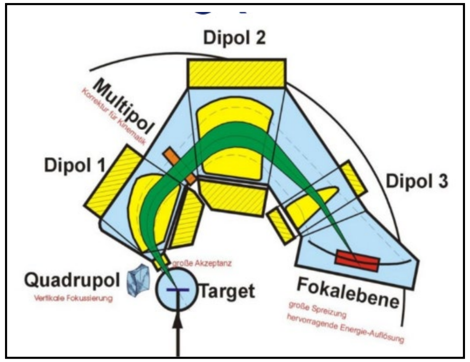
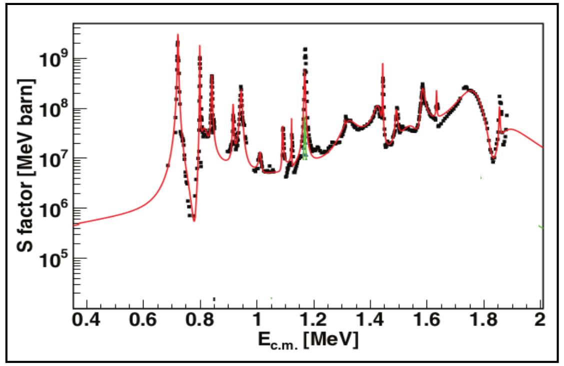
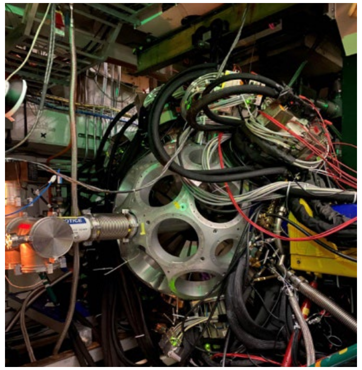
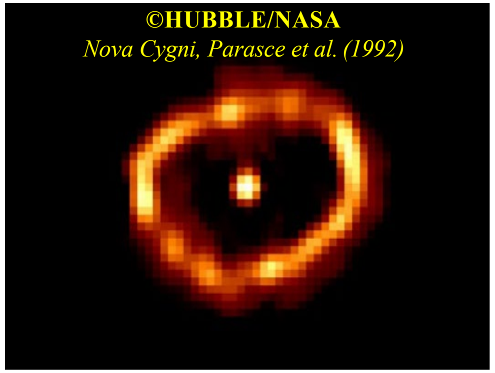








Recent reaction studies of astrophysical interest using transfer reactions

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

EUROPEAN NUCLEAR PHYSICS CONFERENCE 2025 **Caen, 22-26 September 2025**

Reaction cross sections in stellar environments

- **Reactions in quiescent burning stages :**

→ T ~ 0.001 -0.1 GK

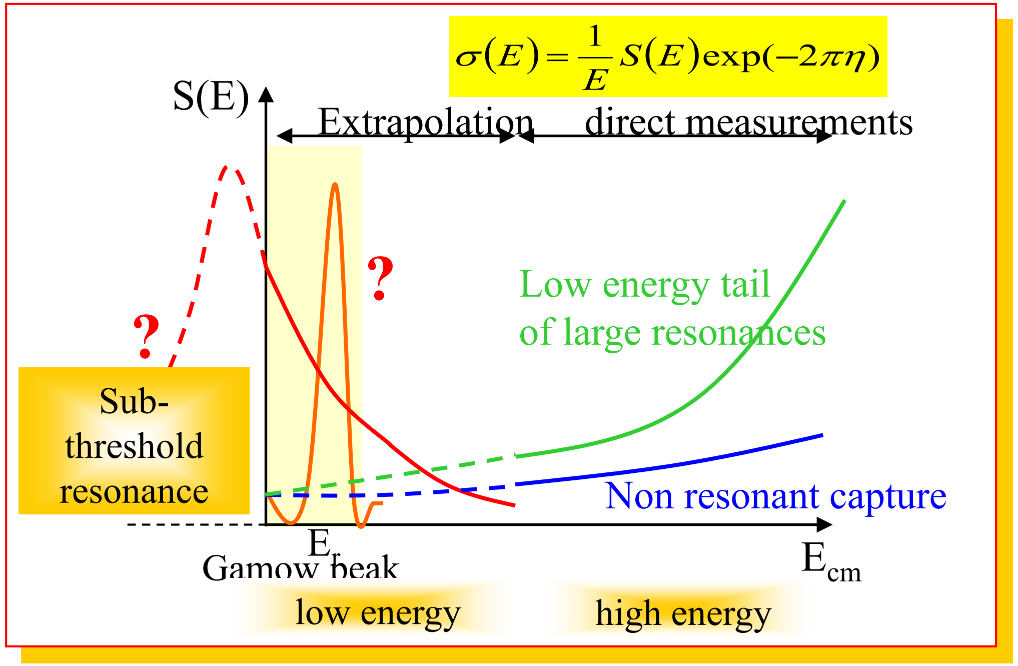
→ tens keV- MeV << Coulomb barrier E_C

→ σ(E) very weak (0.01 fb- ~100 pb)

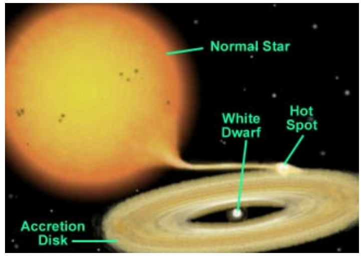
→ Direct measurements are very challenging

→ Often *σ(E)* measured at high energies then extrapolated at stellar energies

↳ what about **resonances** at very low energy & sub-threshold resonances



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



→ T=0. 1-2 GK

→ hundreds keV- few MeV

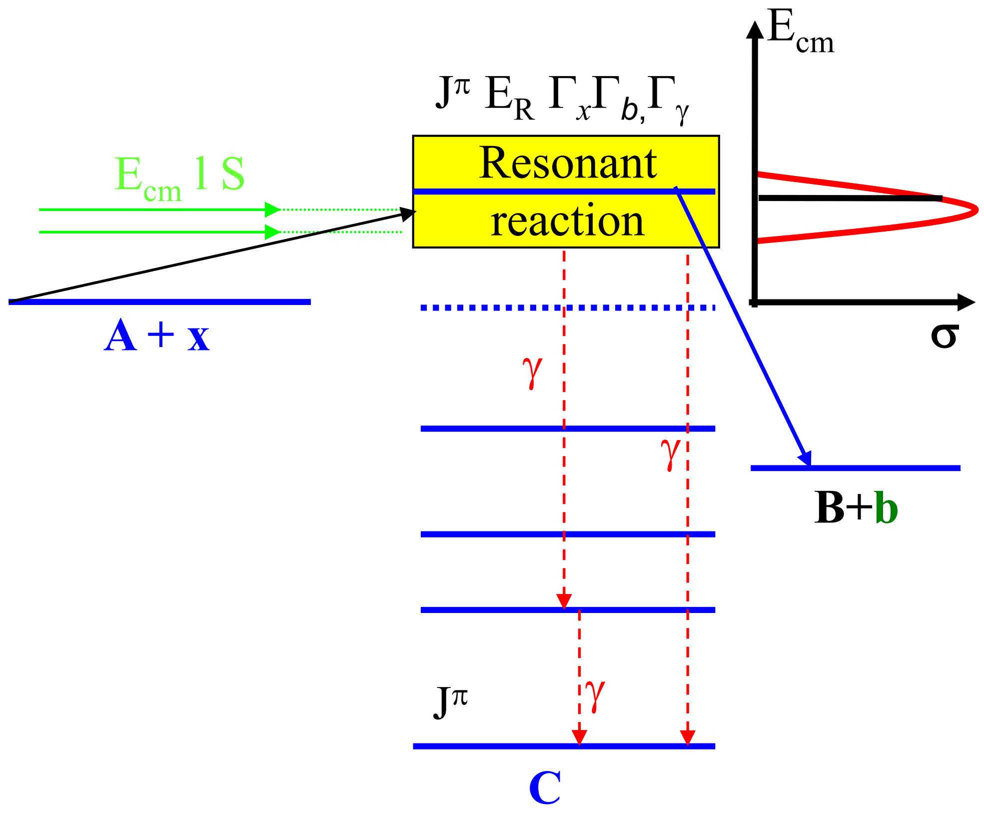
→ σ dominated by **resonances**

→ radioactive nuclei : Low beam intensities ($\sim 10^5$-10^7 p/s) for short lived nuclei, few atoms/cm^2 in targets for longed lived ones

↳ Direct measurements challenging

Ingredients needed to evaluate resonant σ & $N_A\langle\sigma v\rangle$

A+x→C*→B+γ or A+x→C*→B+b



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

$y = b \text{ or } \gamma$

For narrow resonance cases :

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

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

- The resonant reaction rates can be calculated if the resonant parameters (E_R, J^π, $\Gamma_{x,y}$, Γ,...) are known

↓

Transfer reactions can be used to extract these spectroscopic information

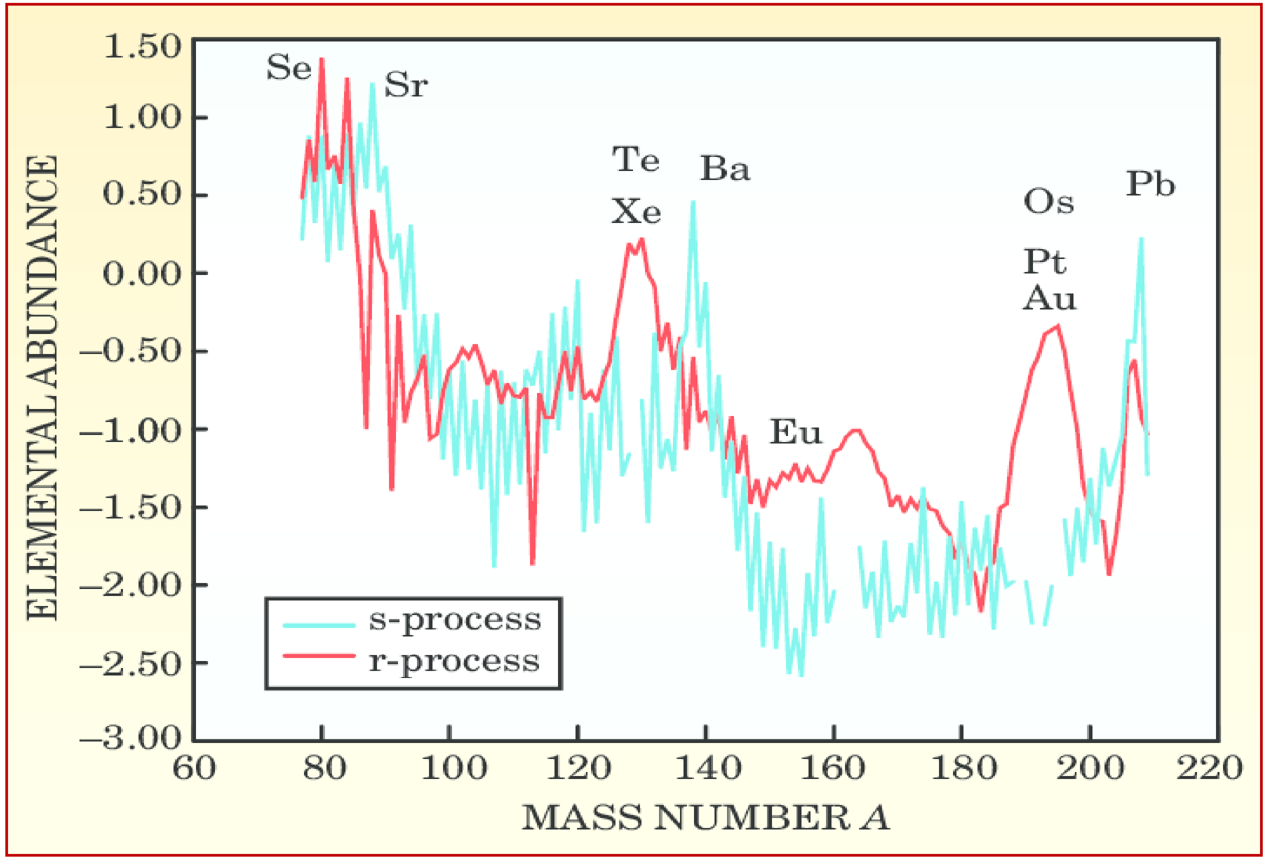
- $E_R = E_x - Q$ is the resonance energy
- Γ_x, Γ_b, Γ_γ are the partial decay widths
- $\Gamma_{tot} = \Gamma_x + \Gamma_b + \Gamma_\gamma$ is the total width
- J_A, J_C J_x : total angular momentum of the nuclei A,C & x

