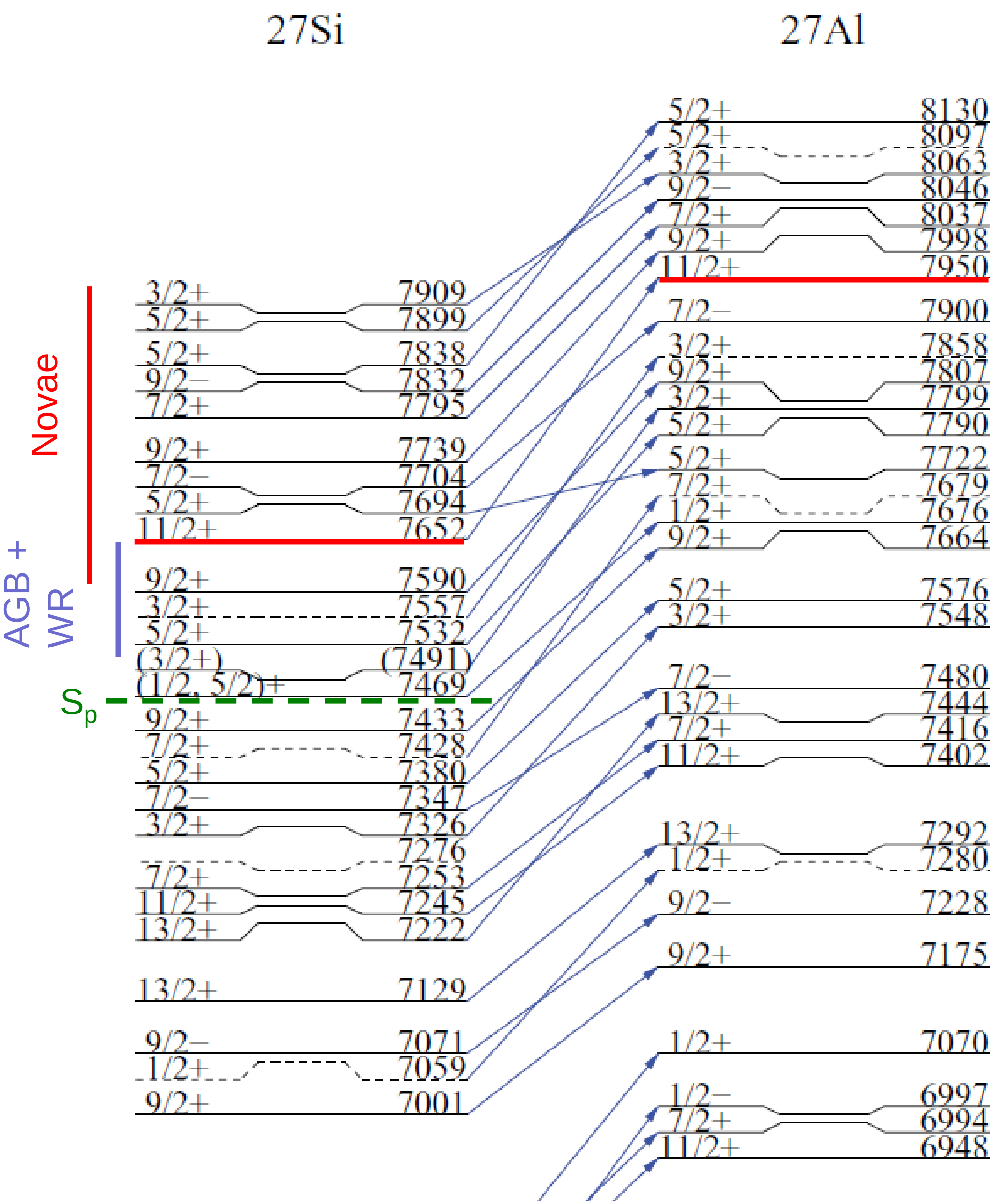


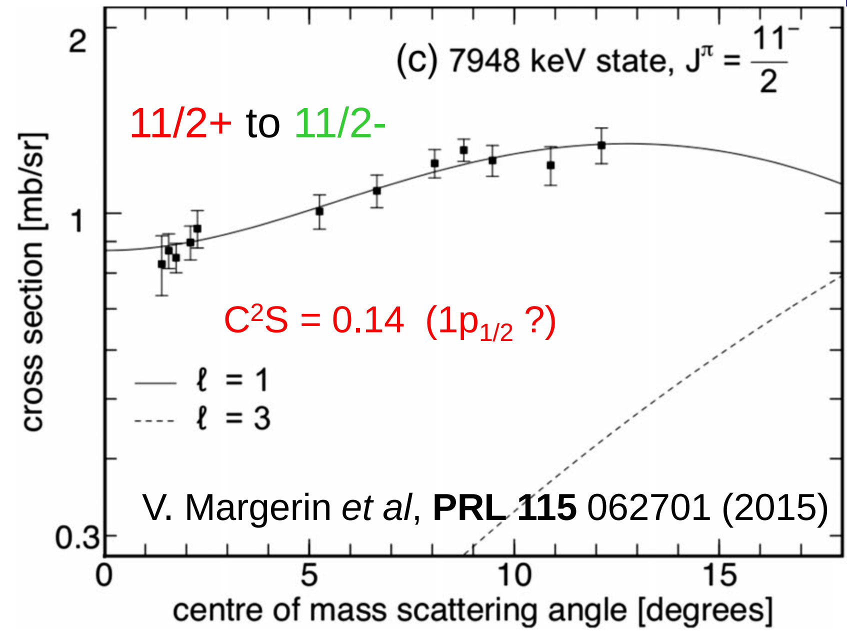
	C^2S	ωγ (μeV)	C^2S	ωγ (μeV)
68-keV	< 0.053	< 3.1e-9	< 0.016 *	< 0.8e-9
127-keV	0.0085(30)	0.026(7)	0.0093(19)	0.025(5)

