(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

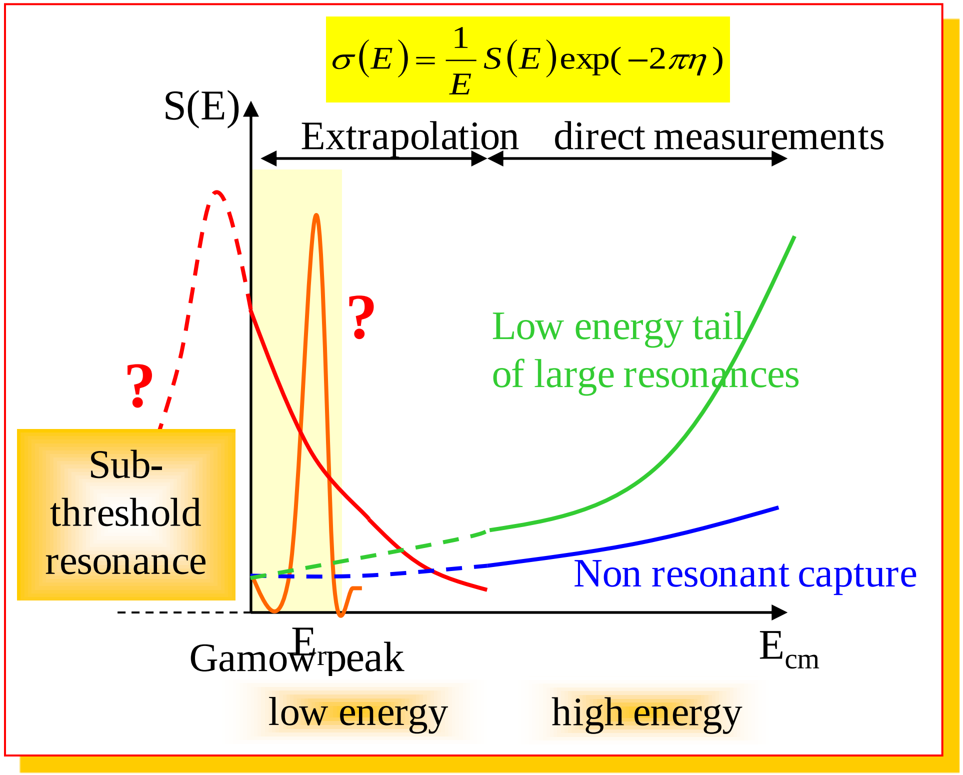
Exploring low-energy nuclear properties: latest advances on reaction mechanisms with light nuclei Workshop
June 1st-2nd 2023 (Brussels)

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)
- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$, $^{22}Ne(\alpha,\gamma)^{25}Mg$
- $^{17}O(\alpha,n)^{20}Ne$, $^{17}O(\alpha,\gamma)^{21}Ne$
- $^{15}O(\alpha,\gamma)^{19}Ne$ (Type I X-ray bursts)

s-process in AGB & massive stars

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



$$\sigma(E)=\frac{1}{E}S(E)\exp(-2\pi\eta)$$

- 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:

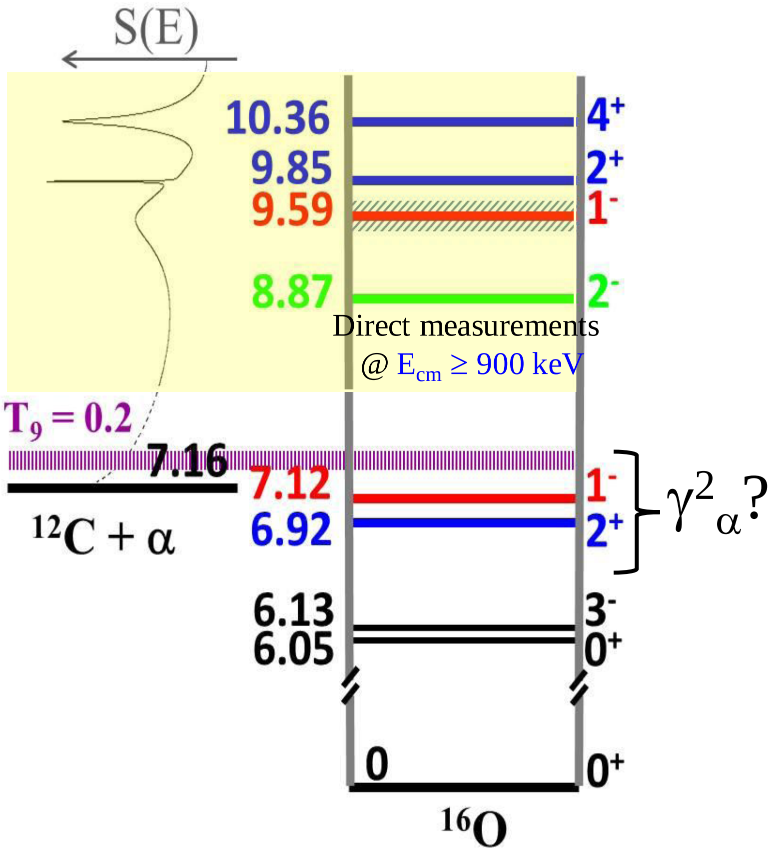
Low beam intensities (~10^5 - 10^7 p/s)
→ direct measurements challenging

Resonant cross-sections & $N_a\langle\sigma v\rangle$ can be calculated if ($\mathbf{E_R}$, $\mathbf{J^\pi}$, $\mathbf{\Gamma_\alpha}$, $\mathbf{\Gamma_n}$, $\mathbf{\Gamma_\gamma}$, $\mathbf{\Gamma_{tot}}$) are known/constrained
➔ (^{7}Li,t) or (^{6}Li,d) α-transfer reactions → $\mathbf{E_R}$, l_α, S_α ⇒ γ^2_α, Γ_α

$^{12}C(\alpha,\gamma)^{16}O$: the challenge of Nuclear Astrophysics

→ Crucial for energetics, nucleosynthesis, final fate of the massive stars,…

- **$^{12}C(\alpha,\gamma)^{16}O$** → 40% incertainty
- T=0.2 GK Gamow peak ~300 keV, $\sigma(E_0) \sim$ **10^{-8}** nb



Direct measurements @ 300 keV → impossible

Need of precise data at high energies
& extrapolation at 300 keV (R-matrix formalism)

BUT

Overlap of various contributions:

- E1 & E2 transitions to the gs:

Effect of the high energy tail of the 1^- & 2^+ sub-threshold resonances (S_α, γ^2_α ?)

$S_\alpha(1^-) \rightarrow$ 0.02-1.08 !?
$S_\alpha(2^+) \rightarrow$ 0.13-1.35 !?

&

Interference effect & cascades ?

⇒ Study of 6.92 & 7.12 MeV states ^{16}O via the transfert reaction $^{12}C(^7Li,t)^{16}O$

Study of ^{16}O states via $^{12}C(^{7}Li,t)^{16}O$ α-transfer reaction

Advantages

- multi-step effects less marked than in (^{6}Li,d) transfer reaction

  Becchetti et al. (78), Cobern et al.(81), Keeley et al (06)

- less momentum mismatch (L_α=1 in ^{7}Li)

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

$$S'_\alpha = \left\langle {}^{7}Li \middle| t \otimes \alpha \right\rangle = 1$$ (Kubo et al)

$$S_\alpha = \left\langle {}^{16}O \middle| {}^{12}C \otimes \alpha \right\rangle$$