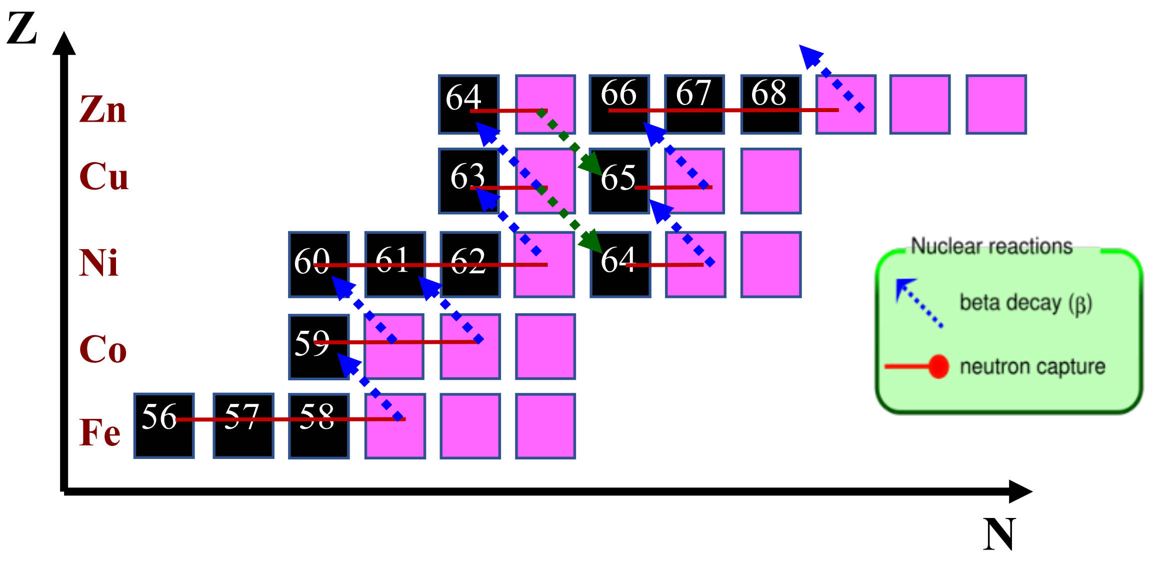
s-process

s-process (s = slow neutron capture process)

$\tau_\beta << \tau_n \quad \Leftrightarrow N_n \sim 10^8 - 10^{11}\ n/cm^3$

→ production of half of the abundance of heavy elements





➢ **Main** component
→ production of 90<A<209 elements in low-mass AGB stars 1-4 $M_\odot$ (T~0.1 GK)

➢ **Weak** component
→ production of 56<A<90 elements in intermediate-mass AGB star (T~0.3 GK) & **massive stars** (T~0.2-1GK)

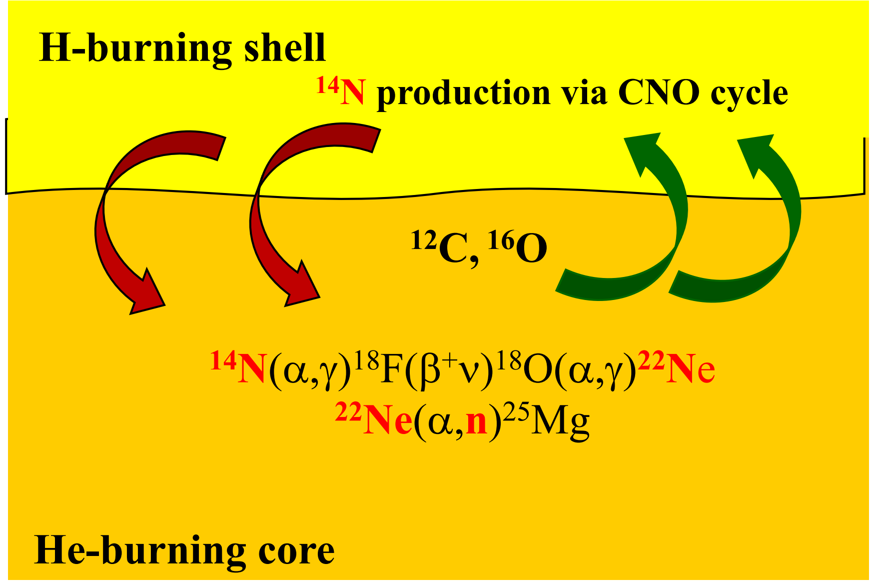
s-process in rotating metal-poor massive stars

Weak s-process → **56<A<90** in **massive stars** M>**8M**$_\odot$

- End of core He burning (T ~$3\cdot10^8$ K, N_n =**10^6** cm^{-3})
- C-shell burning (T~1 GK, N_n =**10^{11}** cm^{-3})

Main neutron source: **$^{22}Ne(\alpha,n)^{25}Mg$**

- **Metal-poor massive stars** ([Fe/H] <-1)→ negligible *s*-process production (low ^{22}Ne & Fe seed abundance)
- With fast rotation induced mixing ➡ ^{22}Ne production in He core strongly enhanced **Nishimura+16, Choplin+18**



↳ large production of *s*-elements between Strontium & Barium 90<A<140

- Enhanced weak s-process (es-process) **Frischknecht+16**

→ Important impact on chemical enrichment in early galaxies.

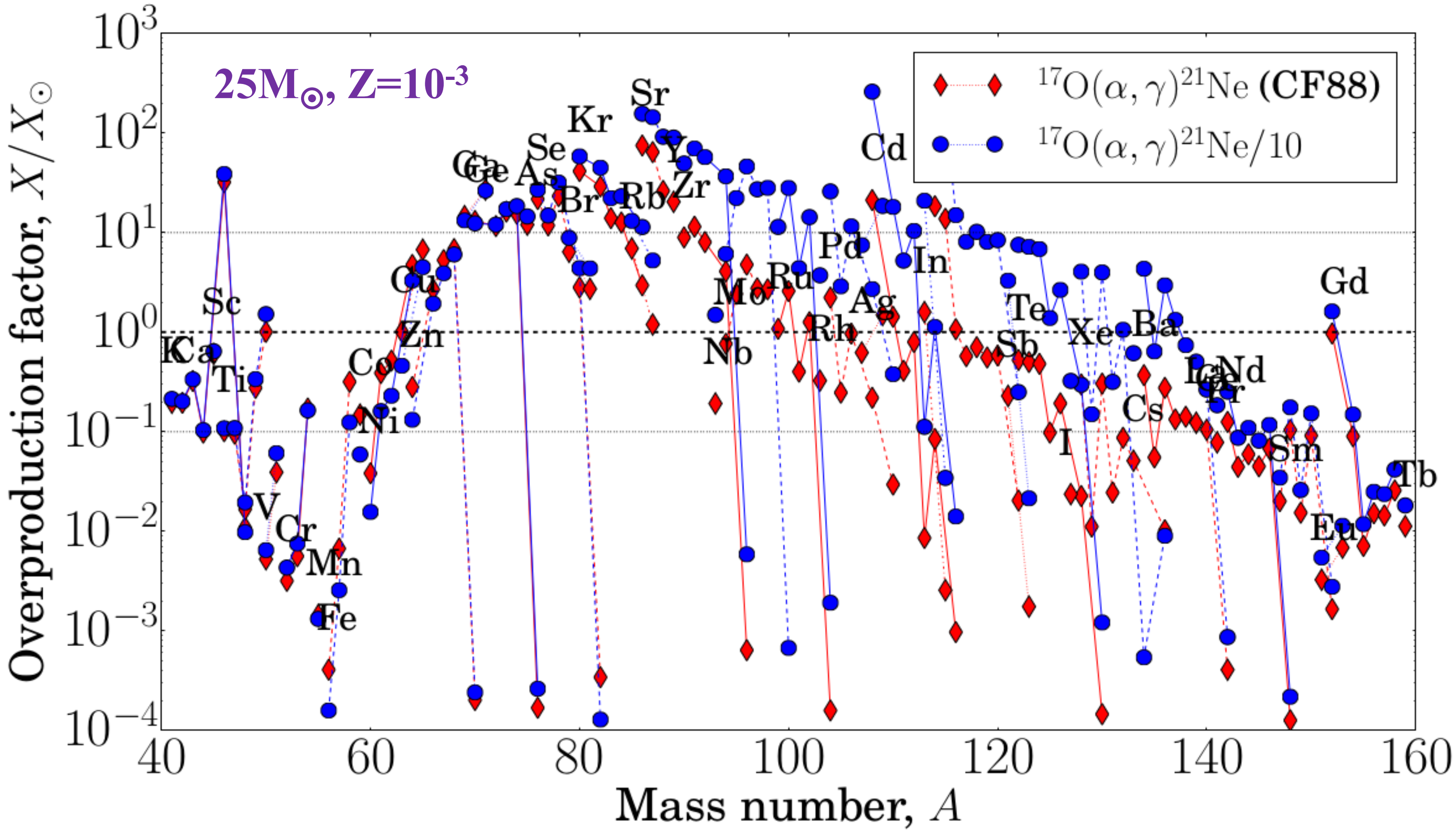
→ Source of heavy elements such as Barium in early universe? **Barbuy+14**

s-process in rotating metal-poor massive stars

But the final abundances of the enhanced weak *s*-process strongly depends on:

$^{16}O(n,\gamma)^{17}O$ neutron poison effect & $^{17}O(\alpha,n)/^{17}O(\alpha,\gamma)$ reaction rate ratio

→ neutron recycling efficiency



Nishimura+MNRAS-2017

Calculation with $^{17}O(\alpha,n)^{20}Ne$ Nacre adopted rate & $^{17}O(\alpha,\gamma)^{22}Ne$ CF88 rate

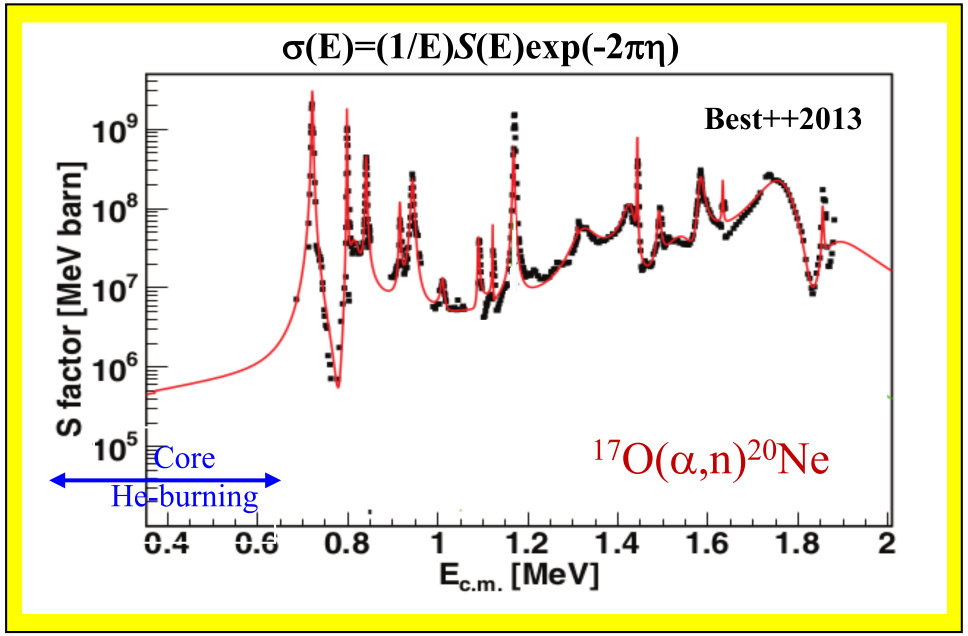
Experimental status on $^{17}O(\alpha,n)^{20}Ne$ and $^{17}O(\alpha,\gamma)^{21}Ne$

- Core He burning: T ~0.2-0.3 GK → $E_{c.m}$~ **0.297-0.646 MeV** → E_x=7.64-8.00 in ^{21}Ne
- Shell Carbon burning: T~1 GK→ $E_{c.m}$~ 0.783-1.5 MeV→ E_x=8.13-8.85 in ^{21}Ne

$^{17}O(\alpha,n)^{20}Ne$ & $^{17}O(\alpha,\gamma)^{21}Ne$ direct measurements:

- **Denker++1994, Best++2013**
- **Best++2011, Taggart++2019**
- **Williams++2022**

