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New determination of $^{17}O+\alpha$ reaction rates and impact on the s-process in metal-poor rotating massive stars

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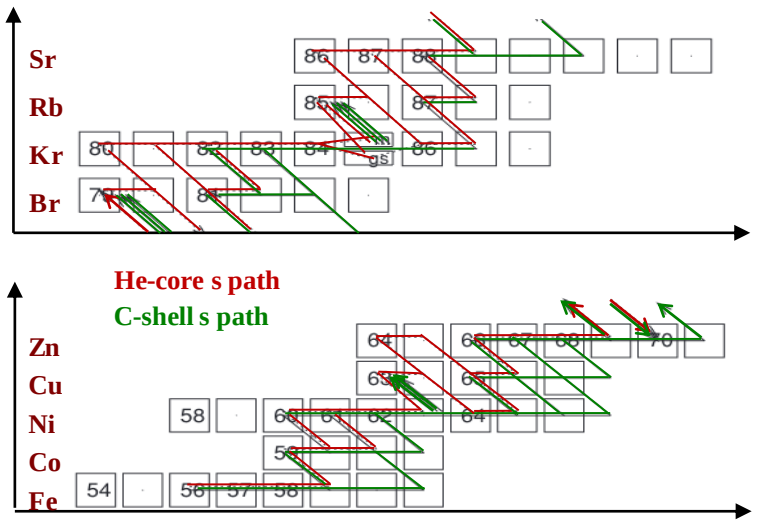
s-process in rotating metal-poor massive stars

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

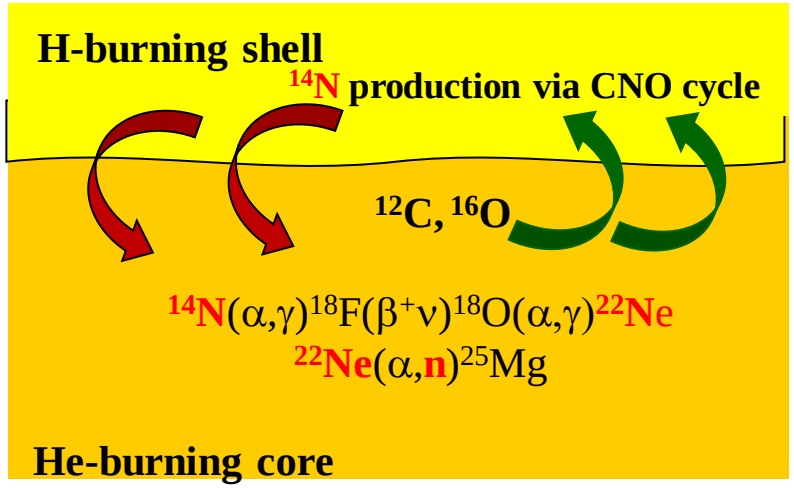
Core He burning ($T \sim 3\cdot10^{8}$ K, $N_n = 10^{6}$ cm^{-3})
&
shell Carbon burning ($T \sim 10^{9}$ K, $N_n = 10^{11}$ cm^{-3})

} ^{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.

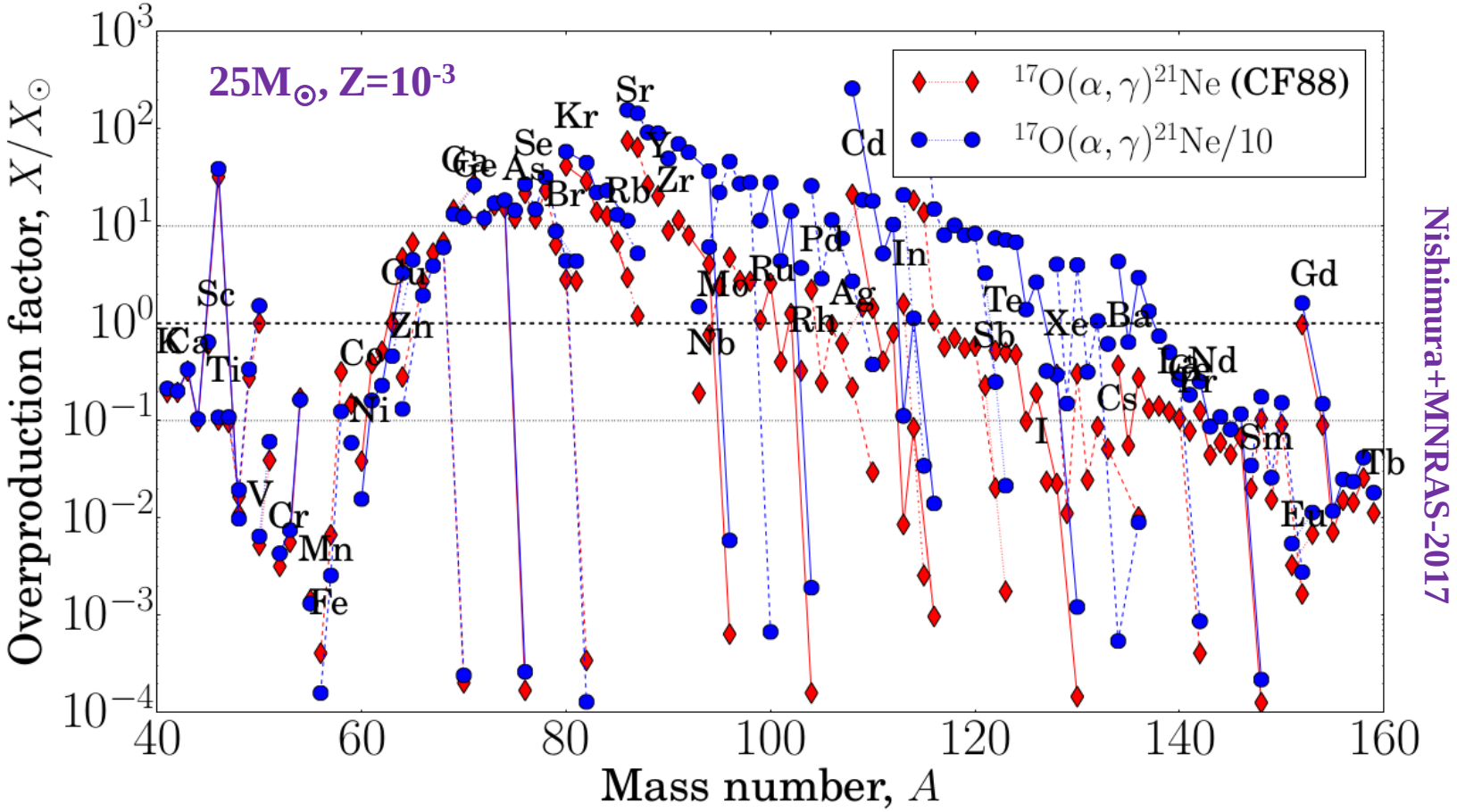
→ Source of heavy elements such as Barium in the early universe? **Barbuy+14**

