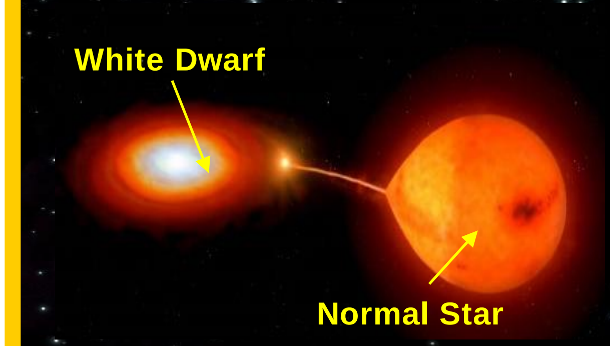
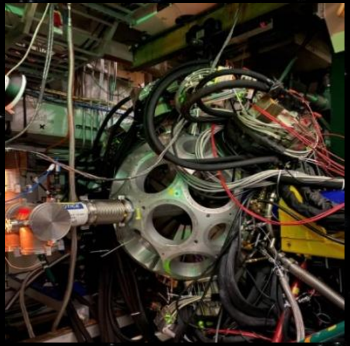
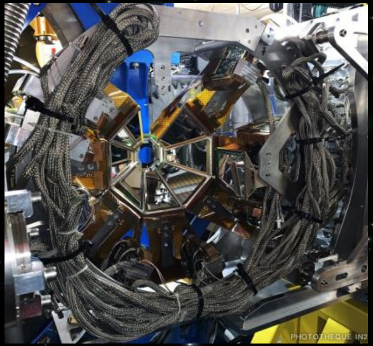
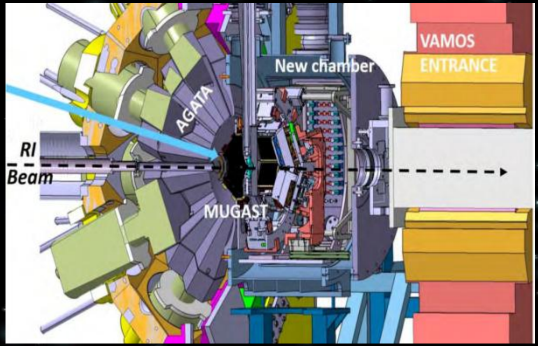
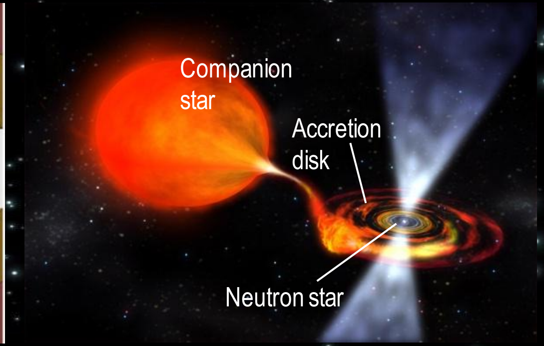










Transfer reactions for nuclear astrophysics studies (present & future)

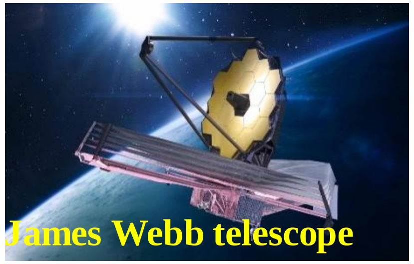
Faïrouz Hammache
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab)

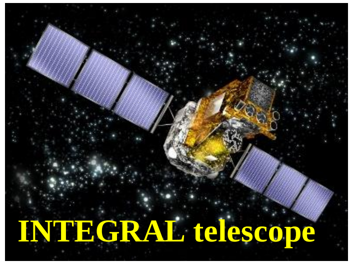
24ième Colloque GANIL Bussang, 21-25 Septembre 2026

From nuclear physics to abundances

Observations
(on earth, meteorites, telescopes, satellites,…)

→ **Observed abundances**





Astrophysics Modelling
(BBN & stellar evolution, nucleosynthesis)

→ **Predicted abundances for each species**

Determine the amount of energy released by nuclear reactions

Reaction Network

Set of differential equations to follow **the time evolution of isotopic abundances :**

$$\frac{dY_i}{dt} = \sum_i N_j^i \lambda_j Y_j + \sum_{j,k} N_{j,k}^i \rho N_A \langle \sigma v \rangle Y_j Y_k$$

Reaction rates (& β decay rates)

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{-E/kT} dE$$

Reaction cross sections

Why using transfer reactions?

- **Reactions in quiescent burning stages :**

→ T ~ 0.001 -0.1 GK
→ tens –hundreds keV << Coulomb barrier E_C
→ σ(E) very weak (0.01 fb- ~100 pb)
→ Direct measurements are very challenging
→ *σ(E)* measured at high energies then extrapolated at stellar energies
→ need to consider resonances at very low energy

- **Reactions in explosive environments (Novae, X-ray bursts,…) :**

→ T=0. 1-2 GK
→ hundreds keV- few MeV
→ σ dominated by **resonances**
→ radioactive nuclei : Low beam intensities (~10^4-10^7 p/s), few atoms/cm^2 in targets for longed lived ones
→ Direct measurements challenging or impossible

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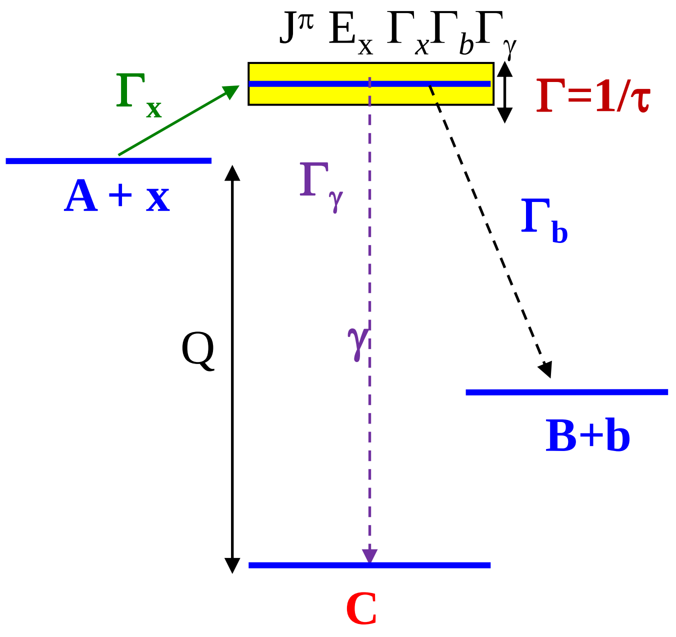
- **For resonant reactions A+x→ C*→B+γ or A+x→ C*→B+b* →**

$$\sigma(E) = \pi\bar{\lambda}^2 \frac{2J_c+1}{(2J_A+1)(2J_x+1)} \frac{\Gamma_x\Gamma_y}{(E-E_R)^2 + \Gamma_{tot}^2/4}$$

y= b or γ



For narrow resonance cases :

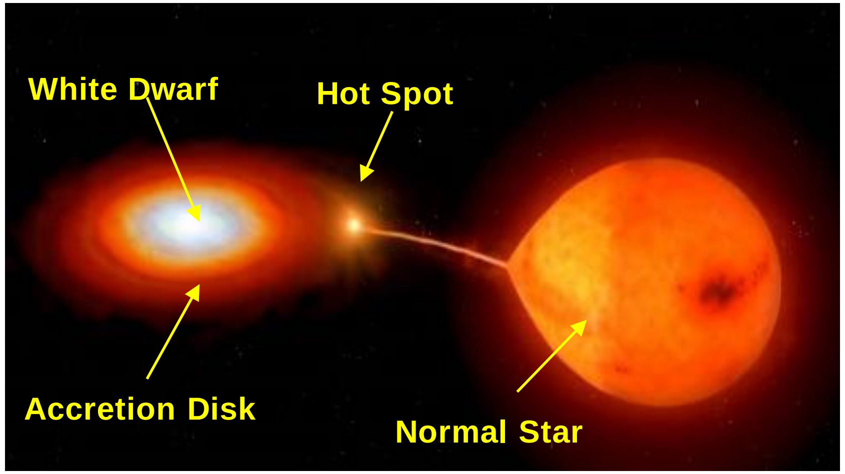
$$\langle\sigma v\rangle = \left(\frac{2\pi}{\mu kT}\right)^{\frac{3}{2}} \hbar(\omega\gamma)_R \exp\left(-\frac{E_R}{kT}\right)$$

$$\rightarrow (\omega\gamma)_R = \frac{2J_c+1}{(2J_A+1)\cdot(2J_x+1)} \frac{\Gamma_x\Gamma_y}{\Gamma_{tot}}$$

- $E_R=E_x$-Q is the resonance energy
- Γ_x, Γ_y are the partial decay widths
- J_A, J_C J_x : total angular momentum of the nuclei A,C & x

} Can be determined from indirect measurements (transfer reactions,…)

Classical novae nucleosynthesis: open questions



Novae: Thermonuclear runaway at the surface of a white dwarf accreting the H rich material of its companion star

Mechanism well established but

- Observed ejected mass << predictions
- Amount of mixing between accreted and white dwarf materials?
- Contribution to ^{26}Al galactic emission

→ Novae produce γ-ray emitters & dust (presolar grains) → key observational constraints

→ The first stellar explosive site with all reaction rates based on experimental information

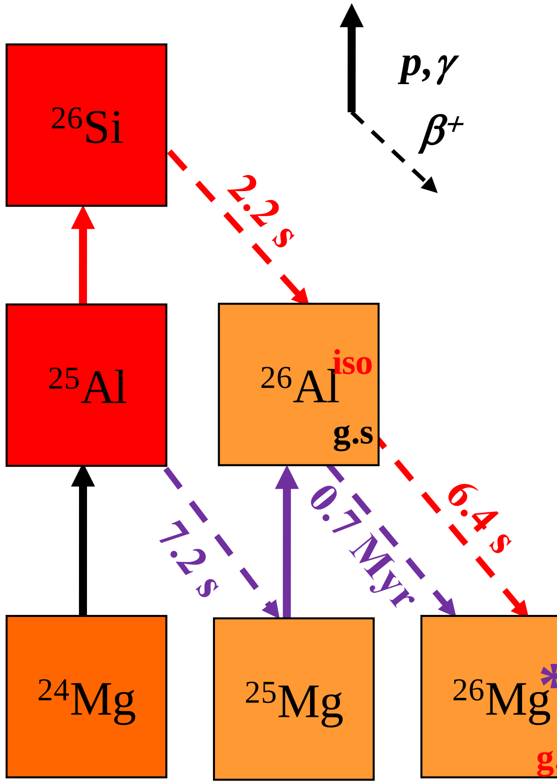
The **3 remaining key reactions** with significant uncertainties:

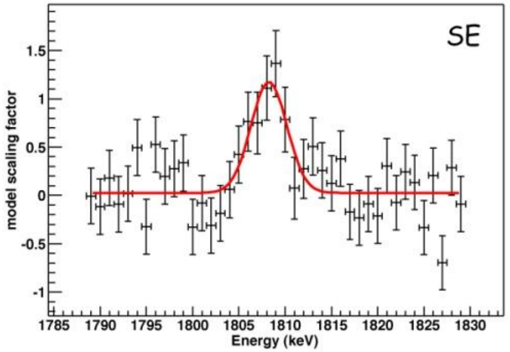
- ^{30}P(p,γ)^{31}S : paternity of novae grains **Woods+2021 (FRIB)**
- ^{18}F(p,α)^{15}O: γ-ray emission ≤ 511 keV **Riley+PRC2021 (Split-Pole/ALTO)**
- **^{25}Al(p,γ)^{26}Si**: Classical novae contribution to the observed galactic ^{26}Al γ-ray emission @ 1.809 MeV?