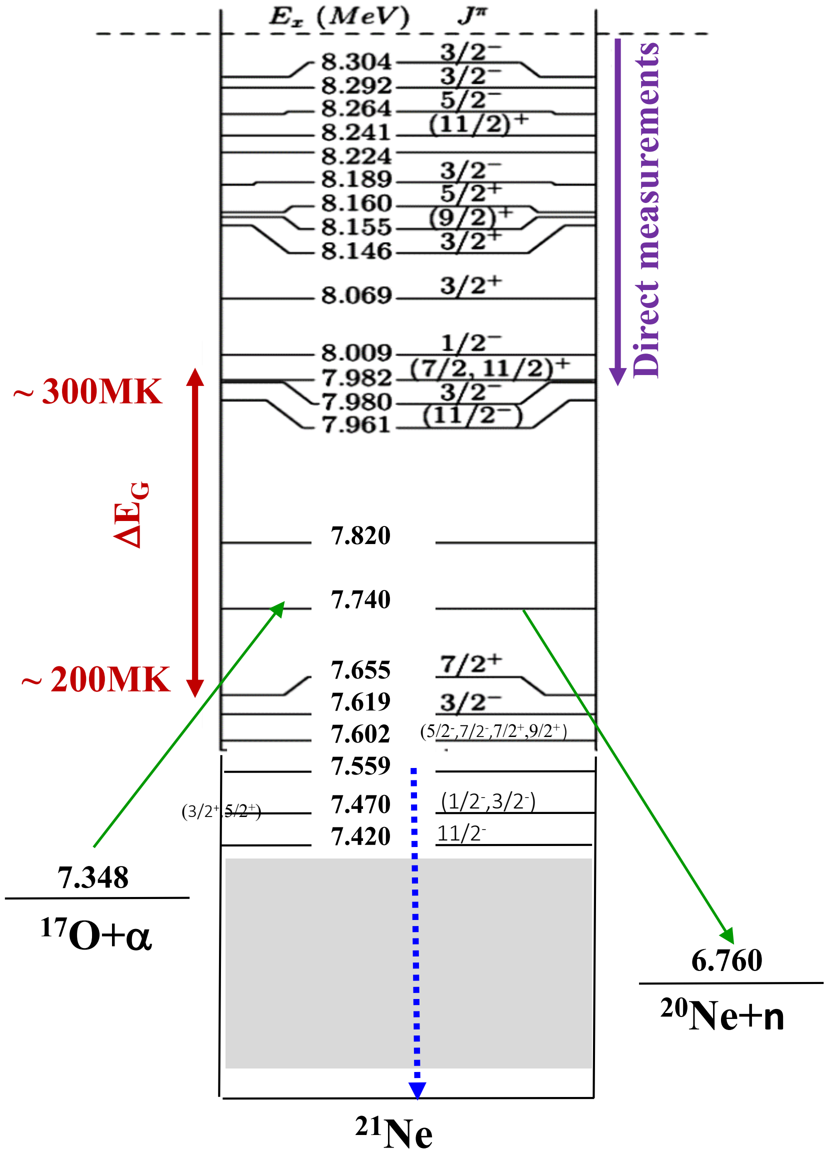
No direct measurements @ Core He burning energies ($E_{c.m}$ <0.630 MeV)



→ few hundreds keV << $E_{Coulomb}$

→ σ(E) very weak (≤ 100 pb)

→ Neutron & γ detection: large background



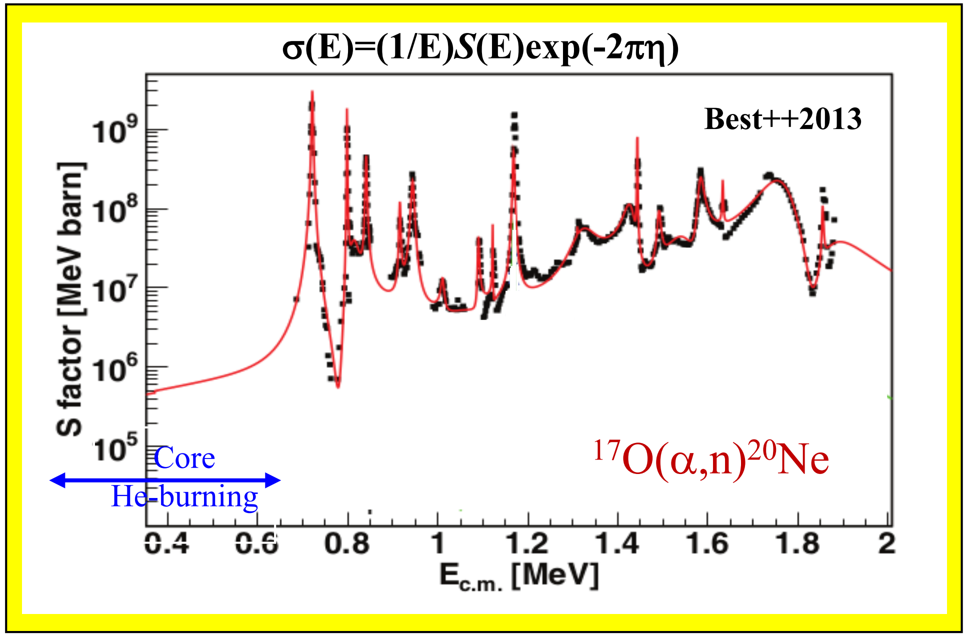
Experimental status on $^{17}O(\alpha,n)^{20}Ne$ and $^{17}O(\alpha,\gamma)^{21}Ne$

- Core He burning: T ~0.2-0.3 GK → $E_{c.m}$~ **0.297-0.646 MeV** → E_x=7.64-8.00 in ^{21}Ne
- Shell Carbon burning: T~1 GK→ $E_{c.m}$~ 0.783-1.5 MeV→ E_x=8.13-8.85 in ^{21}Ne

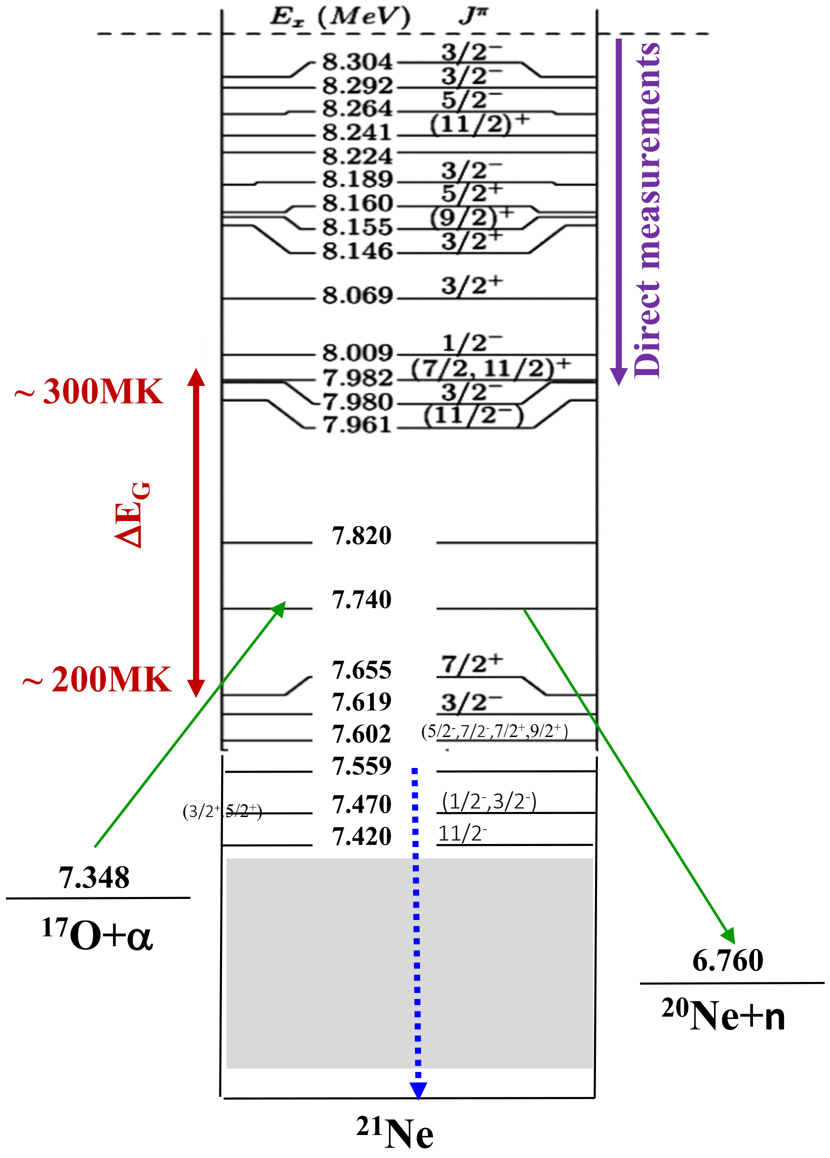
$^{17}O(\alpha,n)^{20}Ne$ & $^{17}O(\alpha,\gamma)^{21}Ne$ direct measurements:

- **Denker++1994, Best++2013**
- **Best++2011, Taggart++2019**
- **Williams++2022**

No direct measurements @ Core He burning energies ($E_{c.m}$ <0.630 MeV)

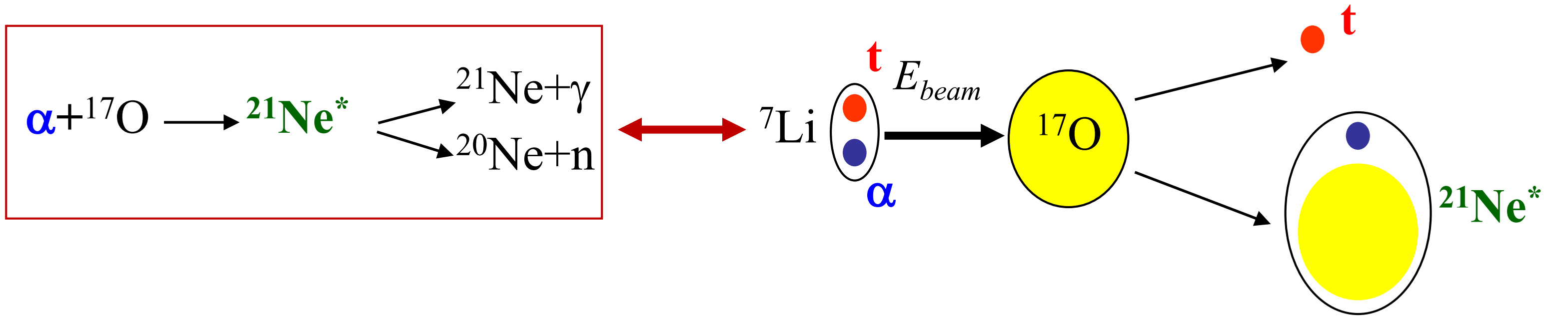


What about Spectroscopy of ^{21}Ne?
→ Known E_x
→ Unknown or poorly known Γ_α, Γ_n, $\Gamma_\gamma/\Gamma_{tot}$
→ Few have spin-parity assignments J^π