ANC

$$\tilde{C}^2 = S_\alpha \frac{r^2 \left|\varphi(r)\right|^2}{W(r)^2})$$

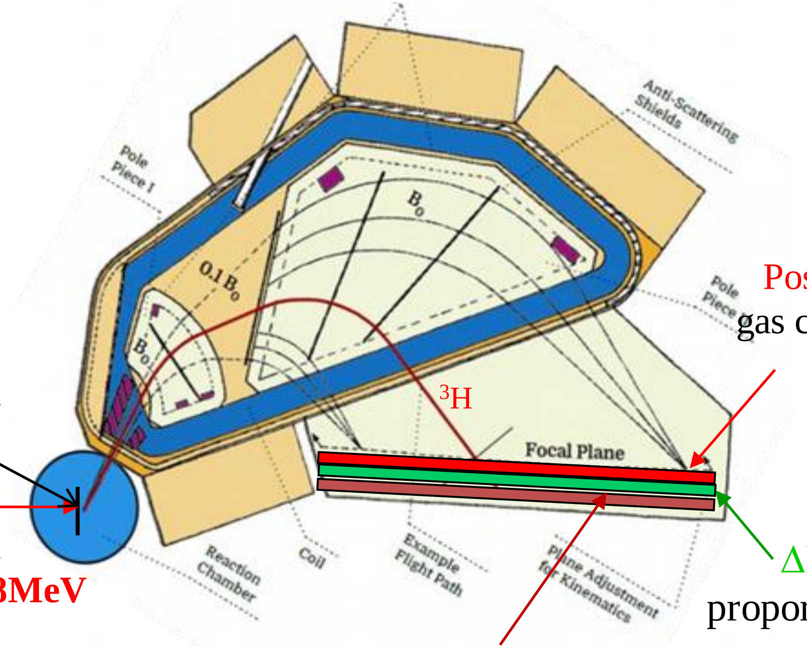
$$\gamma_\alpha^2 = \frac{\hbar^2 r}{2\mu} S_\alpha \left|\varphi(r)\right|^2$$

Detailed and elaborate finite-range DWBA analysis of the data is needed

Experimental Set-up

Split-Pole spectrometer (ALTO-Orsay)

- $\Delta\Omega \sim 1.7$ msr
- $\Delta E/E \sim 5 \times 10^{-4}$



Position gas chamber

^{12}C target

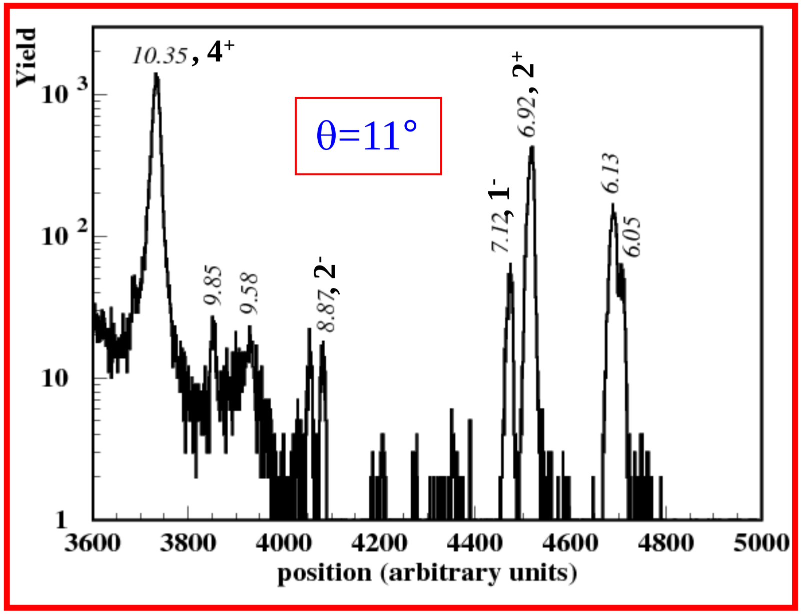
^{3}H

^{7}Li

@ **34,28MeV**

ΔE proportional gas counter

Plastic scintillator (E)

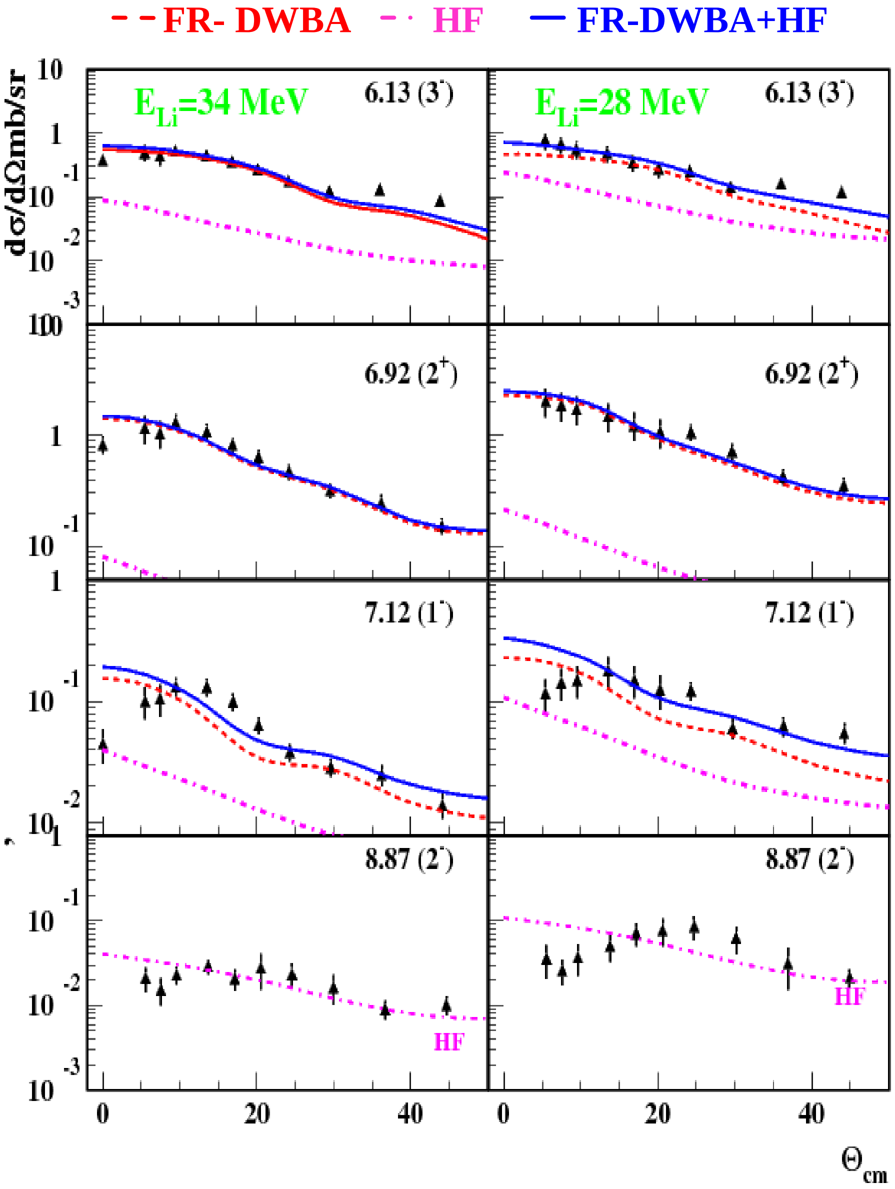


- dσ/dΩ measurements up to 45°

- Strong population of the α cluster 2^+ & 4^+state → direct transfer mechanism
- Population (weak) of the 2^-, 8.87 MeV state → compound nucleus?