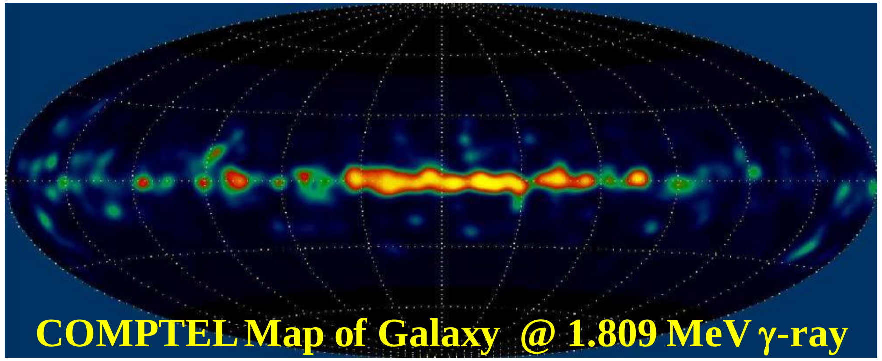
^{26}Al nucleosynthesis

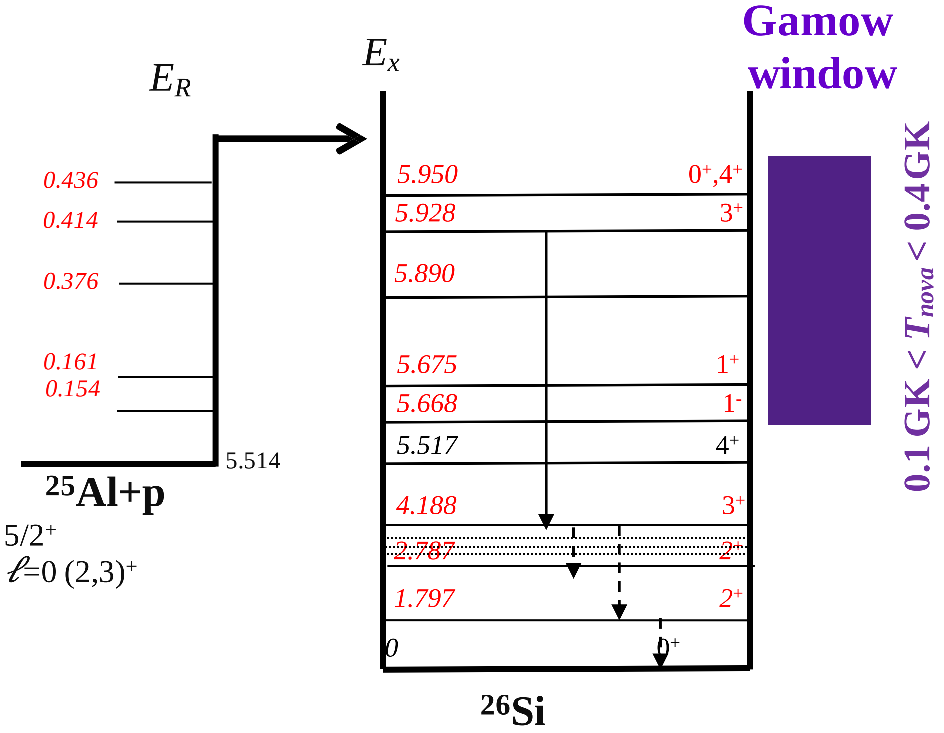
- **Novae contribution to ^{26}Al galactic production 10 – 30 % ?**
- Two sequences to produce ^{26}Al ($T_{1/2}$=7.2 10^5 yr):

  ^{25}Al(p,γ)^{26}Si competes with ^{25}Al(β$^+$)









^{25}Al(p,γ)^{26}Si: $$< \sigma v >_{tot} = \sum_R \left(\frac{2\pi}{\mu_{(^{25}Al,p)} k_B T}\right)^{\frac{3}{2}} \hbar^2 \omega\gamma_R \exp\left(-\frac{E_R}{k_B T}\right)$$

Factor two uncertainty on resonance strengths

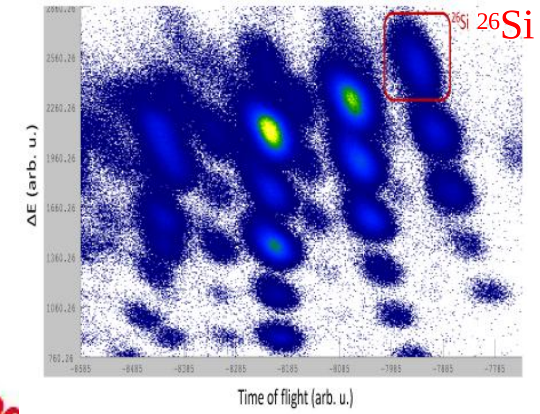
⇒ need to be measured

^{25}Al(p,γ)^{26}Si case: Experiment @ FRIB

→ Studied via d(^{25}Al,nγ)^{26}Si @ FRIB/S800 **C.Fougères et al.**

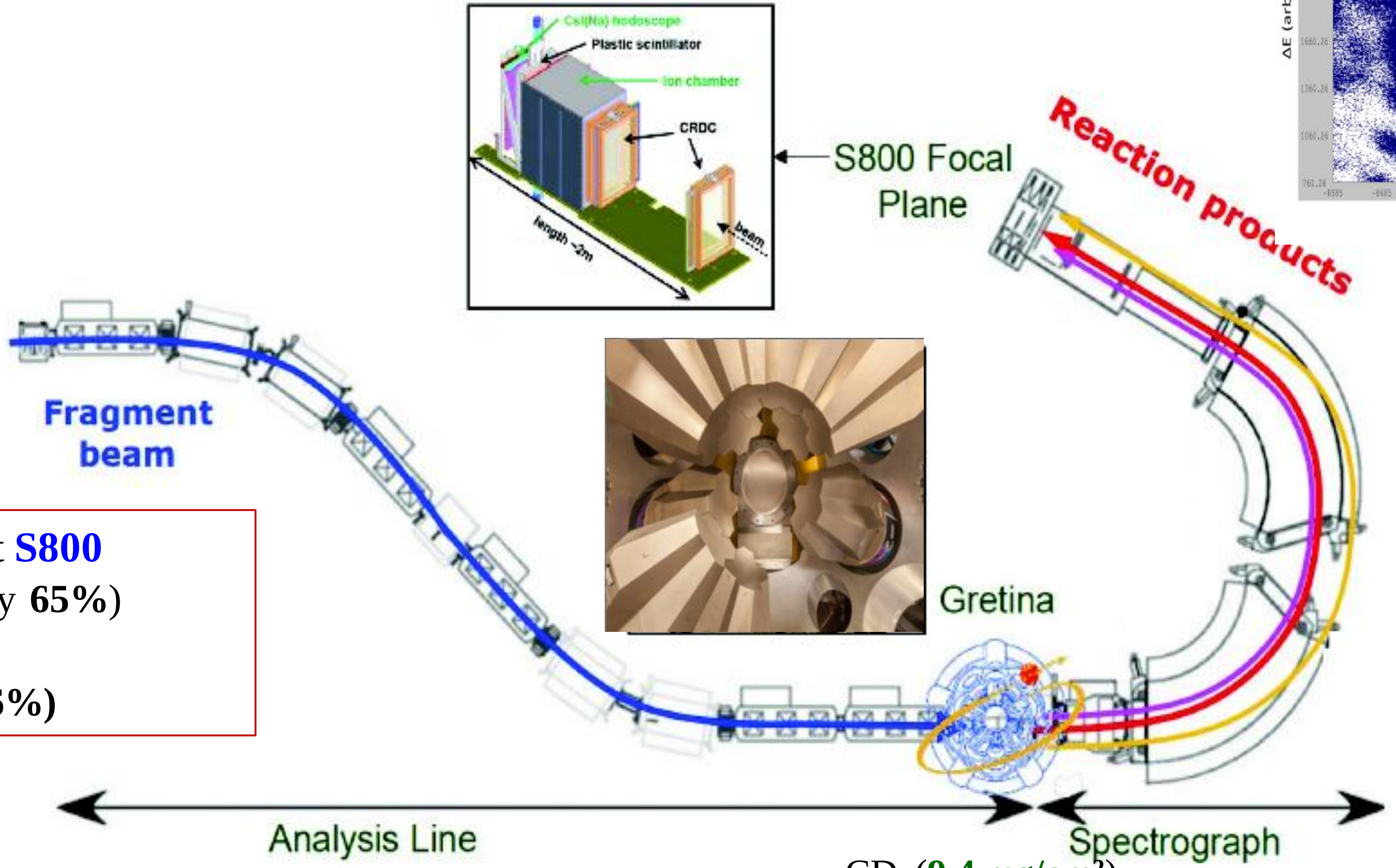
➢ Novel technique: (d,nγ) angle-integrated XS measurement (inspired from **Kankainen+ (2016) EPJ; d(^{26}Al,nγ)^{27}Si → C^{2}S$_p$**)

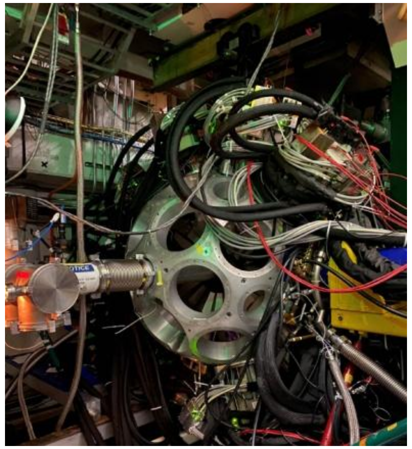
$$\omega\gamma = \frac{N_\gamma}{N_{target} I_{beam} \epsilon^{tot}_{det.} T_{UT}} \times \frac{\Gamma_p^{s.p.}}{\sigma^{DWBA}_{transfer}} \times \frac{(2J+1)}{(2j+1)(2J_{^{25}Al}+1)}.$$



GRETINA&S800@FRIB/ARIS

^{25}Al @ 24 MeV/u
Primary beam ^{28}Si@**10kW**
lowest energy ever used @ S800)
2× 10^6 pps, Purity >95%