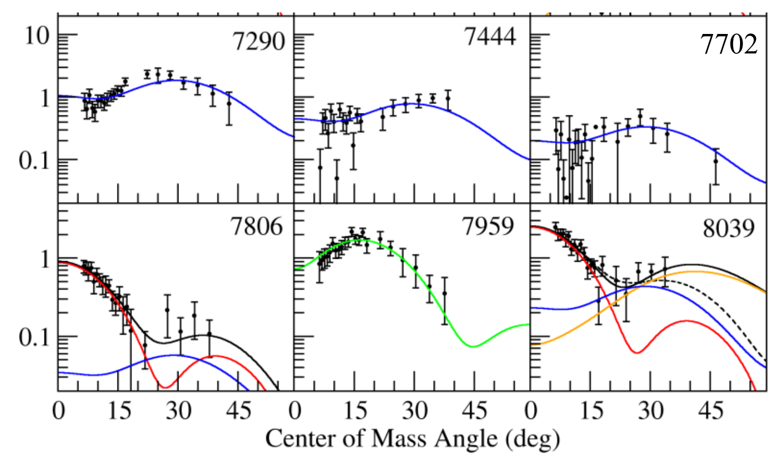
* 0.068(14) 20% mirror uncertainty

Other astrophysically-interesting states – parity of 189 keV resonance

G. Lotay *et al*, **PRC 34** 035802 (2011)





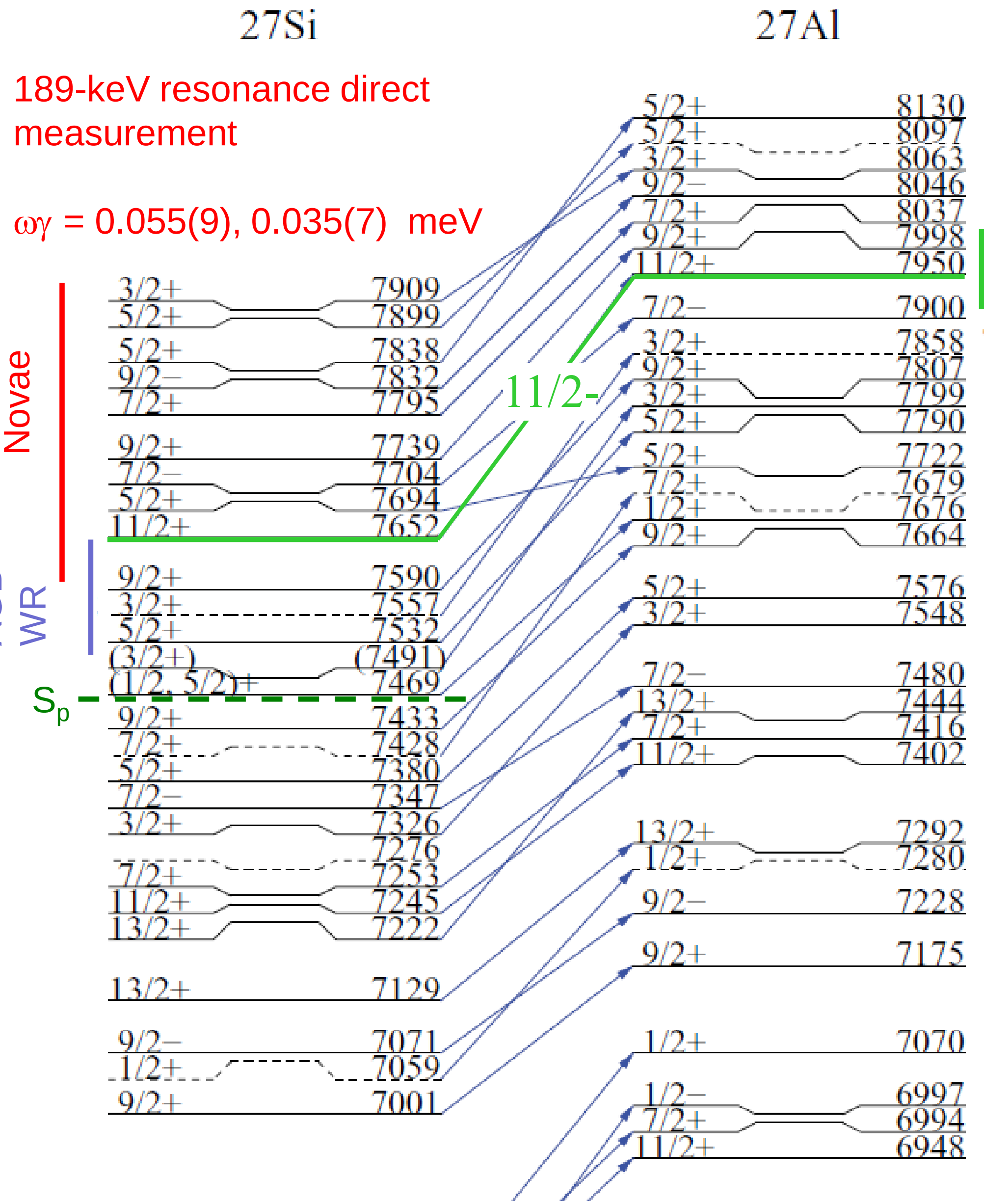


