(α,γ) & (α,n) key reaction studies using (^{7}Li,t) alpha-transfer reactions

Faïrouz Hammache
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab)
fairouz.hammache@ijclab.in2p3.fr

Why studying (α,γ) & (α,n) reactions via α-transfer reactions?

- $^{12}C(\alpha,\gamma)^{16}O$ (massive stars), $^{14}C(\alpha,\gamma)^{18}O$ (AGB stars & ^{19}F)
- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$, $^{22}Ne(\alpha,\gamma)^{25}Mg$
- $^{17}O(\alpha,n)^{20}Ne$, $^{17}O(\alpha,\gamma)^{21}Ne$

} s-process in AGB & massive stars

- $^{15}O(\alpha,\gamma)^{19}Ne$
- $^{18}Ne(\alpha,p)^{21}Na$

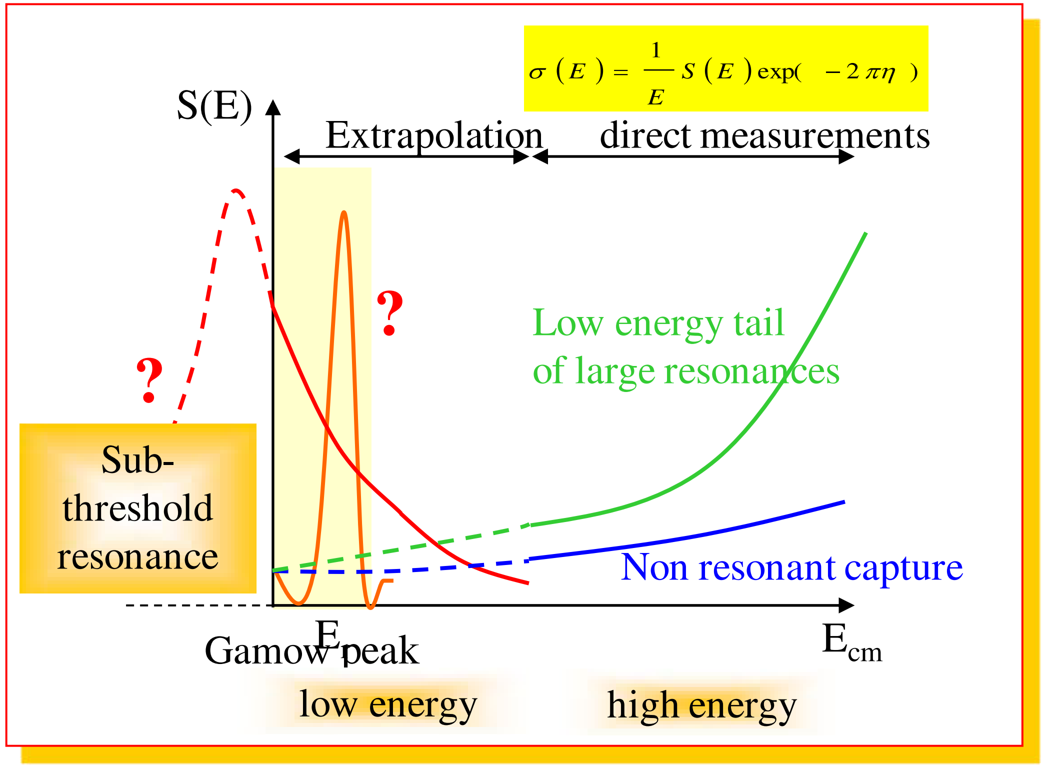
} Type I X-ray bursts

T=0.1-1 GK

→ hundreds keV- MeV << E_C

→ σ(E) very weak (0.01 fb- ~100 pb)

→ Direct measurements are very challenging or impossible



- In case of stable nuclei:

Direct measurements of *σ(E)* at high energies then extrapolation at stellar energies

But:

Problems with extrapolation: resonances at very low energy, sub-threshold resonances

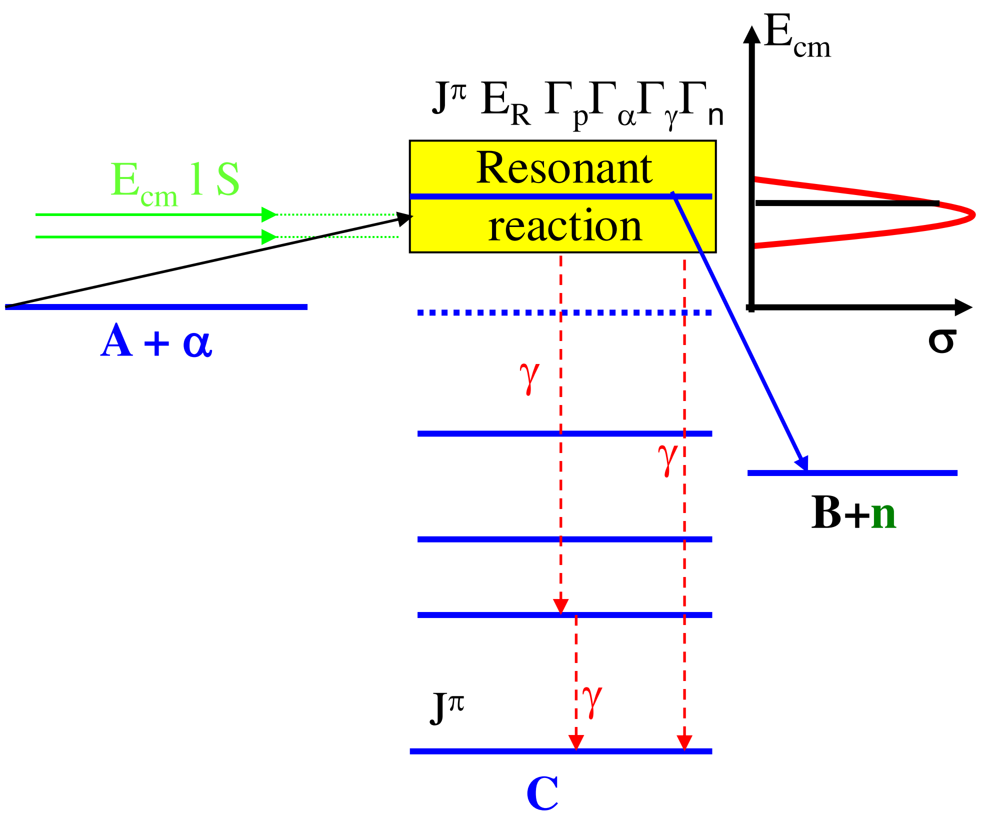
- In case of radioactive nuclei:

Low beam intensities (~10^5 - 10^7 p/s)

→ direct measurements challenging

Resonant (α,γ) & (α,n) reaction cross-sections

$A+\alpha \rightarrow C^* \rightarrow B+\gamma$ or $A+\alpha \rightarrow C^* \rightarrow B+n$



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

$x=\alpha$,
$y=n$ or γ

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

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

Resonant capture only possible for energies:
$E_{cm}=E_R=E_x$**-Q**

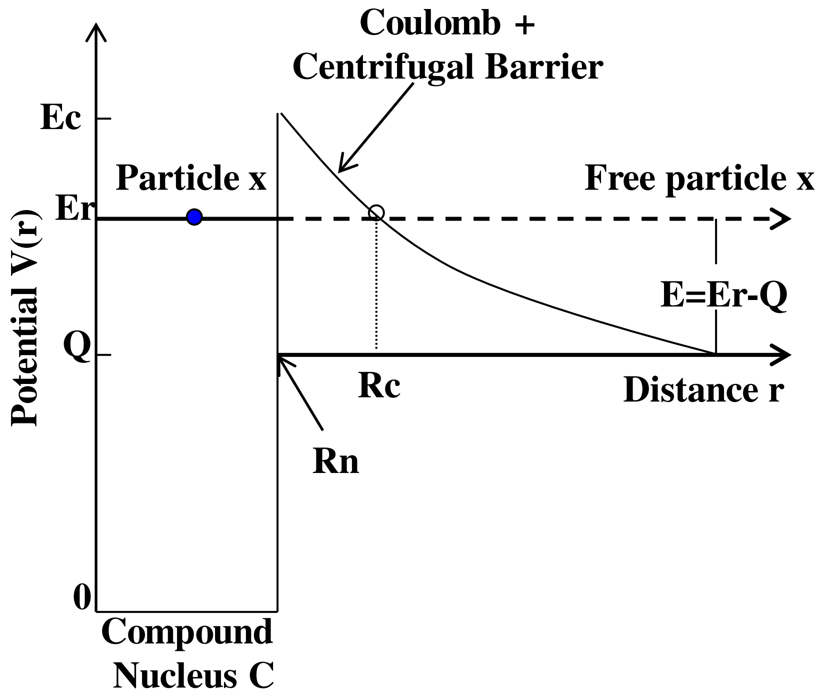
- The resonant reaction rates can be calculated if the resonant parameters (E_R, J_i, $\Gamma_{x,y}$) are known

↓

experiments can be performed to extract these spectroscopic information

Transfer reactions to evaluate the decay partial widths

Let's assume a compound nucleus C in an excited state E_r which has a pure core-particle configuration $\Psi = |A \oplus \alpha>$



The single-particle decay partial width of C into A+α is given by

(See. Illiadis: Nuclear physics of stars)

$$\Gamma_{\alpha}^{s.p} = \left(\frac{\hbar^2}{\mu}\right) R P_l(E,R) |\varphi(R)|^2$$

P_l = penetrability factor

$\varphi(R_n)$ radial wave function of the particle α.

→ For a state with a pure core-particle configuration, $\Gamma_\alpha^{s.p}$ can be calculated

→ In most of cases Ψ is a mixture of configurations and we have $\mathbf{\Gamma_\alpha = S_\alpha \Gamma_\alpha^{s.p}}$

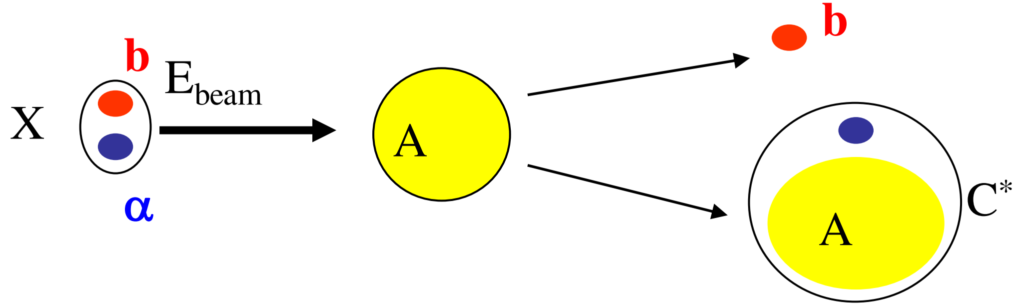
→ $\mathbf{S_\alpha}$ is a measure of the overlap between the initial and final state

→ By determining the **spectroscopic factor** $\mathbf{S_\alpha = <C^*|A \otimes \alpha>^2}$ via transfer reactions, we can calculate $\mathbf{\Gamma_\alpha}$.

Transfer reactions: X(=α+b)+A ⟶ C*(α+A)+b ⟷ α+A ⟶ C* ⟶ C+γ / B+n

- Populate the states of interest in the compound nucleus C* formed by α+A by transferring the particle α from a high-energy projectile **X** assumed to be composite (**X=α+b**) (typical E ~ few tens of MeV >> V_{coul}) to the target nucleus A

What do we measure by detecting b?