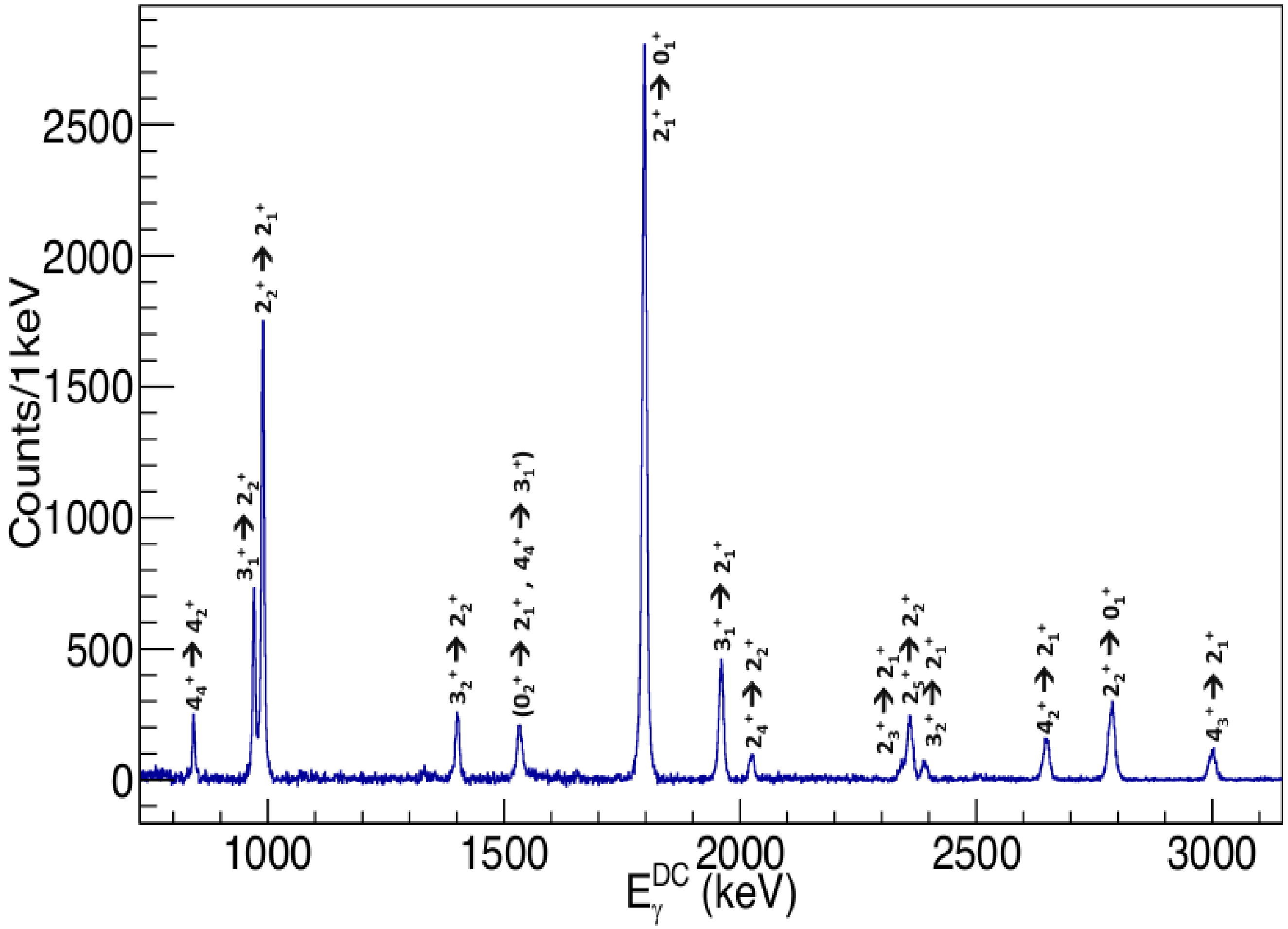


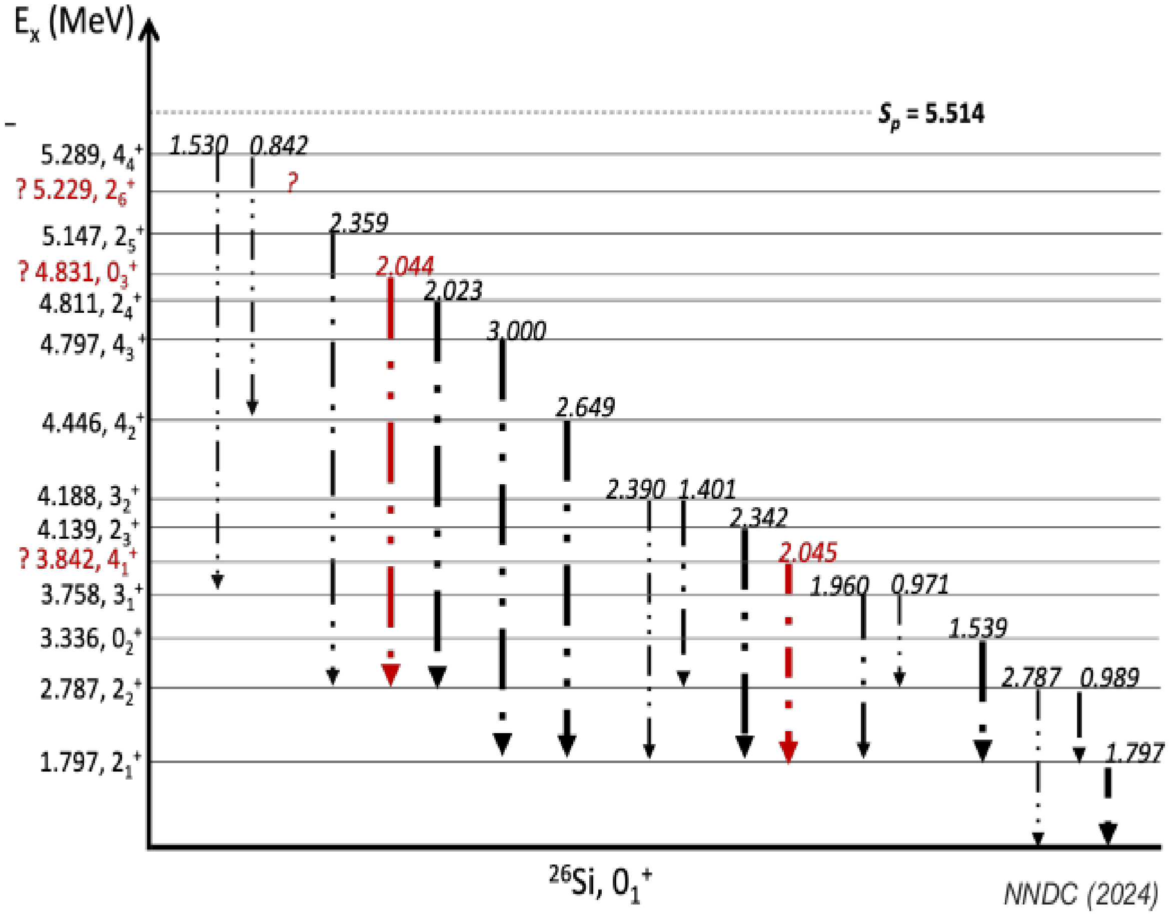
Measurements of ^{26}Si recoils at **S800**
(Transmission **56%**, FP efficiency **65%**)
in coincidence with
γ's in **GRETINA (**efficiency **4.6%)**

CD$_2$ (**9.4 mg/cm^2**)

$^{25}Al(p,\gamma)^{26}Si$ case: p-bound states in ^{26}Si

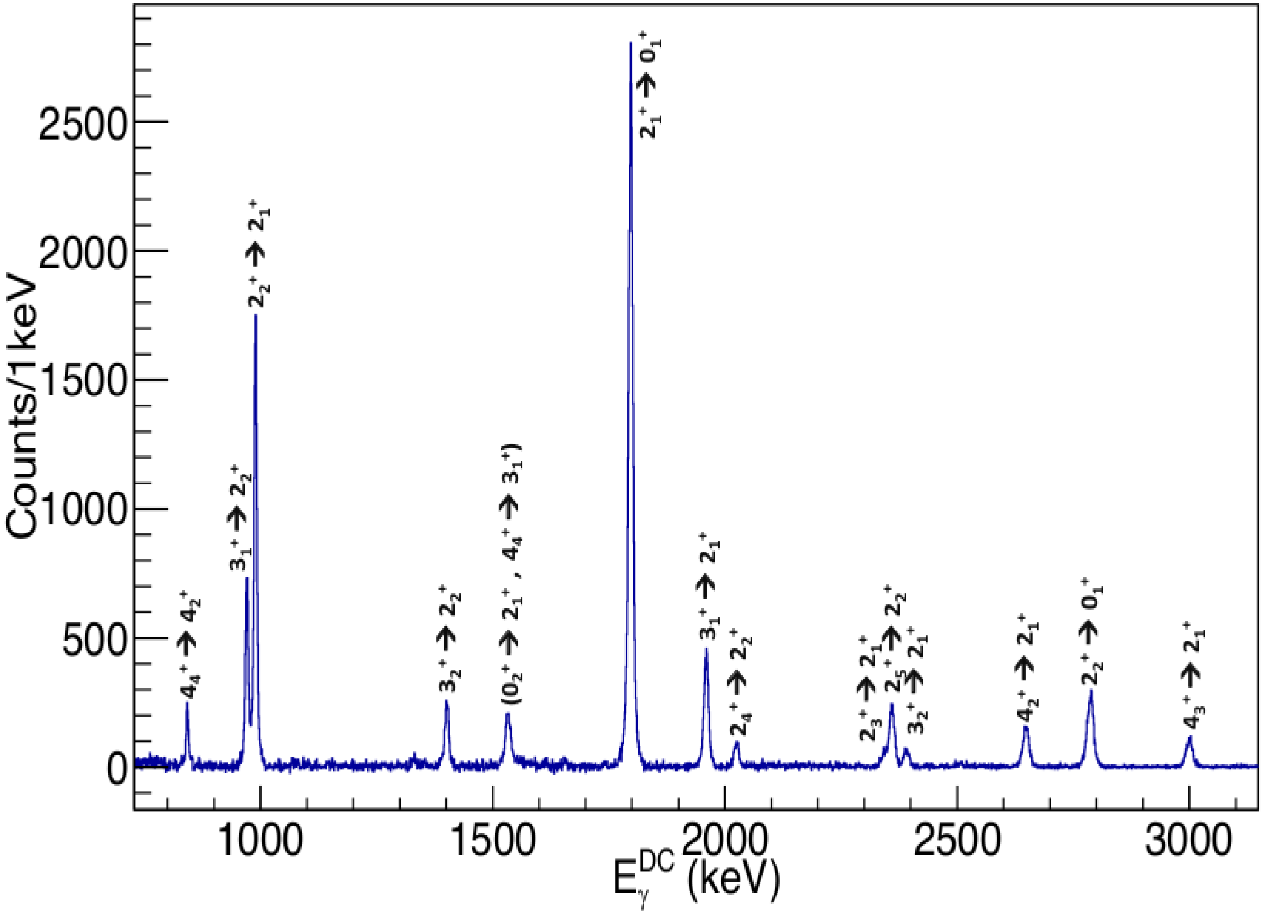
- γ-ray transitions of 11 states in ^{26}Si below S_p were observed among the 14 referenced



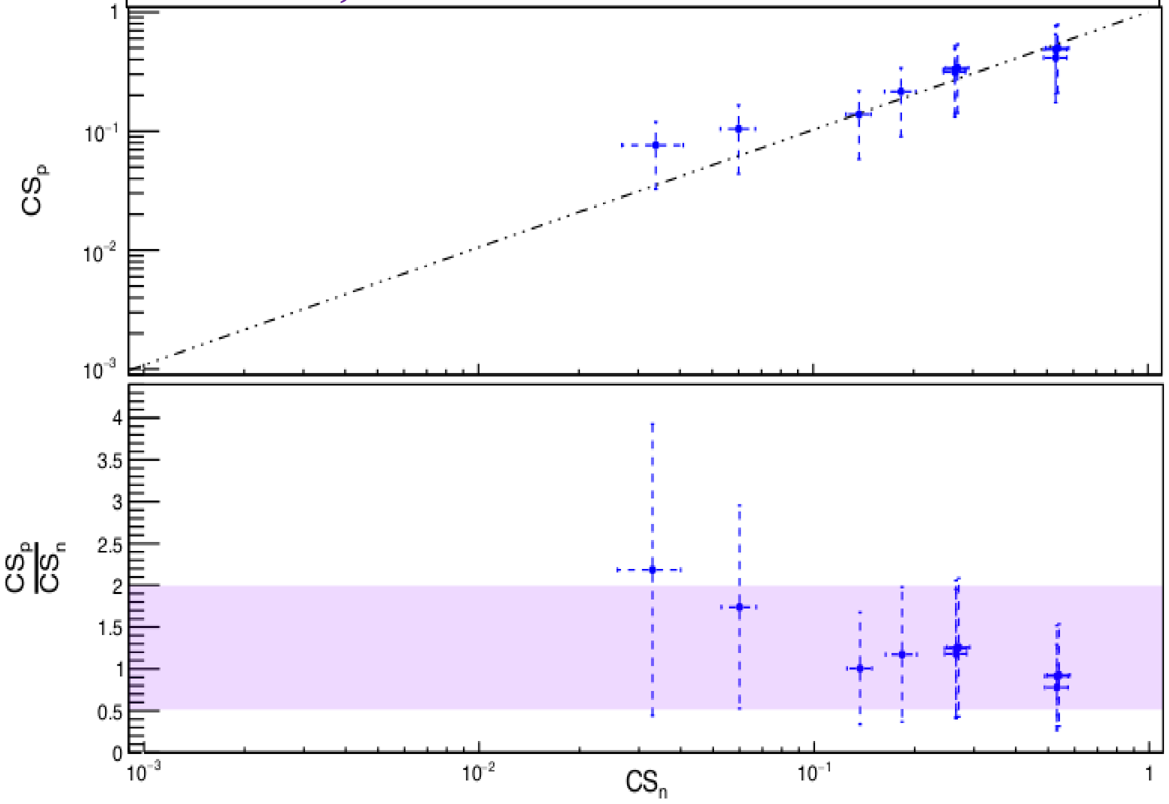


^{25}Al(p,γ)^{26}Si case: **Bound states**

➢ C^{2}Sp of the bound states in ^{26}Si determined for the 1st time ⇒ direct capture rate component of **^{25}Al(p,γ)^{26}Si**

