Measurement of neutron spectroscopic factors in ^{27}Al from the $^{26}Al(d,p)^{27}Al$ reaction and implications for the destruction of ^{26}Al in AGB and WR stars

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Outline

Brief overview of the astrophysical case

Studying the $^{26}Al(p,\gamma)^{27}Si$ rate: going for the mirror ^{27}Al

Experimental set up for the $^{26}Al(d,p)^{27}Al$ reaction

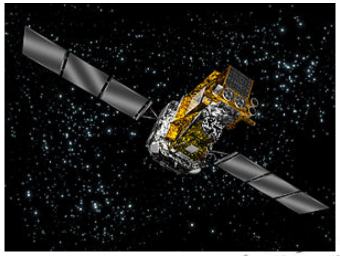
Results at $E_{exc} < 8$ MeV and implications for AGB and WR stars

Results at $E_{exc} > 8$ MeV

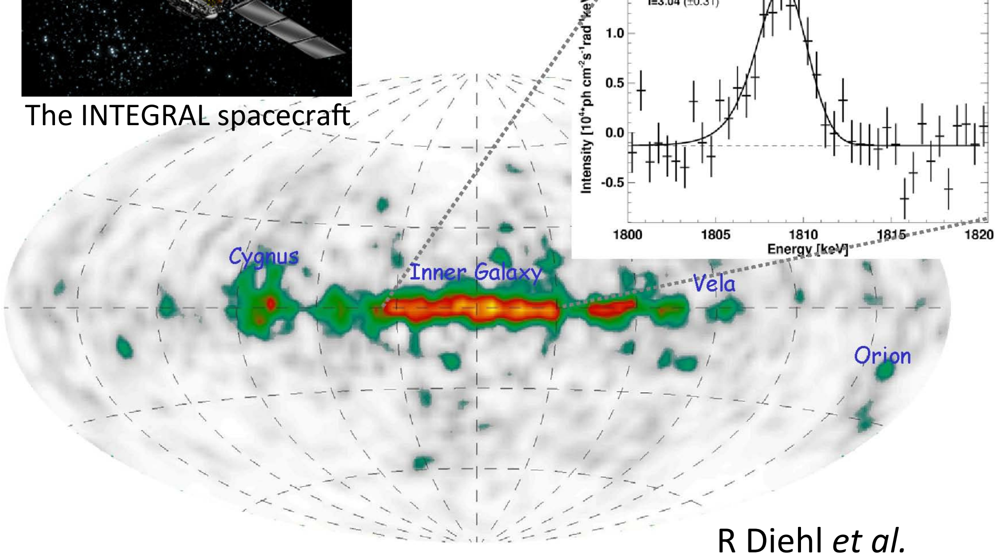
The cosmic γ-ray emitter ^{26}Al

→ Observations from COMPTEL provided first evidence of ongoing nucleosynthesis

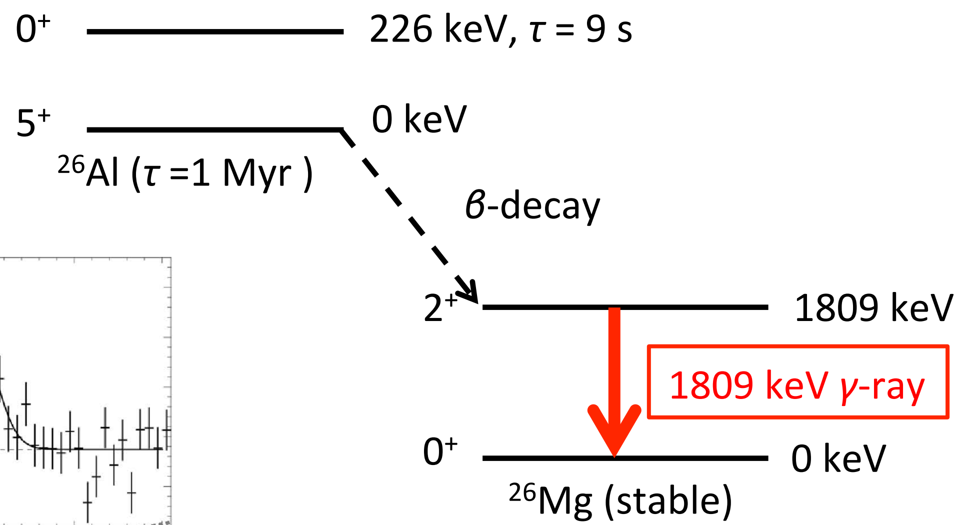
→ Mapping by SPI/INTEGRAL suggests origin from Wolf-Rayet stars and CCSNe