- By measuring the energy and angle of the emitted particle b

⇒ Excitation Level energies of the populated states in C*: E_x (kinematics calculations)

- Differential cross-sections of each populated state: **dσ/dΩ**

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab}^{exp} = \frac{Yield\ (\theta_{lab})}{N_p N_T \Delta\Omega}$$

- Yield = Number of b particles measured at each θ
- N_p= number of projectile ions
- N_T = number of target atoms/cm^2 , ΔΩ= Solid angle

Transfer reactions: X(=α+b)+A ⟶ C*(α+A)+b ⟷ α+A ⟶ C* → C+γ / B+n

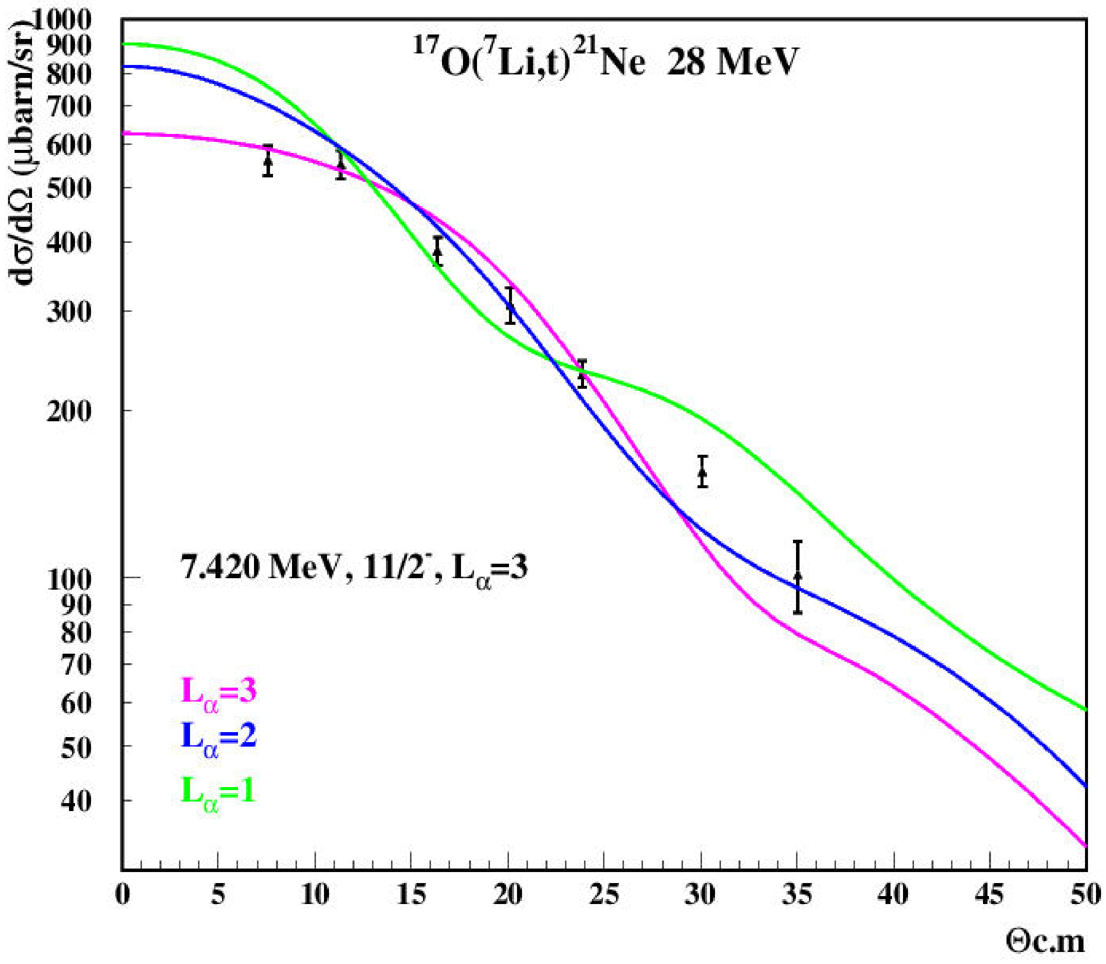
- From the shape of the angular distribution & comparison to a theoretical calculation
  → Angular momentum of the transferred particle
  ⇒ Orbital angular momentum *l* of the single particle bound state

- From the normalisation of the calculations to the data
  → Alpha spectroscopic factor

$$\frac{d\sigma}{d\Omega}\Big|_{exp} = C^2 S'_\alpha S_\alpha \frac{d\sigma}{d\Omega}\Big|_{Th}$$

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

$$S_\alpha = \langle C \,|\, A \otimes \alpha \rangle$$



Theoretical description of transfer reaction

$X(=\alpha+b)+A \longrightarrow C^{*}(\alpha+A)+b$

The Model used to describe transfer reactions in general is: **DWBA** (Distorted Wave Born Approximation) & beyond

DWBA main assumptions:

- Nucleon or cluster transfer occurs directly between the two active channels X+A and C+b: the transferred nucleon or cluster is directly deposited on the final state (no rearrangement in the final nucleus)
- The entrance and exit channels processes are dominated by the elastic scattering → Distorted waves
- The transfer process is weak enough to be treated as a first order perturbation → Born Approximation

DWBA cross section for a transfer reaction can be written as : $\sigma_{tra} \propto \left| \left\langle \chi_f I^C_{\alpha A} \right| \hat{V} \left| I^X_{b\alpha} \chi_i \right\rangle \right|^2$

$\chi_{i,f}$ The distorded wave functions of the initial and final state

$\hat{V}$ Transition operator

$I^C_{\alpha A}(r_{\alpha A})$ & $I^X_{b\alpha}(r_{b\alpha})$ the overlaping functions of the bound states C/X formed by α and A/b

The radial part $I^C_{\alpha A}$ is approximated : $I^C_{\alpha A}(r_{\alpha A}) = S^{1/2}\varphi_{\alpha A}(r_{\alpha A})$ **S** is the spectroscopic factor

$\varphi_{\alpha A}$ Is the radial part of the bound state wave function describing the relative motion α+A in C

From α spectroscopic factors to α-decay reduced widths γ_α^2 or ANCs $\tilde{C}^2$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = C^2 S_\alpha^C S_\alpha^X \left(\frac{d\sigma}{d\Omega}\right)_{DW}$$

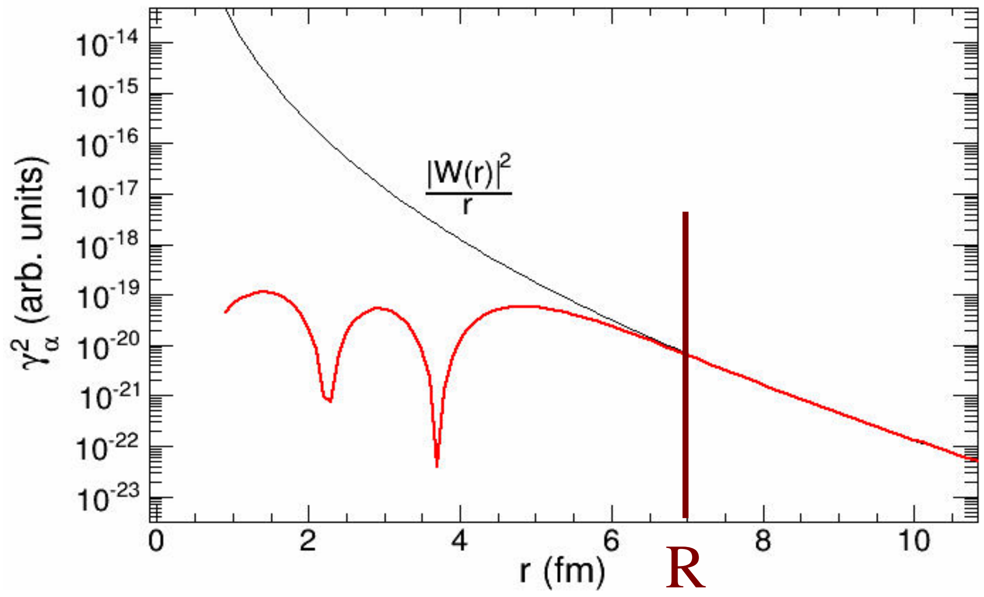
$$S_\alpha^X = \langle X | b \otimes \alpha \rangle \approx 1 \text{ (in most cases)}$$

$$S_\alpha^C = \langle C | A \otimes \alpha \rangle$$

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

$$\tilde{C}^2 = S_\alpha^C \frac{R^2 |\phi(R)|^2}{W(R)^2})$$

W(R): Whittaker function



The calculation has to be done @ a radius R
where $\phi(R)$ reaches its
Coulomb asymptotic behavior

DWBA calculations

- **Codes:** FRESCO, DWUCK,… Thomson, Compt. Phys. Rep. 7, 167 (1988), P.D. Kunz spot.Colorado.edu/~kunz/DWBA.html)

- **DWBA ingredients:**

➢ Appropriate choice of **optical potential** parameters to describe the entrance & exit channels

→ Elastic scattering measurements → X(A,A)X, C(b,b)C or global optical model parametrizations for a given range of mass & energy (Perey & Perey Atom. nucl. Data Tabl. 17 (1976), Daehnick et al. PRC 21,6 (1980),…)

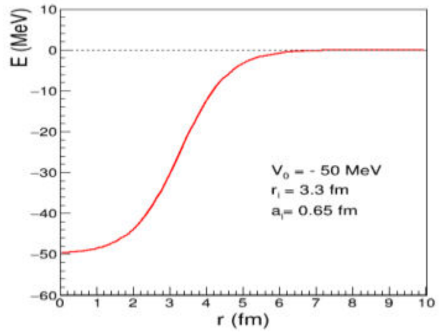
➢ **Binding potential** parameters describing the interaction of the transferred particle with the core in the final & initial nucleus

→The depth V is adjusted to reproduce the binding energy of the bound state

→ Geometry of potential (r_i, a_i) → uncertainty on spectroscopic factor

Wood-Saxon ⟶ $$V(r) = -\frac{V_0}{1+\exp(\frac{r-r_i}{a_i})}$$

V_0: depth of the potential (MeV)
r_i: radius
a_i: diffusivity



Which alpha transfer reactions?