FR-DWBA
& HF calculations

Results: Comparison exp & calculations



→ Good description of the data by DWBA (6.05, 6.13, 6.92, 7.12 , 9.58 et 10.35 MeV)

⬇

Direct transfer mechanism

→ Disagreement at $\theta < 10°$ for the 7.12 MeV

⬇

Multi-step transfer? → dσ/dΩ ↘

↓

No (CDCC calculations of Keeley)

$S_\alpha(2^+)=0.15\pm0.05$

$S_\alpha(1^-)=0.08\pm0.03$

Main source of error

↓

DWBA input parameters

R matrix calculations– E2 & E1 components

$S_\alpha(6.92)=0.15\pm0.05 \rightarrow \quad \gamma_\alpha^2 = 27\pm10\ \mathrm{keV}$

$S_\alpha(7.12)=0.08\pm0.03 \rightarrow \quad \gamma_\alpha^2 = 8\pm3\ \mathrm{keV}$

r=6.5fm

Asymptotic region

$$\tilde{C}^2(2^+) = (2.07\pm0.80)\times10^{10}\ \mathrm{fm}^{-1}$$

$$\tilde{C}^2(1^-) = (4.00\pm1.38)\times10^{28}\ \mathrm{fm}^{-1}$$

In agreement with
ANC sub-coulomb
experiments
Brune+2001, Avila+2014

Multi-level R-matrix analysis

P. Descouvemont DREAM Code

$$R_{CC'} = \sum_\lambda \frac{\gamma_{\lambda C}\gamma_{\lambda C'}}{E_\lambda - E}$$

- Fit E2 & E1 components separately
- Fit
  - $^{12}C(\alpha,\gamma)^{16}O$ astrophysical S-factors (direct data)
  - phase shifts data → $^{12}C(\alpha,\alpha)^{12}C$ measurements

$S_{E2}(300\ \mathrm{keV})$

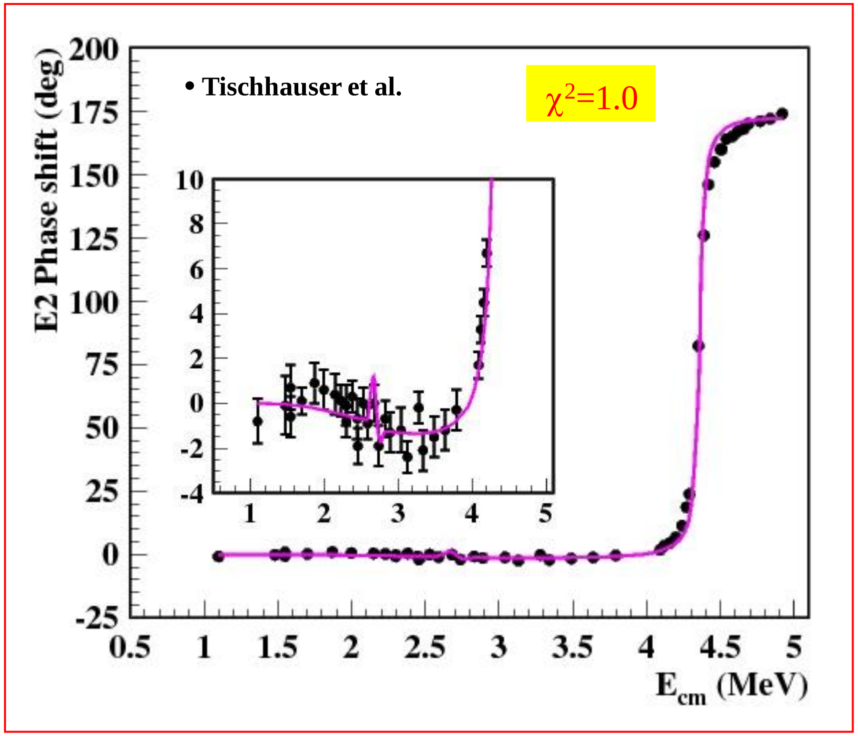
$S_{E1}(300\ \mathrm{keV})$

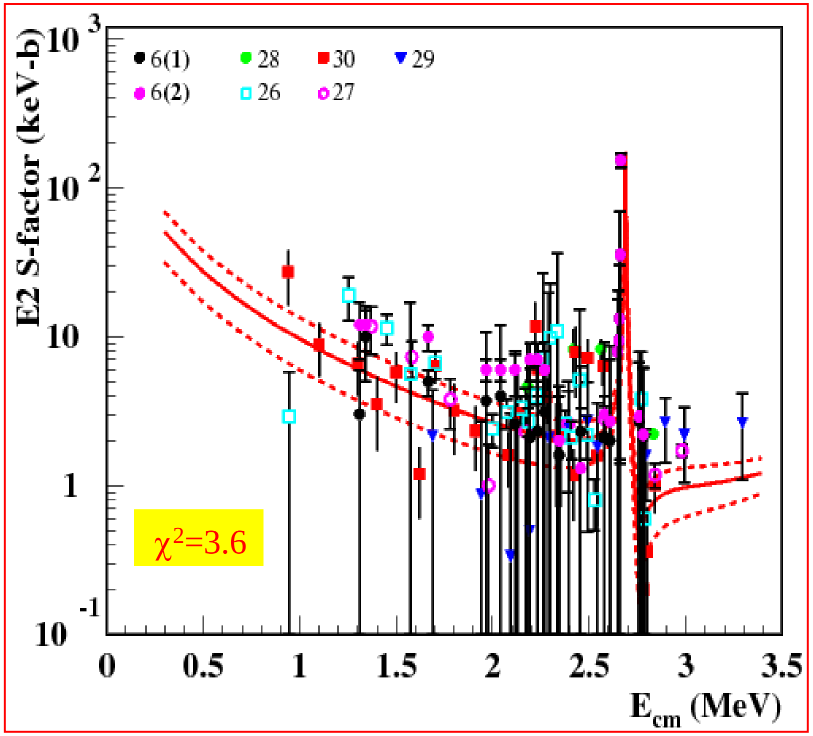
R matrix calculations– E2 component

- E2 Component calculation→ 4 states

→ 6.92, 9.85, 11.52 MeV → fixed resonance parameters

→ Background equivalent state (Er_4, $\Gamma_{\alpha 4}$, $\Gamma_{\gamma 4}$)





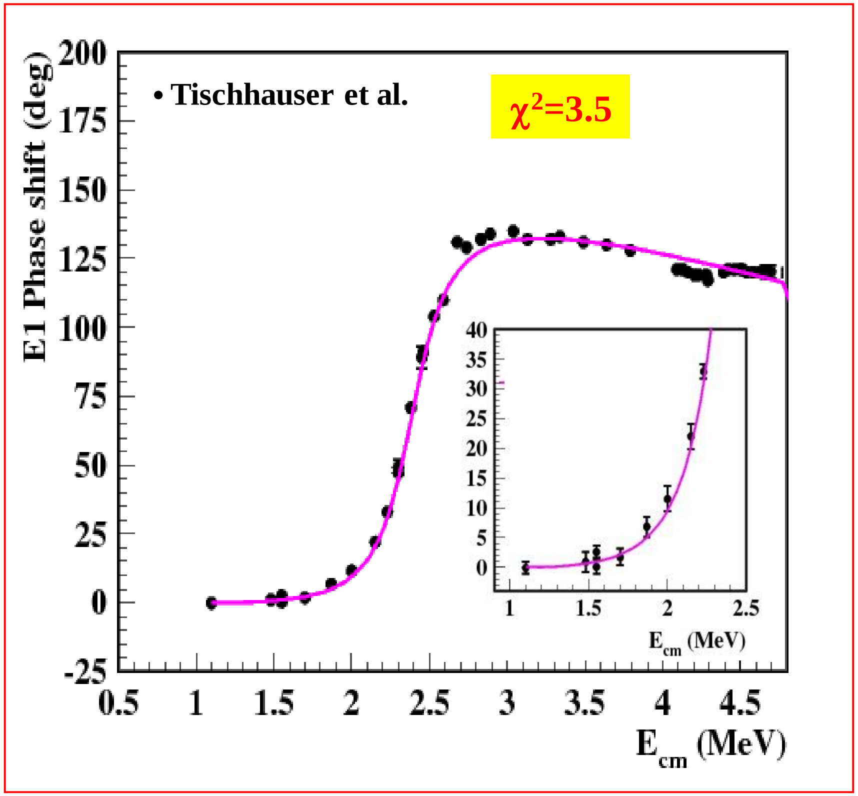
N. Oulebsir, F. Hammache et al. PRC 85, 035804 (2012)