The INTEGRAL spacecraft

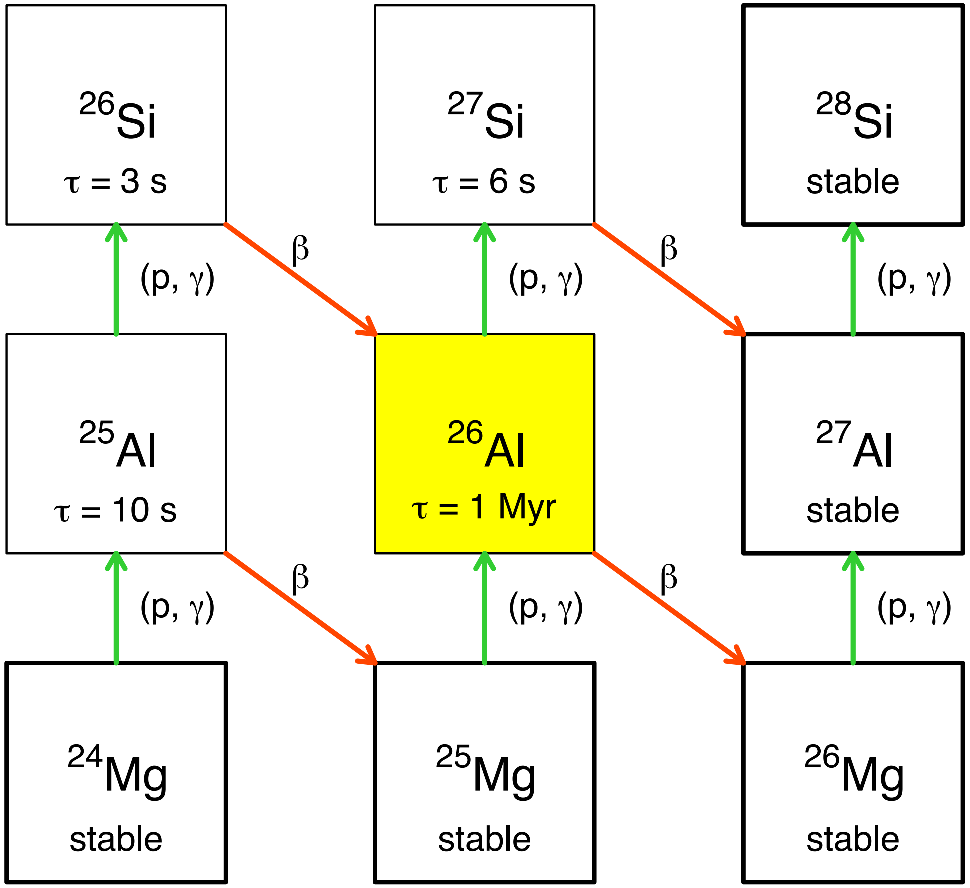


R Diehl *et al.*



The cosmic γ-ray emitter ^{26}Al

- Explosive hydrogen burning (with 0.06 GK<T<0.1 GK) in AGB and in WR stars
  - fast production (vs. ^{26}Al lifetime) at temperatures T <0.1 GK: ^{26}Al in the ground state
  - stellar winds in the star that expel the hydrogen shell and its ^{26}Al content



Destruction of ^{26}Al in AGB and WR stars: investigating the (p, γ) reaction

To determine precisely the ^{26}Al(p, γ)^{27}Si reaction rate we need to study the 127 keV resonance of the ^{26}Al+p system

- Direct measurements of the reaction rate are prevented by low cross section for energies below the coulomb barrier

→ Indirect measurement via the mirror nucleus ^{27}Al using the transfer reaction ^{26}Al(d,p)^{27}Al

WHY is studying the mirror ^{26}Al+n relevant?

1) The cross section is related to the spectroscopic factor (C2S)

2) C2S in mirror nuclei are similar:
   one can either first compute the Asymptotic Normalisation Coefficients in one nucleus and then use approximate formulae to obtain the mirror ANC, hence the desired C2S

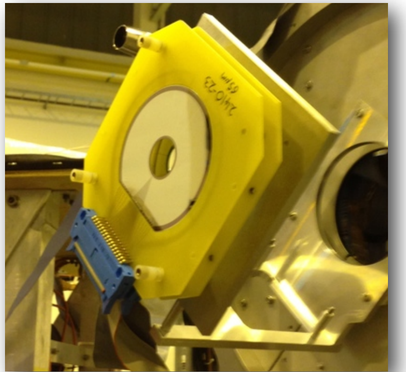
   or it has been shown that within 20% (true) mirror state have the same C2S

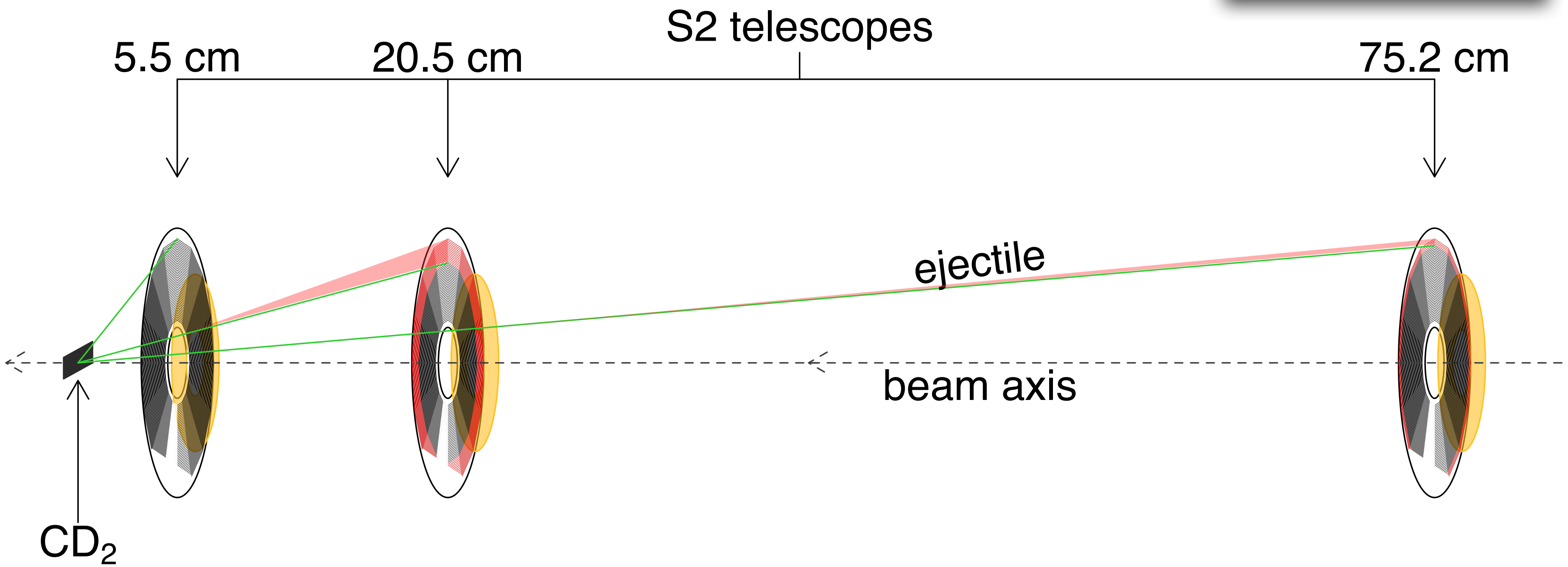
(and goodbye ANCs)

Experimental set up

- Very intense ^{26}Al radioactive beam (~1pnA) with E_{beam}= 6 MeV/u. At ISAC facility, TRIUMF, Canada
- 3(+1) S2 silicon strip detectors upstream, forward COM angles (closest detector moved even closer in later part of experiment)
- COM angular coverage at 8 MeV 0.5 to ~30 degrees