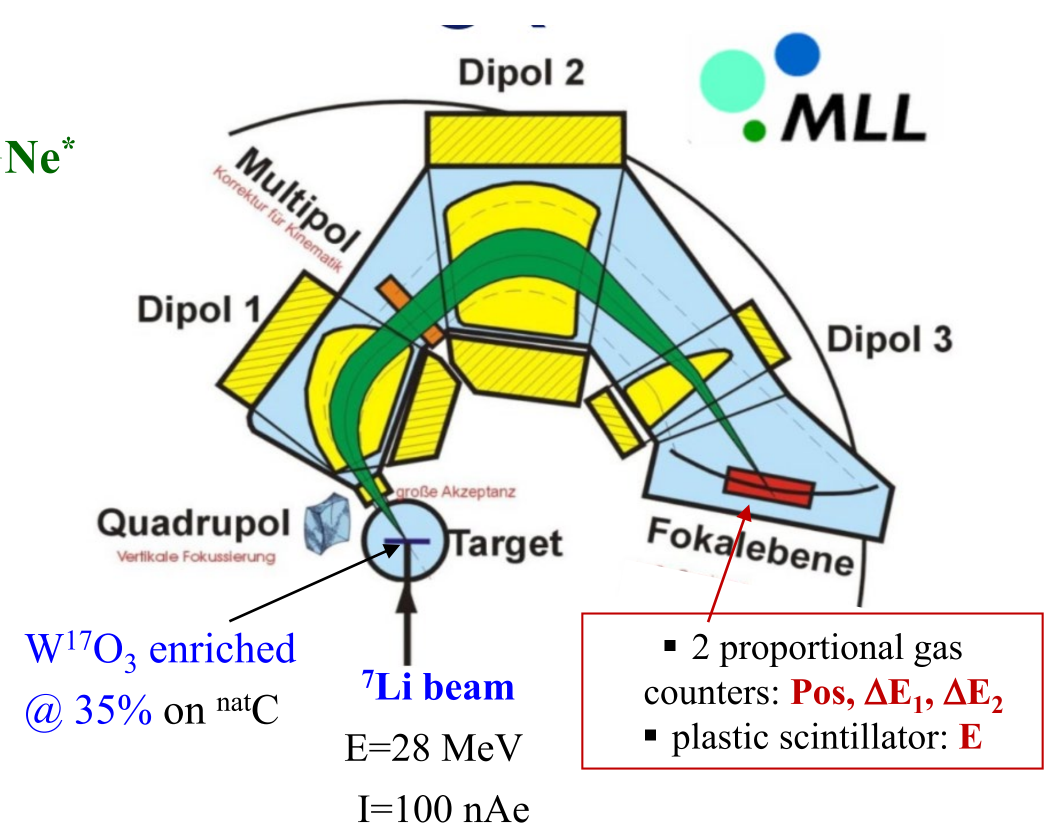


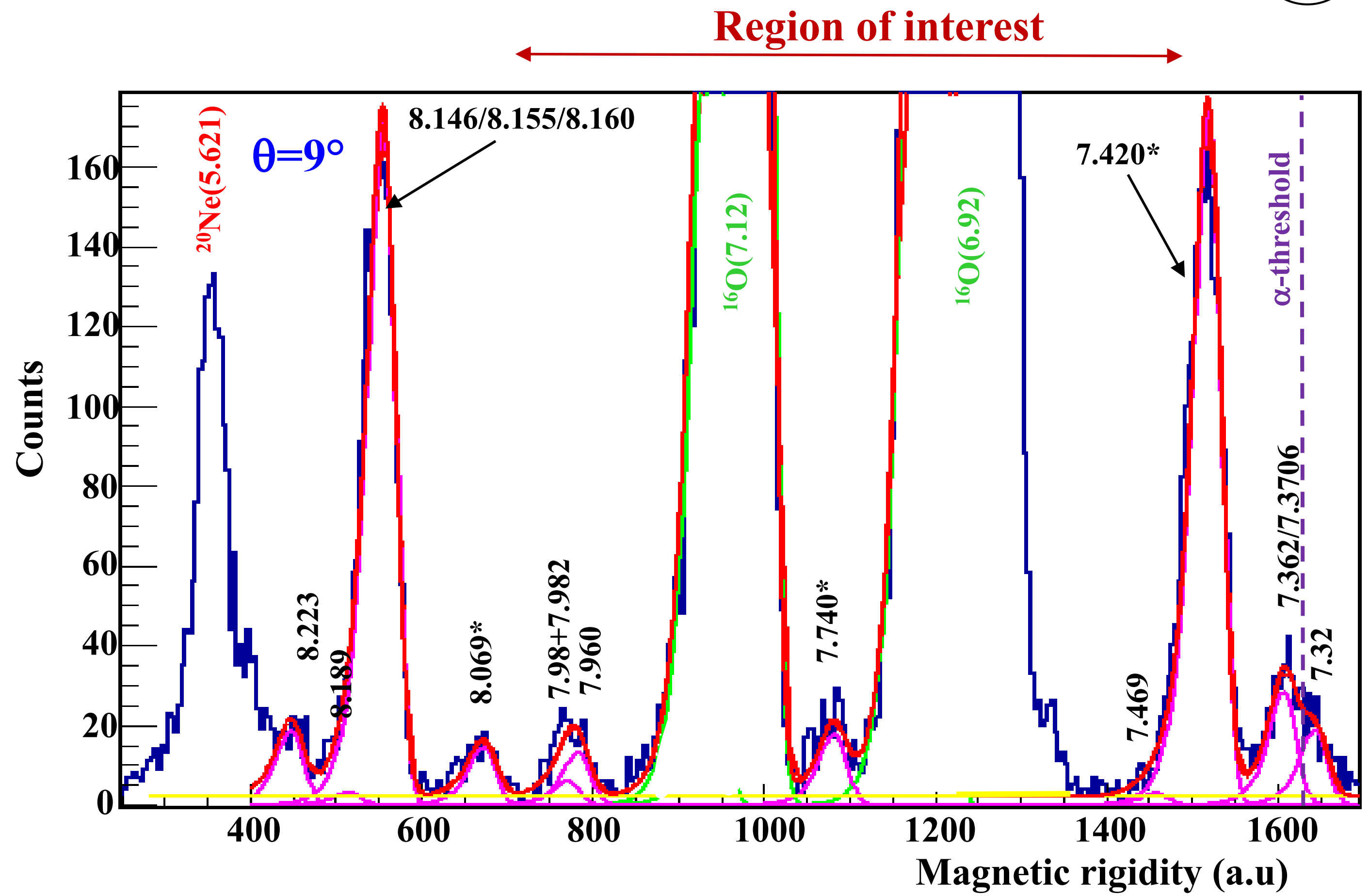
- Neutron transfer reaction → S_n→ Γ_n **Frost-Schenk++MNRAS2022**
- α-transfer reaction → S_α→ Γ_α (present work/MLL-exp)

Study of ^{21}Ne states via ^{17}O(^{7}Li,t)^{21}Ne α-transfer reaction



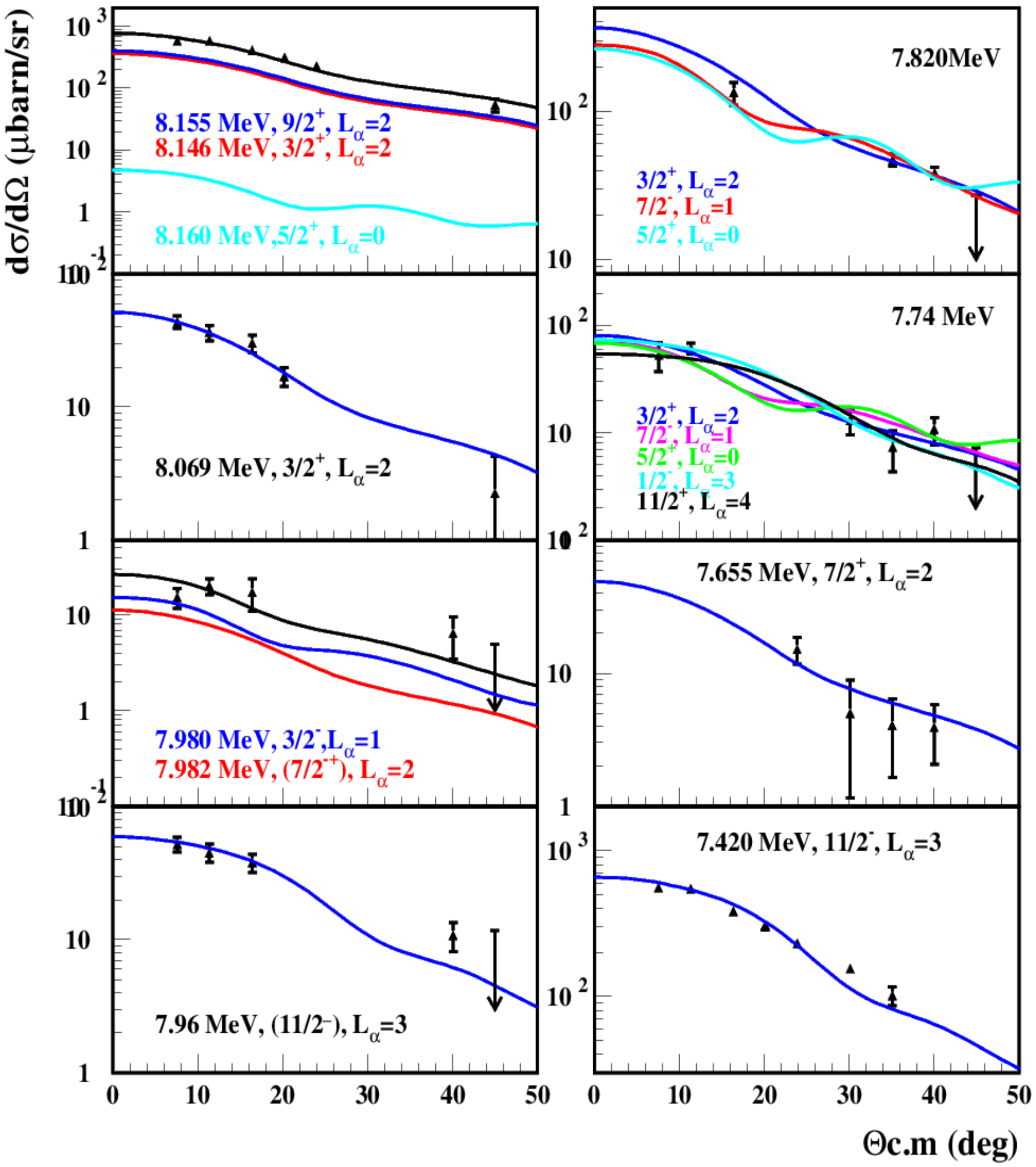
Q3D spectrometer





Experimental energy resolution (FWHM) : ~ 30 keV (6°) - 71 keV (36°)

FR-DWBA calculations



- From the normalisation of the DWBA (Distorded Wave Born Approximation) calculations (FRESCO code) to the data → Spectroscopic factor

$$\left.\frac{d\sigma}{d\Omega}\right|_{exp} = C^2 S'_\alpha \, S_\alpha \left.\frac{d\sigma}{d\Omega}\right|_{FR-DWBA}$$

$S'_\alpha = < {}^7Li\, | t \otimes \alpha > = 1$ **Kubo et al PRC 1978)**

$S_\alpha = < {}^{21}Ne^* \, | {}^{17}O \otimes \alpha >$

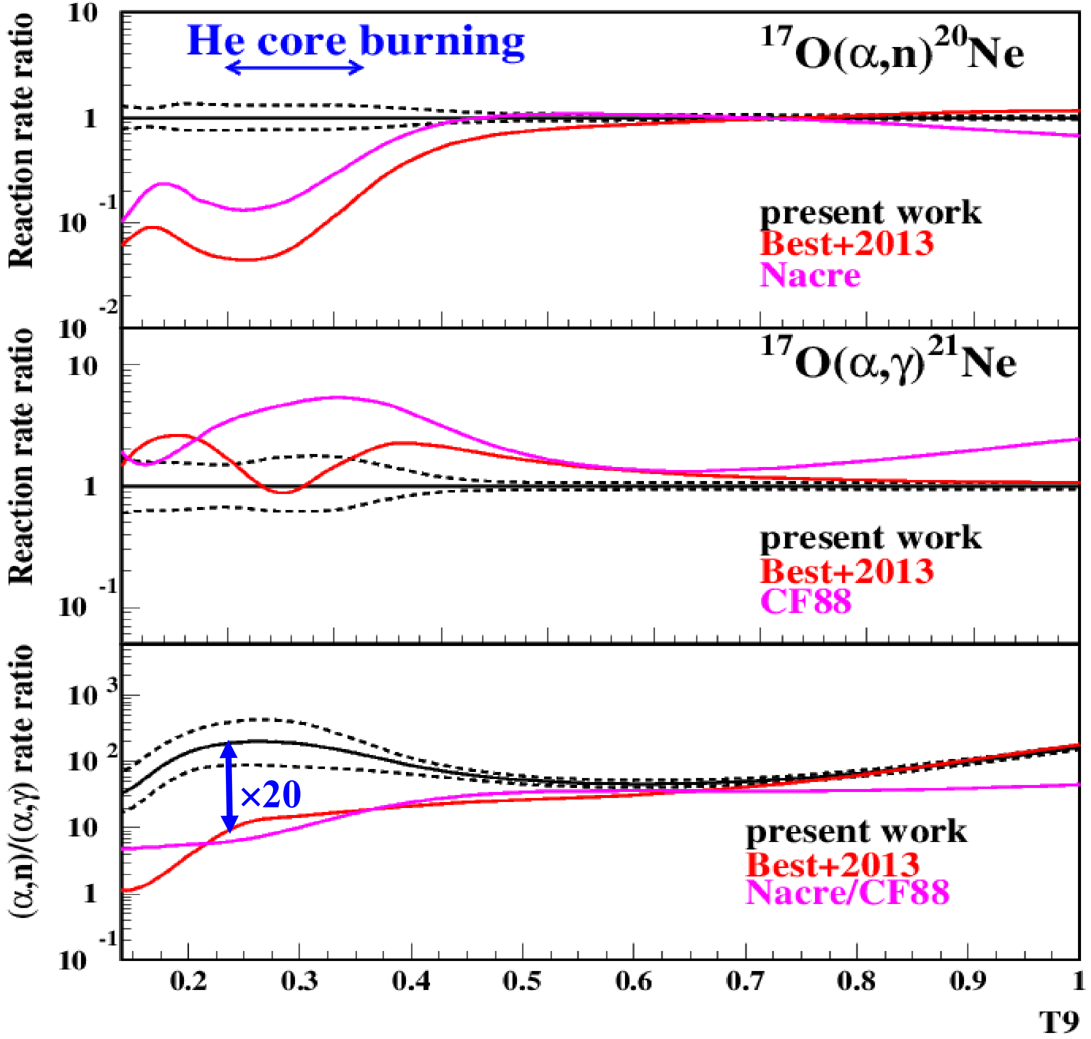
$$S_\alpha \rightarrow \Gamma_\alpha = 2P_l \frac{\hbar^2 R}{2\mu} S_\alpha |\phi(R)|^2$$

P_l = Coulomb & centrifugal penetrability factor
φ(R) radial part of the $\alpha + {}^{17}O$ wave function

- Γ_α uncertainty: 3- 40% (stat), **35%** (optical potentials)

$^{17}O(\alpha,n)$ & $^{17}O(\alpha,\gamma)$ new reaction rates & impact on the s-process in low Z massive stars