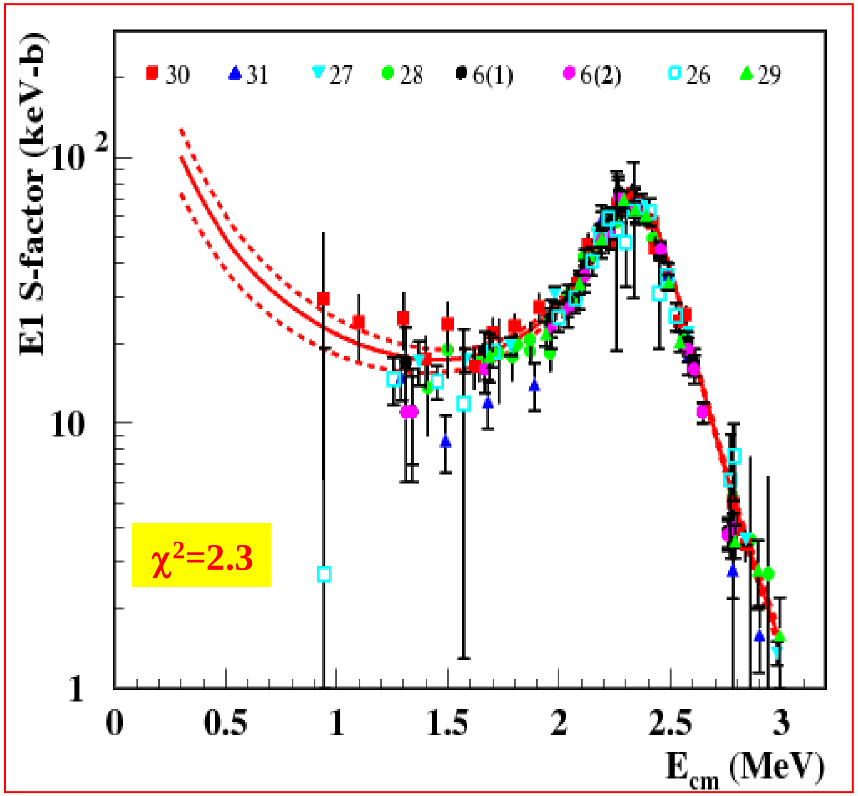
S_{E2}(300 keV)=50±19 keV-barn

R matrix calculations– E1 component

- E1 Component calculation→ 3 states

→ 7.12, 9.58 → fixed resonance parameters
→ Background equivalent state (Er_3, $\Gamma_{\alpha 3}$, $\Gamma_{\gamma 3}$)



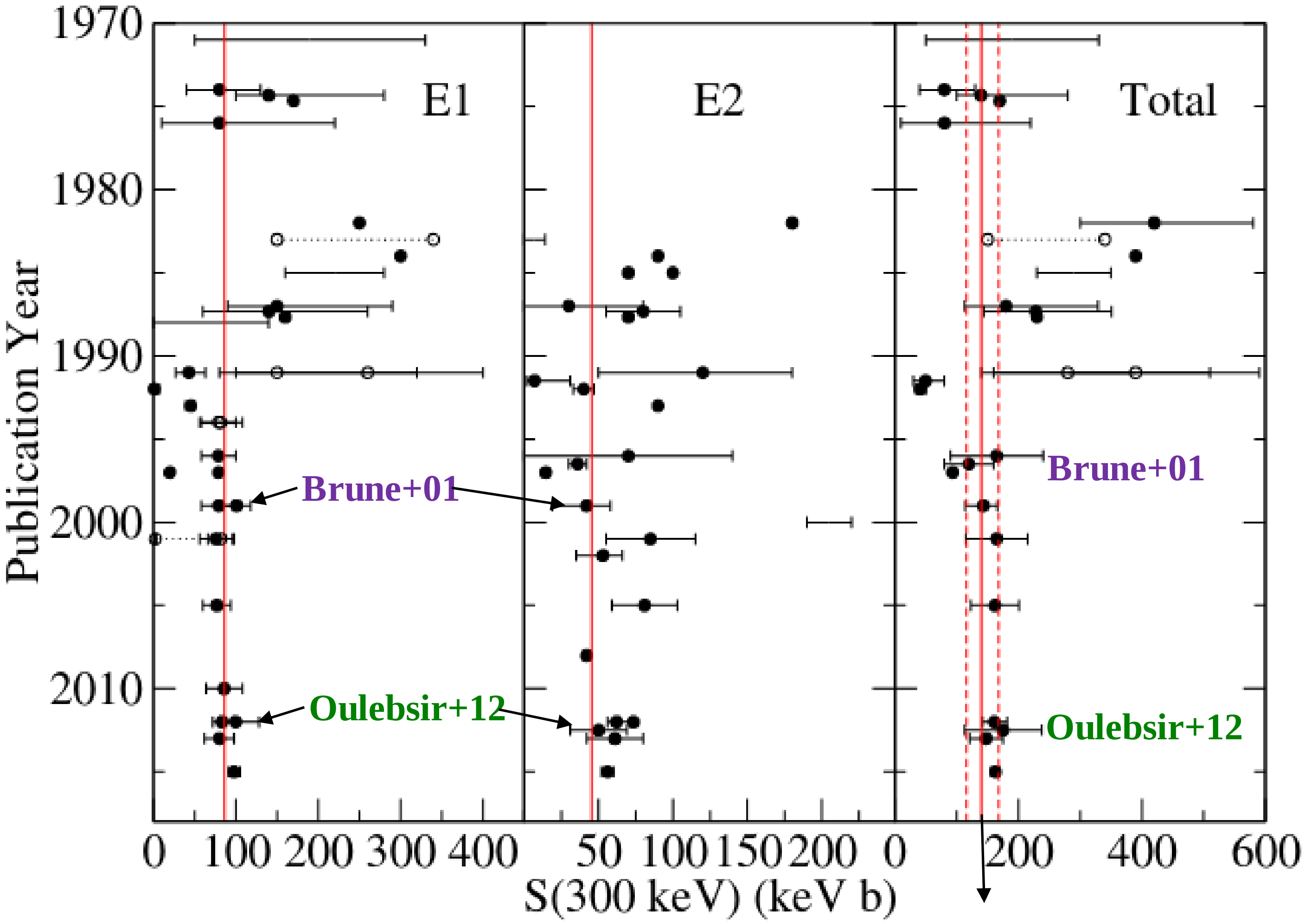


N. Oulebsir, F. Hammache et al. PRC 85, 035804(2012)

S_{E1}(300 keV)=100±28 keV-barn

S_{E1}(0.3 MeV), S_{E2}(0.3 MeV) & S_{tot}(0.3 MeV) over time

Credits: deBoer+17



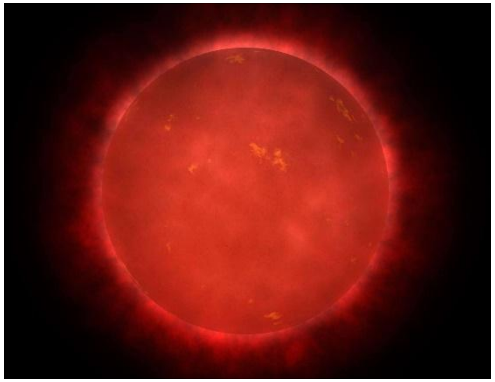
S_{tot} =140±21 keV-b

→ From MC analysis of all existing data including ANC's from transfer reactions (**deBoer+17**)

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

- Metal-poor massive stars → negligible *s*-process production (low ^{22}Ne & Fe seed abundance)