S2 telescope detector:





maximal angle trajectory for a given detector

collimator used to eliminate beam backscattering on detectors

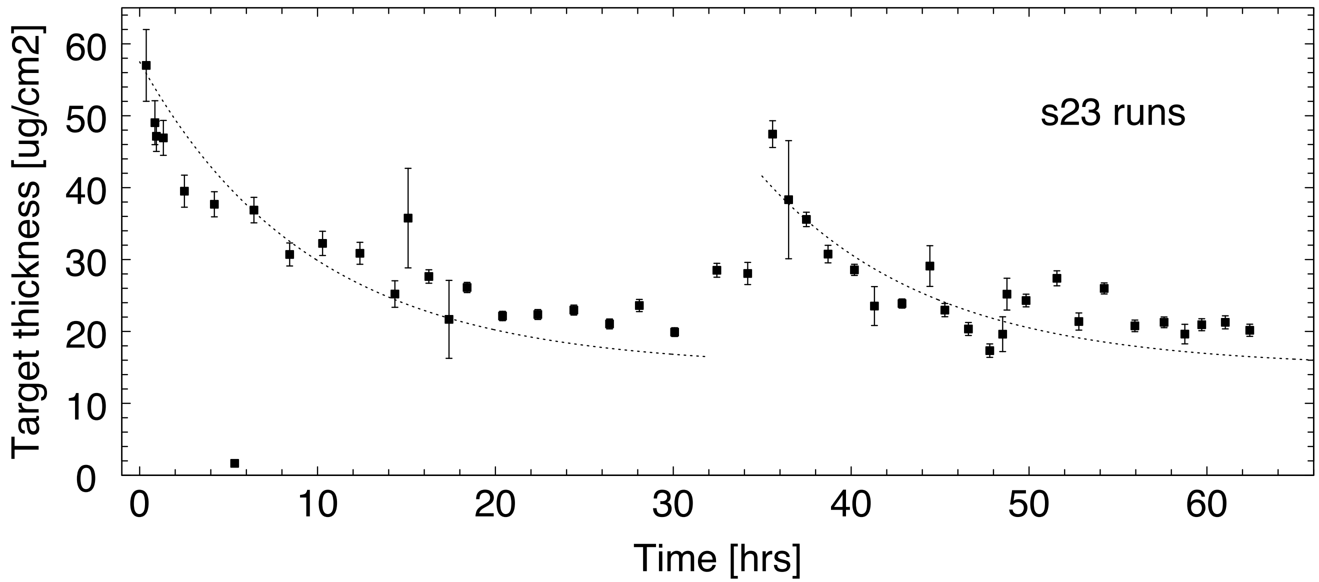
detector shadowing

Inside TUDA

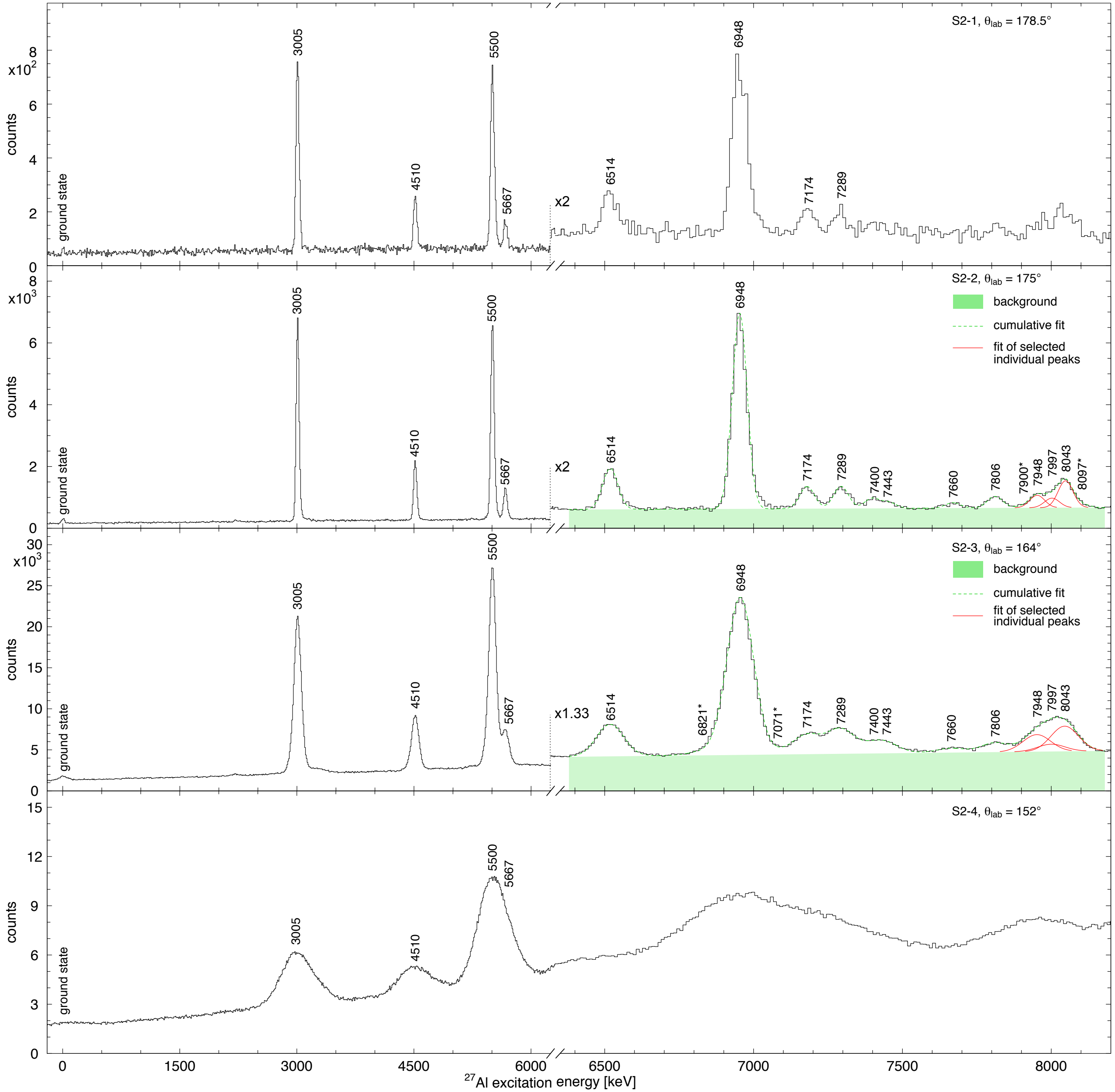
Target thickness and deuteron content

- Measurement of E_{loss} of alpha-particles in the target before the experiment: thickness at t0 (59(7) ug/cm^2)