- **(^{7}Li,t), (^{6}Li,d) alpha transfer reactions:** → to evaluate (α,n) & (α,γ) reactions by extracting $S_\alpha \rightarrow \Gamma_\alpha$

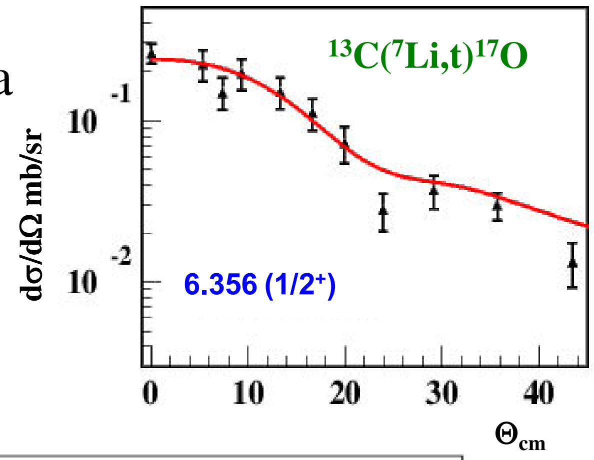
Note: - (^{7}Li,t) → less affected by multi-step effects **F.H and N. de Séréville, fphy.2020.602920 & references therein**

→ cross-sections to low spin states enhanced because of the non-zero α-angular momentum in ^{7}Li:

$J^\pi(^7Li)=1/2^+$ $J^\pi(t)=3/2^+ \Rightarrow L_\alpha=1$ → less momentum mismatch

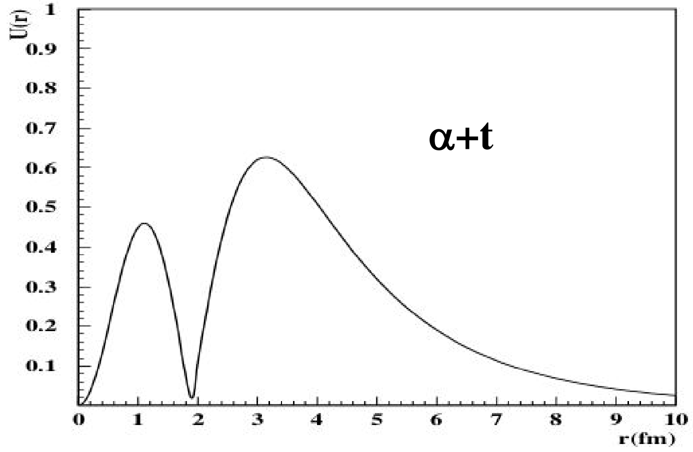
→ angular distributions → stronger direct features: more forward pronounced maxima

→ populate more selectively states with α structure



- e.g : - ^{13}C(^{7}Li,t)^{17}O for ^{13}C(α,n)^{16}O **Pellegriti et al. PRC (R) 2008**
  ^{12}C(^{7}Li,t)^{16}O for ^{12}C(α,γ)^{16}O **Oulebsir et al. PRC 2012**
  ^{7}Li(^{22}Ne,t)^{26}Mg (ANC) for ^{22}Ne(α,n)^{25}Mg **Jayatissa et al. PRC 2020**

⟶ Cluster transfer ⇒ Describe the interaction potential of <α+t|^{7}Li> overlaps for (^{7}Li,t) transfer → Finite range DWBA (FR-DWBA)

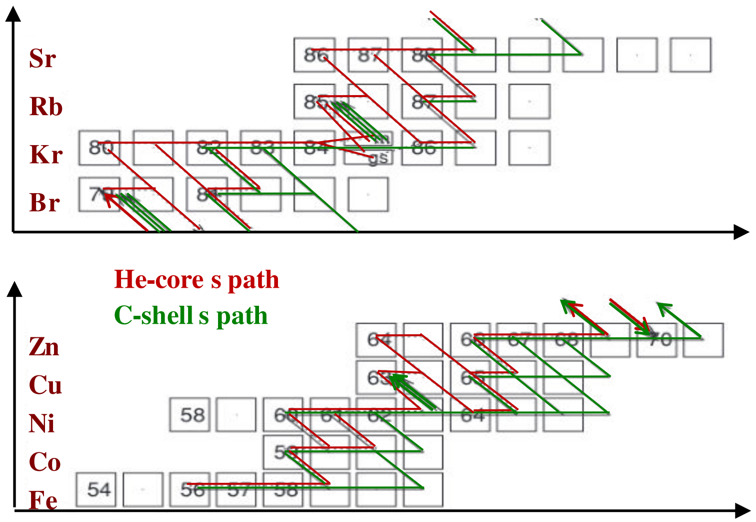


s-process in rotating metal-poor massive stars

- *s*-process nucleosynthesis → half of the abundance of heavy elements in Universe
- 60<A<90 (weak s-process component) → massive stars M>8M$_\odot$

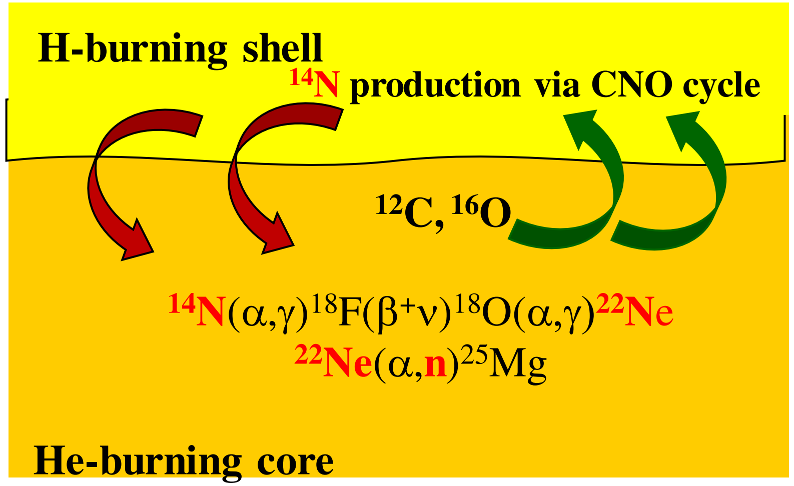
Core He burning (T ~3·10^8 K, $N_n = 10^6$ cm^{-3})
&
shell Carbon burning (T~10^9 K, $N_n = 10^{11}$ cm^{-3})

} ^{22}Ne(α,n)^{25}Mg



Pignatari+ 2010

- Metal-poor massive stars → 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**

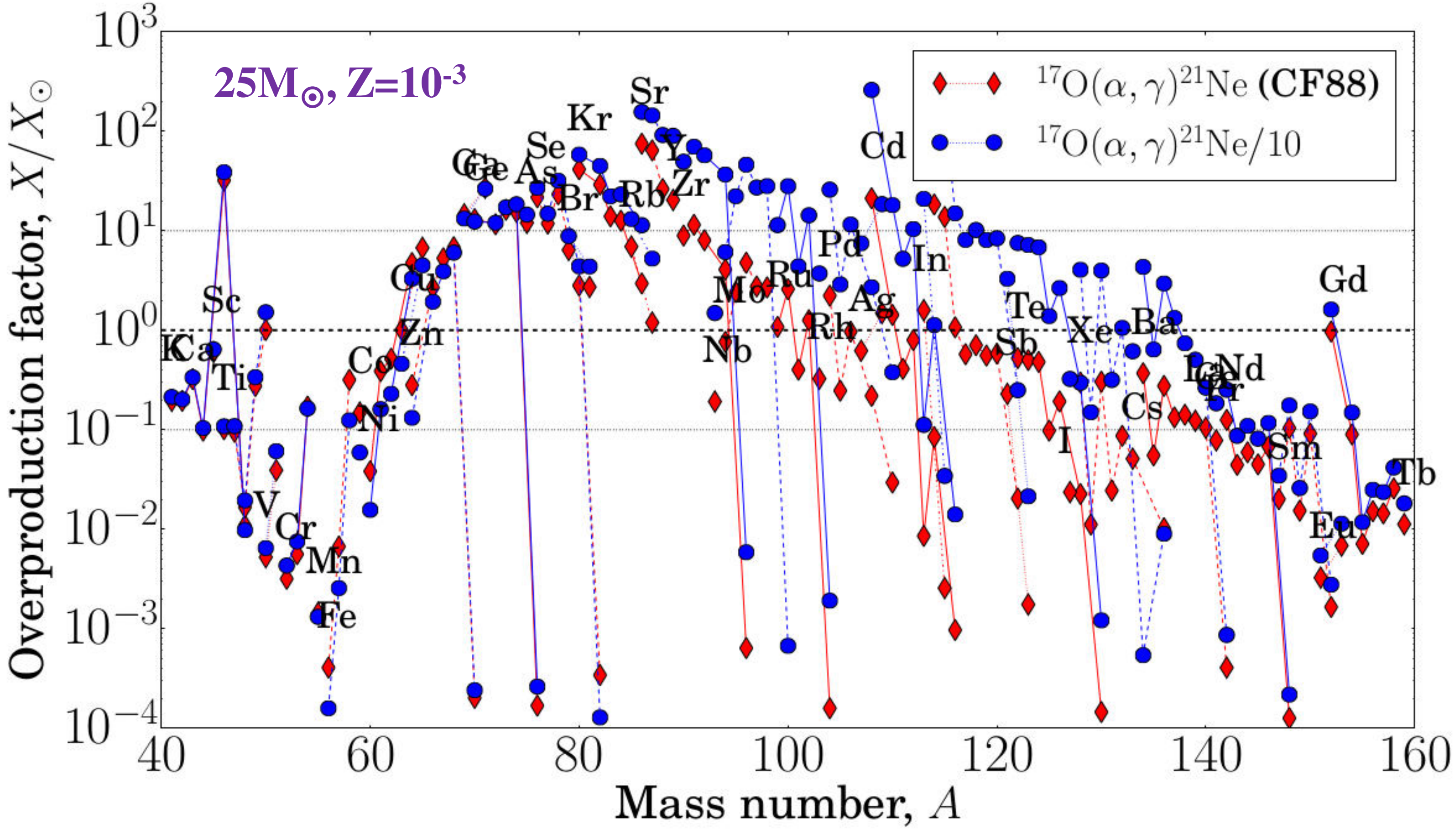
→ Origin of the observed enhanced s-elements in globular cluster NGC6522 **Barbuy+09** & in CEMP stars **Beers+05** ?

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

Present 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 → $0.63 \leq E_{cm} \leq 1.8$MeV**
- **Best +2011, Taggart+2019**
- **Williams+2022**

$0.63 \leq E_{cm} \leq 1.33$MeV (Best +2011, Taggart+2019, Williams+2022)

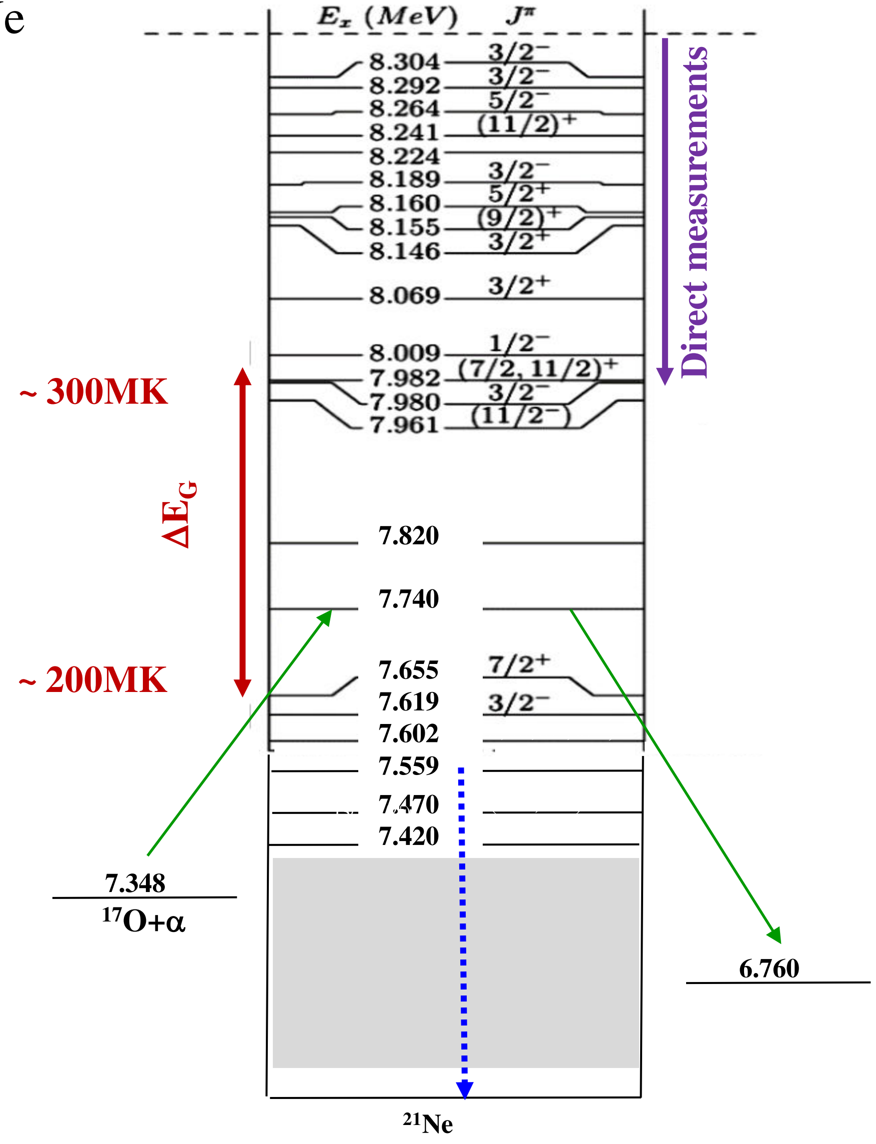
- No direct measurements @ $E_{cm}<0.63$ MeV (Core He burning)