With fast rotation induced mixing

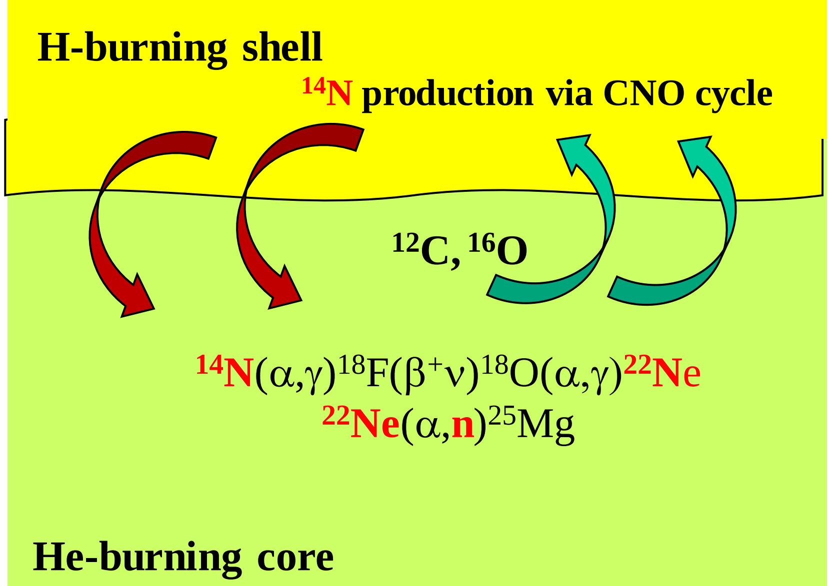
Nishimura+16, Choplin+18

⇒ ^{22}Ne production in He core strongly enhanced

⬇

large production of *s*-elements between Strontium & Barium

90<A<140



H-burning shell

^{14}N production via CNO cycle

^{12}C, ^{16}O

^{14}N(α,γ)^{18}F($\beta^+\nu$)^{18}O(α,γ)^{22}Ne

^{22}**Ne**(α,**n**)^{25}Mg

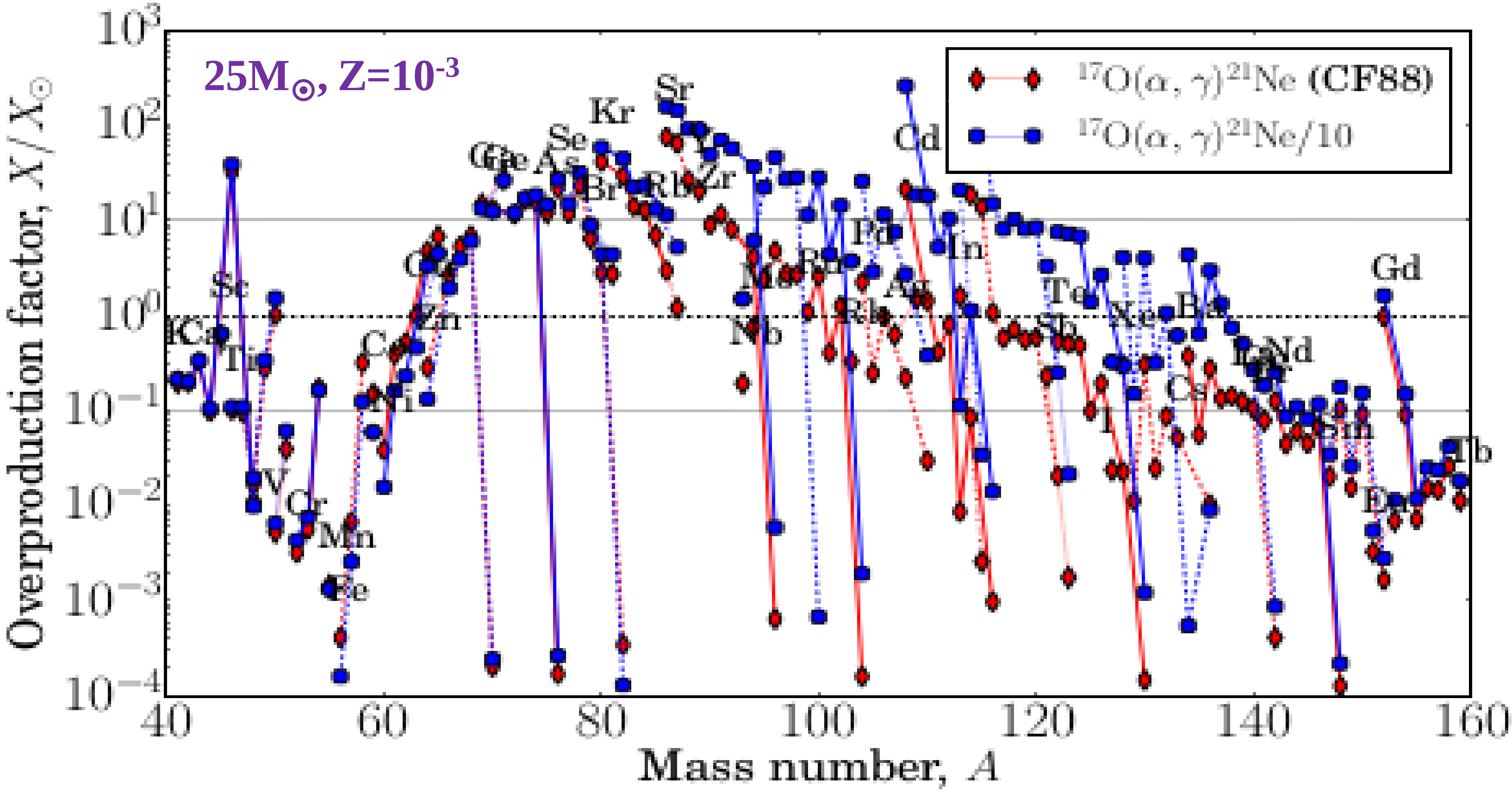
He-burning core

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=7.62-8.00 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:

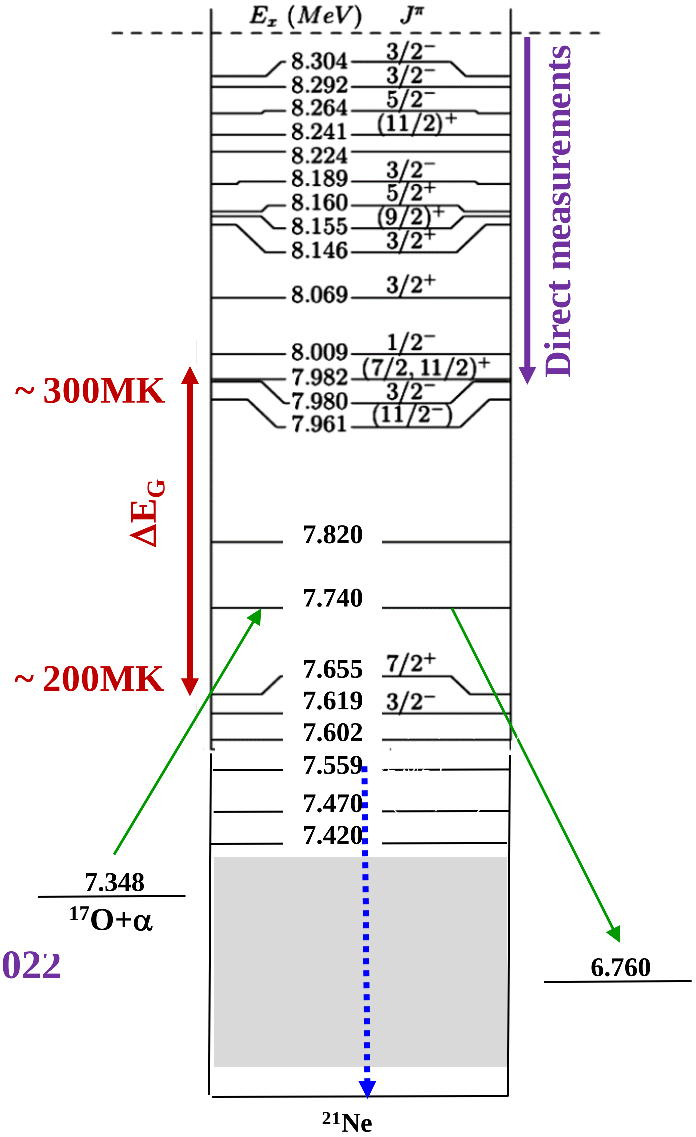
- **Denker+1994, Best+2013** → **0.63≤E_{cm}≤1.8MeV**
- **Best +2011, Taggart+2019** } **0.63≤E_{cm}≤1.33MeV**
- **Williams+2022**