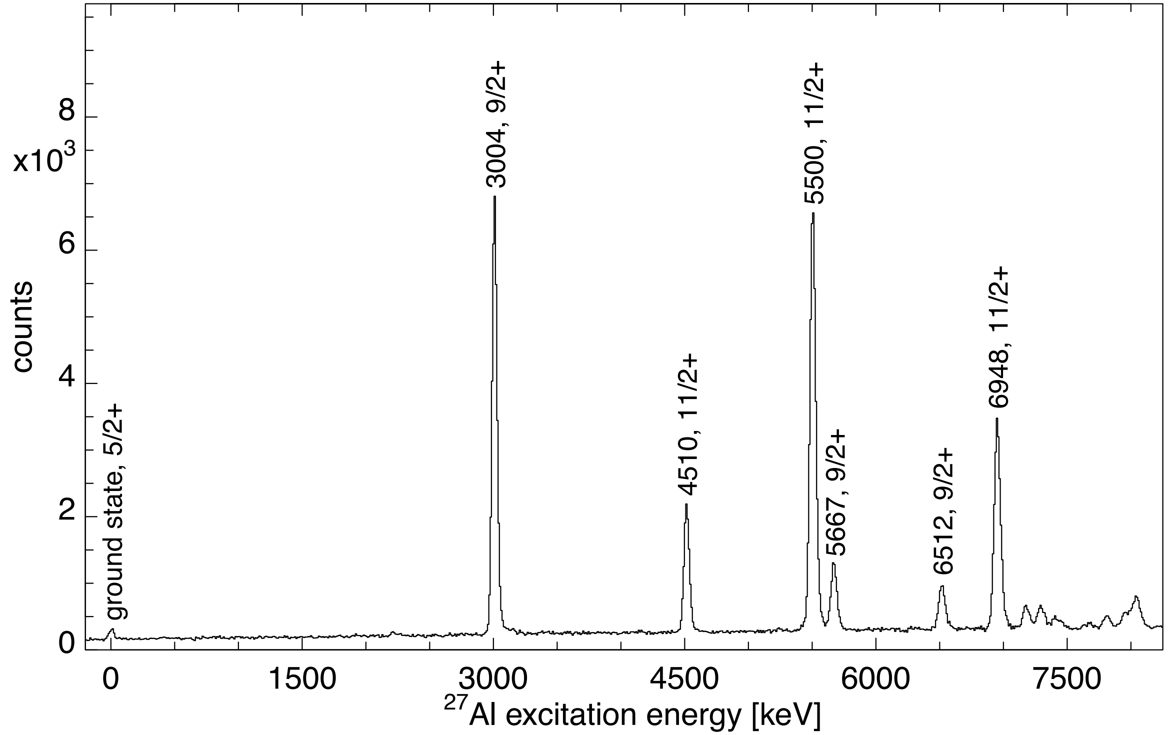
- Ratio beam intensity to number of counts in the 3 MeV line: tracking of deuteron content



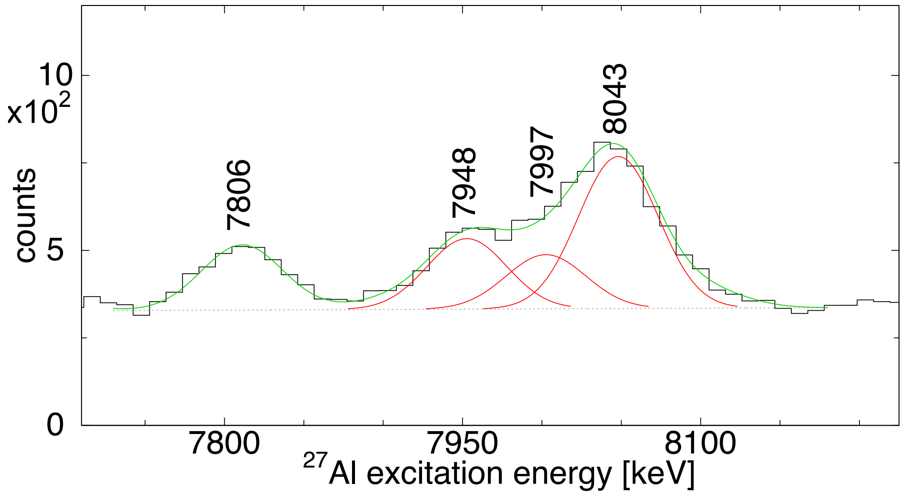
Lower energy spectra and the region of interest for AGB and WR stars



Measurement of neutron C2S for the ^{26}Al+n system via the ^{26}Al(d,p) reaction

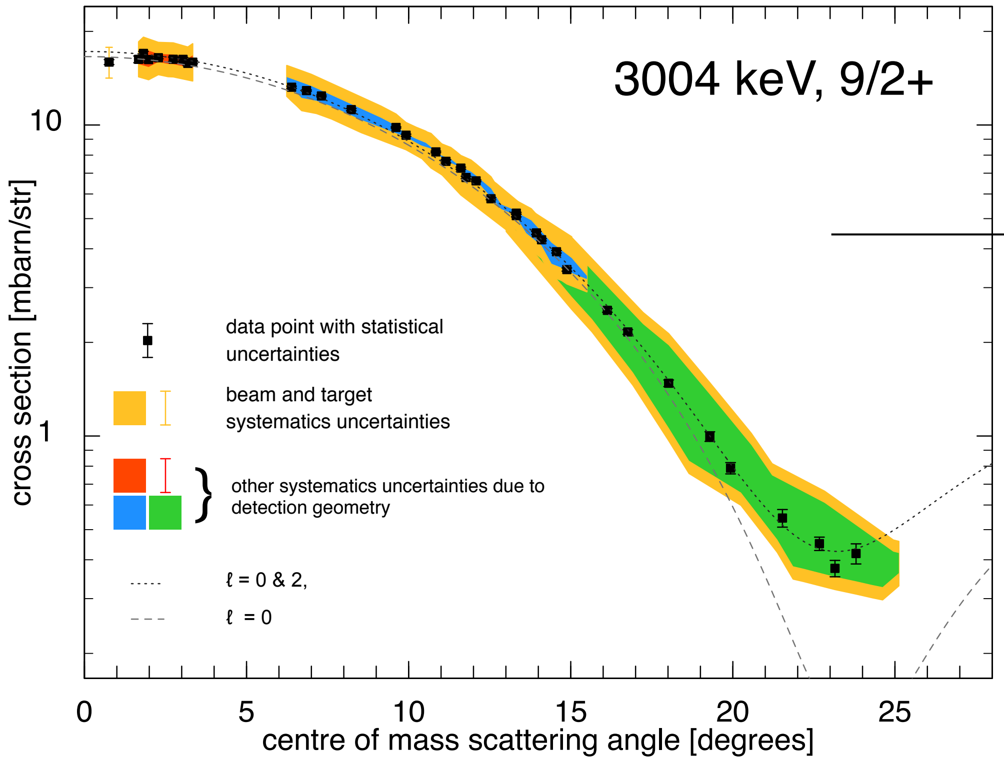


- proton spectrum at 175 degrees (lab angle) ~2.5 degrees (com)
- FWHM as low as 35 keV