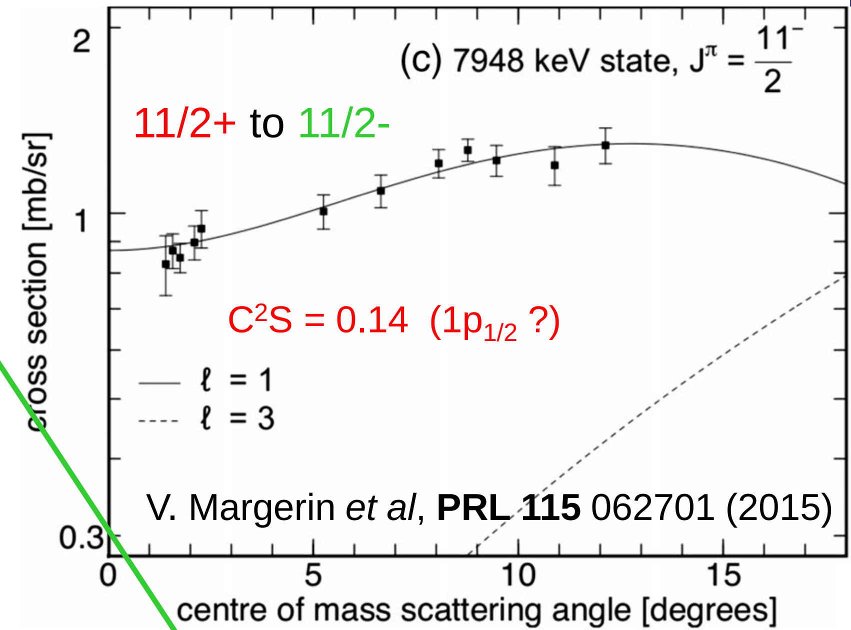
Other astrophysically-interesting states – parity of 189 keV resonance

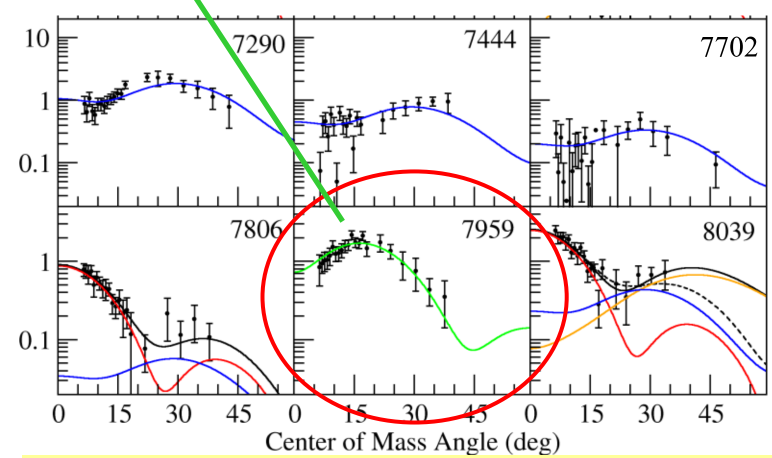
G. Lotay *et al*, **PRC 34** 035802 (2011)