- Spectroscopy of ^{21}Ne: E_x, S_α or Γ_α, J^π, $\Gamma_\gamma/\Gamma_{tot}$,Γ_n …

  ↳ $^{17}O(\alpha,n)$ and $^{17}O(\alpha,\gamma)$ rates (core He burning)

→ Unknown or poorly known S_α (Γ_α) & Γ_n , $\Gamma_\gamma/\Gamma_{tot}$
→ Few have spin-parity assignments

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

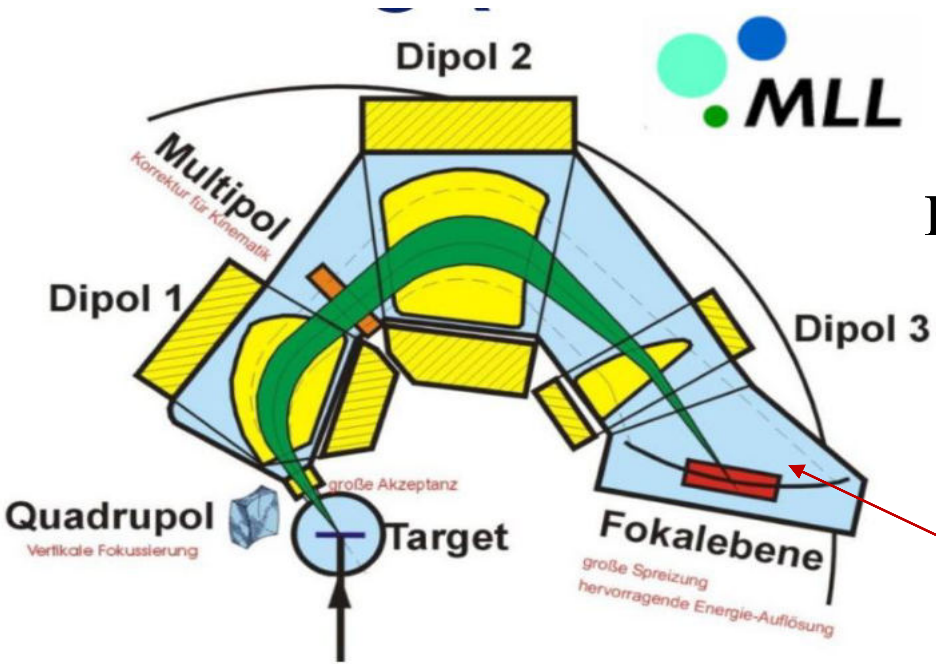


Study of ^{21}Ne states via ^{17}O(^{7}Li,t)^{21}Ne α-transfer reaction

F.H, P. Adsley, L. Lamia, S. Harrouz,N. de Séréville+coll

Q3D spectrometer (MLL)

- **Beam ^{7}Li**: E=28 MeV
  I=100 nAe
- **Targets**:
  - W^{17}O$_3$ (41 μg/cm^2) enriched at 35% on ^{nat}C
  - W^{nat}O$_3$ (39 μg/cm^2) on ^{nat}C
- **Solid angle**: 6 to 12.4 msr
- **Energy resolution ΔE/E** ~ 2 x 10^{-4}



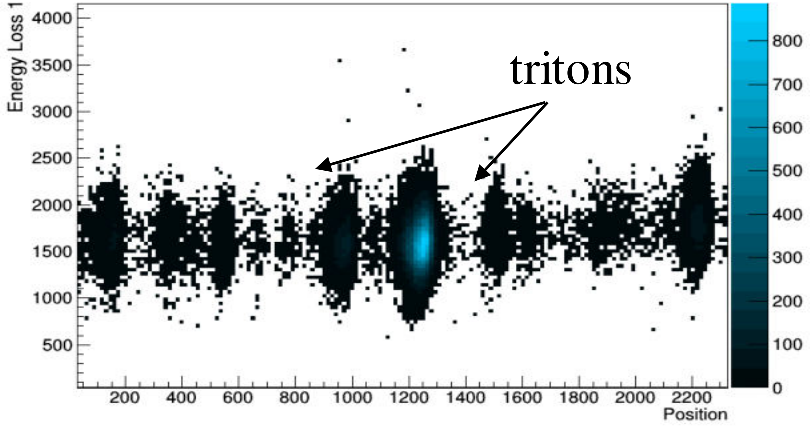
Beam

Bρ=mv/q

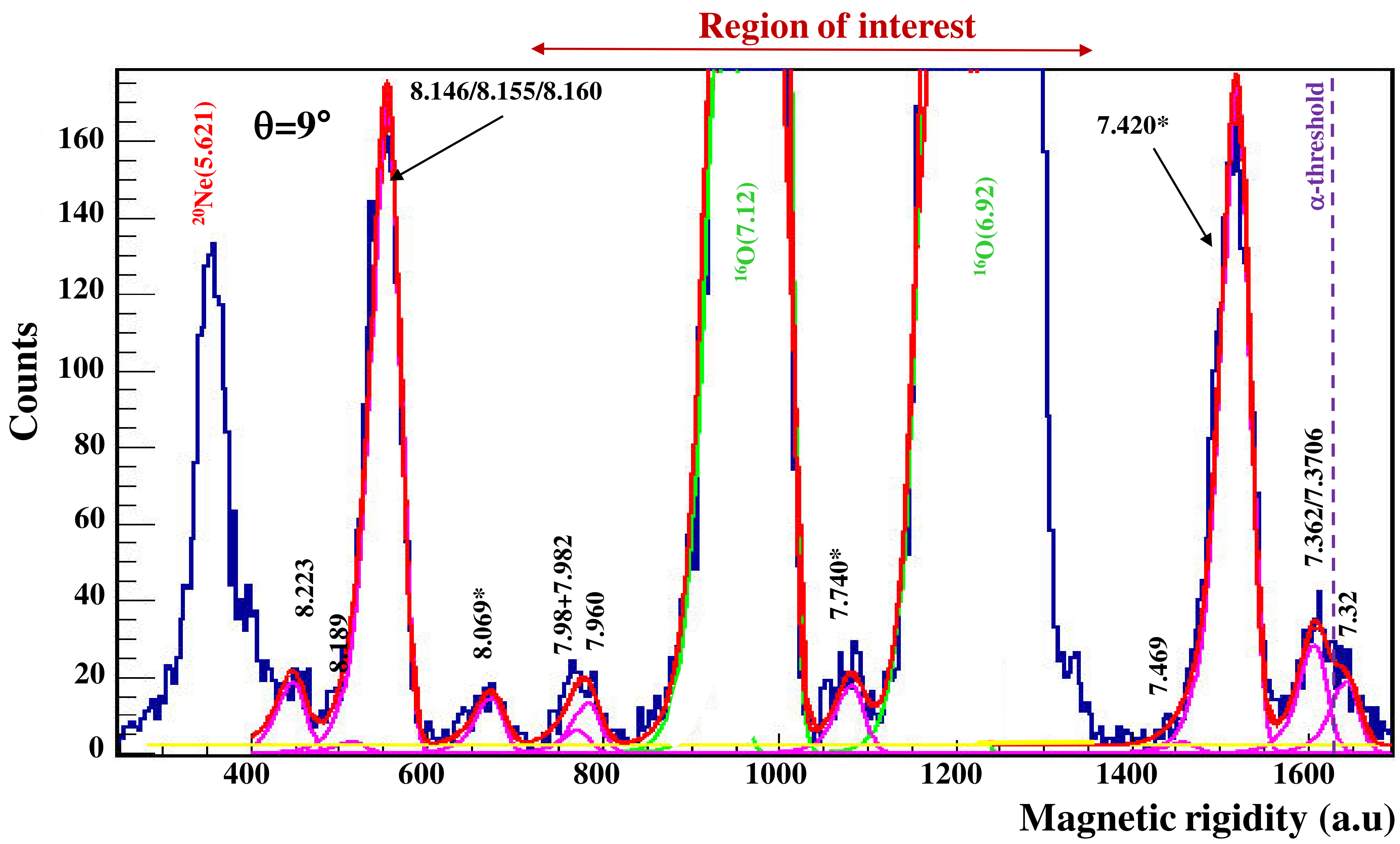
- 2 proportional gas counters: **Pos, ΔE$_1$, ΔE$_2$**
- plastic scintillator: **E**

dσ/dΩ measurements:

- 9 angles θ_{lab}= 6°-36° ⇒ θ_{cm} → 7.5°- 45°
- on W^{17}O$_3$ & on W^{nat}O$_3$ for calibration & background evaluation
- At 3 different times at 6° to check the stability of the target