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



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

} **$0.63 \le E_{cm} \le 1.33$MeV**

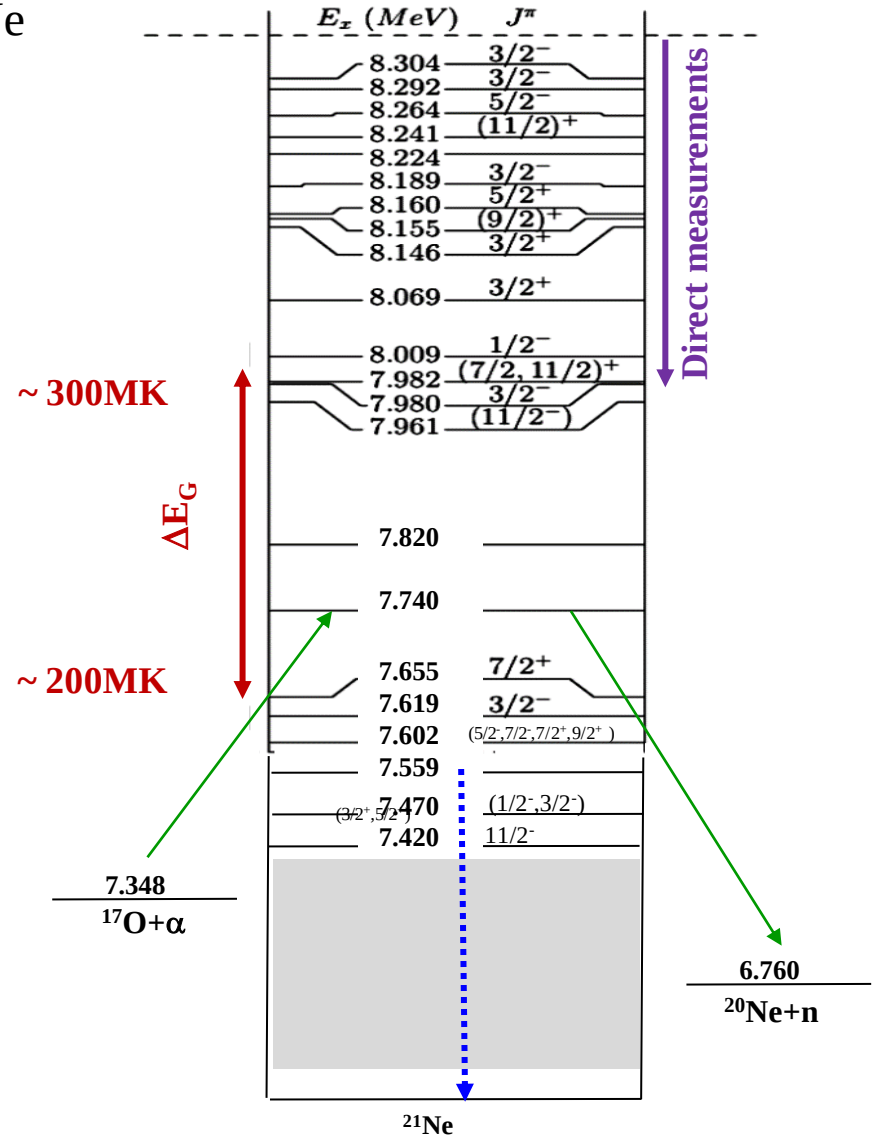
- No direct measurements @ E_{cm}<0.63 MeV (Core He burning)