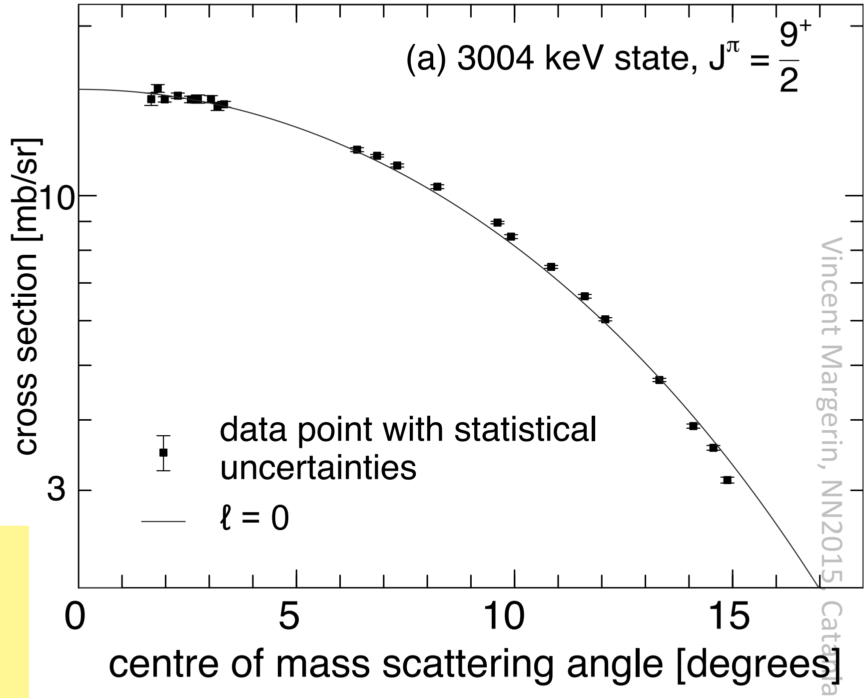
State in ^{27}Si	Resonance energy [keV]	Analog in ^{27}Al
7589, 9/2+	127	7806, 9/2+
7651, 11/2-	189	7948, 11/2-

Measurement of neutron C2S for the ^{26}Al+n system via the ^{26}Al(d,p) reaction

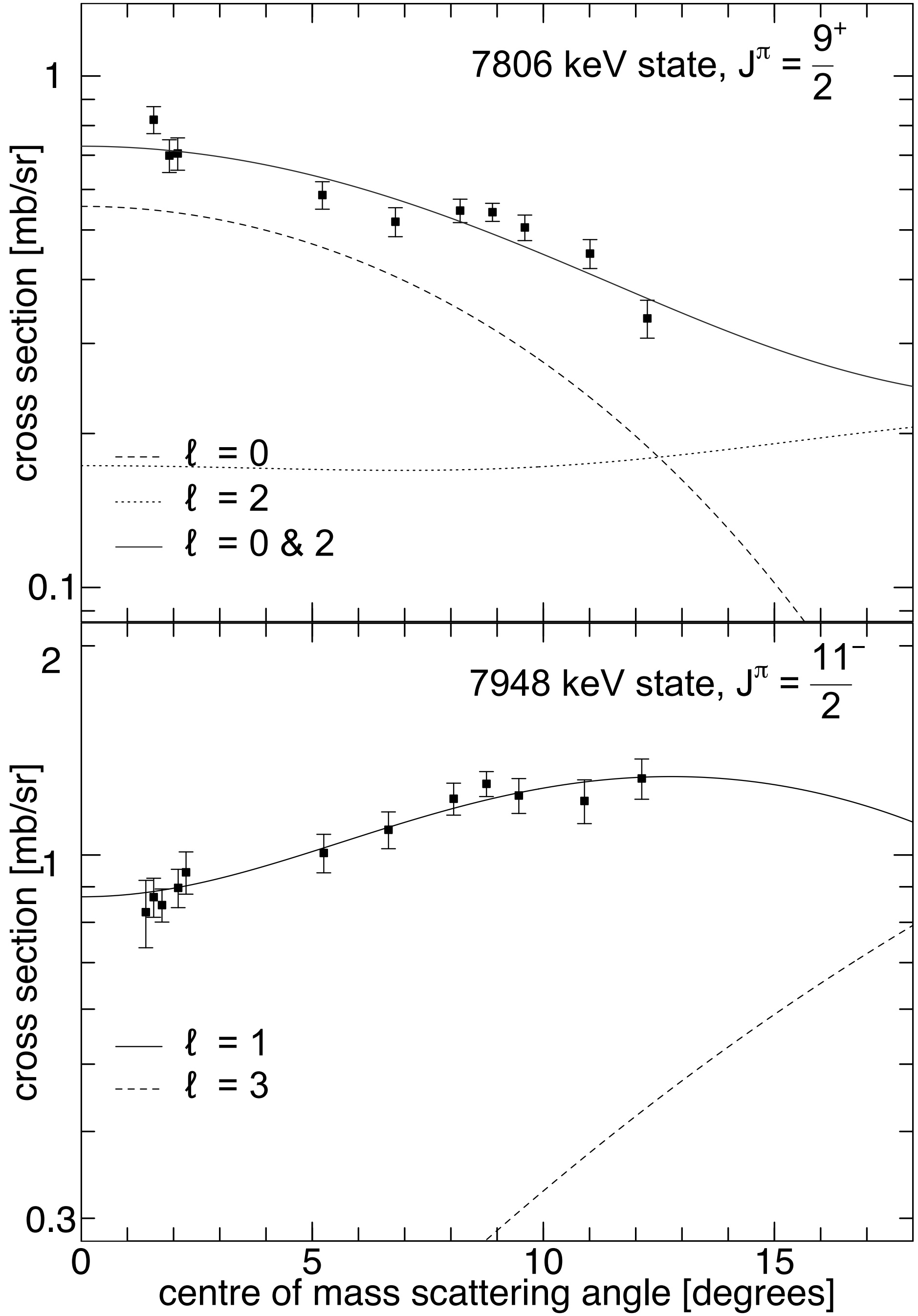


$$\frac{d\sigma(E)}{d\Omega}(\text{exp.}) = S_{\ell j} \times \frac{d\sigma(E)}{d\Omega}(\text{theory})$$

s-wave C2S: 0.49(9)
d-wave C2S: 0.22(6)



Calculation made using the TWOFNR code:
- deuteron: adiabatic wave approximation
- entrance (^{26}Al+p and +n) and exit (^{27}Al+p) potentials: Koning Delaroche, NPA 713 (2003) 231
- neutron geometry for exit ^{26}Al+n: varied upon l-value for transfer (Gade *et al.*, PRC 77 (2008) 044306)



NOT PRELIMINARY !!!