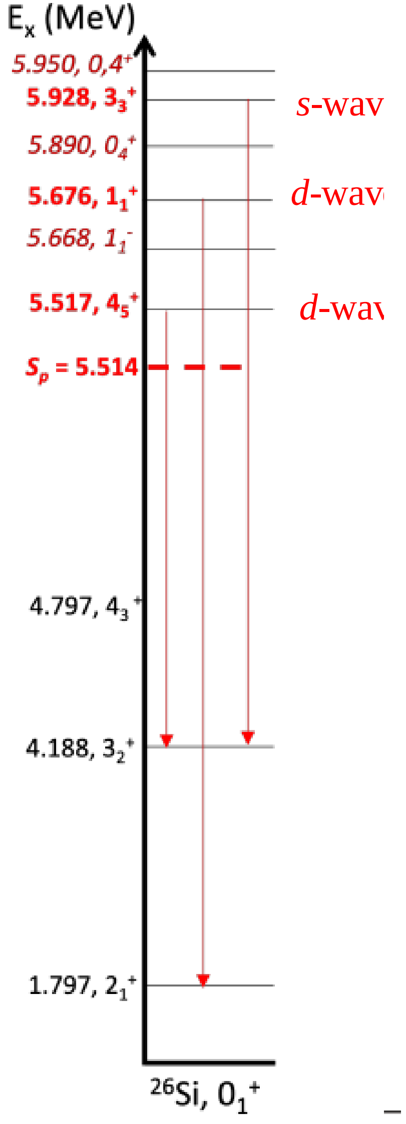


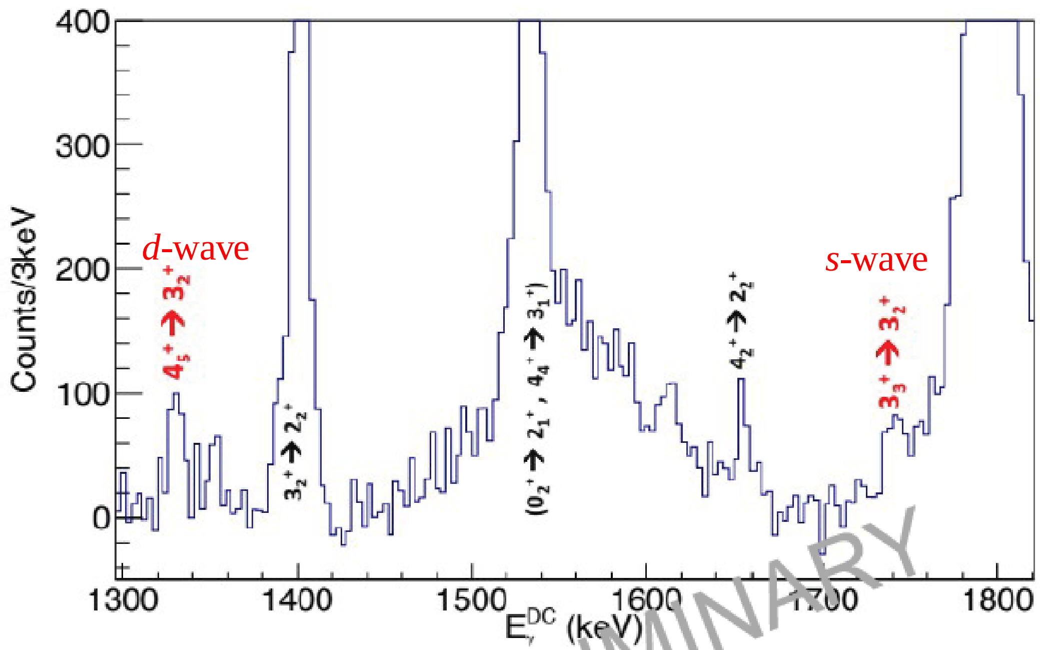
Comparison with few analog states in ^{26}Mg
Burlein+84, Arciszewski+84

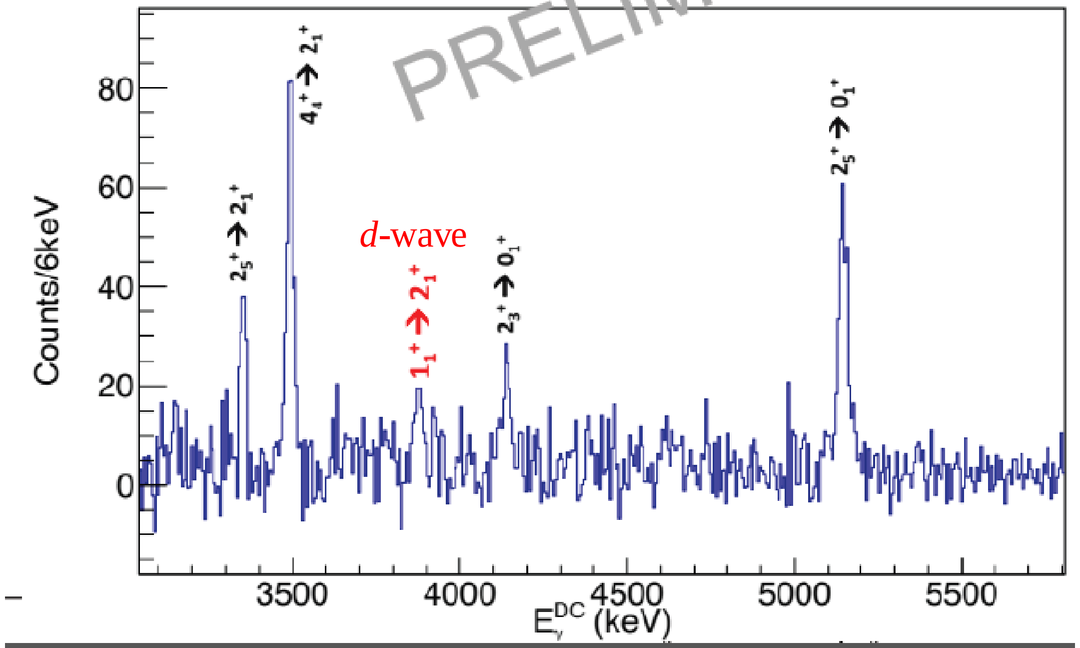


→ new data on ^{26}Mg: ALTO/SPILT-POLE experiment N. Giha et al.

$^{25}Al(p,\gamma)^{26}Si$ case: Resonant states







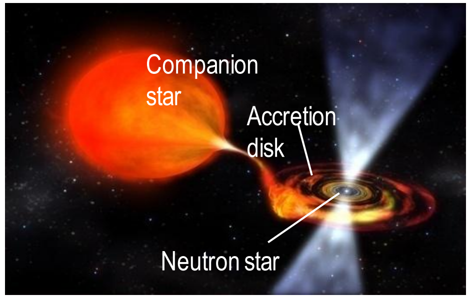
- Three resonant states of interest are identified in ^{26}**Si** ($>S_p$)
- **Resonance strength measurement (First time)**

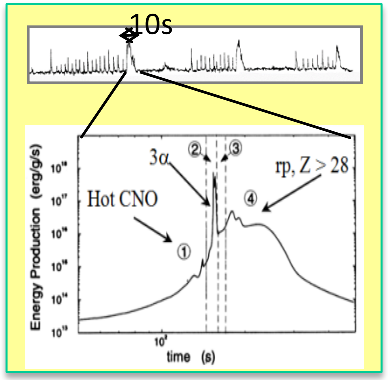
	5676 keV $\ell = 2$ 1_1^+	**5928 keV** $\ell = 0$ 3_3^+	
ωγ (meV)	$< 2.6 \times 10^{-6}$	$23(13)$	**Laird+ (2023)**
ωγ (meV)	$2(1) \times 10^{-6}$	$35(15)$	**Present work (preliminary)**

Next:

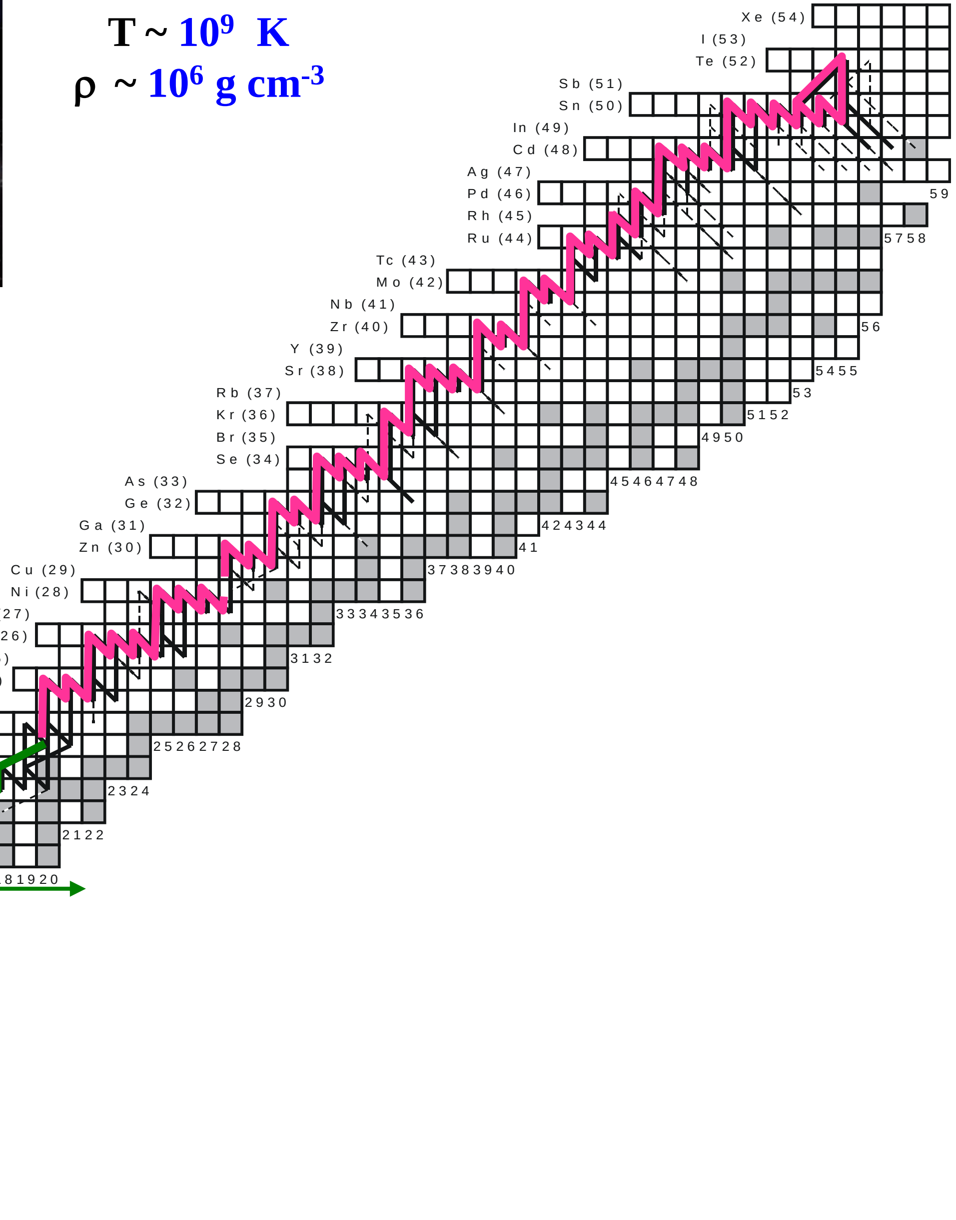
- Re-evaluation of $^{25}Al(p,\gamma)^{26}Si$ rate
- Constrain novae contribution to ^{26}Al galactic amount