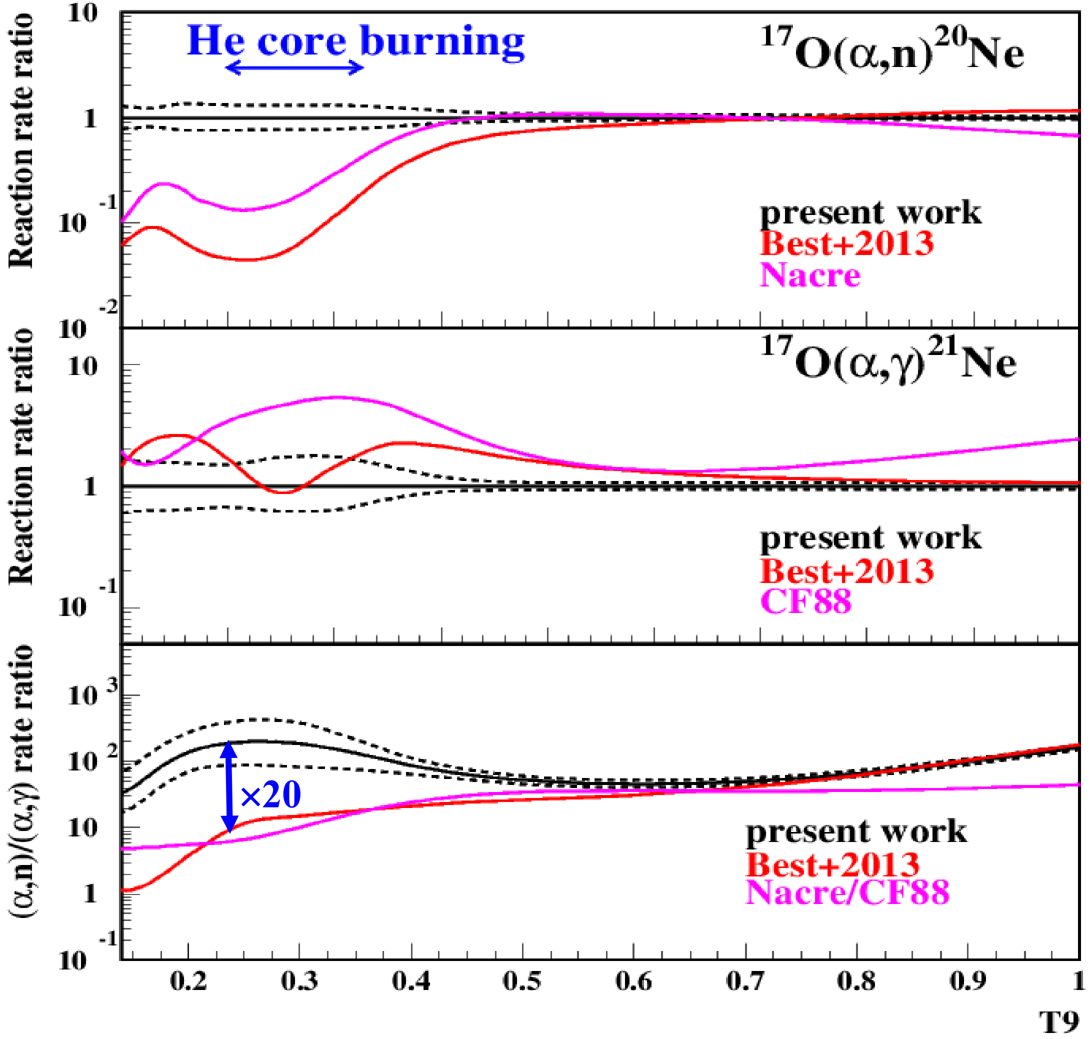
Reaction rates calculations:



→ **Better neutron efficiency recycling** with a factor of about **20** with the **present rates** than Best+2013 rates

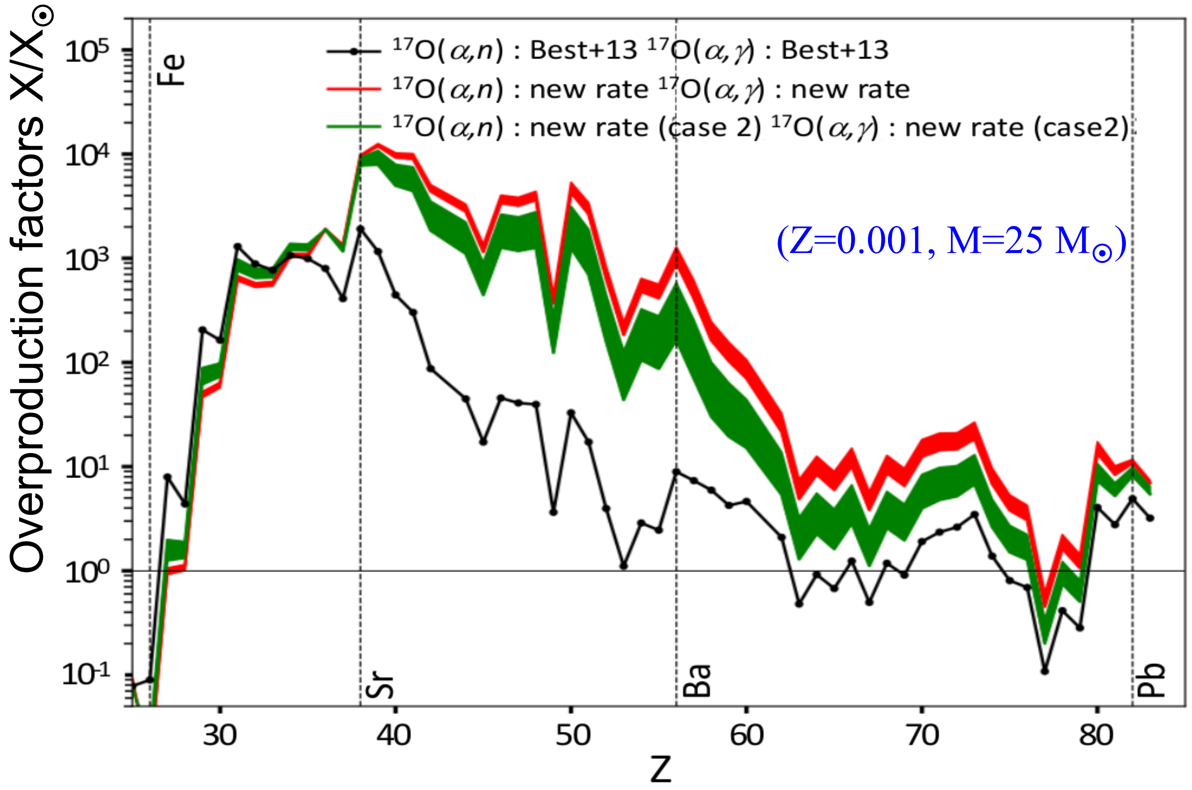
$^{17}O(\alpha,n)$ & $^{17}O(\alpha,\gamma)$ new reaction rates & impact on the s-process in low Z massive stars

Reaction rates calculations:



→ **Better neutron efficiency recycling** with a factor of about **20** with the **present rates** than Best+2013 rates

Nucleosynthesis calculations:



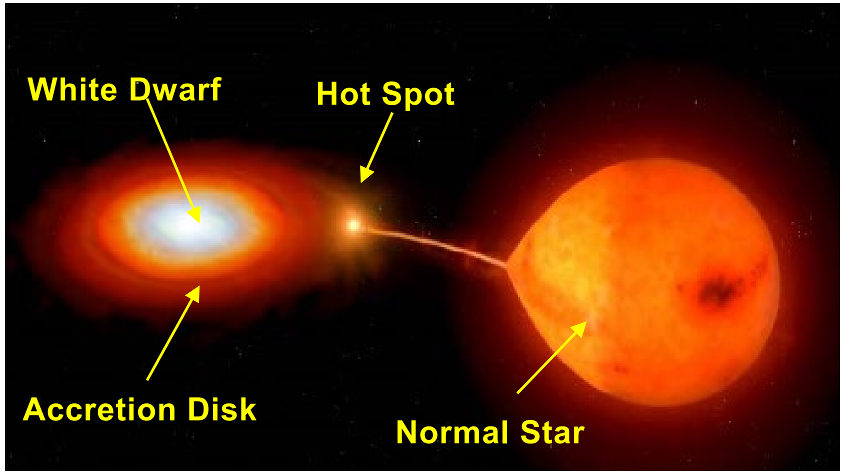
F. H, P. Adsley, L. Lamia et al., Phys Rev Lett 132, 182701 (2024)

→**Large enhancement** (> factor 30 (>20)) of elements 40 < Z < 60 with the present **new rates** in comparison to previous rates

→ **Two order** of magnitude (~**×30 (case2)**) on **Barium** : largest effect

→ In line with the observation of an enhanced s-process in CEMP-s(Carbon Enhanced Metal poor) stars **Hansen+2016**

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

- Ejected mass << observed mass
- Amount of mixing between accreted and white dwarf materials?
- Compact star mass

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

→ soon the first stellar explosive site with all reaction rates based on experimental information **J.José+2009**

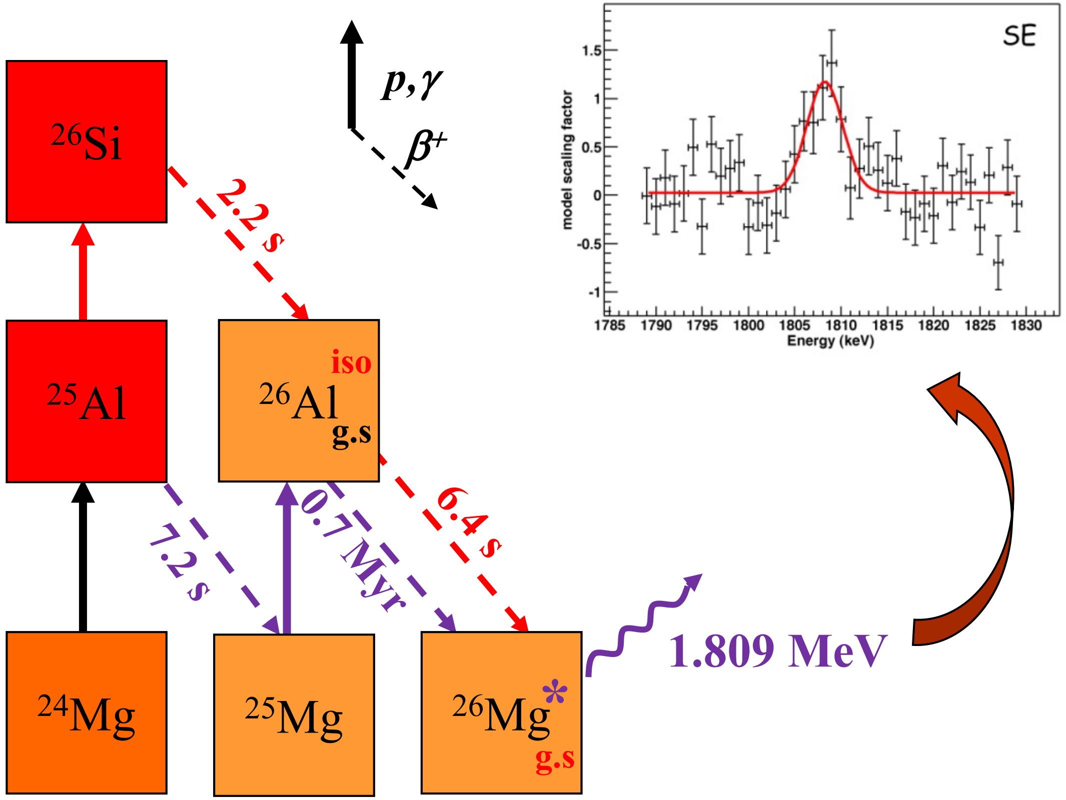
The **3 remaining key reactions** with significant uncertainties:

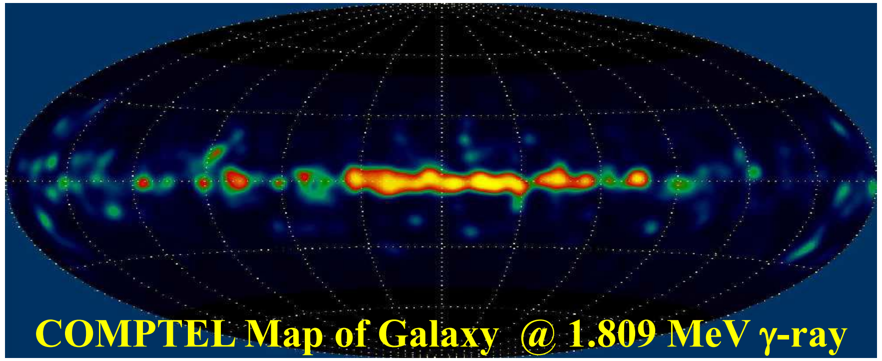
- $^{30}P(p,\gamma)^{31}S$: paternity of novae grains **Woods+2021? (FRIB)**
- $^{18}F(p,\alpha)^{15}O$: γ-ray emission ≤ 511 keV **Riley+PRC2021 (Split-Pole/ALTO)**
- **$^{25}Al(p,\gamma)^{26}Si$**: Classical novae contribution to the observed galactic ^{26}Al γ-ray emission @ 1.809 MeV?