- 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

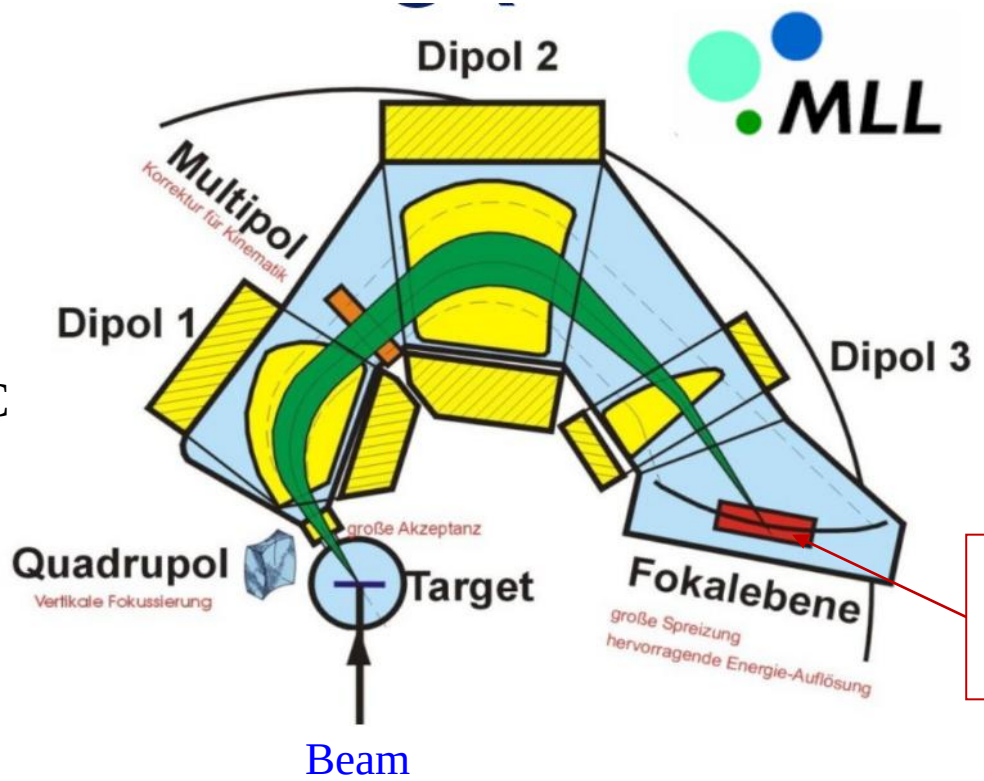
- Neutron transfer reaction → S_n→ Γ_n **Frost-Schenk+MNRAS2022**
- α-transfer reaction → S_α→ Γ_α (present work/MLL-exp)



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

Q3D spectrometer (MLL)

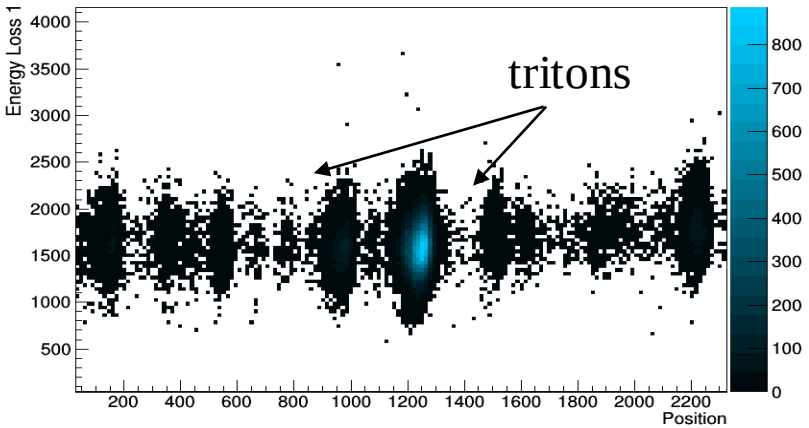
- **Beam ^{7}Li**: E=28 MeV
  I=100 nAe
- **Targets**: $W^{17}O_3$ (41 µg/cm^2) enriched at 35% on ^{nat}C
  $W^{nat}O_3$ (39 µg/cm^2) on ^{nat}C
- **Solid angle**: 6 to 12.4 msr
- **Energy resolution ΔE/E** ~ 2 x 10^{-4}