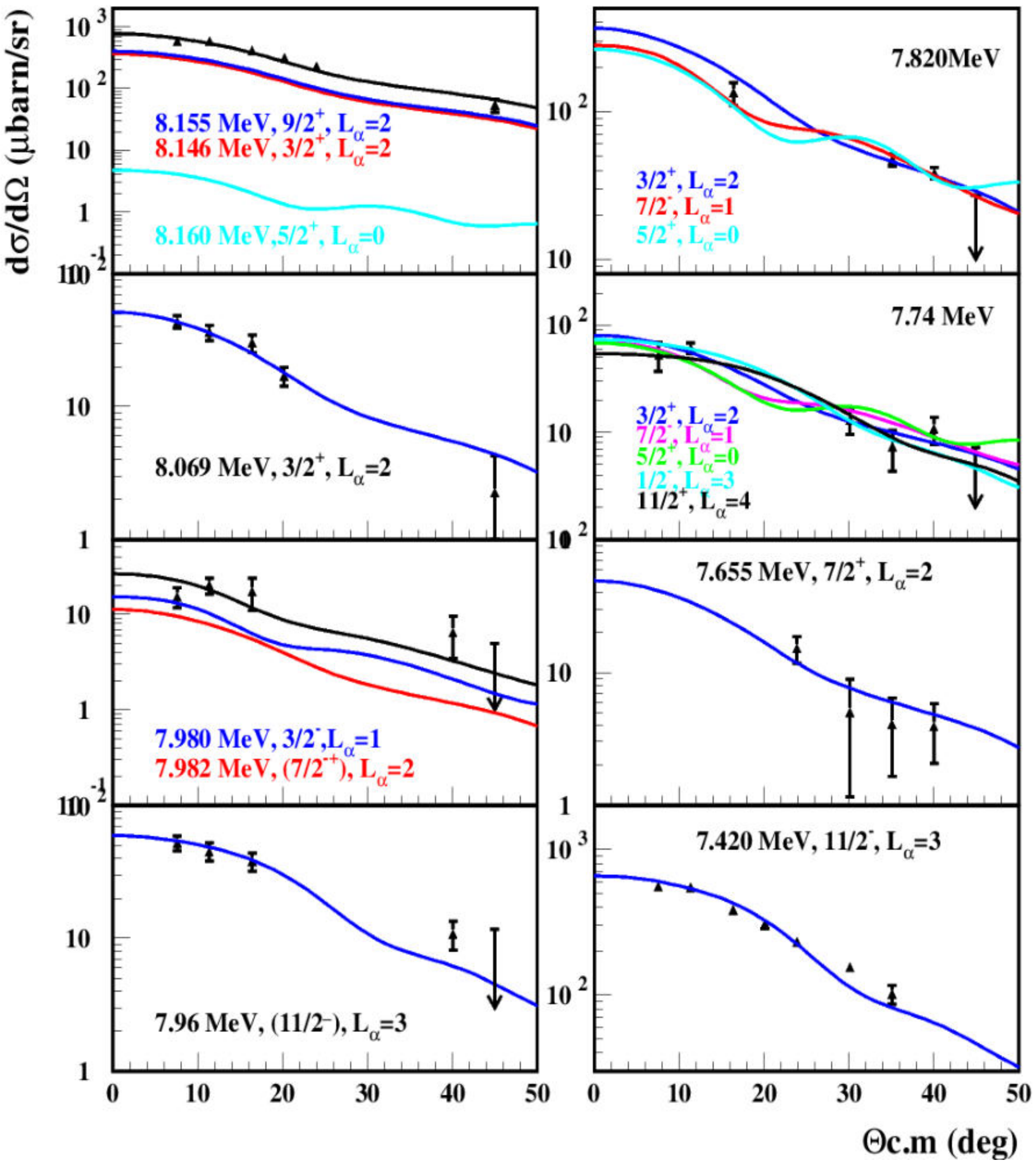
Excitation energy spectrum of ^{21}Ne



- Fit with multiple skewed gaussians with common width & exponential factor

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

FR-DWBA calculations



- Good description of the data by DWBA ➔ Direct transfer mechanism

- Triplet 8.160/8.155/8.146: Fit with 3 components
  $\rightarrow S_\alpha$ of 8.146 & 8.160 MeV derived from Γ_α **Best+2013**
  $\Rightarrow S_\alpha$(8.155 MeV)=0.15 **(present work)**

- Doublet 7.980/7.982 MeV: Fit with 2 components
  $\rightarrow S_\alpha$ of 7.98 MeV deduced using $\omega\gamma(\alpha, n)$ **Denker+94**
  $\Rightarrow S_\alpha$(7.982 MeV)=0.005 **(present work)**

- 7.820 MeV
  $\rightarrow$ Best χ^2 for L_α=0,1 & good for L_α=2
  $\rightarrow L_\alpha=0 \rightarrow S_\alpha$ =0.61 (unlikely)

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

@ R=7.5 fm

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

$^{17}O(\alpha,n)$ & $^{17}O(\alpha,\gamma)$ reaction rates & $(\alpha,n)/(\alpha,\gamma)$ rate ratio

Rates calculations:

RateMC code **Longland+2013**

- For Er < 721 keV & Er=807 keV: Γ_α (**present work**)

Γ_α (7.82MeV) for $L_\alpha=1$ ($L_\alpha=0$ in Best+2013)
Γ_α (7.74 MeV) for $L_\alpha=0$ (as in Best+2013)

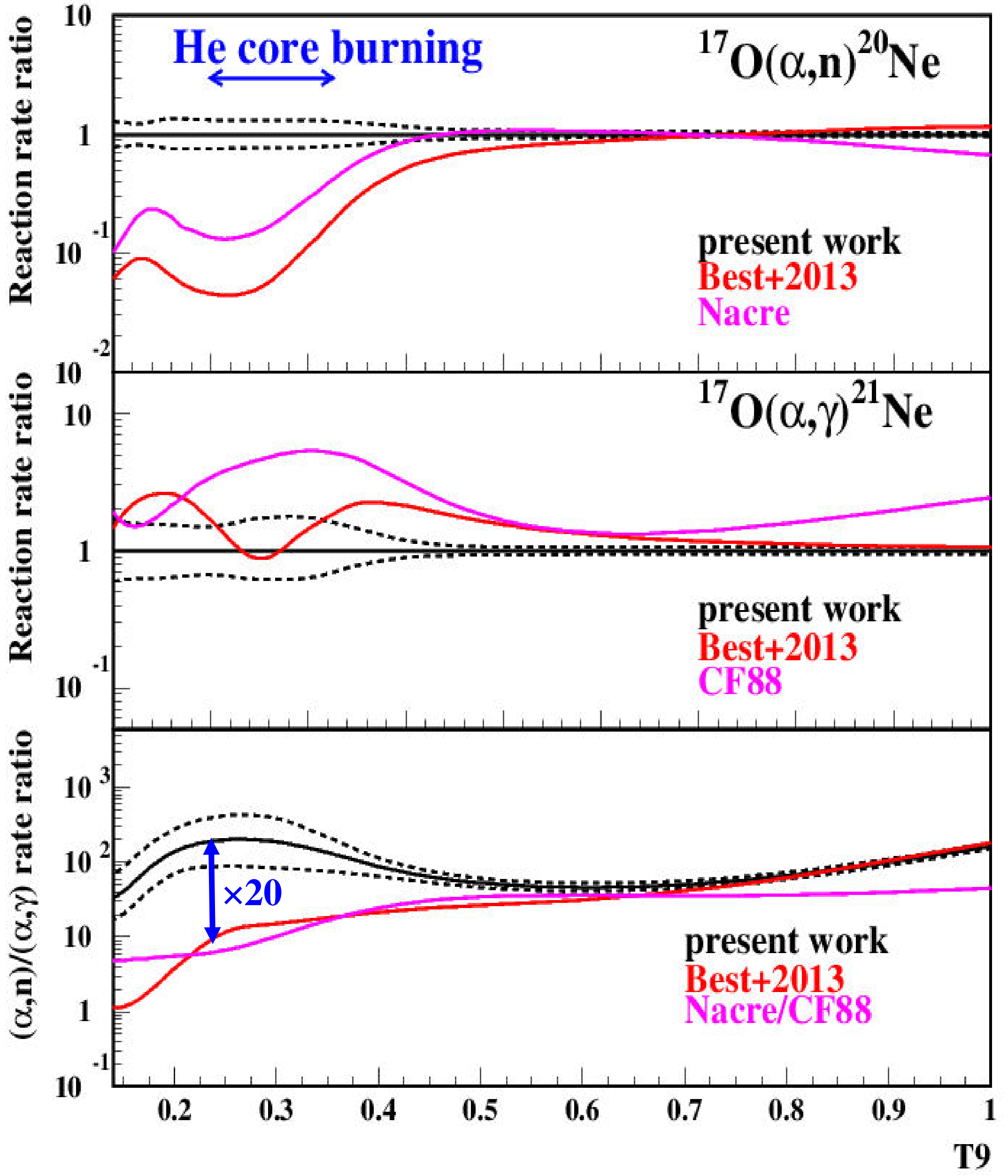
→ Γ_n **Frost-Schenk+2022**

- For Er≥ 721 keV :
  → Γ_α & Γ_n (**Best+2013** direct measurement)

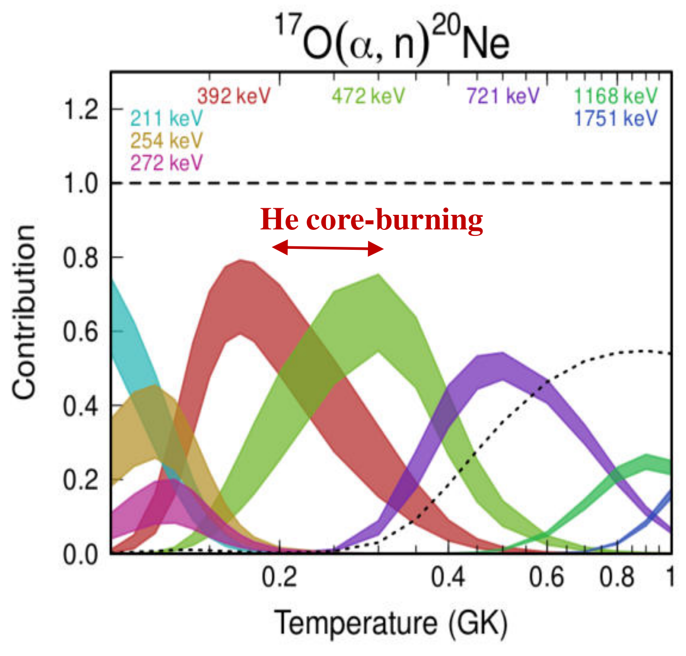
- Γ_γ from:

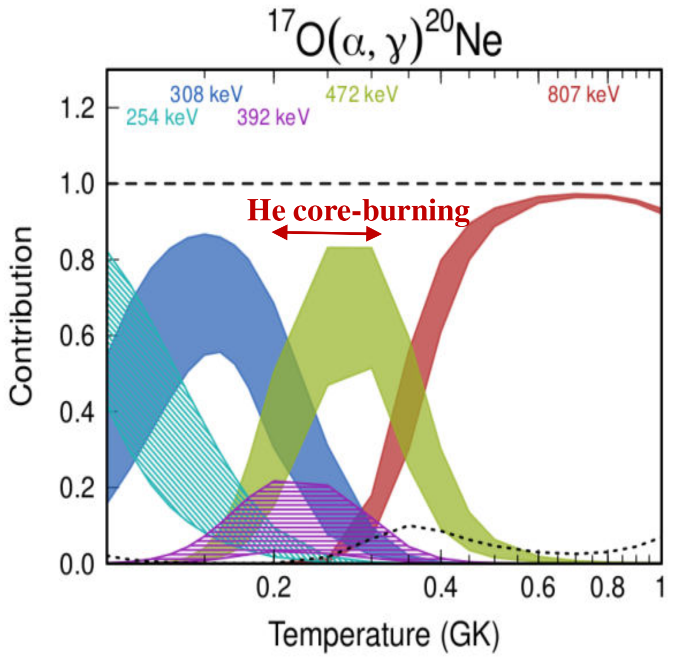
→ systematics of $<\tau>_{meas}$ **(Rolfs+72)**
→ $\omega\gamma(\alpha,\gamma)$ **Williams+2022** combined with present Γ_α & Γ_n **(Frost Schenk+22)**
→ when no Γ_n → Γ_γ/Γ_n **Best+2013**