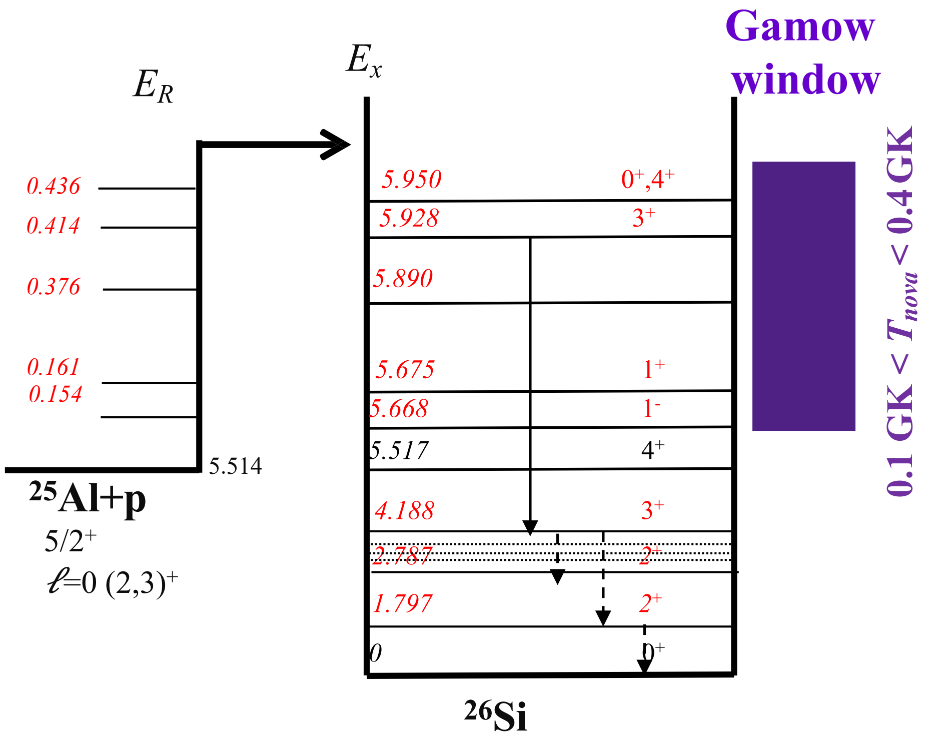
^{26}Al nucleosynthesis

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

Factor two uncertainty on resonance strengths

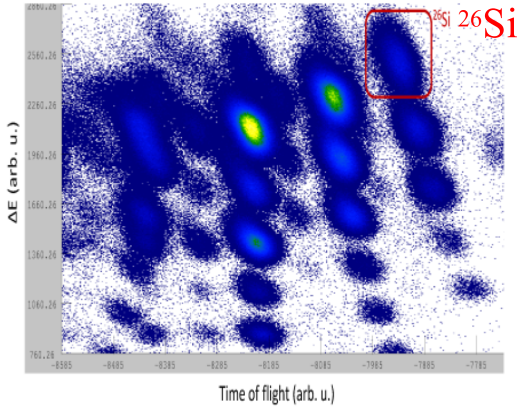
⇒ need to be measured

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

→ Studied via d(^{25}Al,nγ)^{26}Si @ FRIB/S800 **C.Fougères, F.H, N de Séréville, F. de Oliveira+coll**

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

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

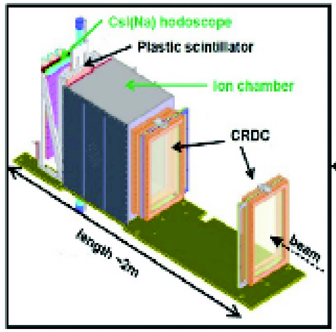


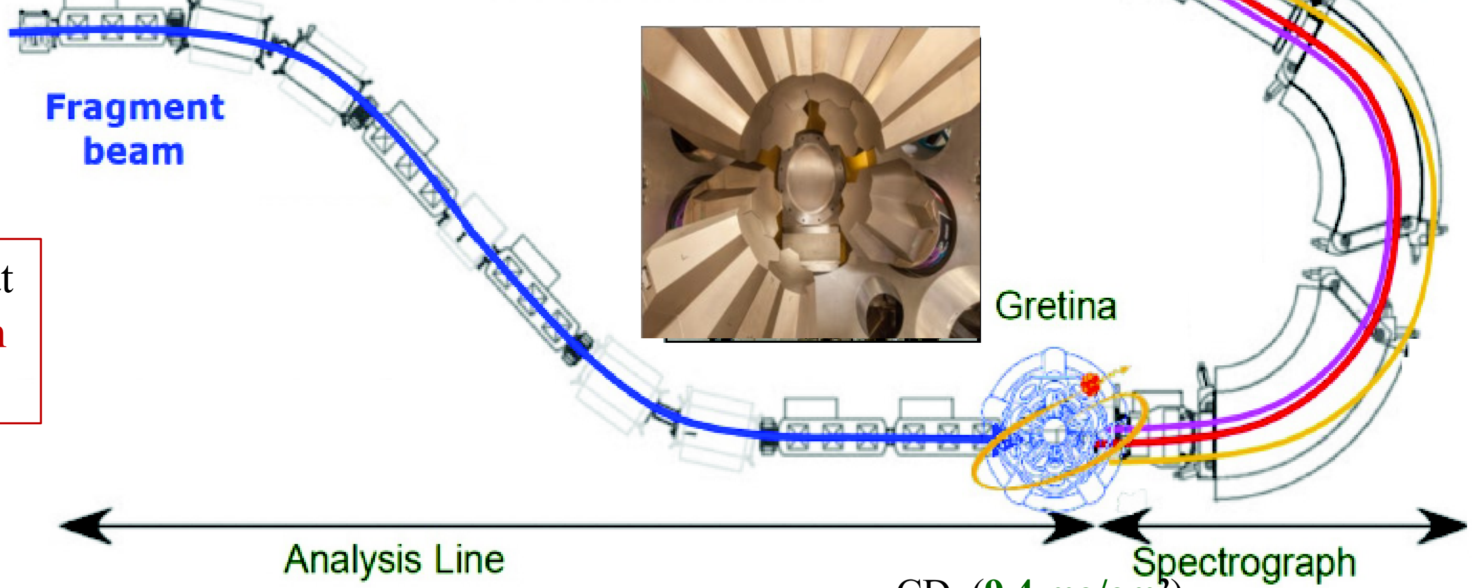
GRETINA&S800@FRIB/ARIS

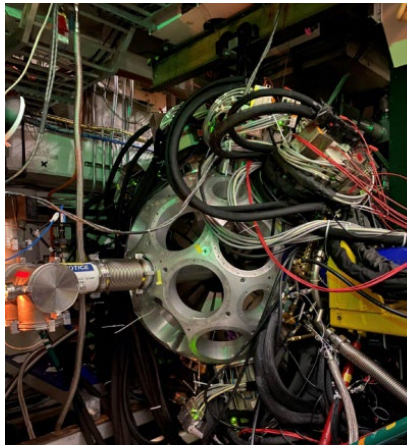
^{25}Al @ 24 MeV/u

lowest energy ever used @ S800)

2× 10^6 pps, Purity >95%





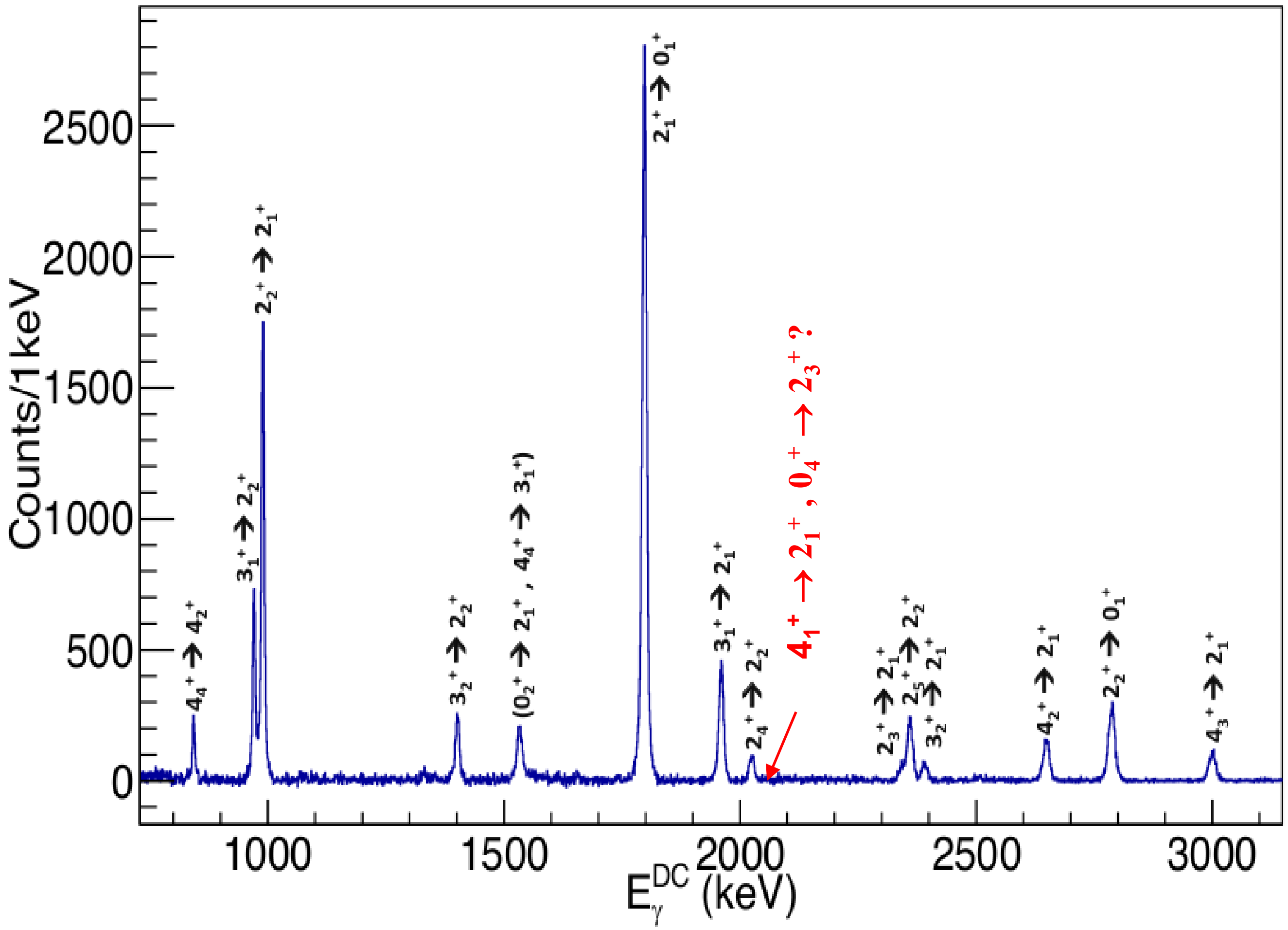


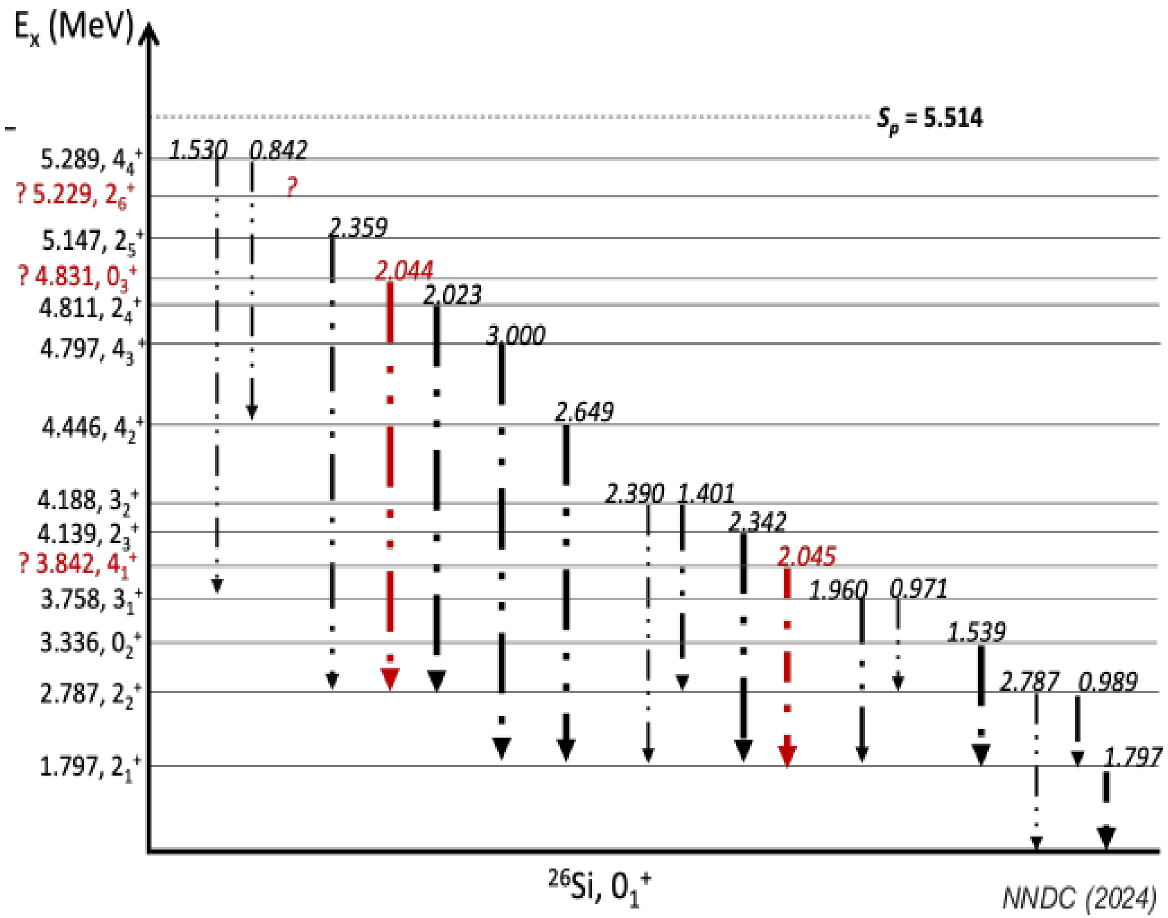
Measurements of ^{26}Si recoils at **S800** in coincidence with γ's in **GRETINA**