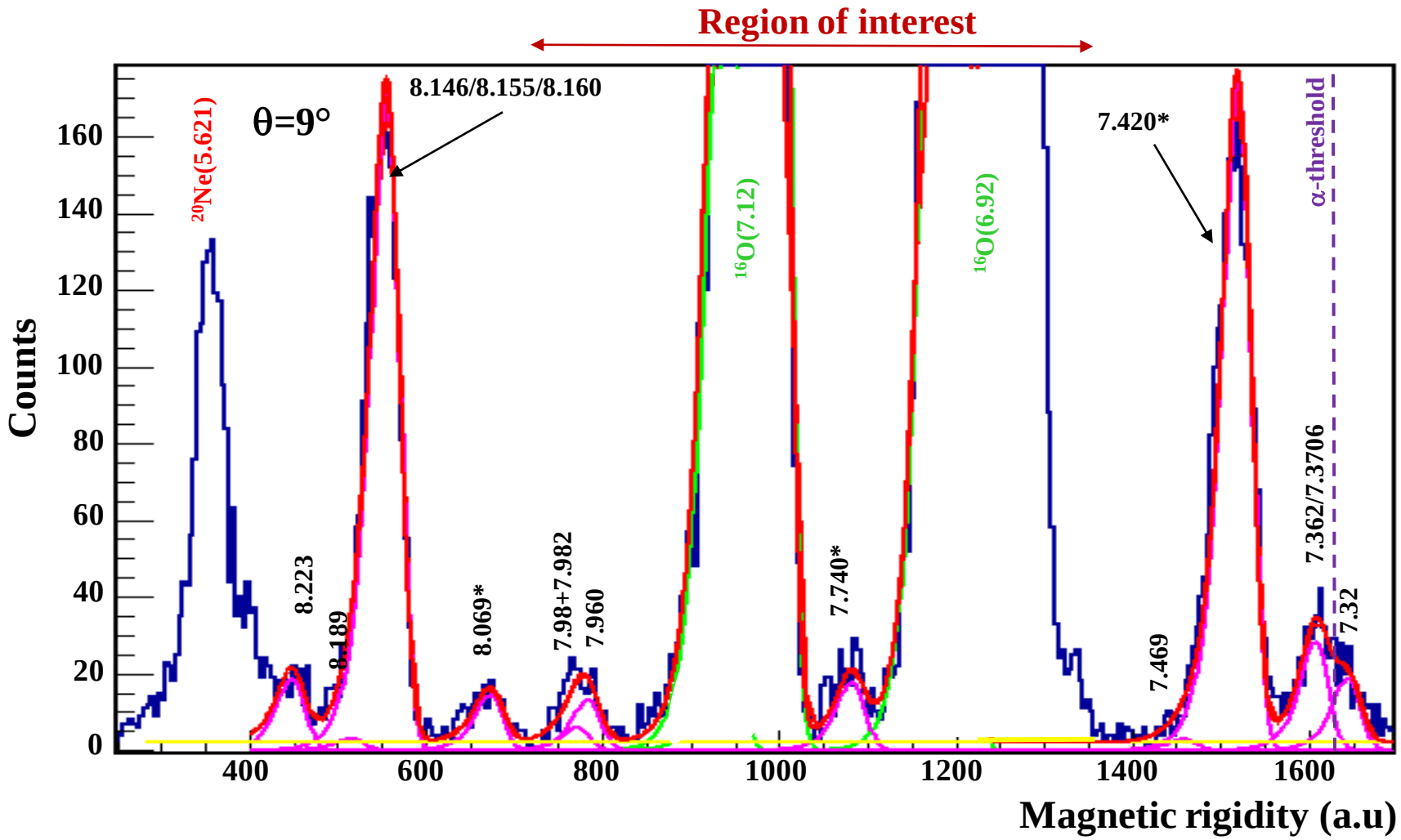
- 2 proportional gas counters: **Pos, ΔE_1, ΔE_2**
- plastic scintillator: **E**