Case II: $^{15}O(\alpha,\gamma)^{19}Ne$ & X-ray burst nucleosynthesis





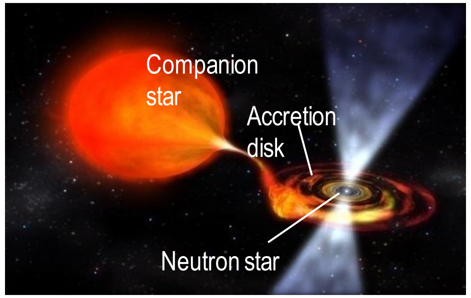
$T \sim 10^9$ K
$\rho \sim 10^6$ g cm^{-3}

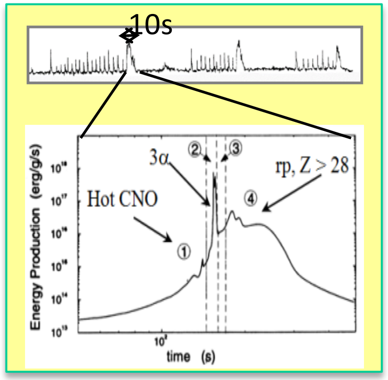


Courtesy to H.Schatz

- Triggered by $3\alpha \rightarrow {}^{12}C$ reaction & Hot CNO break-out
- (α,p) process: $(\alpha,p)(p,\gamma)$ - Up to A< 60
- rp-process: (p,γ) & β+ decay up to A ~80 -100

Case II: $^{15}O(\alpha,\gamma)^{19}Ne$ & X-ray burst nucleosynthesis





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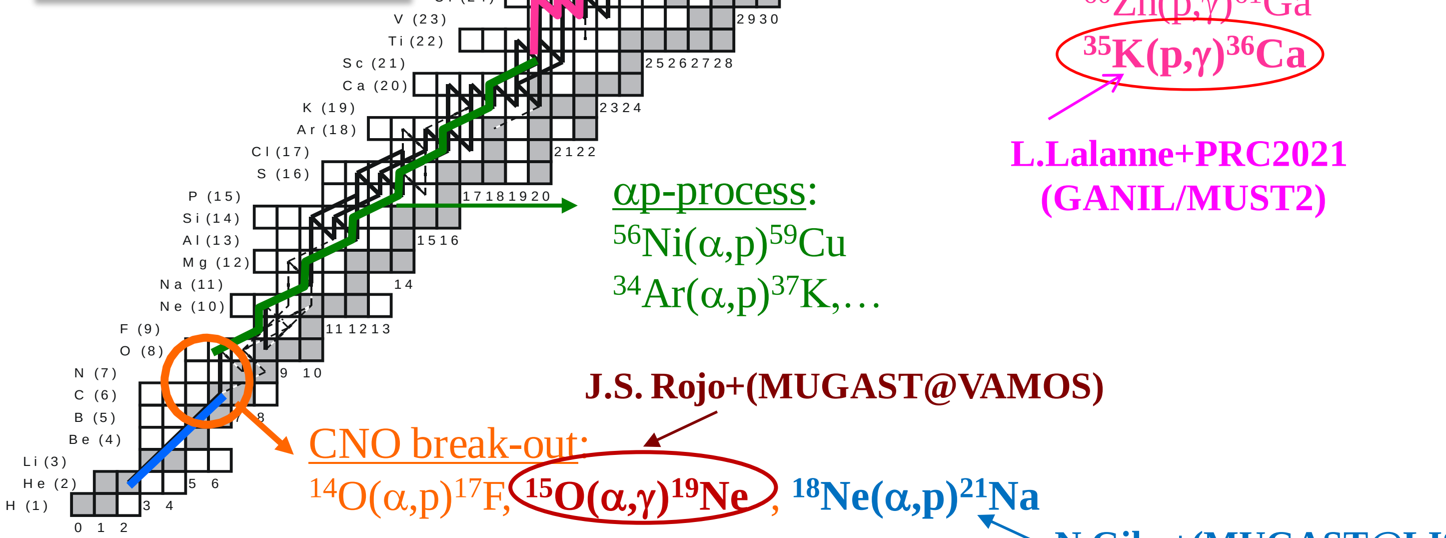


Courtesy to H.Schatz

αp-process:
$^{56}Ni(\alpha,p)^{59}Cu$
$^{34}Ar(\alpha,p)^{37}K$,…

rp-process:
$^{59}Cu(p,\gamma)^{60}Zn$
$^{60}Zn(p,\gamma)^{61}Ga$
$^{35}K(p,\gamma)^{36}Ca$

L.Lalanne+PRC2021 (GANIL/MUST2)

J.S. Rojo+(MUGAST@VAMOS)

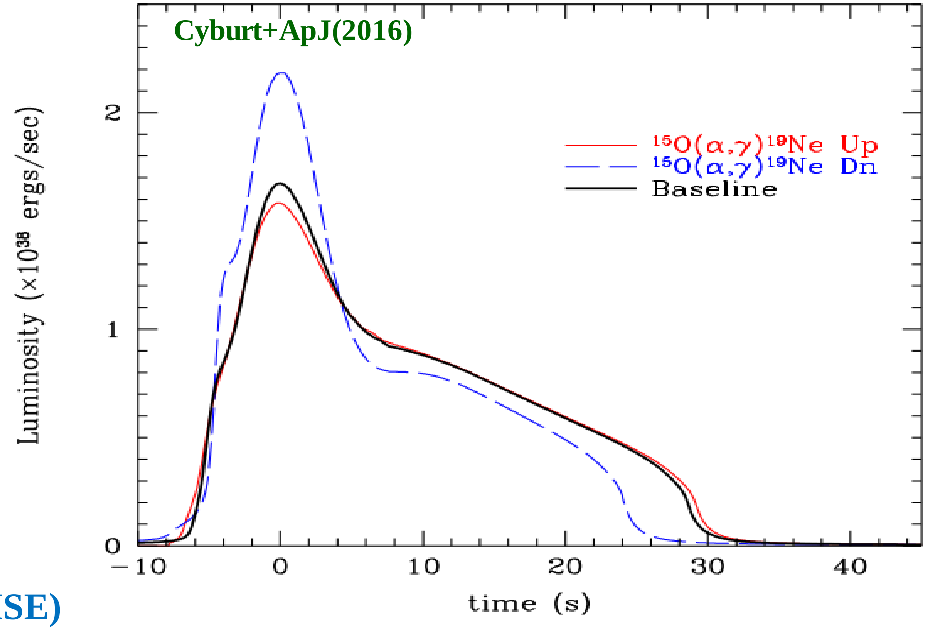
CNO break-out:
$^{14}O(\alpha,p)^{17}F$, $^{15}O(\alpha,\gamma)^{19}Ne$, $^{18}Ne(\alpha,p)^{21}Na$

N.Giha+(MUGAST@LISE)

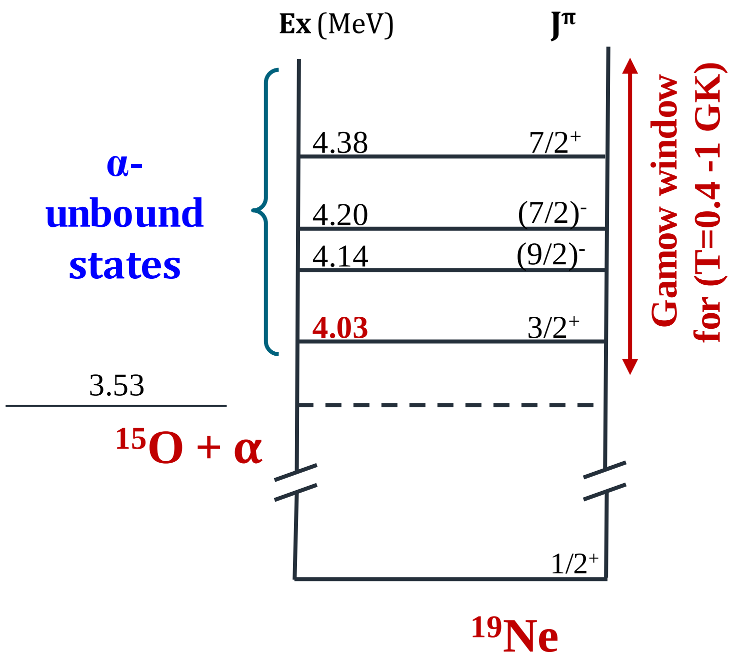
- Triggered by $3\alpha \rightarrow {}^{12}C$ reaction & Hot CNO break-out
- (α,p) process: $(\alpha,p)(p,\gamma)$ - Up to A< 60
- rp-process: (p,γ) & β+ decay up to A ~80 -100

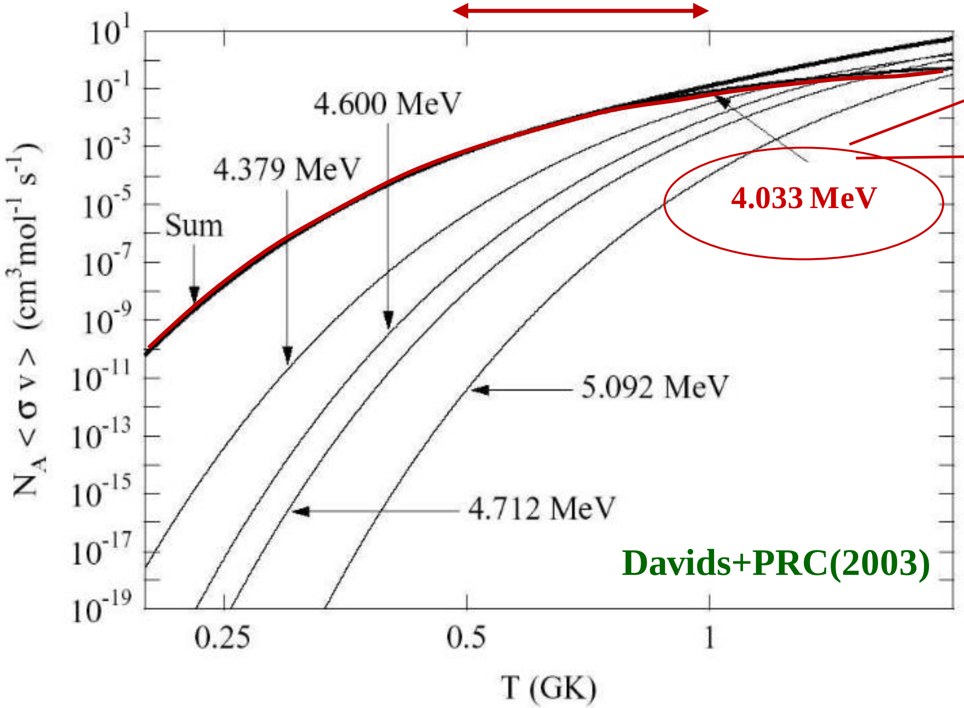
Sensitivities studies: **Cyburt+(2016) , A. Parikh+ (2013)**

- Strong impact of $^{15}O(\alpha,\gamma)^{19}Ne$ on total luminosity
  - Regulates flow between HCNO cycle and rp-process
  - Drives X-ray burst energy and light curves.