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

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

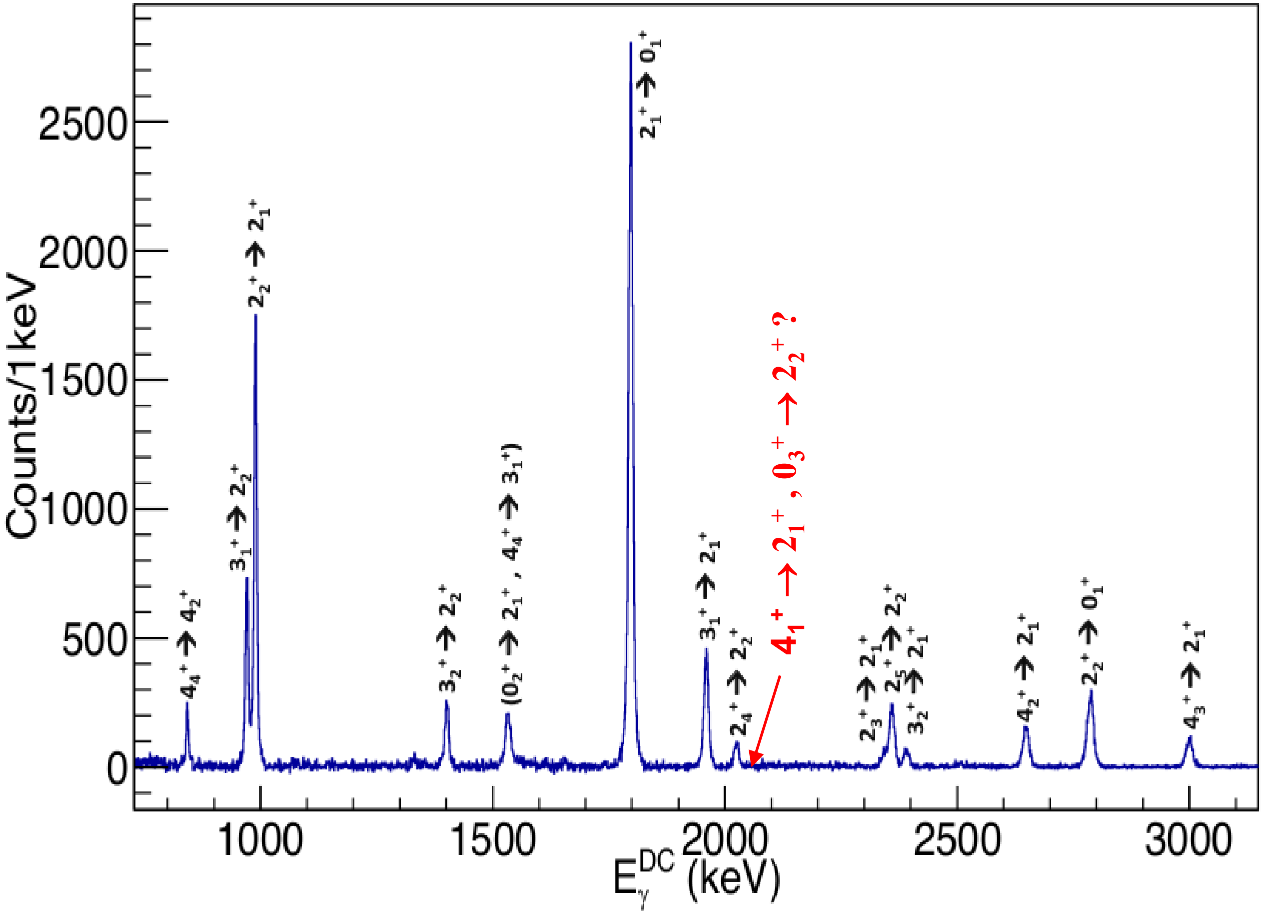
➢ γ-ray transitions of 11 states in ^{26}Si below S_p were observed among the 14 referenced



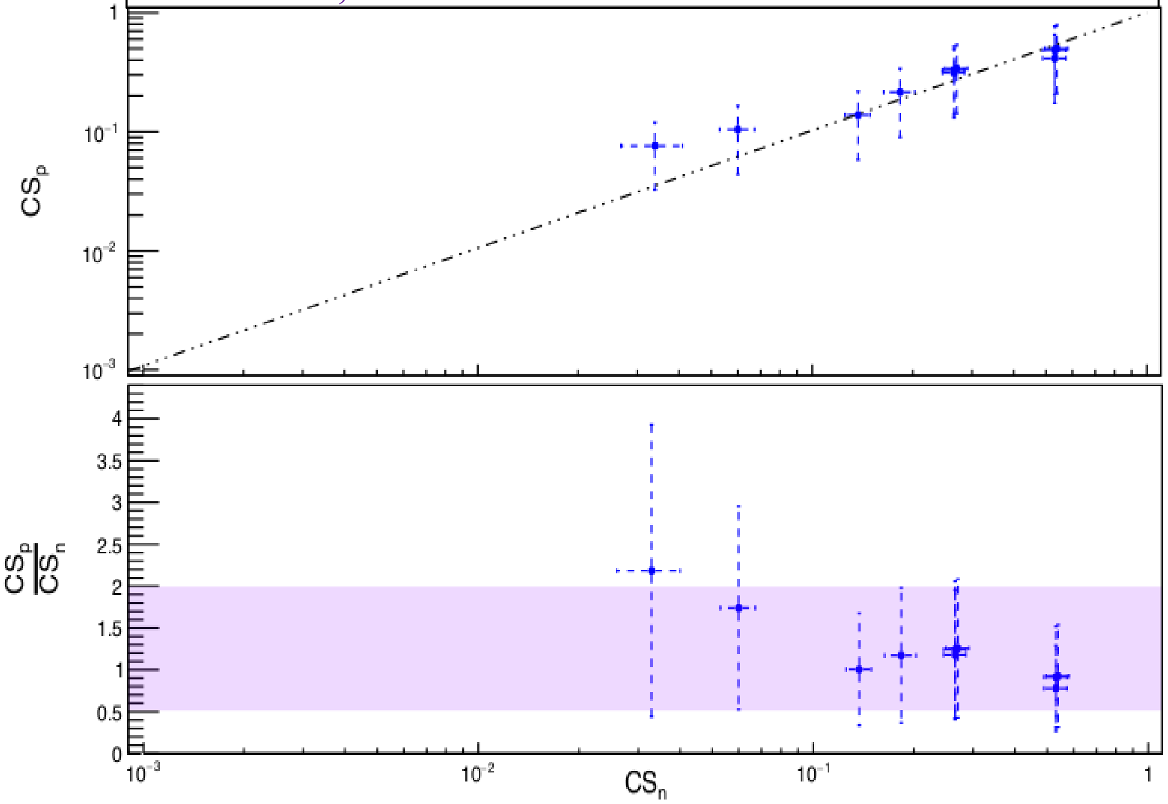


^{25}Al(p,γ)^{26}Si case: Bound states

➢ 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**



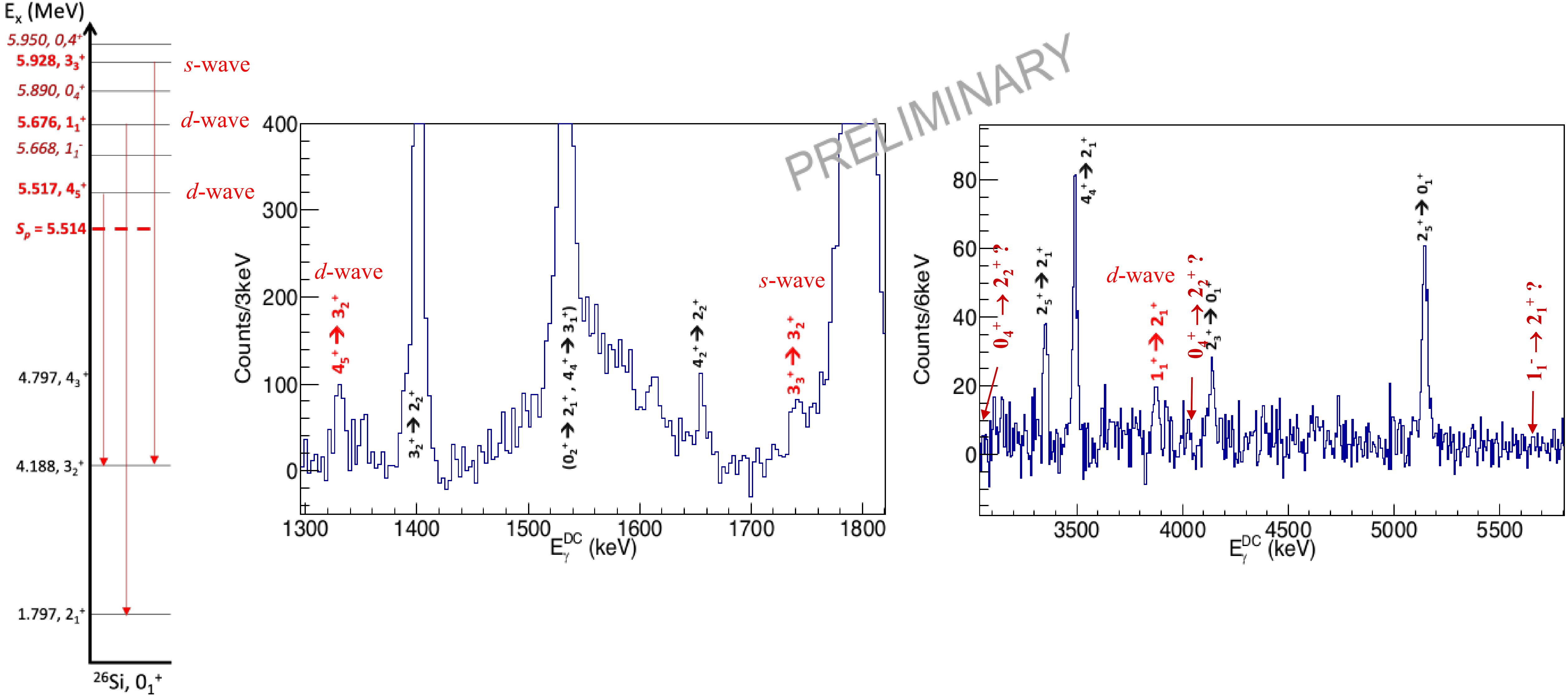
Comparison with few analog states in ^{26}Mg
Burlein+84, Arciszewski+84



→ new data on ^{26}Mg: ALTO/SPILT-POLE experiment (Orsay, 2024)

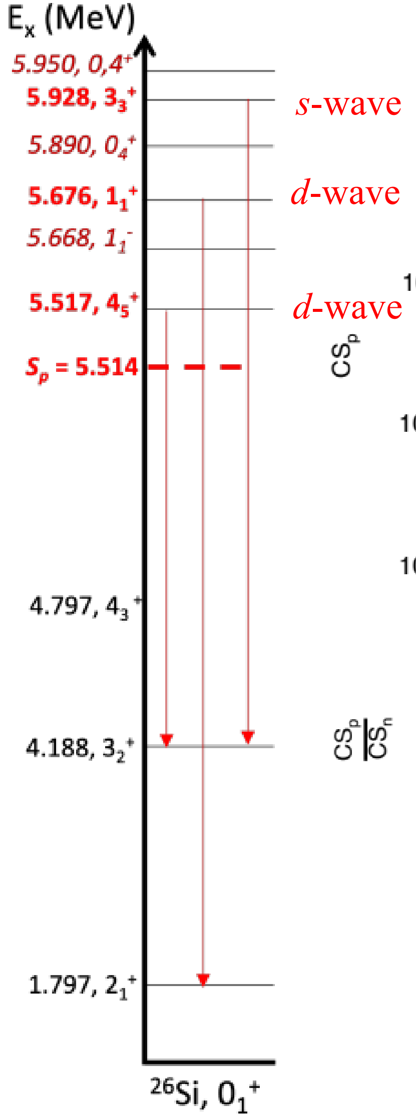
$^{25}Al(p,\gamma)^{26}Si$ case: Resonant states