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



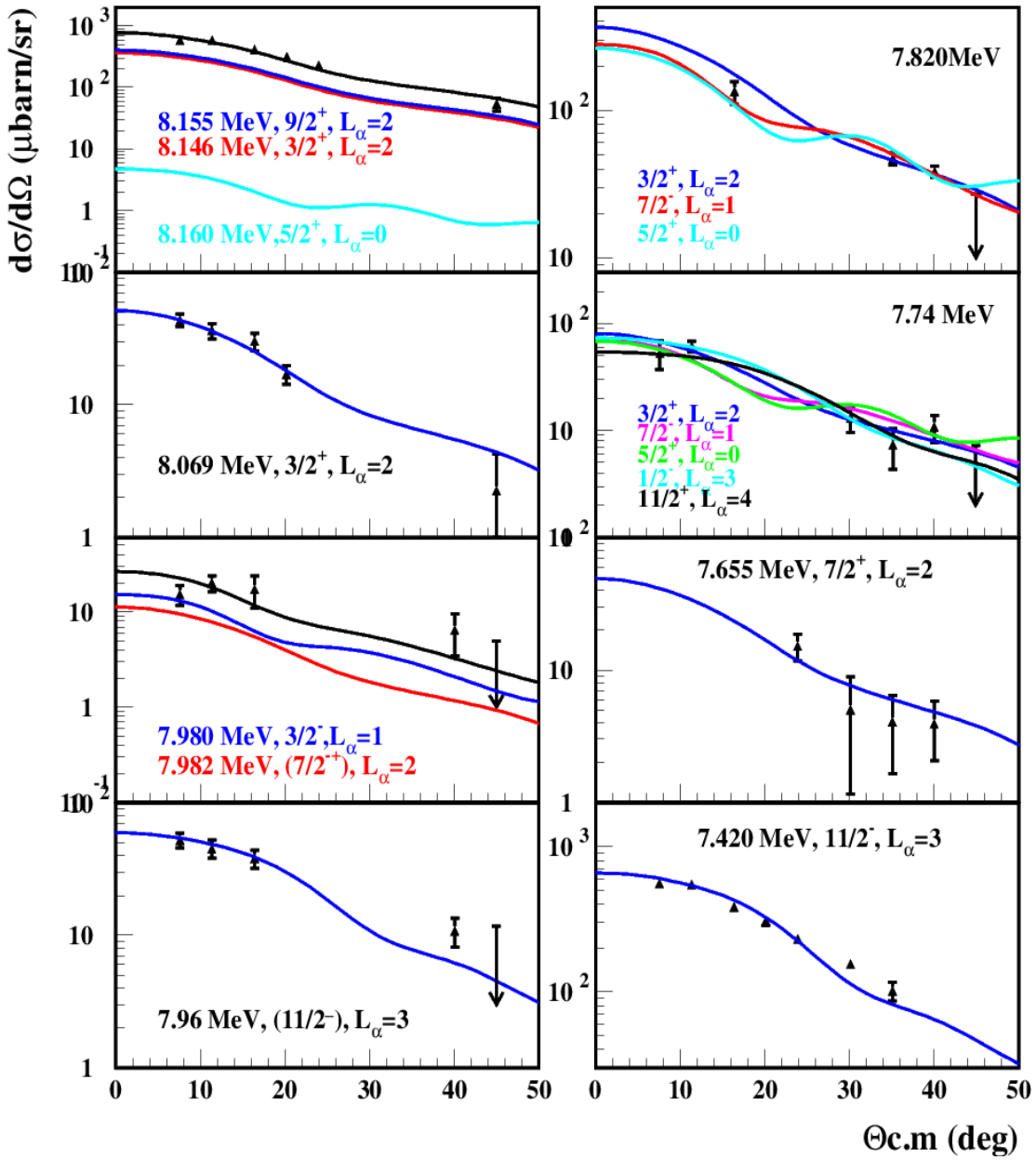
Excitation energy spectrum of ^{21}Ne



- 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
  → S_α of 8.146 & 8.160 MeV derived from Γ_α **Best+2013**
  ⇒ S_α(8.155 MeV)=0.15 **(present work)**

- Doublet 7.980/7.982 MeV: Fit with 2 components
  → S_α of 7.98 MeV deduced using ωγ(α, n) **Denker+94**
  ⇒S_α(7.982 MeV)=0.005 **(present work)**

- 7.820 MeV
  → Best χ^2 for L_α=0,1 & good for L_α=2
  → L_α=0 → S_α =0.61 (unlikely)

$$C^2 S_\alpha \rightarrow \Gamma_\alpha = 2P_l \frac{\hbar^2 R}{2\mu} C^2 S_\alpha |\varphi(R)|^2 \ @\ R = 7.5\ fm$$

- 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 (except 632 keV) & Er=807 keV:

→ Γ_α (**present work**)

Γ_α (7.82MeV) for L_α=1 (L_α=0 in Best+2013)
Γ_α (7.74 MeV) for L_α=0 (as in Best+2013)