- 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

→ 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)

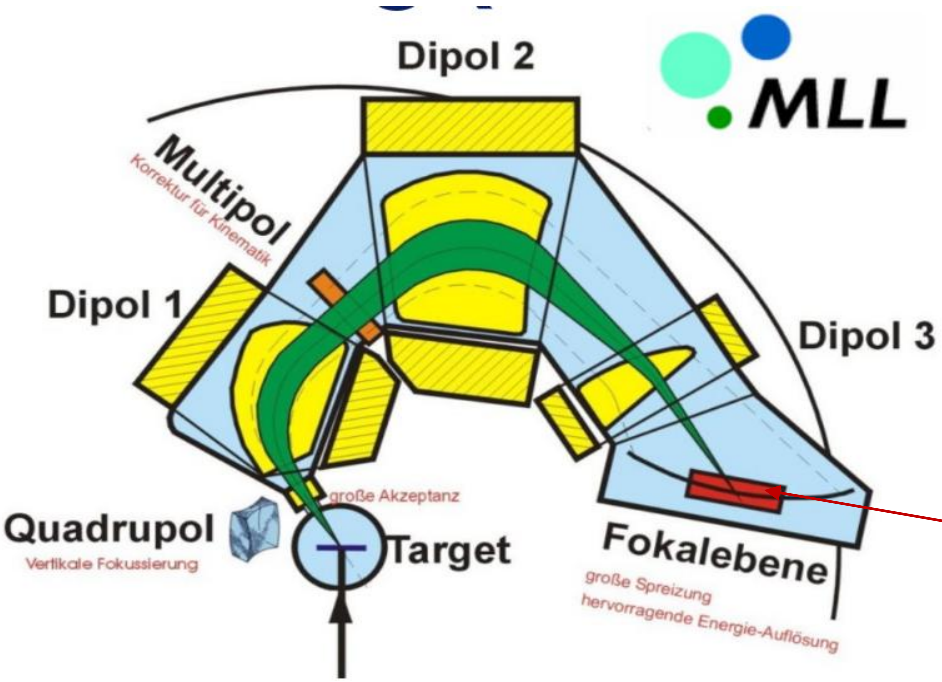
Study of ^{21}Ne states via ^{17}O(^{7}Li,t)^{21}Ne α-transfer reaction

Q3D spectrometer (MLL)

- $\Delta\Omega \sim 6$ to 12.4 msr
- $\Delta E/E \sim 2 \times 10^{-4}$

➢ Targets (manufactured at LNS Catania):

- 41 $\mu g/cm^2$ ^{17}O enriched (35%) WO_3 target on ^{nat}C
- 39 $\mu g/cm^2$ natural WO_3 target on ^{nat}C

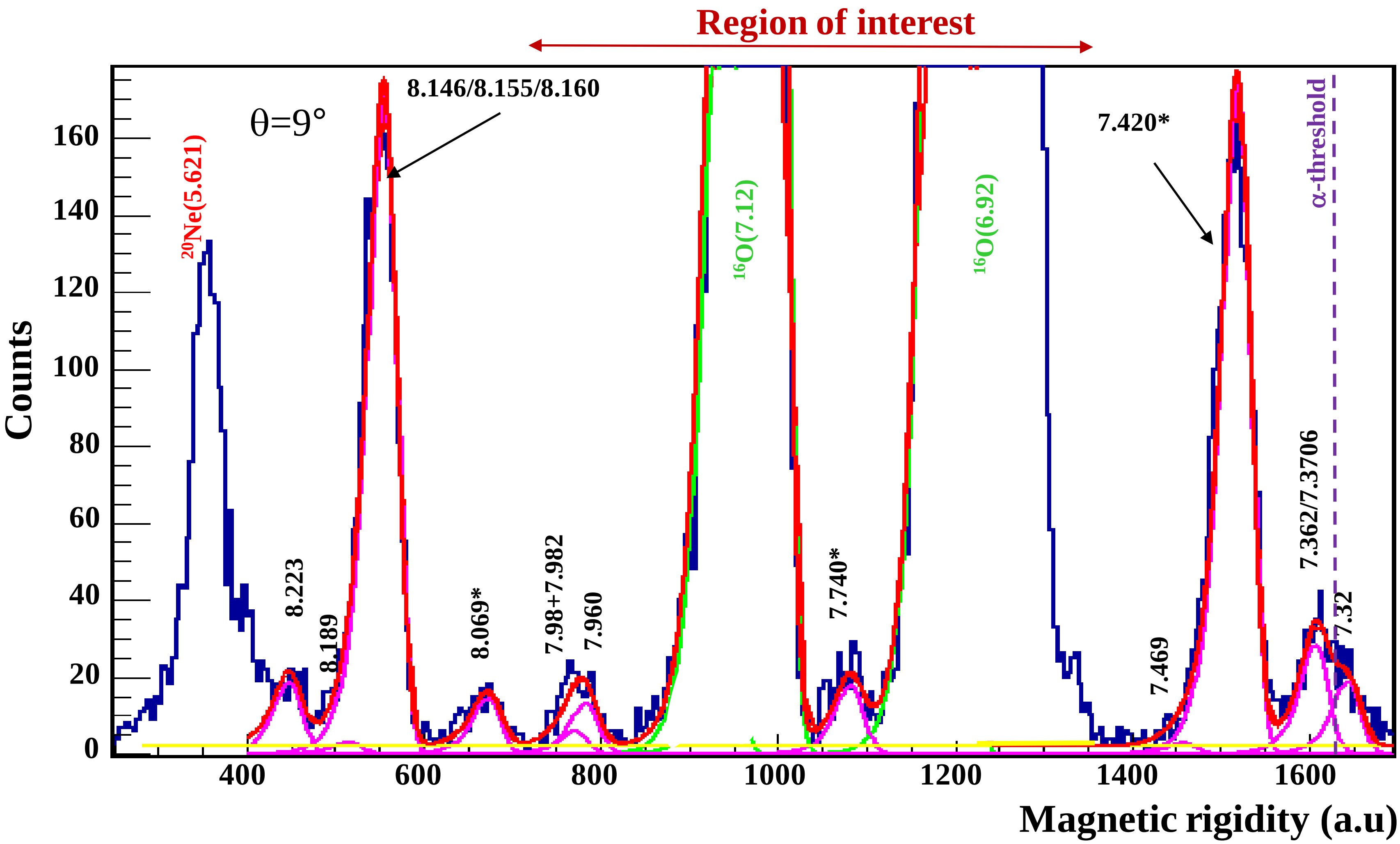


Pos, ΔE_1, ΔE_2, E
2 proportional gas counter
& plastic scintillator

^{7}Li @ 28 MeV
I=100 nAe

➢ $d\sigma/d\Omega$ measurements @ $\theta_{lab} = 6^{\circ}$-$36^{\circ} \Rightarrow \theta_{cm} \rightarrow 7.5^{\circ}$- 45° on enriched target & on natural target for calibration & background evaluation