189-keV resonance direct measurement

ωγ = 0.055(9), 0.035(7) meV





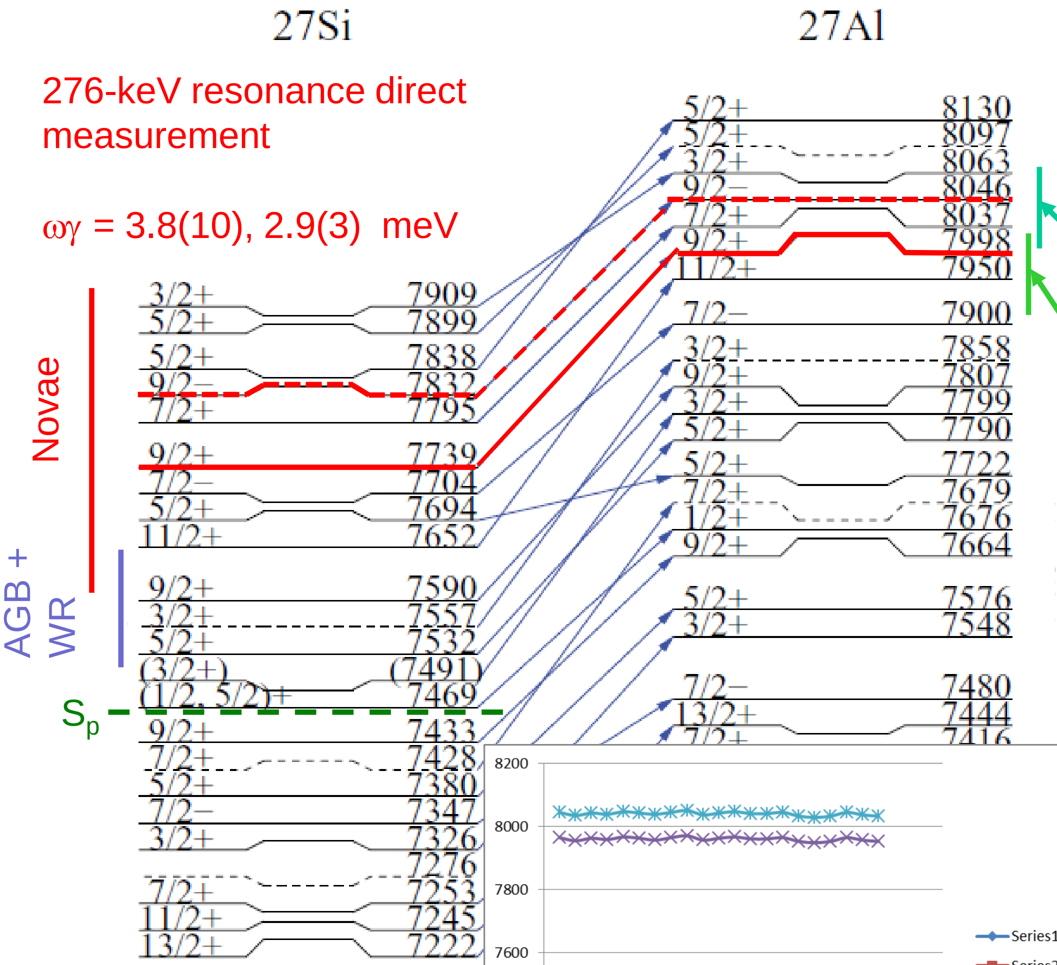


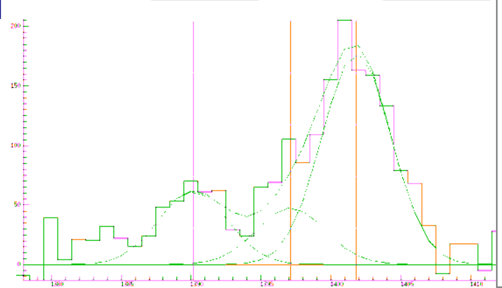
$C^2S = 0.056$ ($2p_{3/2}$) **ωγ = 0.040(10) meV**

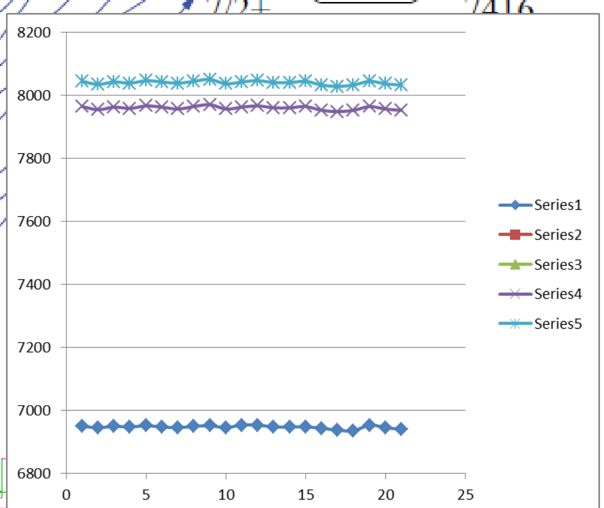
Or $C^2S = 0.166$ ($1p_{1/2}$) ωγ = 0.114(30) meV