127 keV resonance

- Best fit is obtained by mixing of s- and d-waves:
  - s1/2 C2S: $9.5(36) \times 10^{-3}$
  - d5/2 C2S: $8.5(34) \times 10^{-2}$
- This is 4.5 times higher than a previous measurement by Vogelaar *et al.*'s (upper limit) of 2.2×10^{-3}

189 keV resonance

- State previously known as **11/2**+ but this shows odd L transfer, hence **11/2-**:
  - p1/2 C2S: 0.15(7)
- This equates to a strength of **56(23) μeV**
  - this is in good agreement with the two previous measurements:

  55(9) μeV (Vogelaar, PhD thesis, 1989)

  35(7) μeV (Ruiz *et al.*, 2006)

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Results from Pain *et al.* PRL May 2015

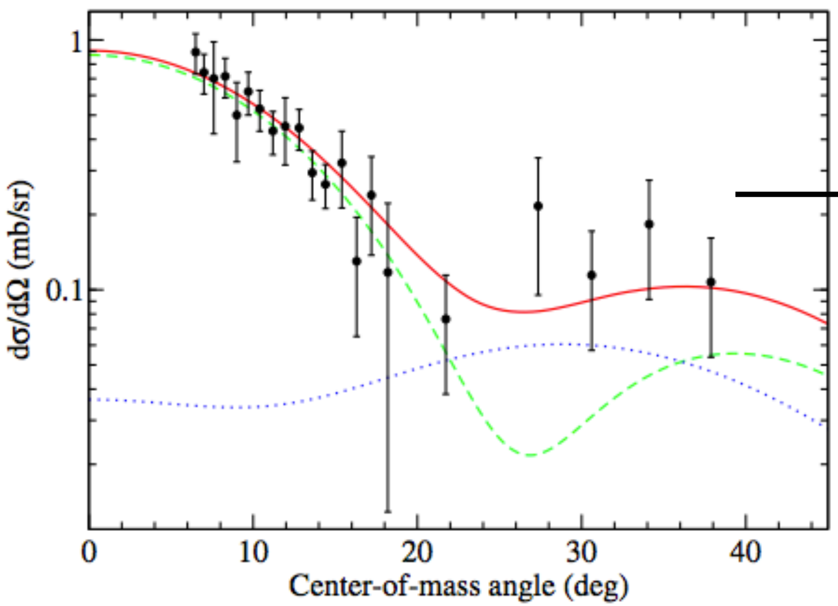
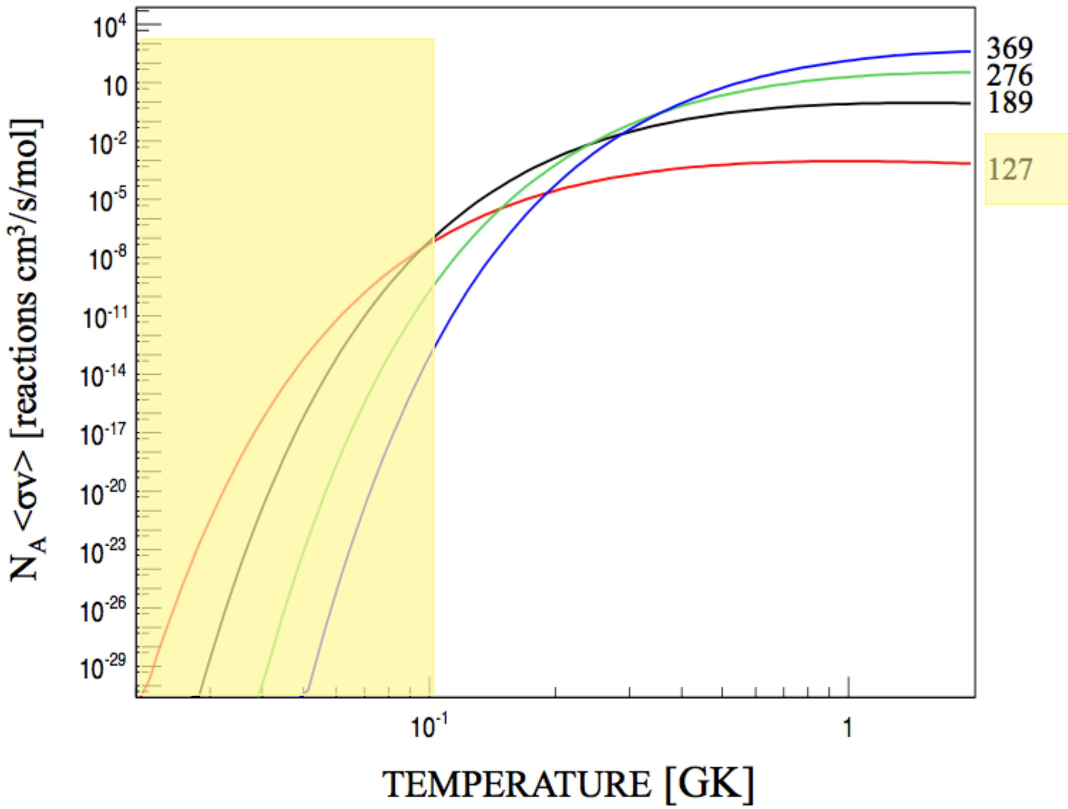


FIG. 2 (color online). Differential cross sections for the peak at 7805(7) keV, fitted with a combination of $\ell_n = 0$ and 2 neutron transfer calculations (solid red curve). The dashed (green) and dotted (blue) curves show the individual contributions to the fit. Error bars represent the statistical uncertainty in the proton yields stemming from Gaussian fits to the excitation energy spectrum at each angle.