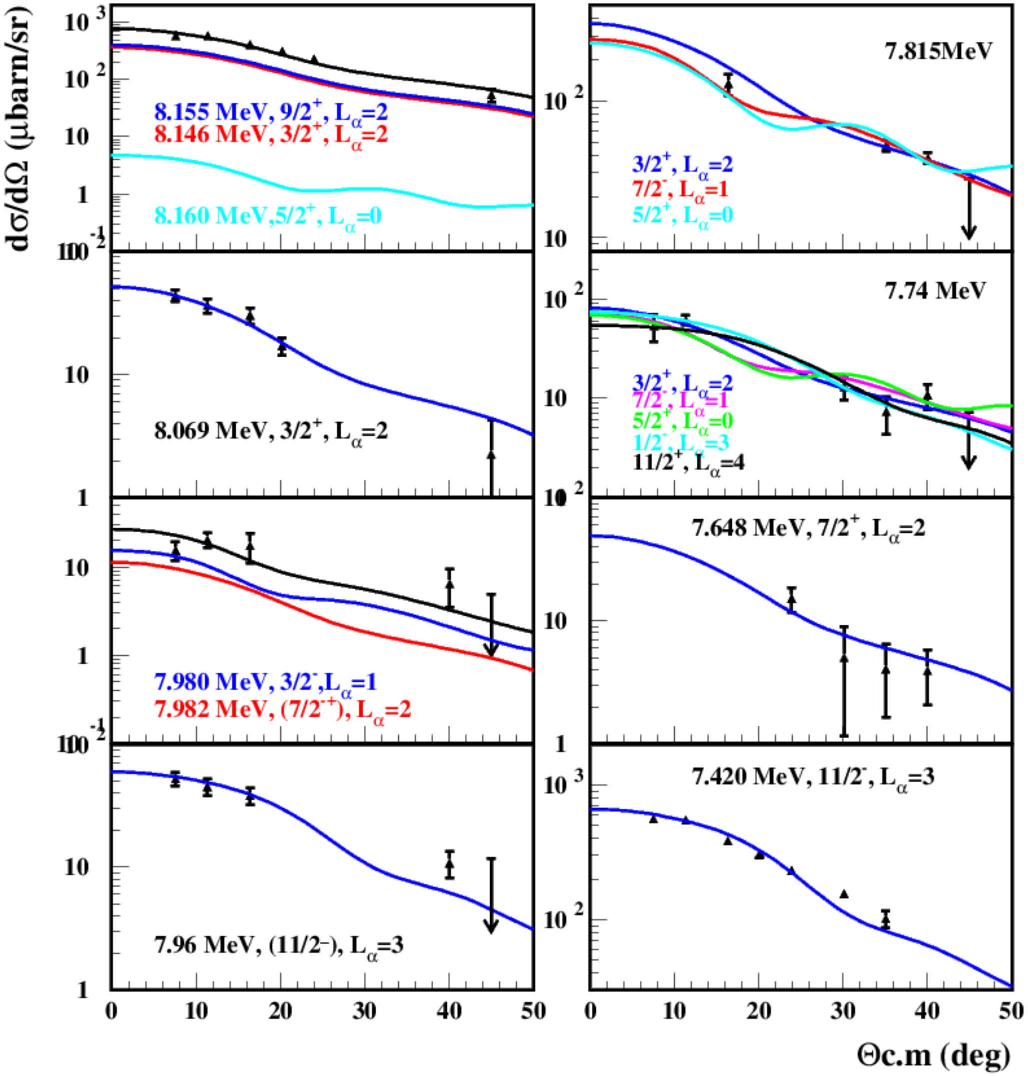
Excitation energy spectrum of ^{21}Ne



- 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)**

- 7.815 MeV

  →Best χ^2 for L_α=0,1 & good for L_α=2

  →L_α=0 → S_α =0.66 (unlikely)

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

- 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+13**

☐ For Er < 721 keV & Er=807 keV :

→ Γ_α (**present work**)

Γ_α (7.81MeV) determined with $L_\alpha=1$
Γ_α (7.74 MeV) determined with $L_\alpha=0$

→ Γ_n **Frost-Schenk+2022**

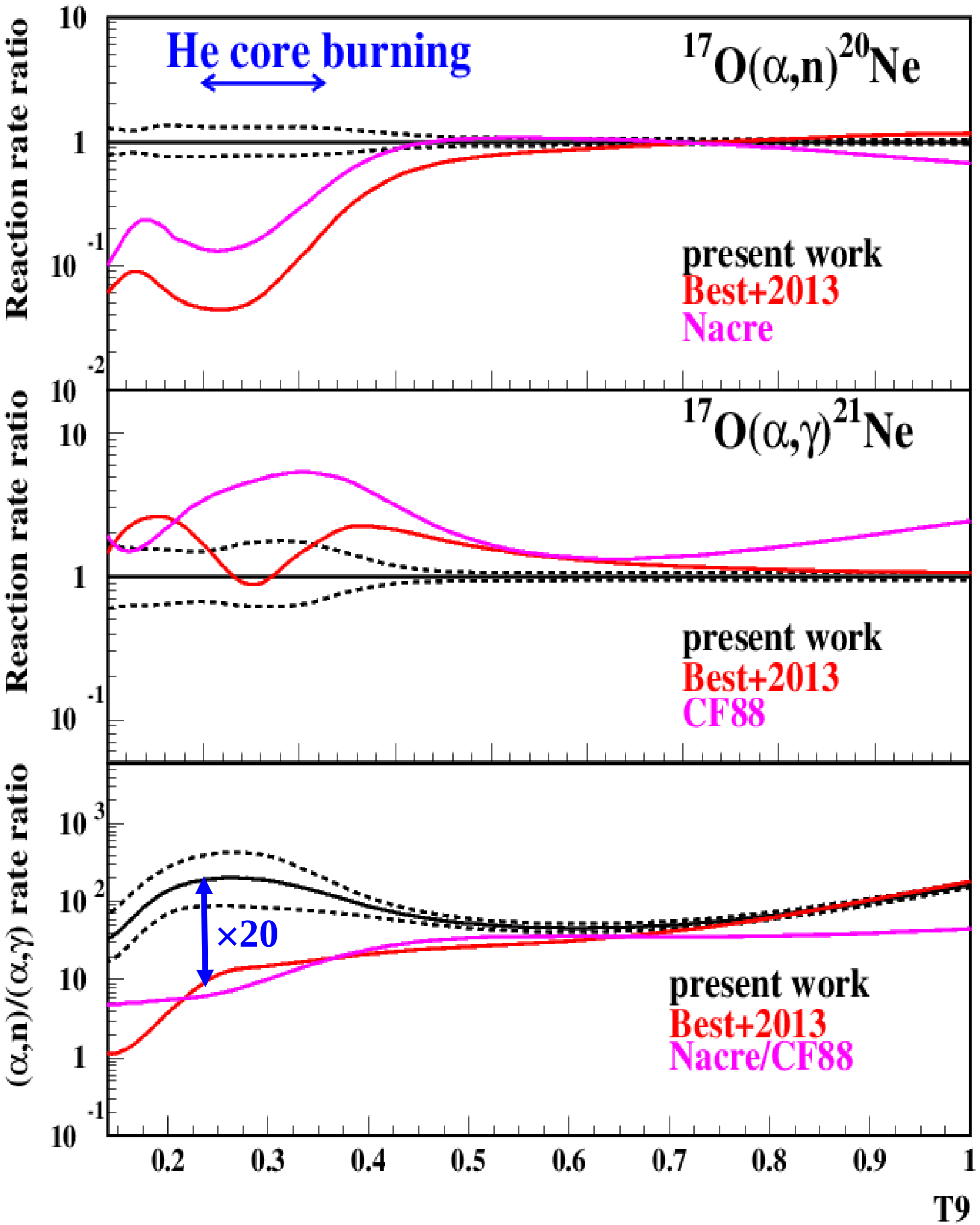
☐ For Er≥ 721 keV : Γ_α & Γ_n (**Best+2013** direct measurement)

☐ Γ_γ from:

→ systematics of $<\tau>_{meas}$ **(Rolfs+72)**

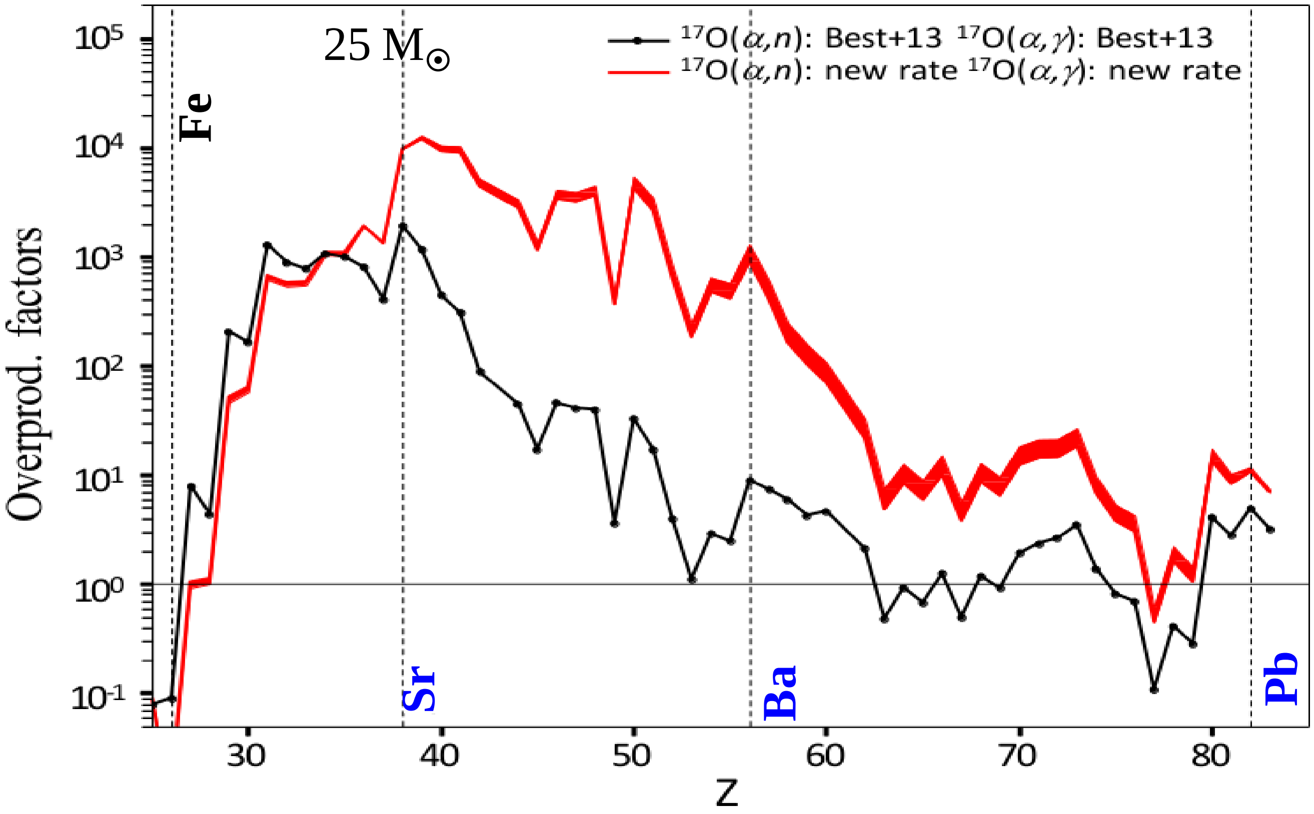
→ $\omega\gamma(\alpha,\gamma)$ **Williams+2022** combined with present Γ_α & Γ_n **(Frost-Schenk+22)**

→ Better neutron efficiency recycling with a factor of about **20** with the **present recommended rates** than Best+13 rates



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)



A.Choplin calculations

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

→ **Two order** of magnitude on **Barium**: largest effect

Collaboration

^{12}C(^{7}Li,t)^{16}O experiment

N. Oulebsir, **F.H,** P. Roussel, M.G. Pellegriti,
L. Audouin, D. Beaumel, S. Fortier

IPN-Orsay (IJCLab)

N. Oulebsir, A. Bouda
(**Université A.Mira - Béjaïa**)

J. Kiener, A. Lefebvre-Schuhl, V. Tatischeff
CSNSM-Orsay (IJCLab)

P. Descouvemont (**ULB-Brussels**)

L. Gaudefroy (**GANIL-Caen**)

Thanks

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

F.H, S. Harrouz, N. de Séréville, A. Meyer
IJCLab-Orsay

P. Adsley
(Ithemba)

L. Lamia, M. La Cognata, G. Pizzone, S. Romano, A.Tumino
LNS, Catania

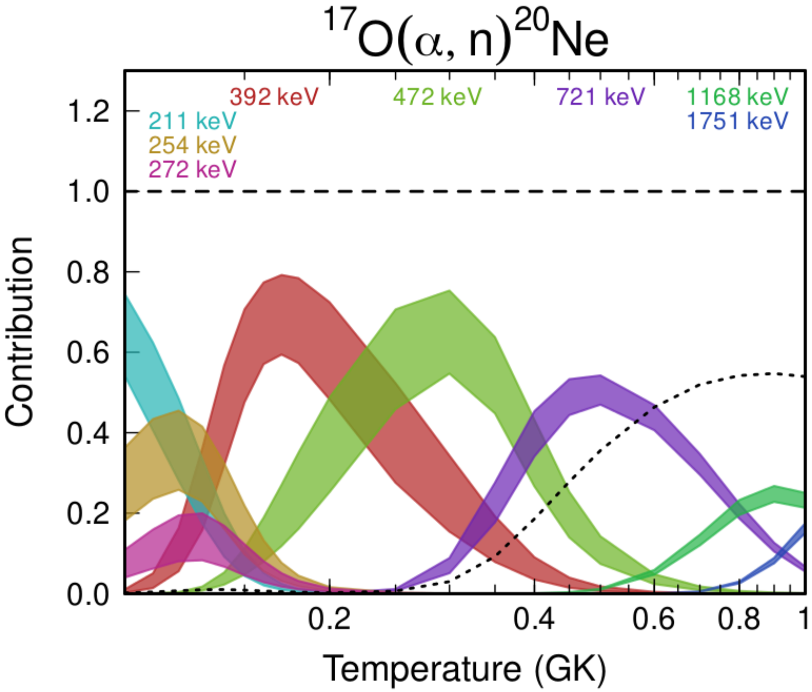
A. Choplin
(ULB-Brussels)

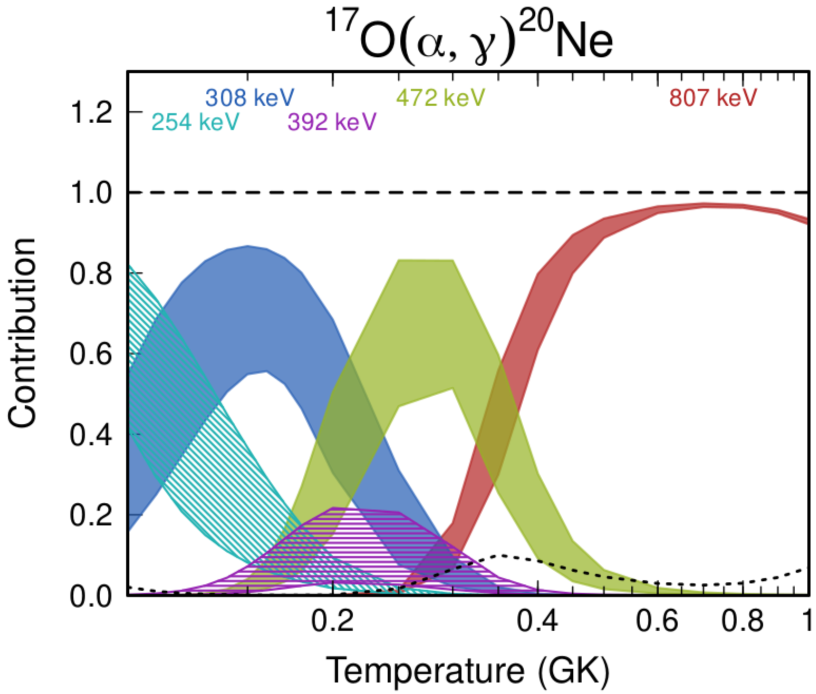
B. Bastin, F. De Oliveira, C. Fougères
(GANIL-Caen)

T. Faestermann, H.F Wirth, R. Hertenberger
(MLL)

S. Palmerini
(Perugia-university)

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 keV (Ex=7.655 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

^{17}O(α,n) & ^{17}O(α,γ) reaction rates (α,n)/(α,γ) rate ratio

Worst case: **7.810 MeV** **l_α=2 → 3/2$^+$ or 7/2$^+$** **& no 7.74 MeV**