(preliminary) Speculation on 276 keV resonance

G. Lotay *et al*, **PRC 34** 035802 (2011)







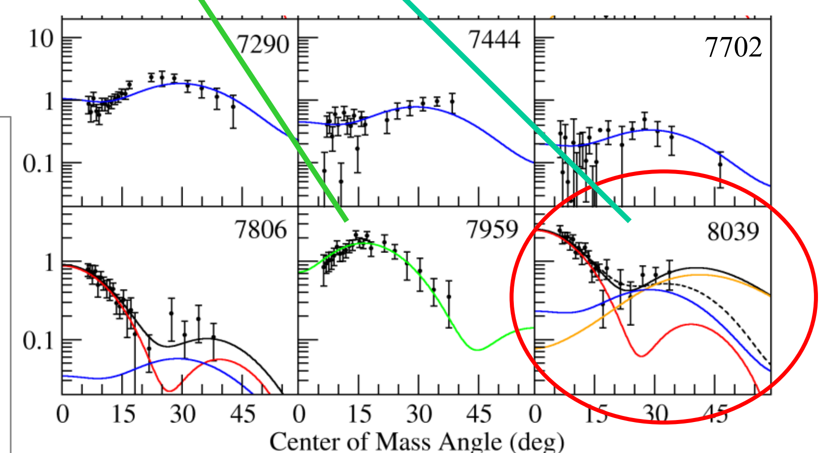
A. Kankainen *et al*., **Eur. Phys. J. A 52** (2016) 6

Could the 9/2+ be 9/2-?

Argument based on integrated $^{26}Al(d,n)$ cross section and SM predictions (s=d)

Data require: $C^2S = 0.02$ $(2s_{1/2})$
$C^2S = 0.1$ $(1d_{3/2})$

And could the 9/2- be a 9/2+?



$C^2S = 0.030$ $(2s_{1/2})$ **ωγ = 5.3(15) meV**
$C^2S = 0.177$ $(1d_{3/2})$

Summary

- ^{26}Al extremely well-studied astronomical signature (first detected radioisotope, first Galactic map)
- Low lying resonances for the ^{26}Al(p,γ)^{27}Si destruction mechanism (massive stars) poorly constrained
- Measured single-particle SFs of mirror levels via ^{26}Al(d,p) for constraining stellar reaction rate
  - 127-keV resonance strength constrained, ~4 times stronger than previously adopted upper limit
  - First experimentally-derived upper limit for 68 keV resonance (order of magnitude reduction)
  - 127-keV resonance dominates at temperatures for massive stars
  - Excellent agreement with Edinburgh/TRIUMF result
  - Support the reassignment of 189 keV resonance to negative parity
  - Evidence for ell = 0 strength around 8 MeV, but centroid at 8039 keV –perhaps 8046 9/2- state really 9/2+? (mis-assignment of 7832 (^{27}Si) and 8046 (^{27}Al) keV pair, given (^{3}He,d) distribution?)

- Really want gamma rays in (d,p) measurement for these studies

Collaborators

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Constraint of the Astrophysical $^{26g}Al(p,\gamma)^{27}Si$ Destruction Rate at Stellar Temperatures