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



Resonances contribution to the rates

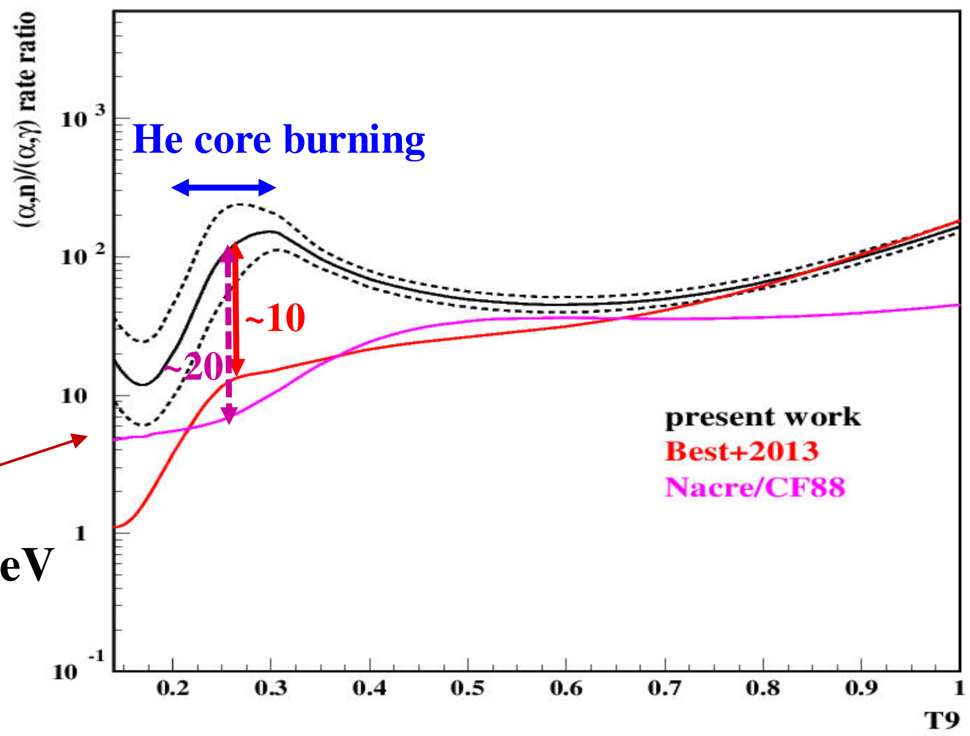




- Er=392 (Ex=7.74 MeV) & 472 keV (Ex=7.82 MeV) **contribute the most** to the (α,n) rate
- Er=308 (Ex=7.65 MeV) & 472 keV (Ex=7.82 MeV) **contribute the most** to the (α,γ) rate

→ **Ex=7.74 MeV** unknown L_α & J^π
→ **Ex=7.82 MeV** L_α =0,1,2 & L_n=2,3 ⇒ J^π=$5/2^+$, $7/2^-$, $3/2^+$

Key resonances
↓
J^π need to be constrained

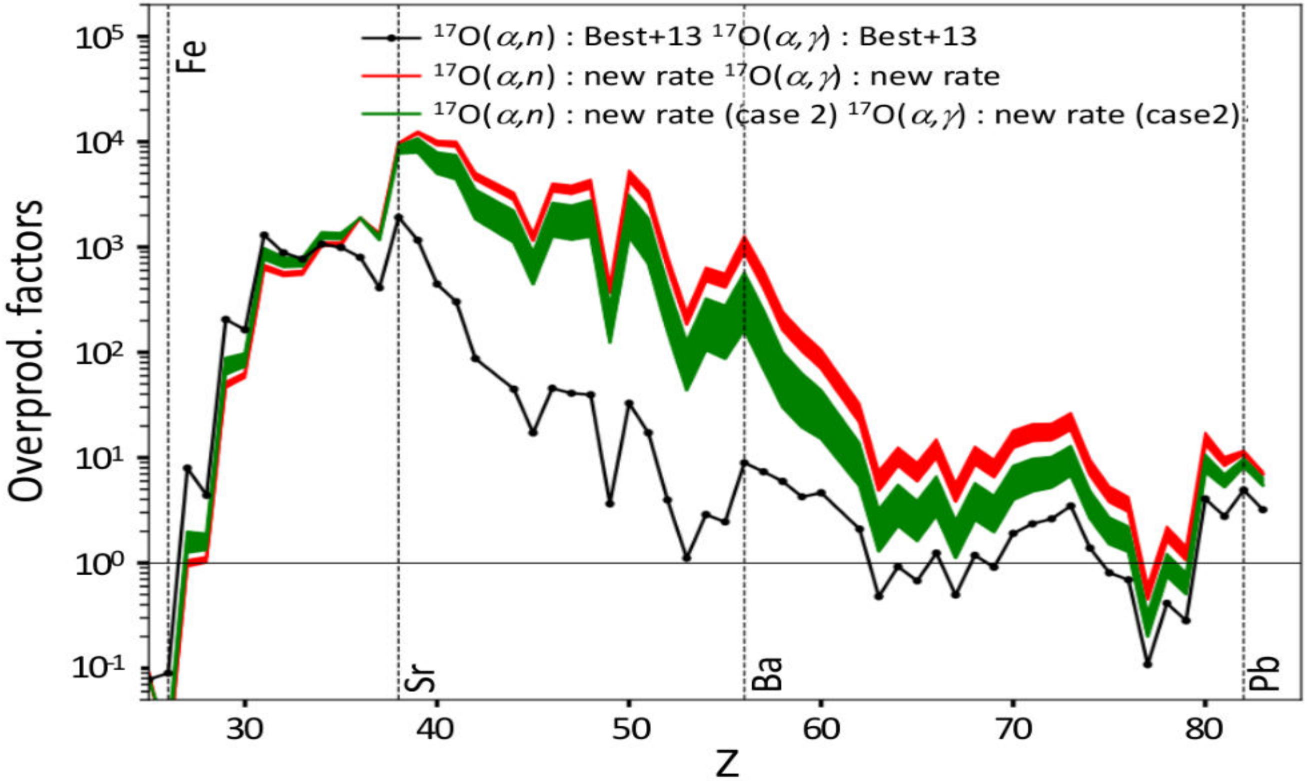


With the least favorable case: 7.82 MeV L_α=2 → $3/2^+$ or $7/2^+$ & no 7.74 MeV

Present (α,n)/(α,γ) rate ratio ~ 10 × rate ratio Best+2013

Impact on the s-process in rotating poor-metal massive stars

- One-zone nucleosynthesis calculation mimicking the core He-burning phase of a low metallicity rotating massive star (Z=0.001, M=25 $M_\odot$)

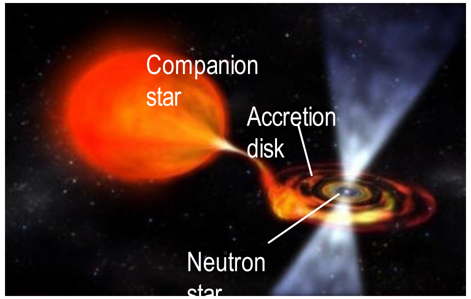


→ **Large enhancement** (>1.5 dex (>1.3 dex)) of elements 40 < Z < 60 with the present **new rates** in comparison to **Best+13** rates

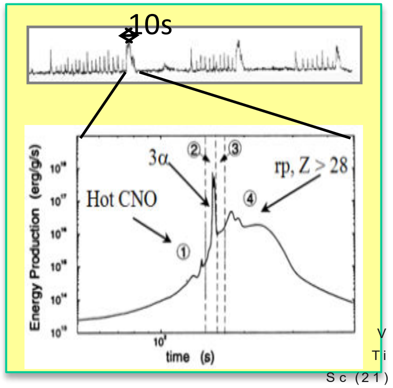
→ **Two order** of magnitude (**~1.5 dex (case2)**) on **Barium** : largest effect

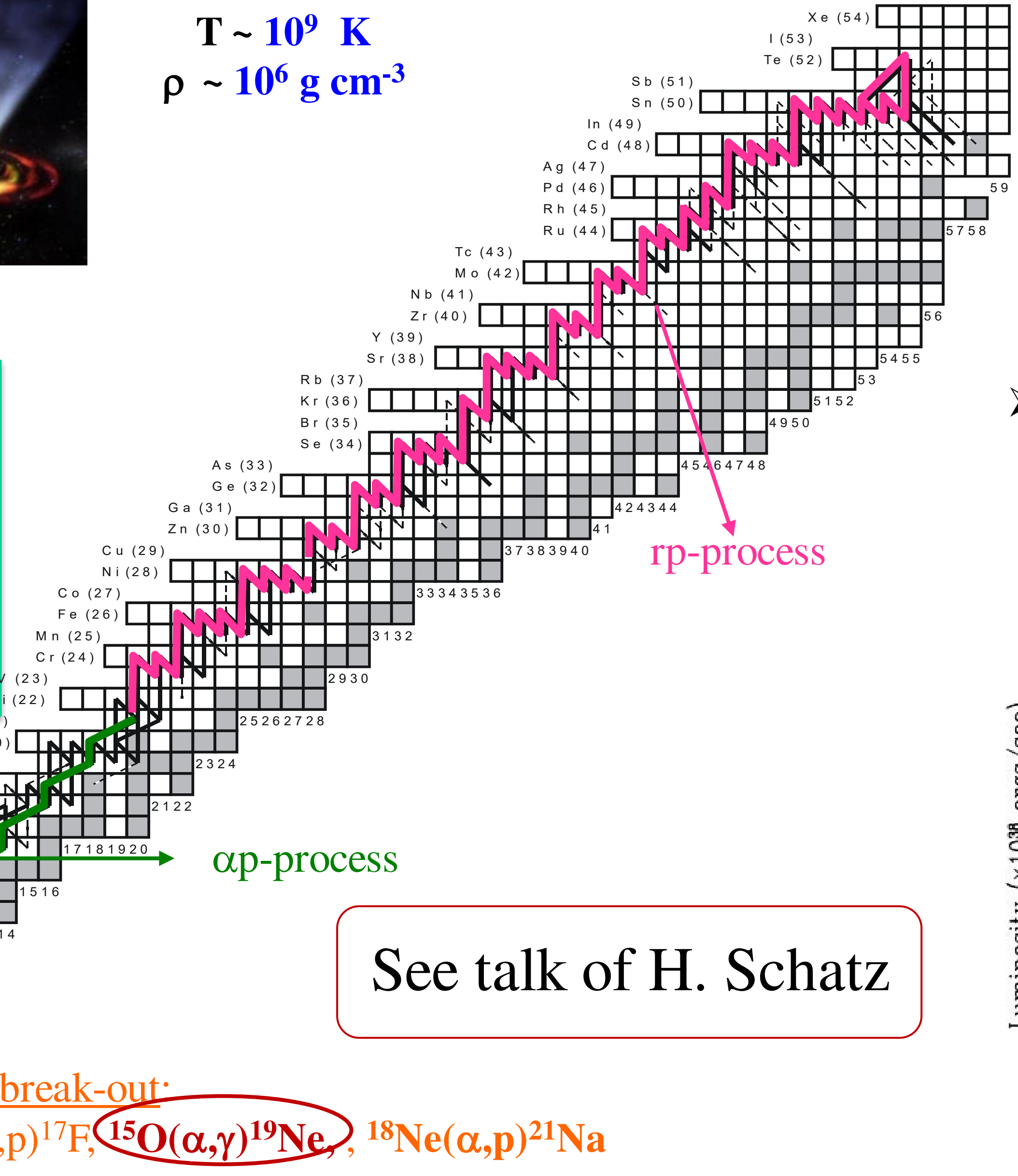
F. H, P. Adsley, L.Lamia+submitted to PRL