$^{15}O(\alpha,\gamma)^{19}Ne$: Present Status & strategy





- Biggest contribution to $N_A\langle\sigma v\rangle$
  E_R= 500 keV, J=3/2$^+$, lα=1
  $\rightarrow \omega\gamma_\alpha \approx 0.5 \times (2J_R+1) \times \Gamma_\alpha$

- Direct measurement very challenging → Small cross section & radioactive nuclei ($T_{1/2}(^{15}O)$=122 s)

- Previous determinations of Γ_α → combined measurements of α–branching ratio B_α and state lifetime $\tau \propto 1/\Gamma$

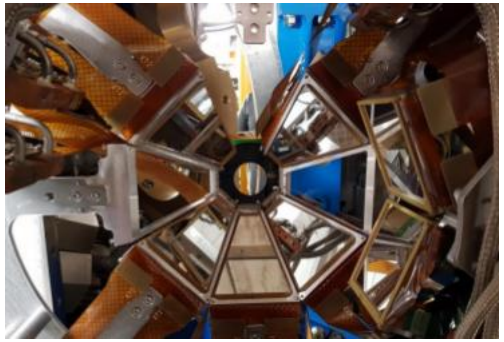
$$\Rightarrow \quad \Gamma_\alpha = \frac{\Gamma_\alpha}{\Gamma} \times \Gamma = B_\alpha \times \Gamma$$

- Γ_α =17±13 μeV with B_α consistent with zero at 90% confidence Tan+(2009)
- Γ_α = 24±18 μeV with combining τ's measurements Fortune+(2010)

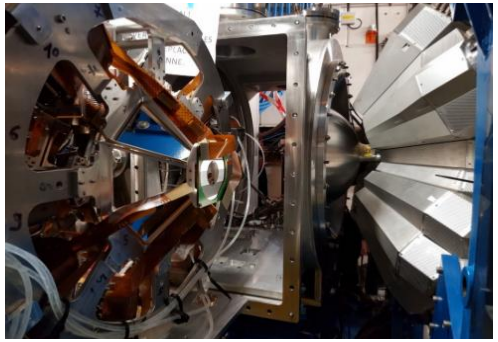
- Determine Γ_α → via C^2S_α measurement using via $^{15}O(^7Li,t)^{19}Ne$ transfer reaction in **inverse kinematics**

$^{7}Li(^{15}O,t)^{19}Ne^{*}(\gamma)^{19}Ne$ @ SPIRAL1/GANIL

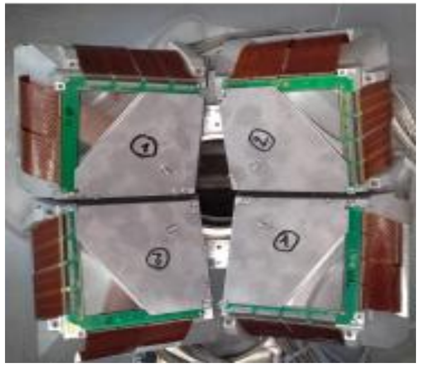
J.Sanchez Rojo et al.



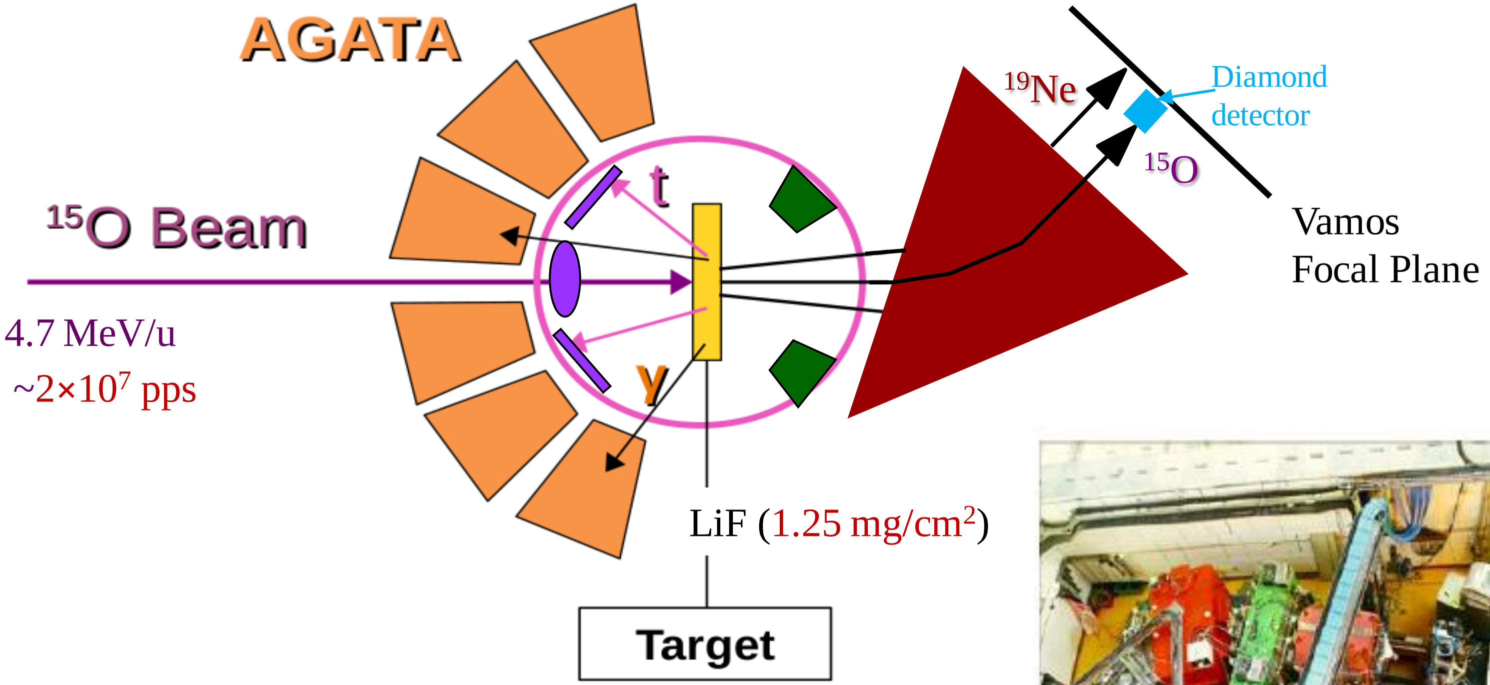
MUGAST
- DSSD 500 μm
- Trapezoid (5)
- Annular (1)
- Square shapes (2)
- 128 + 128 strips



AGATA @ 18 cm
- 45 HPGe
- E(1 MeV) ~8% w/add-back



MUST2
- DSSSD 300 μm+CsI
- 128 +128 strips
- 10 × 10 cm^2



VAMOS @ 0°

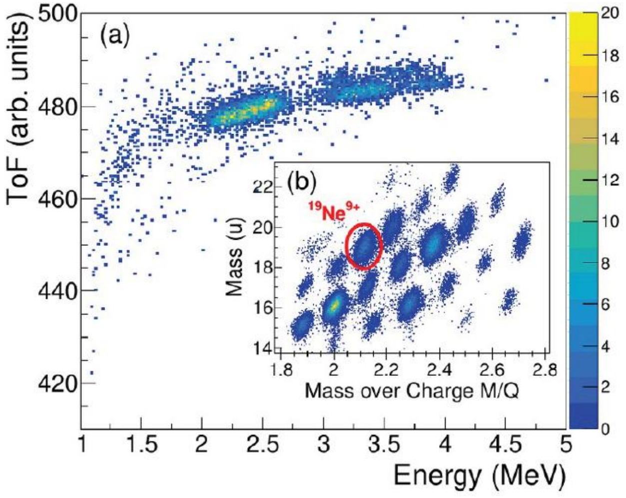
$\Delta\Theta \pm 7°$
$\Delta B\rho \pm 5\%$

➤ **Triple coincidence:**

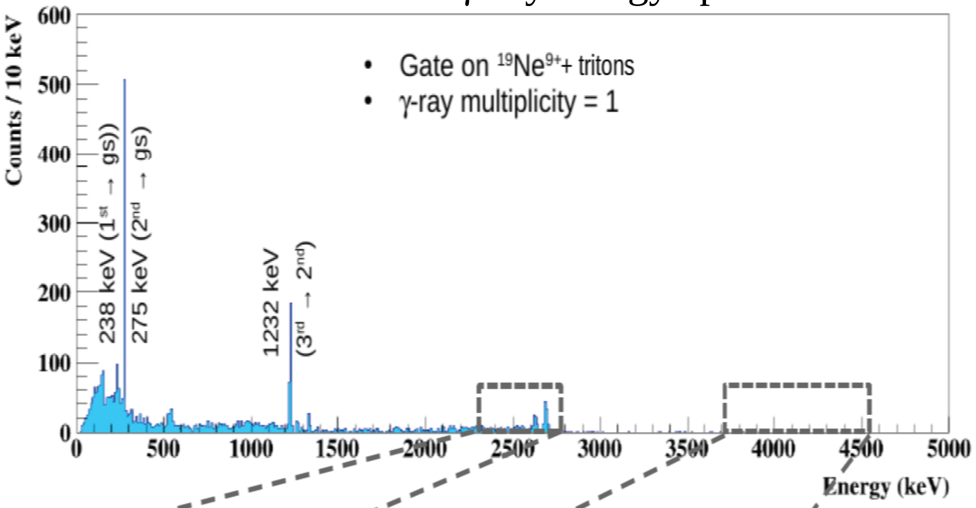
AGATA – HPGe for **prompt-γ** &
MUGAST-DSSDE for light particle t &
VAMOS-Spectrometer for ^{19}Ne recoil