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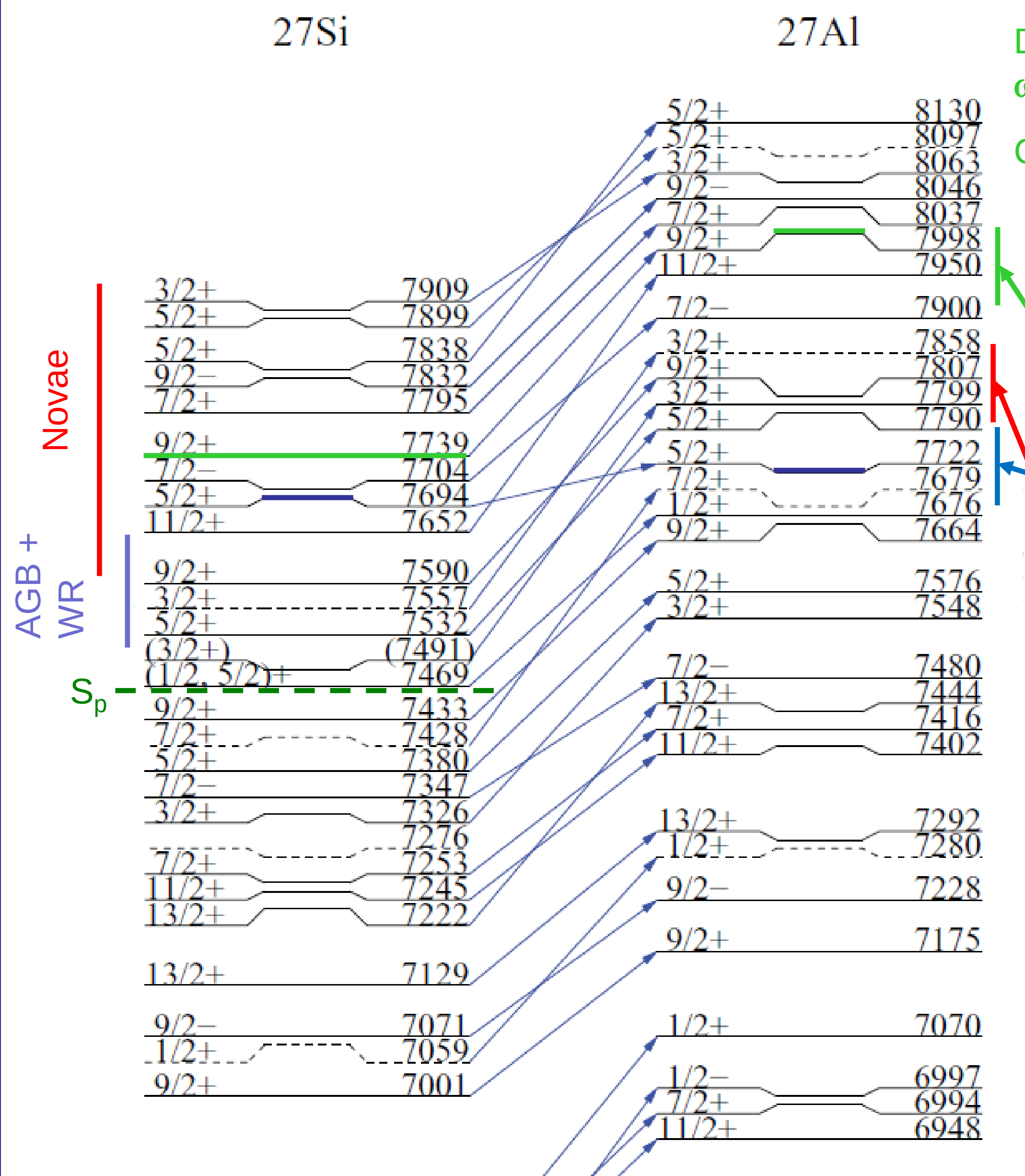
Cross checks on other resonances – 231 keV and 189 keV



189 keV resonance

Direct measurement (p,γ):
$\omega\gamma$ = 0.055(9), 0.035(7) meV

Current data (d,p): C^2S = 0.056(5) ($2p_{3/2}$)
$\omega\gamma$ = 0.040(10) meV

231 keV resonance

Direct measurement (p,γ):
$\omega\gamma$ < 0.040 (calorimetry), < 0.010 (branching ratio assumption) meV [*Vogelaar thesis*]

Current data (d,p): C^2S = 0.17(5) ($1d_{3/2}$)
$\omega\gamma$ = 0.019(6)