C2S s_{12}: 10(3) x 10^{-3}
obvious L=2 component too

ADWA calculations made using FRESCO

Contribution of each resonances to the reaction rate



- Over the temperature range $0.06<T_9<0.1$ the 127 keV resonance dominates the destruction rate of ^{26}Al

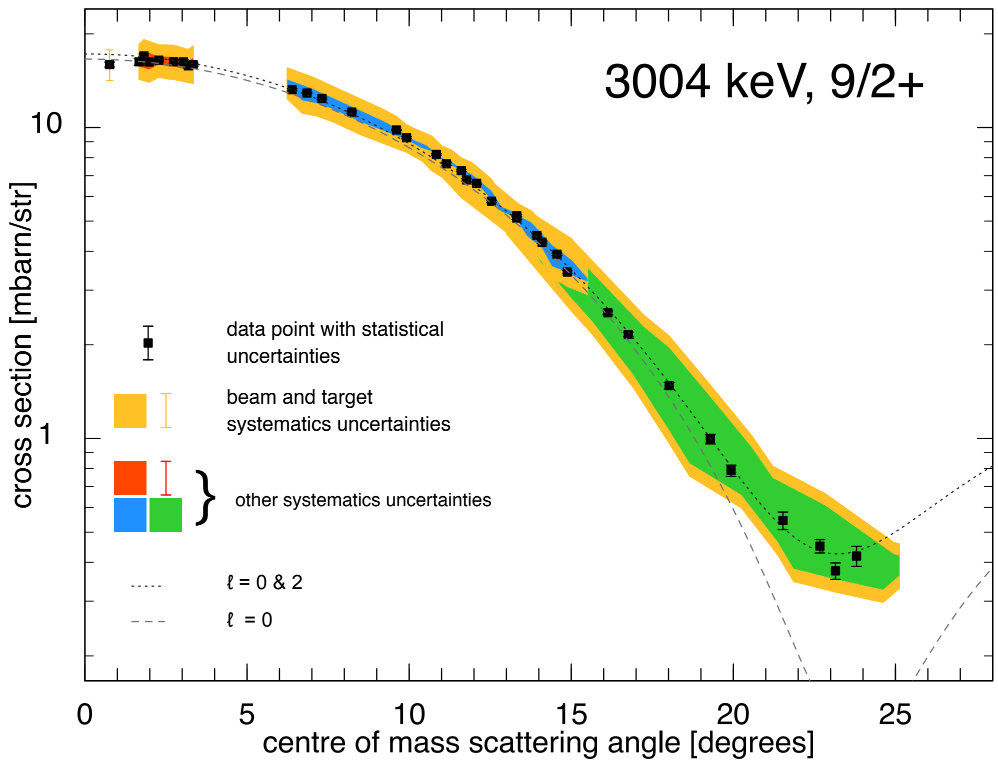
Conclusions

- First (indirect) measurement of the strength of the 127 keV resonance via mirror nucleus study
- Parity of the 189 keV resonance changed from + to -, measured strength still in accordance with direct measurement
- The mirror state to the 68 keV resonance not observed
- The 127 keV resonance dominates the destruction rate in the temperature range [0.06 GK,0.1 GK], i.e. in AGB and WR stars
- Still require measurement of the proton C2S via $^{26}Al(^{3}He, d)^{27}Si$

QUESTIONS?

Destruction of the cosmic γ-ray emitting nucleus ^{26}Al in Wolf-Rayet and AGB Stars

V. Margerin, G. Lotay, P. Woods, M. Aliotta, G. Christian, B. Davids, T. Davinson,
D. Doherty, J. Fallis, D. Howell, O. Kirsebom, A. Murphy, A. Rojas, C. Ruiz, J. Tostevin



s-wave C2S: 0.49(9)

d-wave C2: 0.22(6)

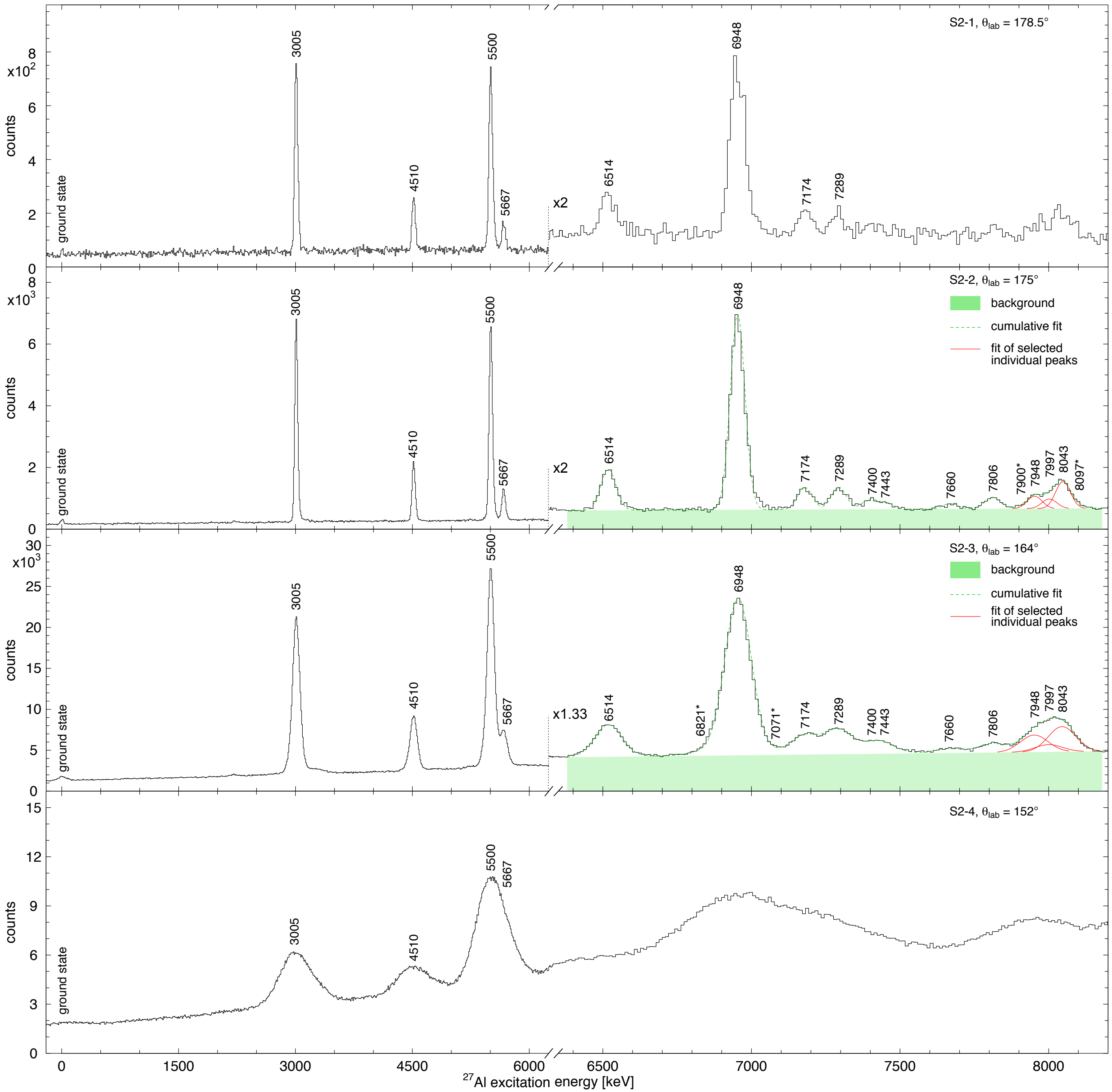
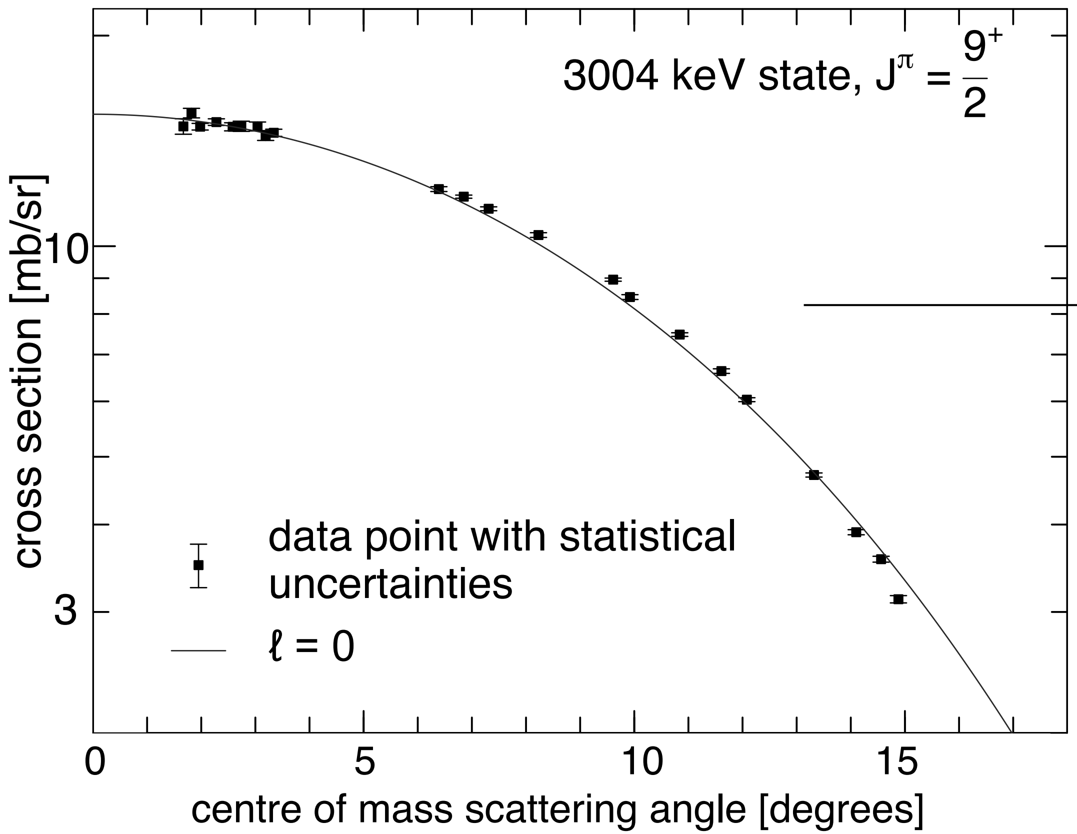