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



T ~ 10^9 K
ρ ~ 10^6 g cm^{-3}





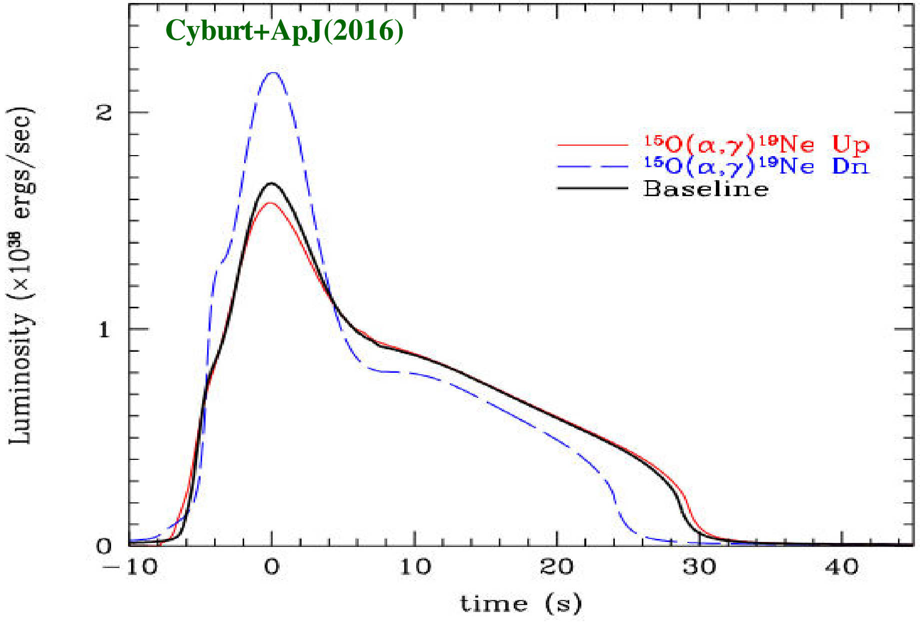
Courtesy to H.Schatz

See talk of H. Schatz

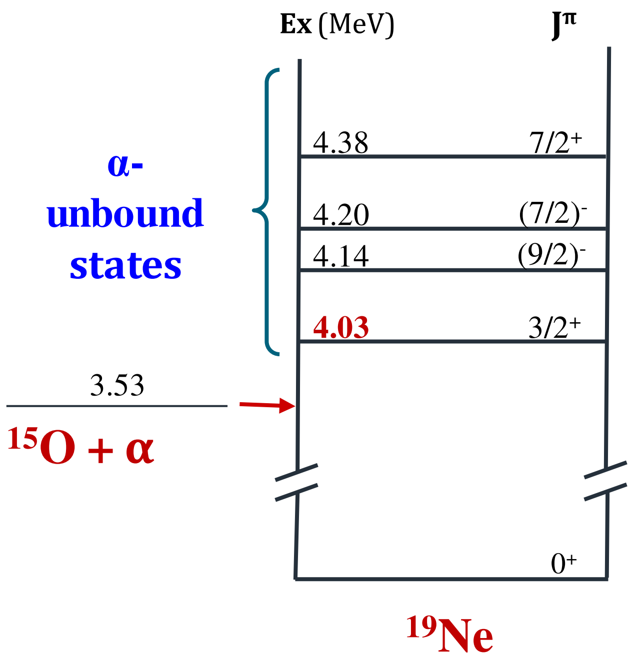
- Triggered by 3α → ^{12}C reaction & Hot CNO break-out
- (α,p) process: (α,p)(p,γ) - Up to A< 60
- rp-process: (p,γ) & β+ decay up to A ~80 -100

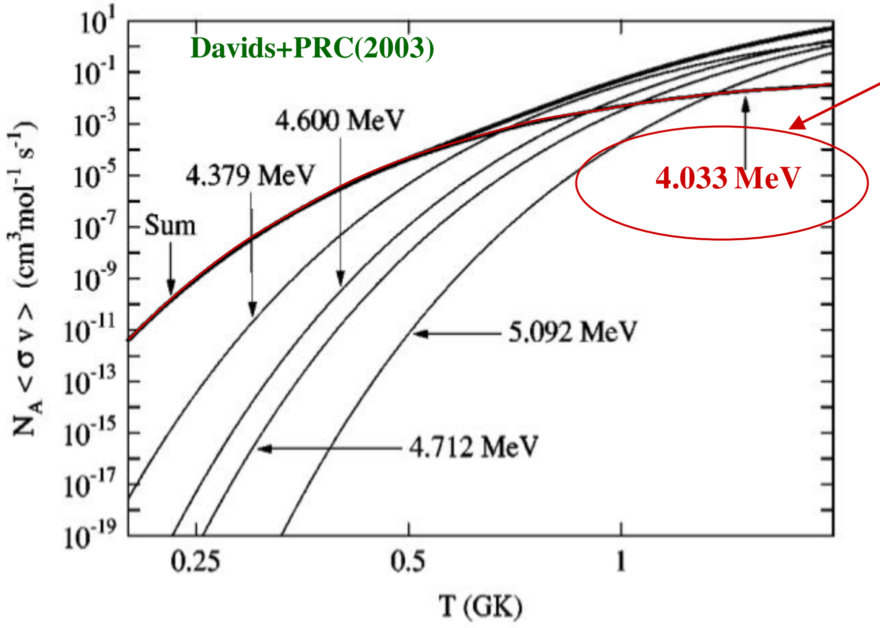
Sensitivities studies: **Cyburt+(2016) , A. Parikh+ (2013)**

- 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





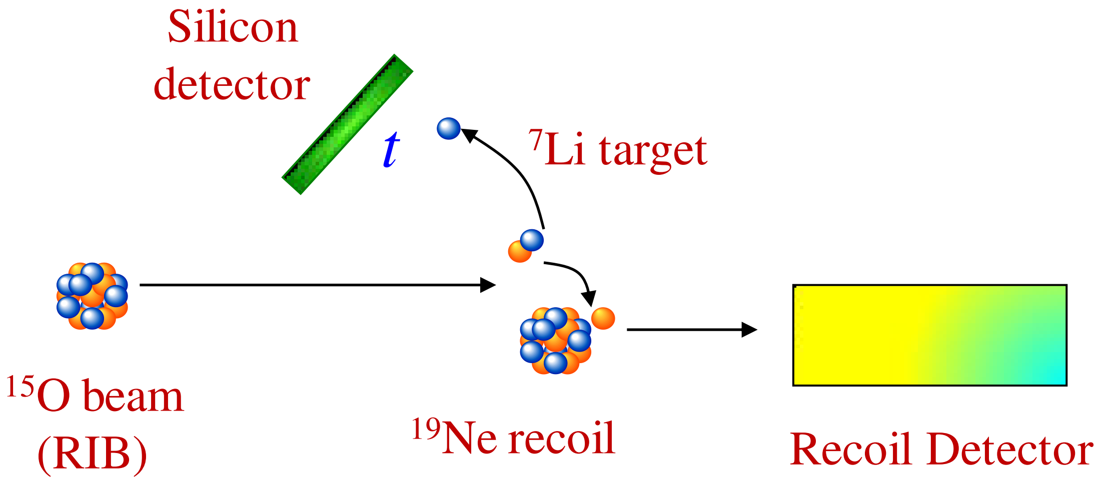
- Biggest contribution to $N_A\langle\sigma v\rangle$
- $\omega\gamma_\alpha \propto \Gamma_\alpha$ determination consistent with zero at 90% confidence level **Tan+PRL07 & PRC05**

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

Alternative:

Measure σ(α,γ) via **$^{15}O(^{7}Li,t)^{19}Ne$** transfer reaction in **inverse kinematics**

→ **Forward θ_{cm}** ↔ **backward θ_{lab}**



Experimental characteristics for α-transfer reactions with RIB

$$Y = N/t = N_{proj} \times N_{target} \times d\sigma/d\Omega \times \Delta\Omega$$

(^{7}Li,t) with stable beam

- I_{beam} ~ 100 pnA, q = 3+ → N_{proj} ~ 2.10^{11} pps
- target thickness ~ 100 µg/cm^2 → N_{target} ~ 4.10^{18} at/cm^2
- $\Delta\Omega$ ~ 5 msr (e.g. Split-pole, Q3D magnetic spectrometers)

→ $N_{proj} \times N_{target} \times \Delta\Omega$ ~ 4 s^{-1} mb^{-1} sr

(^{7}Li,t) with RIBs

- Beam intensity: Typical 10^5 pps [^{15}O ~ 10^7 pps] → 6 orders of mag. less wrt stable beams ☹
- Light particle detection system (tritons)
  → need of large coverage detection system : silicon array $\Delta\Omega$ ~ 2π sr
  → 3 orders of mag. higher wrt stable beams ☺
- Target thickness
  → Typical ~ mg/cm2 (one order of mag. higher)
  → Compromise between statistics and energy resolution ☺ ☹

→ $N_{proj} \times N_{target} \times \Delta\Omega$ ~ 0.04 s^{-1} mb^{-1} sr

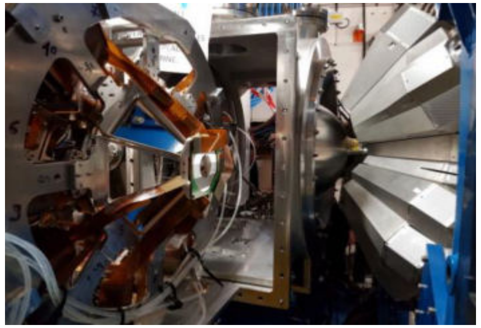
Very challenging experiments… but feasible!