→ Γ_n **Frost-Schenk+2022**

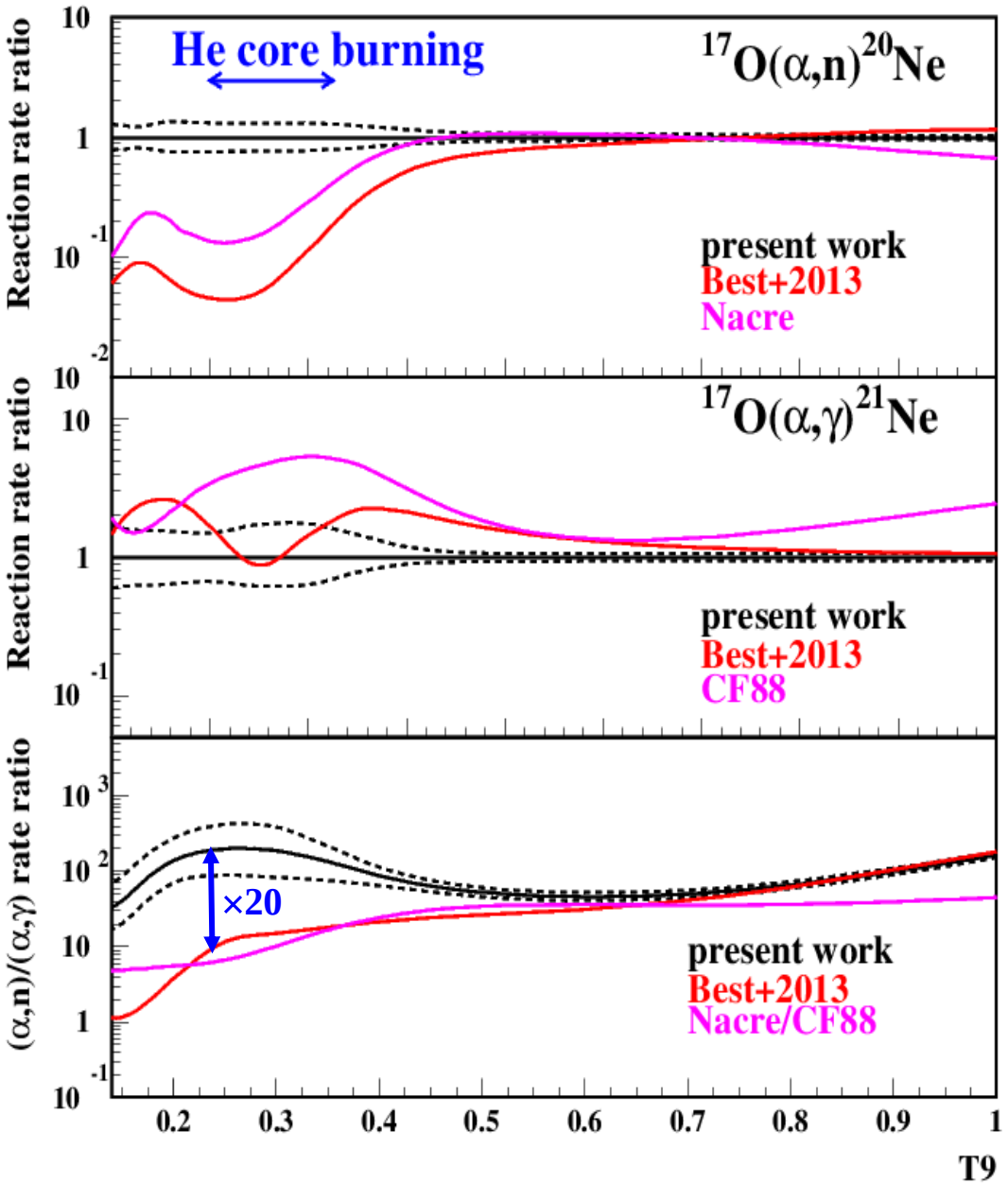
- For Er≥ 721 keV :

→ Γ_α & Γ_n (**Best+2013** direct measurement)

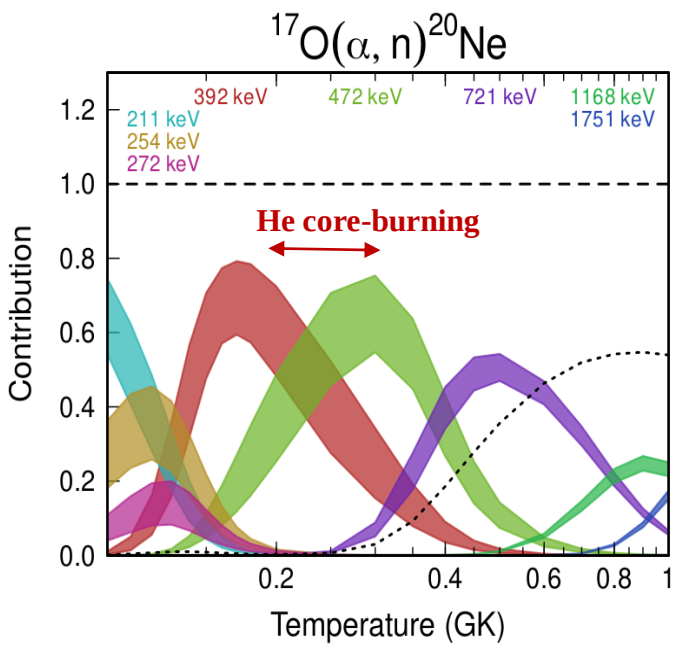
- Γ_γ from:

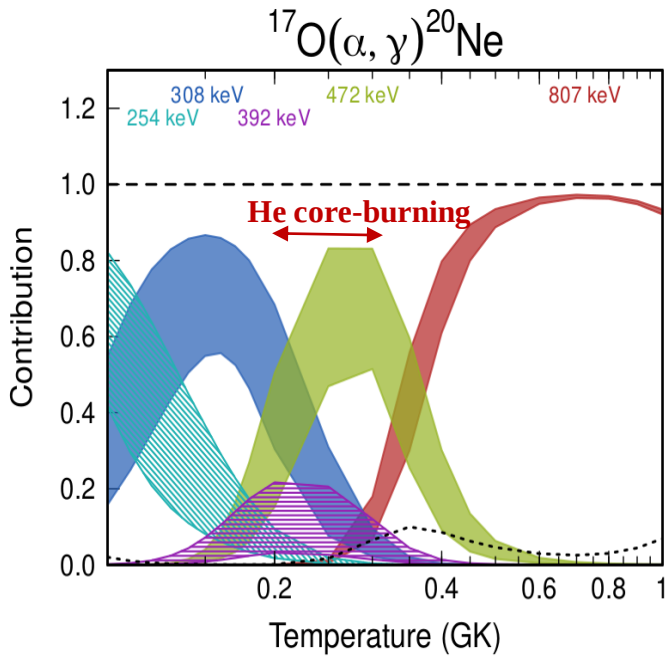
→ systematics of $<\tau>_{meas}$ **(Rolfs+72)**
→ when no Γ_n → Γ_γ/Γ_n **Best+2013**