FIG. 1: Excitation spectra.

Measurement of neutron C2S for the ^{26}Al+n system via the ^{26}Al(d,p) reaction



$$\frac{d\sigma(E)}{d\Omega}(\text{exp.}) = S_{\ell j} \times \frac{d\sigma(E)}{d\Omega}(\text{theory})$$

s-wave C2S: 0.49(9)

Uncertainty includes systematics from, principally, beam intensity and target thickness (deuteron content)

Calculation made using the TWOFNR code:

- deuteron: adiabatic wave approximation
- entrance (^{26}Al+p and +n) and exit (^{27}Al+p) potentials: Koning Delaroche, NPA 713 (2003) 231
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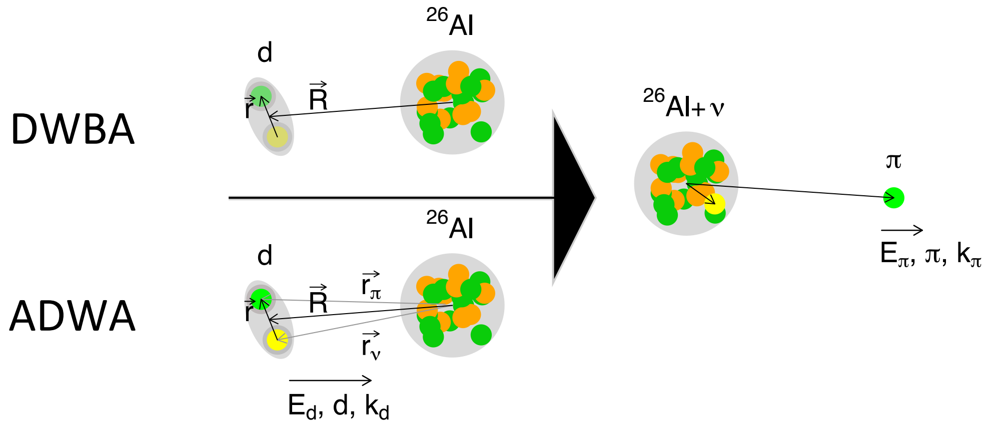

TABLE I: Potential parameter for the adiabatic wave approximation representation of the ^{26}Al$(d,p)^{27}$Al reaction.

Channel	V_V (MeV)	W_V (MeV)	r_V (fm)	a_V (fm)	W_S (MeV)	r_{wS} (fm)	a_{wS} (fm)	V_{SO} (MeV)	W_{SO} (MeV)	r_{SO} (fm)	a_{SO} (fm)	r_C (fm)
^{26}Al+d: proton (39%)	55.194	0.498	1.167	0.674	7.053	1.295	0.532	5.672	-0.024	0.967	0.590	1.33
^{26}Al+d: neutron (61%)	51.988	0.580	1.167	0.674	7.528	1.295	0.540	5.615	-0.033	0.967	0.590	1.33
^{27}Al+p	50.485[a]	1.763	1.169	0.674	7.737	1.295	0.533	5.373	-0.090	0.970	0.590	1.33
^{26}Al+n	varied[b]		*					$\ell.\sigma = 6$				

Using Koning-Delaroche potential
* depending on the transfer and from HF calculation