$^{15}O(\alpha,\gamma)^{19}Ne$ case: Experiment & results

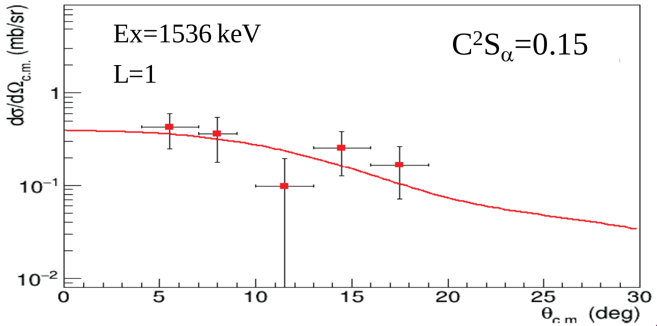
VAMOS & MUGAST PID

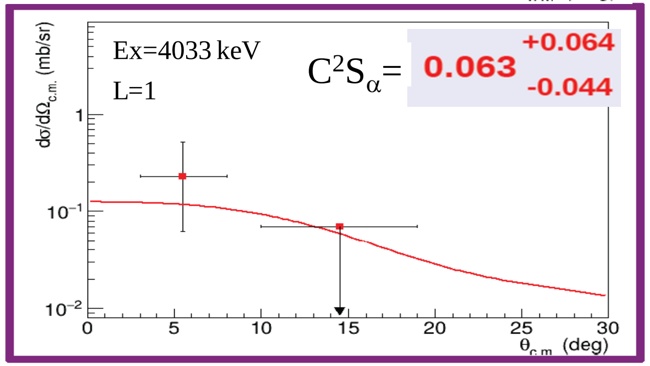


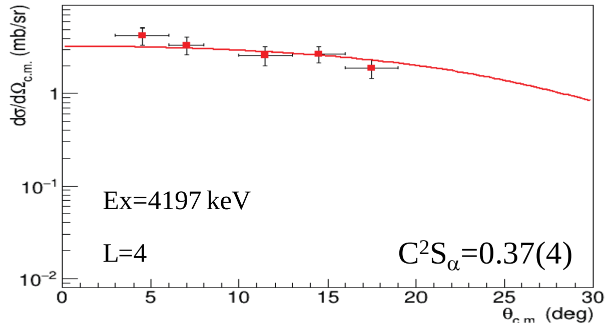
AGATA γ-ray energy spectrum



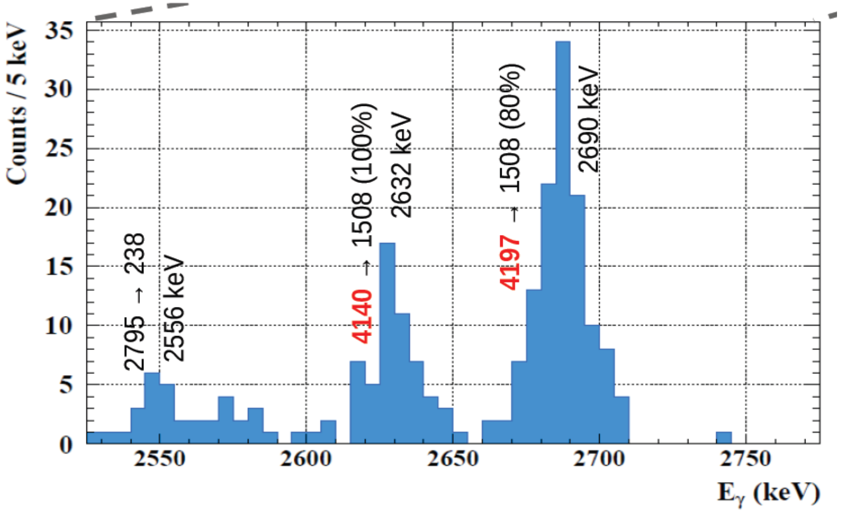
Angular distributions & FR-DWBA calculations



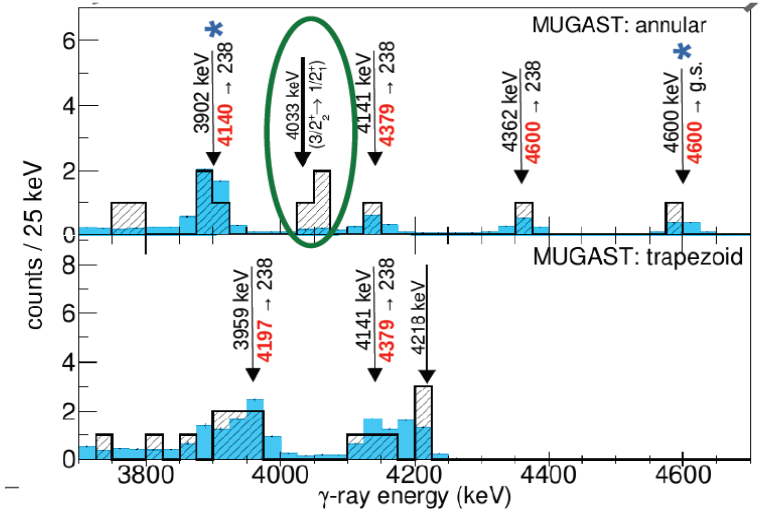




γ-ray transitions from the doublet @ **4140 & 4197 keV**



Observation of **4033 keV→g.s** transition



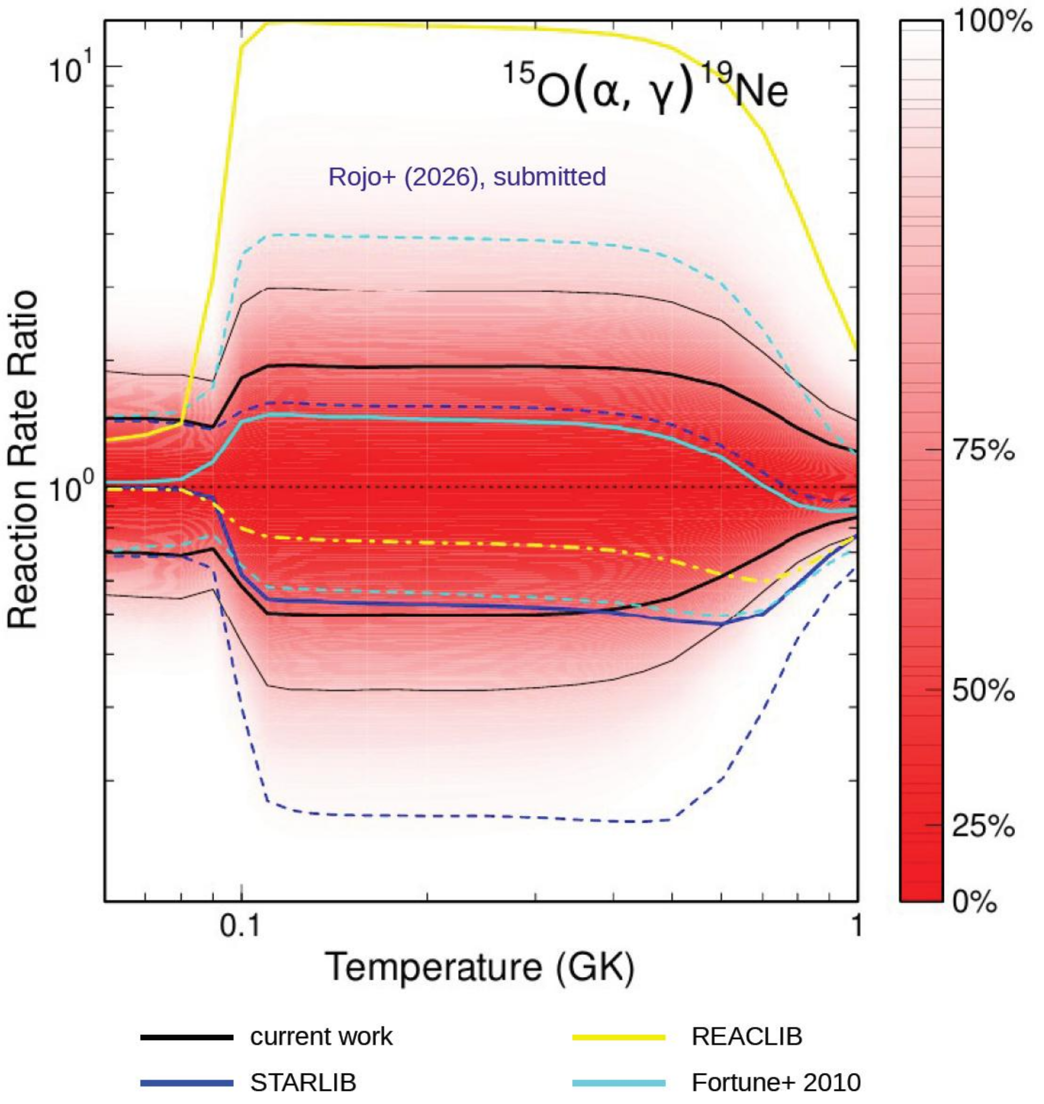
- ➢ Good agreement(within a factor 2) with analog states in ^{19}F
- ➢ Small C^2S_α for the 4033 keV state

$^{15}O(\alpha,\gamma)^{19}Ne$ case: Updated reaction rate

Alpha particle width: $C^2S_\alpha \rightarrow \Gamma_\alpha = 2P_l \frac{\hbar^2 R}{2\mu} C^2 S_\alpha |\phi(R)|^2$

	Present work		Tan+ (2009)			Fortune+ (2010)	
E_x (keV)	Γ_α (μeV)	B_α (x 10^{-4})	Γ_α (μeV)	B_α (x 10^{-4})	τ (fs)	Γ_α (μeV)	τ (fs)
4033	$11.2^{+10.9}_{-5.9}$		**17 (13)**	2.9 (2.1)	13^{+9}_{-6}	**24 (18)**	7.9 (1.5)
4140	0.93 (13)	0.3	**44 (20)**	12 (5)	18^{+2}_{-3}		
4197	11.7 (1.1)	8.2	**18 (9)**		43^{+12}_{-9}		

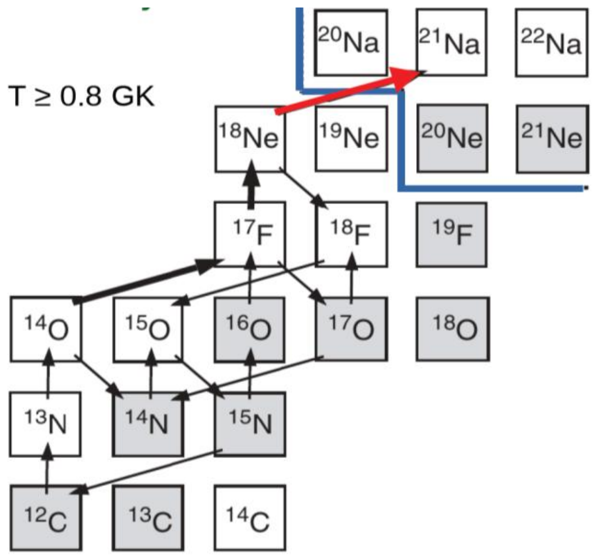
- ➢ Good agreement with literature
  - → Γ_α(4033 keV) determined from a single experiment
  - → Γ_α of the 4140 & 4197 keV doublet determined for each component



- ➢ Present recommended rate compatible with previous rates
- ➢ Rate uncertainty (68% coverage) is 2 times smaller than the spread of existing rates

Perspectives: X-ray burst nucleosynthesis

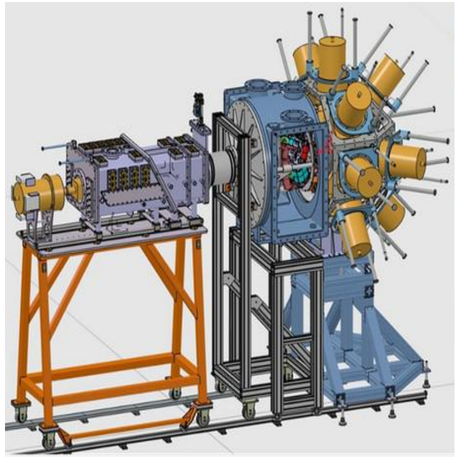
- The $^{18}Ne(\alpha,p)^{21}Na$ break out reaction from hot CNO cycle



Strategy: Resonance strength: $\omega\gamma = \omega \frac{\Gamma_\alpha \Gamma_p}{\Gamma} = \omega \Gamma_\alpha \times BR_p$

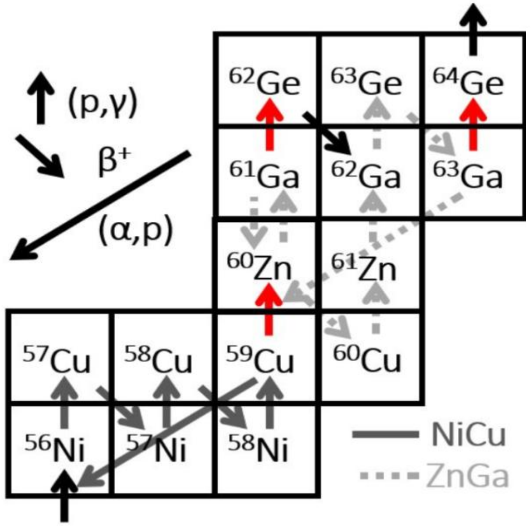
- Γ_α from (^{7}Li,t) α-transfer reaction
- BR_p from proton decay measurement
- p_0 vs p_1 decay from $^{21}Na^*$ prompt γ-ray decay