→ **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

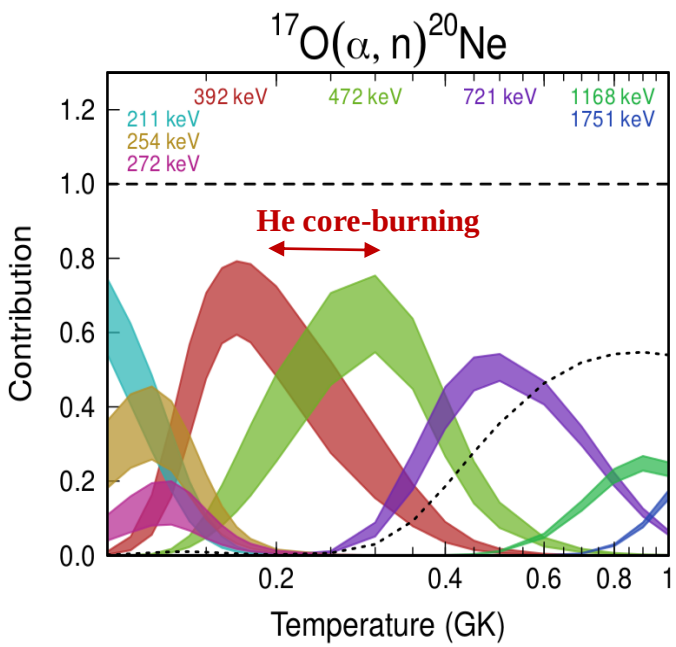
→ **Ex=7.82 MeV** L_α =0,1,2 & L_n=2,3 ⇒ J^π=5/2$^+$, 7/2$^-$, 3/2$^+$