- Relatively long: ~10 days
- Relatively "low" statistics

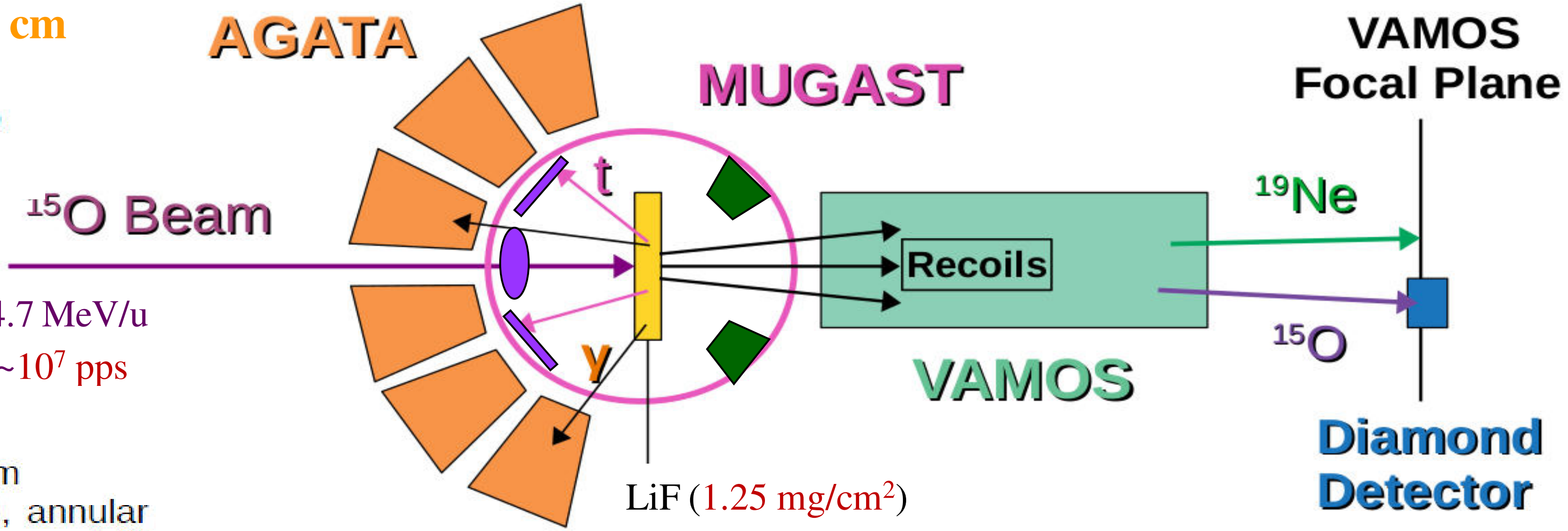
$^{15}O(\alpha,\gamma)^{19}Ne$ case: Experiment & results

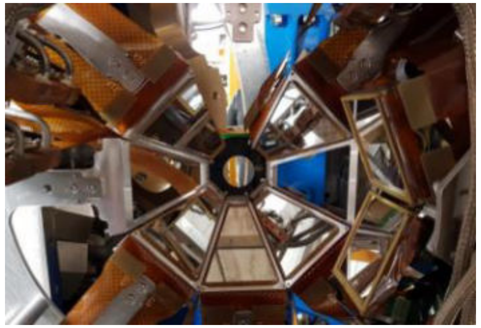
⇒ Studied via $^{7}Li(^{15}O,t)^{19}Ne^{*}(\gamma)^{19}Ne$ @ **SPIRAL1/GANIL**

J.Sanchez Rojo, C. Diget, N. de Séréville & AGATA-MUGAST-VAMOS coll

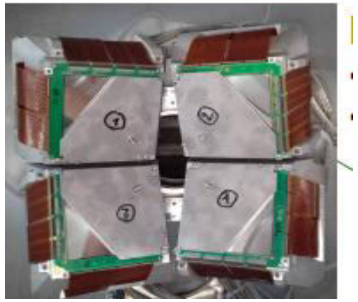


AGATA @ 18 cm
- 37 crystals
- ε(1 MeV) ~ 8% w/ add-back





MUGAST
- DSSSD 500 µm
- Trapezoid (x5), annular (x1) and square (x2) shapes
- 128+128 strips



MUST2
- DSSSD 300 µm + CsI
- 128+128 strips

➢ **Triple coincidence:**

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

VAMOS @ 0°2
- ΔΘ ± 7°
- ΔBρ ± 10° (~)

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

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

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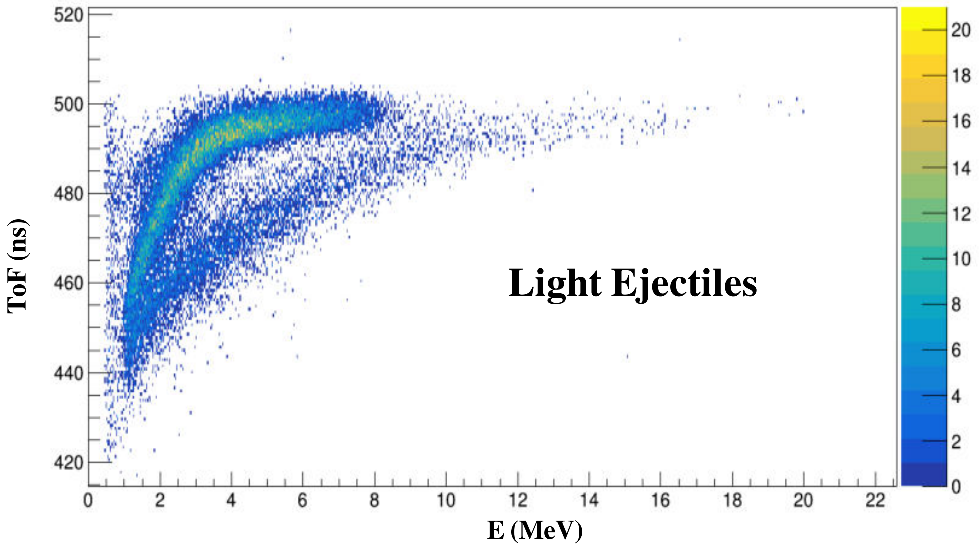

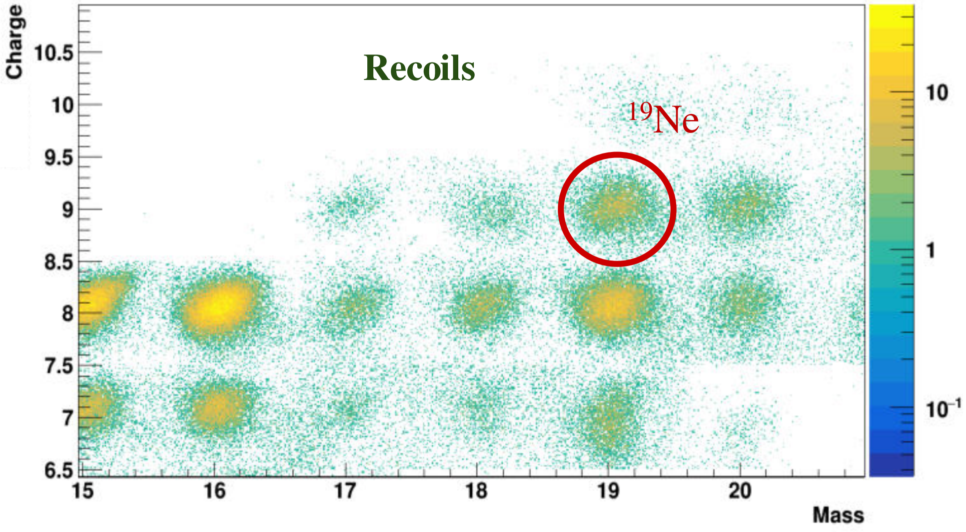

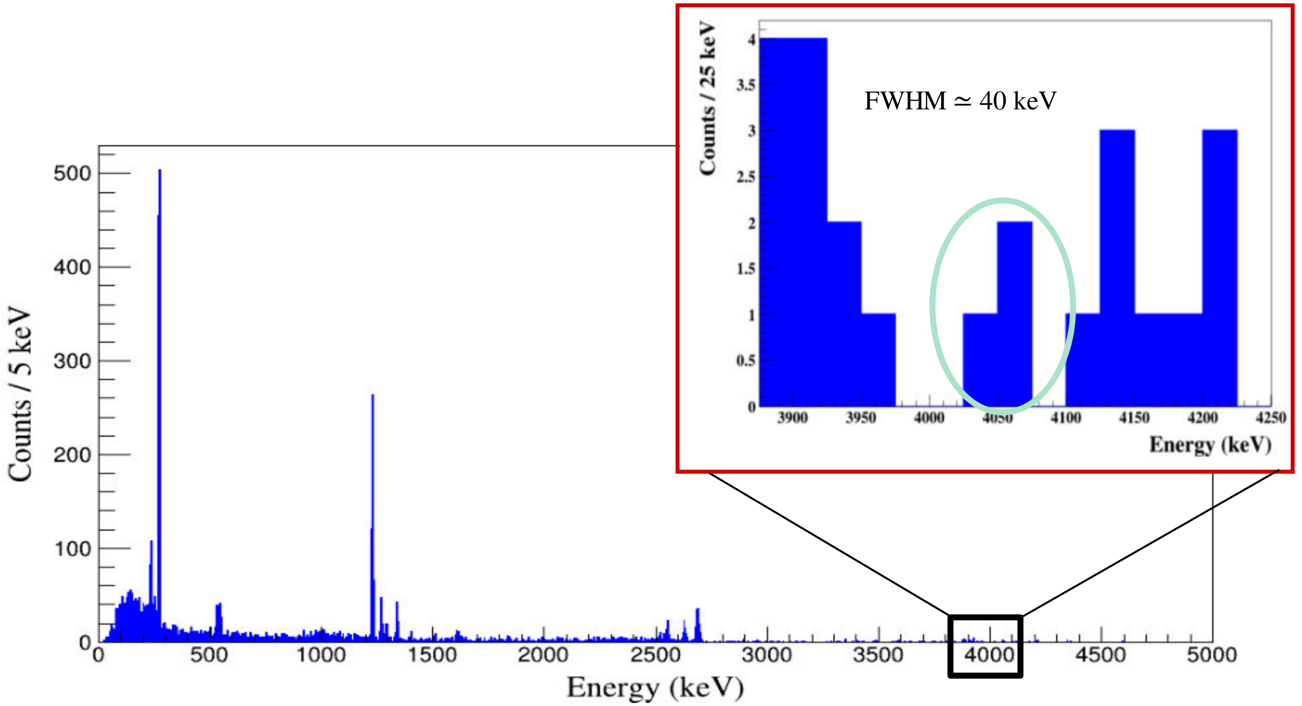

$$N=3^{+2.9}_{-1.6}$$

Not consistent with zero at 95% confidence level!

→ $\omega\gamma_\alpha$ (present work) < $\omega\gamma_\alpha$(previous) by a factor 5

- ➢ **$^{15}O(\alpha,\gamma)^{19}Ne$** reaction rate smaller than previous estimations
- ➢ **$^{18}Ne(\alpha,p)^{21}Na$** the competitive breakout channel…

J.Sanchez+(in prep)

Summary

Advantages of alpha-transfer reactions

- High cross sections
- Can be used to extract alpha partial widths (spectroscopic factors) , angular momenta, resonance energy of key resonant reaction cross-sections

Limitations & warnings

- Sensitivity of the spectroscopic factors to potential parameters → **30-40%** uncertainty
- Be aware about other possible reaction mechanisms:

→ Multi-step transfer

→ Compound nucleus : Hauser-Feschbach calculations (statistical model) needed

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Collaboration

$^{17}O(^{7}Li,t)^{21}Ne$ experiment

FH, P. Adsley (Texas AM), L. Lamia (LNS-Catania), D. S. Harrouz (IJCLab-Orsay) , N. de Séréville (IJCLab-Orsay), B. Bastin (GANIL), A. Choplin (ILB-Brussels), T. Faestermann (MLL), C. Fougères (GANIL), R. Hertenberger (MLL), R. Hirschi (Keele), M. La Cognata (LNS-Catania), A. Meyer (IJCLab-Orsay), S. Palmerini (Perugia), R. G. Pizzone (LNS-Catania), F.de Oliveira Santos (GANIL), S. Romano (LNS-Catania), A. Tumino (LNS-Catania) and H.-F. Wirth (MLL)

$^{15}O(^{7}Li,t)^{19}Ne$ experiment

J.Sanchez Rojo (York),
C. Diget (York),
N. de Séréville (IJCLab-Orsay)
&
AGATA-MUGAST-VAMOS collaboration

THANK YOU FOR YOUR ATTENTION