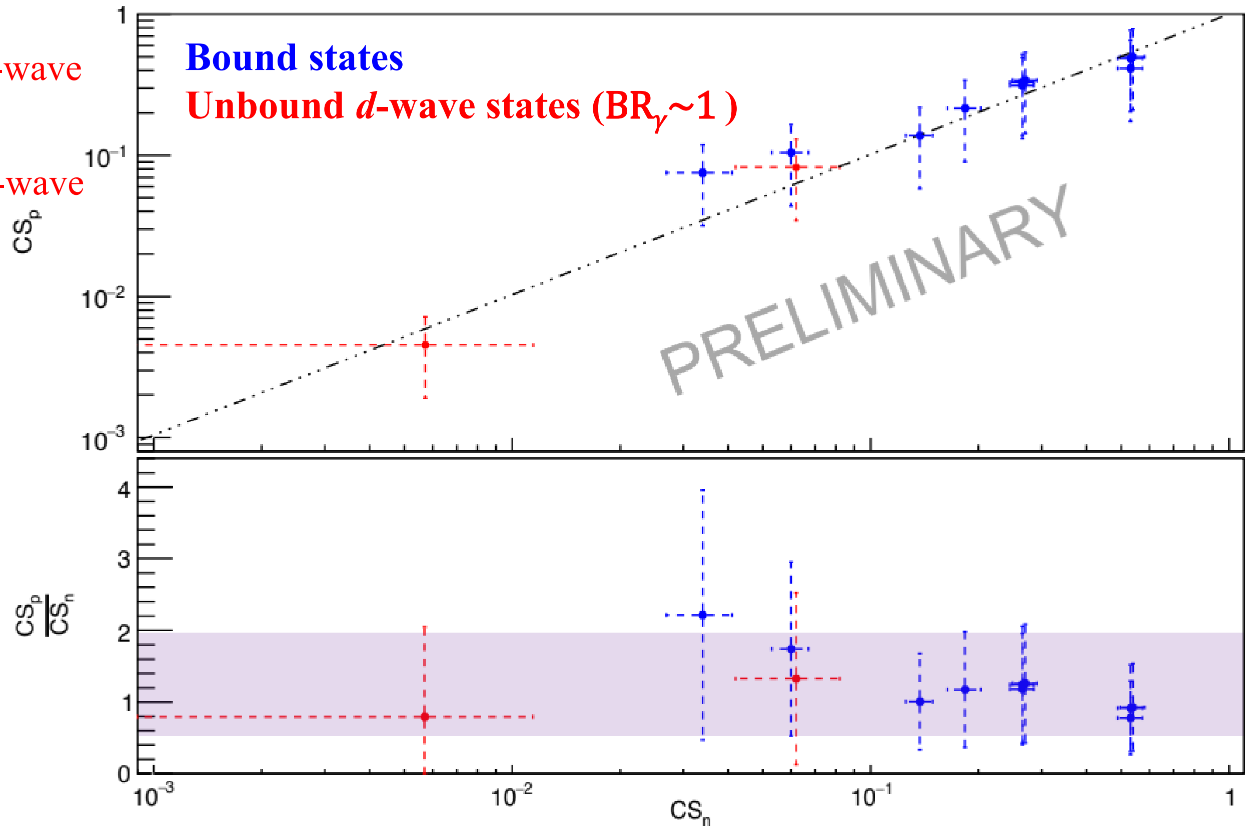
➢ Three resonant states among six of interest are identified in ^{26}**Si** ($>S_p$)



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

- **Three resonant** states among six of interest are identified in ^{26}**Si** ($>S_p$)



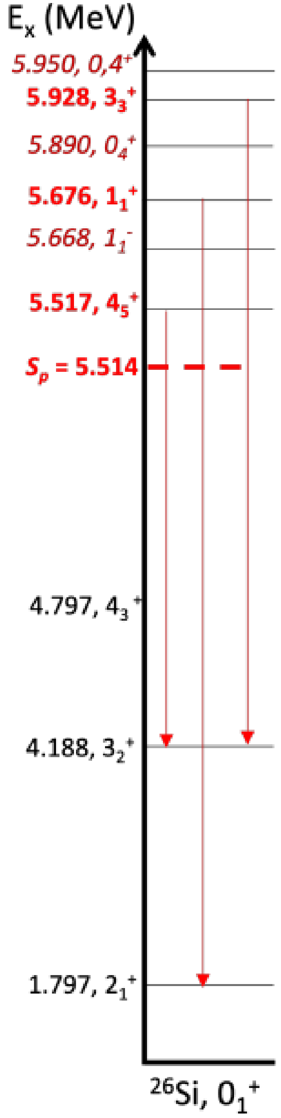


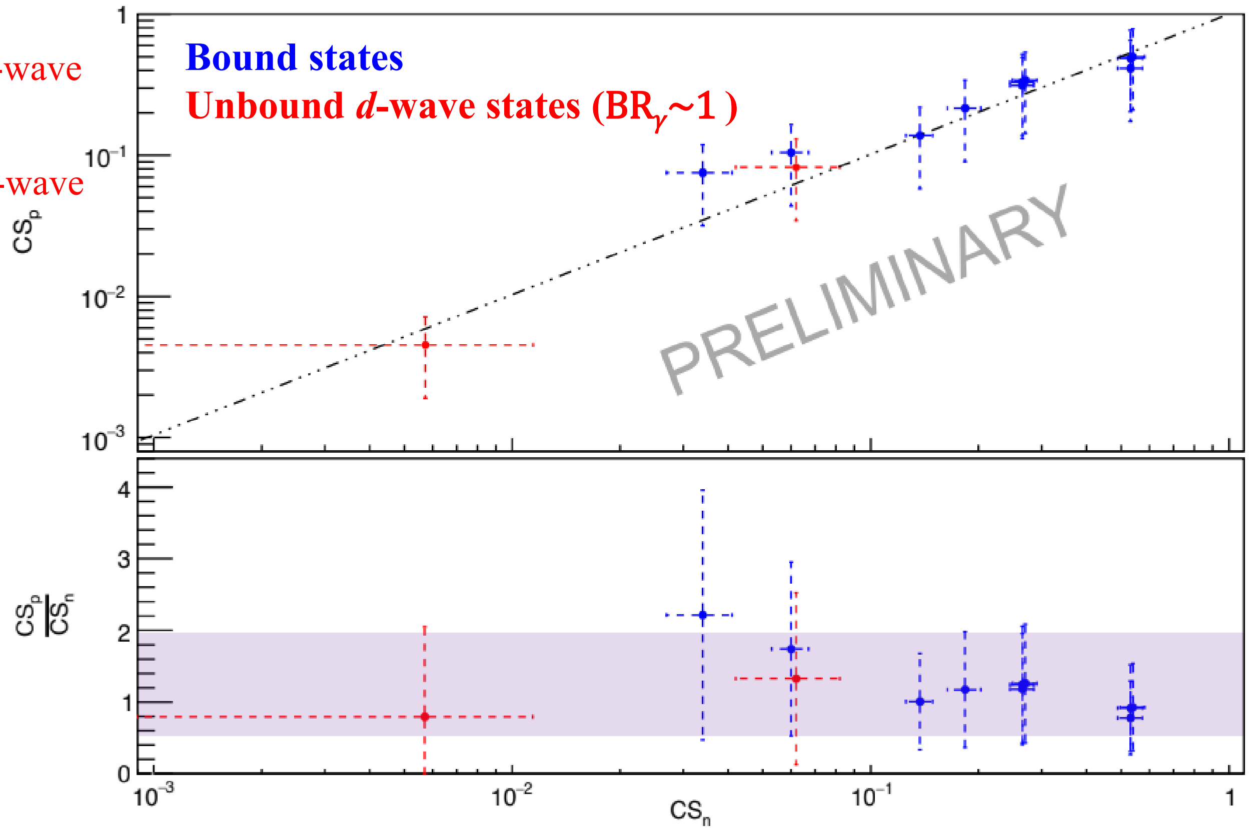
Resonance strength (meV)

	1_1^+	3_3^+
Laird et al (2023)	$< 2.6 \times 10^{-6}$	23(13)
Present work (preliminary)	$2(1) \times 10^{-6}$	35(15)

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

- ➢ Three resonant states among six of interest are identified in ^{26}**Si** ($>S_p$)





Resonance strength (meV)

	1_1^+	3_3^+
Laird et al (2023)	$< 2.6 \times 10^{-6}$	23(13)
Present work (preliminary)	$2(1) \times 10^{-6}$	35(15)

Ongoing analysis

Next:

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

Thanks to the collaboration & your attention

PHYSICAL REVIEW LETTERS **132,** 182701 (2024)

Experimental Determination of α Widths of ^{21}Ne Levels in the Region of Astrophysical Interest: New ^{17}O + α Reaction Rates and Impact on the Weak *s* Process

F. Hammache,[1,*] P. Adsley,[2,3,†] L. Lamia,[4,5,6] D. S. Harrouz,[1] N. de Séréville,[1] B. Bastin,[7] A. Choplin,[8] T. Faestermann,[9] C. Fougères,[7] R. Hertenberger,[10] R. Hirschi,[11,12] M. La Cognata,[4] A. Meyer,[1] S. Palmerini,[13,14] R. G. Pizzone,[4] F. de Oliveira Santos,[7] S. Romano,[4,5,6] A. Tumino,[4,15] and H.-F. Wirth[10]

[1]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[2]*School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa*
[3]*iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa*
[4]*Laboratori Nazionali del Sud—Istituto Nazionale di Fisica Nucleare, Via Santa Sofia 62, 95123 Catania, Italy*
[5]*Dipartimento di Fisica e Astronomia E. Majorana, Universitã di Catania, Catania, Italy*
[6]*Centro Siciliano di Fisica Nucleare e Struttura della Materia-CSFNSM, Catania, Italy*
[7]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3, Boulevard Henri Becquerel, 14076 Caen, France*
[8]*Institut d'Astronomie et d'Astrophysique, Université libre de Bruxelles, CP 225, B-1050 Brussels, B*
[9]*Physik Department E12, Technische Universität München, D-85748 Garching, Germany*
[10]*Fakultät für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*
[11]*Astrophysics Research Center, Keele University, Staffordshire ST5 5BG, United Kingdo*
[12]*Kavli IPMU (WPI), University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8583, Japan*
[13]*Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, Perugia, Italy*
[14]*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia, Italy*
[15]*Facoltà di Ingegneria e Architettura, Università degli Studi di Enna, Italy*

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

INFN LNS

TEXAS A&M UNIVERSITY

cea

GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3

FRIB

Angle-integrated measurement of the $d(^{25}\mathrm{Al},n\gamma)^{26}$Si transfer reaction to probe resonance strengths in $^{25}\mathrm{Al}(p,\gamma)^{26}$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]

[1]*Physics Division, Argonne National Laboratory, Lemont, IL 60439, USA*
[2] *CEA DAM DIF, F-91297 Arpajon, France*
[3]*Laboratoire de Physique des 2 Infinis Irène Joliot-Curie, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[4]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3, Caen, France*
[5]*Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA*
[6]*Center for Exotic Nuclear Studies, Institute for Basic Science, Daejeon, 34126, Korea*
[7]*Department of Physics, University of Illinois Chicago, Chicago, IL 60607, USA and*
[8]*INFN-Laboratori Nazionali del Sud, Catania, Italy*

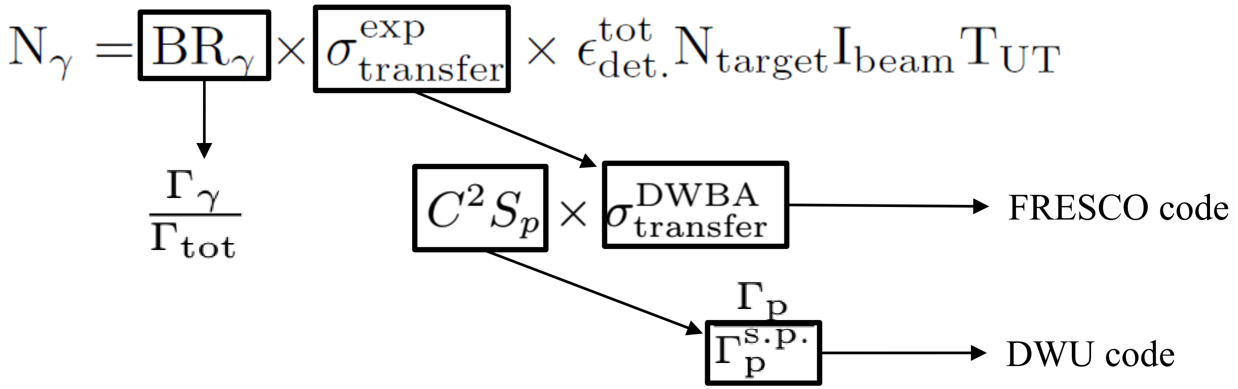
Accessing $\omega\gamma$ via angle-integrated measurement

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

Extension of recent method to measure $\boldsymbol{C^2S_p}$ (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 $\sigma_{\mathrm{transfer}}$



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

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