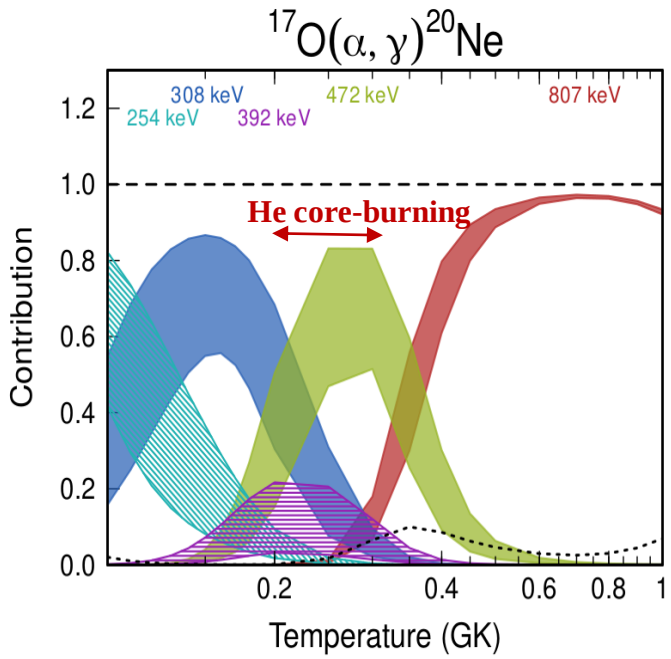
Key resonances

↓

J^π need to be constrained

Resonances contribution to the rates





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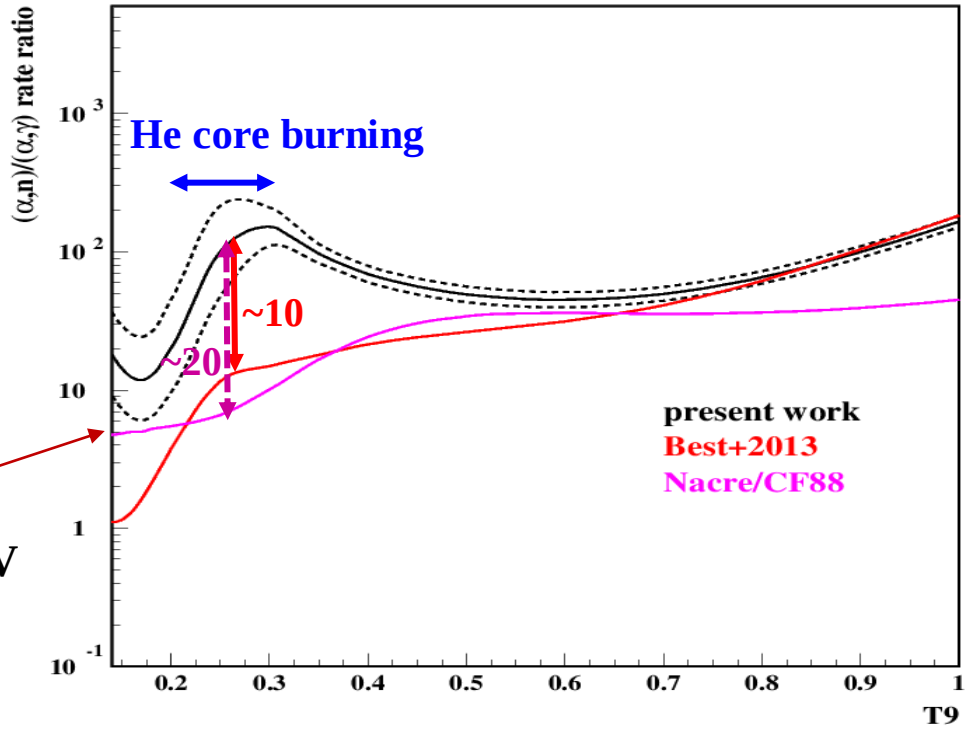
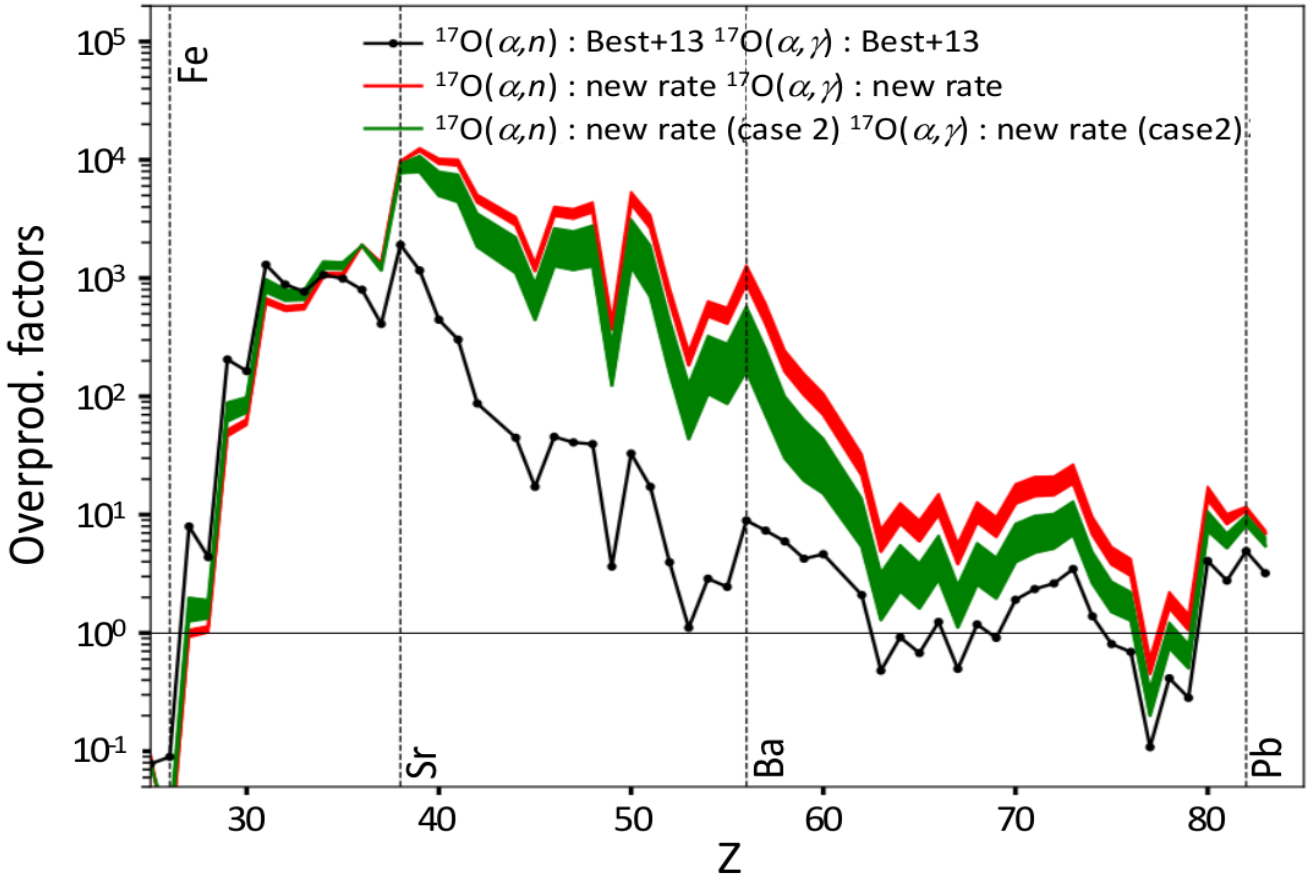


With the least favorable case: 7.82 MeV L_α=2 → 3/2$^+$ or 7/2$^+$ & no 7.74 MeV

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

Conclusion

- First measurement via $^{17}O(^{7}Li,t)$ transfer reaction of the α-spectroscopic factors & α-widths of ^{21}Ne states within the Gamow window for He-core burning massive stars.

- Present **$^{17}O(\alpha,n)/^{17}O(\alpha,\gamma)$** reaction rate ratio is **larger** by a factor of ~**20** than Best+13 ratio at T=0.2-0.3 GK

- Large enhancement (more than 1.5 dex) of the weak s-process between 40<Z<60 rotating poor-metal massive stars

- The spin-parity of the two key resonances at Ex=7.74 & 7.82 MeV need to be measured in the future

Collaboration

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Thank you

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