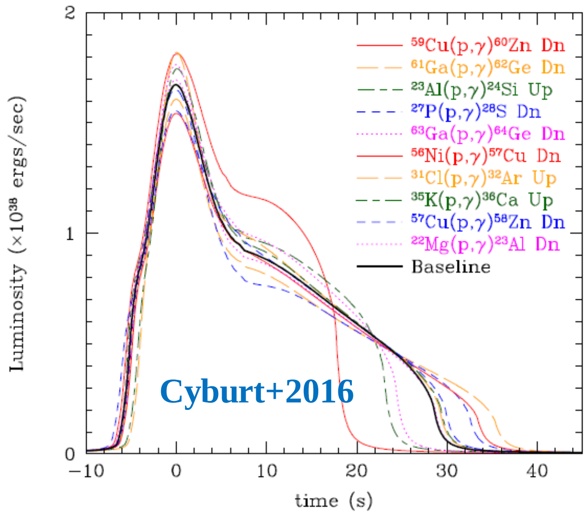
→ Experiment using MUGAST + EXOGAM + ZDD @ LISE/GANIL & ^{18}Ne SPIRAL1 beam



- Successful commissioning in 2026
- Experiment scheduled in 2027

- The $^{59}Cu(p,\gamma)^{60}Zn$ reaction & the NiCu cycle





Strategy: Resonance strength from (d,nγ) angle integrated cross-section method

$$\omega\gamma = \omega \times \frac{\Gamma_{s.p.}}{\sigma_{DWBA}} \times \frac{N_\gamma}{N_{target} I_{beam} \Delta t}$$

→ $^2H(^{59}Cu,n\gamma)^{60}Zn$ using ^{59}Cu SPIRAL1 beam @ 5 AMeV with AGATA @ VAMOS

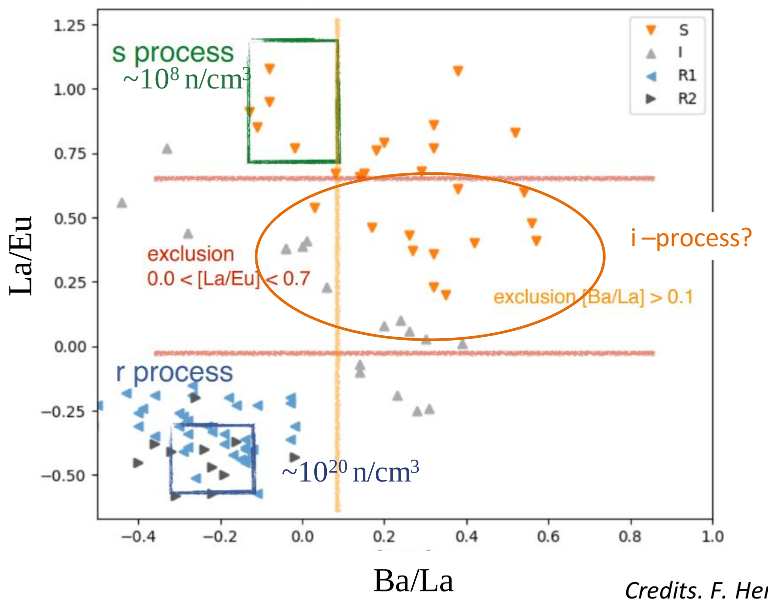
\+ decay scheme from complementary fusion-evaporation experiment with AGATA @ Legnaro

Perspectives: i-process

Intermediate neutron capture process (*i*-process)

- Needed to explain some CEMP-r/s stars ([C/Fe]>1 objects) observations
- Neutron density: 10^{13}-10^{15} cm^{-3} & neutron source: $^{13}C(\alpha,n)^{16}O$ reaction
- Site candidates: Low-Z AGB stars, Post-AGB stars, Rapidly accreting WDs,…

JINAbase observations (Abohalima & Frebel APJs 2018)

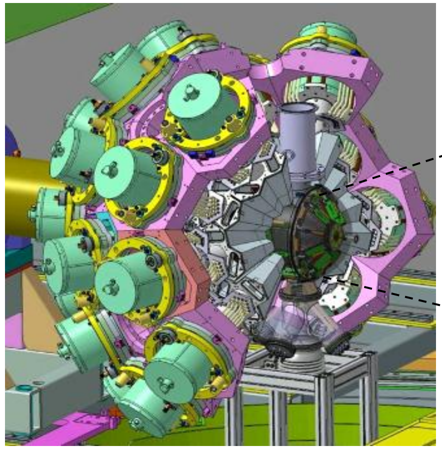


Credits. F. Herwig

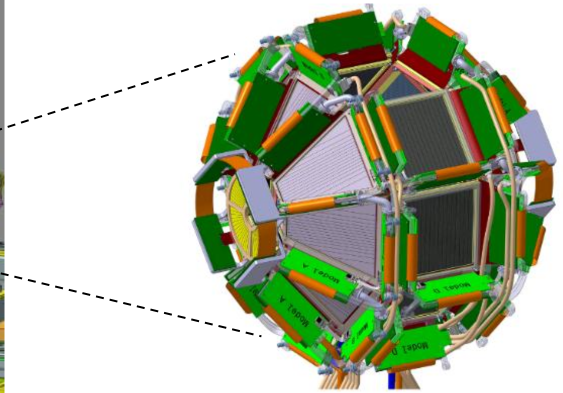
- Sensitivity studies in RAWD **Denissenkov et al, MNRAS (2021)** → (n,γ) cross-sections on **^{135}I, ^{137}Xe, ^{136,137}Cs, $^{140-141}$Ba,…** have strong impact on La/Eu and Ba/La ratios & *i*-process understanding

Experimental approach (indirect): (Long term future)

- **(d,pγ) surrogate method** to deduce the (n,γ) cross-section
- **GRIT-AGATA @ SPES** → radioactive beams (> 10^6 pps) at intermediate energies (~ 10 MeV/u)



AGATA



GRIT

Collaboration

Angle-integrated measurement of the $d(^{25}\text{Al},n\gamma)^{26}\text{Si}$ transfer reaction to probe resonance strengths in $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ relevant for the production of ^{26}Al in novae
FRIB experiment with GRETINA - S800

C. Fougères[1,2], F. Hammache[3], F. de Oliveira Santos[4], N. de Séréville[3], C. Benetti[5], A. Gade[5], S. Gillespie[5], J. Swartz[5], J. Pereira[5], D. Weisshaar[5], S. M. Ali[5], H. Arora[5], M. L. Avila[1], L. Balliet[5], K. Bhatt[1], T. Beck[5], S. Ahn[6], J. Chung-Jung[5], L. Dienis[4], P. Farris[5], V. Girard-Alcindor[3], S. Giraud[5], J. Huffman[5], H. Jacob[3], D. Kim[6], M. Kuich[5], C. Maher[5], F. Montes[5], C. Müller-Gatermann[1], D. Neto[7], M. Portillo[5], B. M. Sherrill[5], O. B. Tarasov[5], A. Tumino[8], and R. Zegers[5]

Measurement of the $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ X-ray burst trigger reaction through first α particle-transfer reaction onto an exotic ion beam

J.S. Rojo,[1,2] N. de Séréville,[3] P. Adsley,[4,5] C.Aa. Diget,[1] A. M. Laird,[1] M. Assié,[3] E. Clément,[6] A. Lemasson,[6] D. Ramos,[6] F. Galtarossa,[7] A. Matta,[8] V. Girard-Alcindor,[6,3] J. José,[9] M. L. Avila,[10] D. Barrientos,[11] B. Bastin,[6] D. Beaumel,[3] M. A. Bentley,[1] G. Benzoni,[12] Y. Blumenfeld,[3] A. Bracco,[12,13] S. Brambilla,[12] W. Catford,[14] B. Cederwall,[15] S. Chen,[1] M. Ciemala,[16] F. Delaunay,[8] F. Didierjean,[17] G. Duchêne,[17] J. Dudouet,[17] J. Eberth,[18] F. Flavigny,[8] C. Fougères,[6] G. de France,[6] S. Franchoo,[3] A. Gadea,[19] J. Gibelin,[8] A. Gillibert,[20] V. González,[21] A. Gottardo,[7] F. Hammache,[3] L. J. Harkness,[22] H. Hess,[18] A. Jungclaus,[23] N. Jovancevic,[3] M. Labiche,[24] L. Lalanne,[3] S. Leblond,[6] S. M. Lenzi,[25,26] S. Leoni,[12,13] J. Ljungvall,[3] A. Lohstroh,[27] A. Lopez-Martens,[3] A. Maj,[16] R. Menegazzo,[25] D. Mengoni,[26,25] B. Million,[12] D. R. Napoli,[7] J. Nyberg,[28] F. de Oliveira-Santos,[6] Zs. Podolyak,[14] A. Pullia,[12,13] B. Quintana,[29] D. Ralet,[6] C. Reardon,[1] F. Recchia,[25,26] P. Reiter,[18] K. Rezynkina,[7,17] M. D. Salsac,[20] E. Sanchis,[21] M. Şenyiğit,[30] M. Siciliano,[7,20,31] J. Simpson,[24] D. Sohler,[32] I. Stefan,[3] O. Stezowski,[33] J. J. Valiente-Dobón,[19,7] D. Verney,[3] and M. Zielińska[20]

Submitted to PRL

THANK YOU

For

Your attention

Accessing $\omega\gamma$ via angle-integrated measurement

$$\omega\gamma = \frac{(2J+1)}{(2j+1)(2J_{^{25}Al}+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}$$

Extension of recent method to measure C^2S_p (NSCL) via $d(^{26}\mathrm{Al},n\gamma)^{27}\mathrm{Si}$ *Kankainen, EPJ **52** (2016)*

Direct transfer $d(^{25}\mathrm{Al},n\gamma)^{26}\mathrm{Si}$

Tagging of $^{26}\mathrm{Si}^*$ on γ-ray transitions → angle-integrated measurement of cross-section $\sigma_{\mathrm{transfer}}$

$$\mathrm{N}_\gamma = \boxed{\mathrm{BR}_\gamma} \times \boxed{\sigma^{\mathrm{exp}}_{\mathrm{transfer}}} \times \epsilon^{\mathrm{tot}}_{\mathrm{det.}} \mathrm{N}_{\mathrm{target}} \mathrm{I}_{\mathrm{beam}} \mathrm{T}_{\mathrm{UT}}$$

$$\mathrm{BR}_\gamma \rightarrow \frac{\Gamma_\gamma}{\Gamma_{\mathrm{tot}}}$$

$$\sigma^{\mathrm{exp}}_{\mathrm{transfer}} \rightarrow \boxed{C^2S_p} \times \boxed{\sigma^{\mathrm{DWBA}}_{\mathrm{transfer}}} \rightarrow \text{FRESCO code}$$

$$C^2S_p \rightarrow \frac{\Gamma_{\mathrm{p}}}{\boxed{\Gamma^{\mathrm{s.p.}}_{\mathrm{p}}}} \rightarrow \text{DWU code}$$

$$\omega\gamma = \frac{\mathrm{N}_\gamma}{\mathrm{N}_{\mathrm{target}} \mathrm{I}_{\mathrm{beam}} \epsilon^{\mathrm{tot}}_{\mathrm{det.}} \mathrm{T}_{\mathrm{UT}}} \times \frac{\Gamma^{\mathrm{s.p.}}_{\mathrm{p}}}{\sigma^{\mathrm{DWBA}}_{\mathrm{transfer}}} \times \frac{(2J+1)}{(2j+1)(2J_{^{25}Al}+1)}$$

Uncertainties = systematic $\lesssim 30\%$ (from optical potentials) & statistical $(1/\sqrt{N_\gamma})$