Neutron sources for the s-process and their experimental studies

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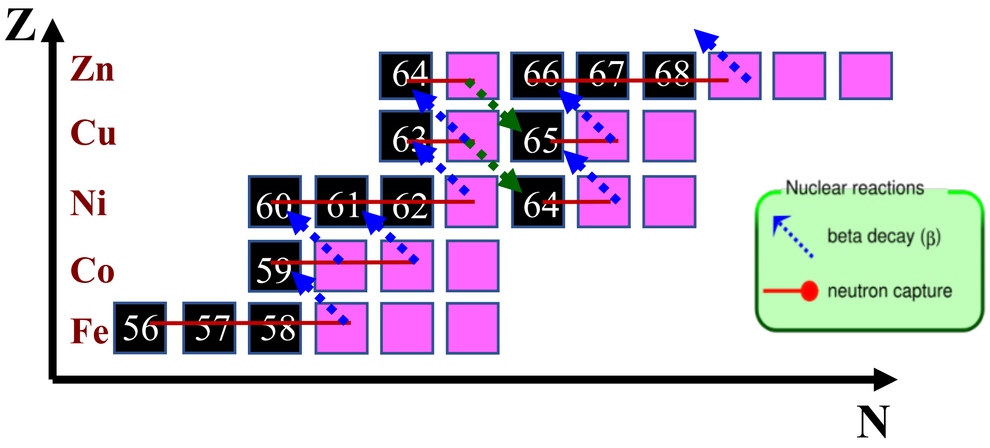
s-process

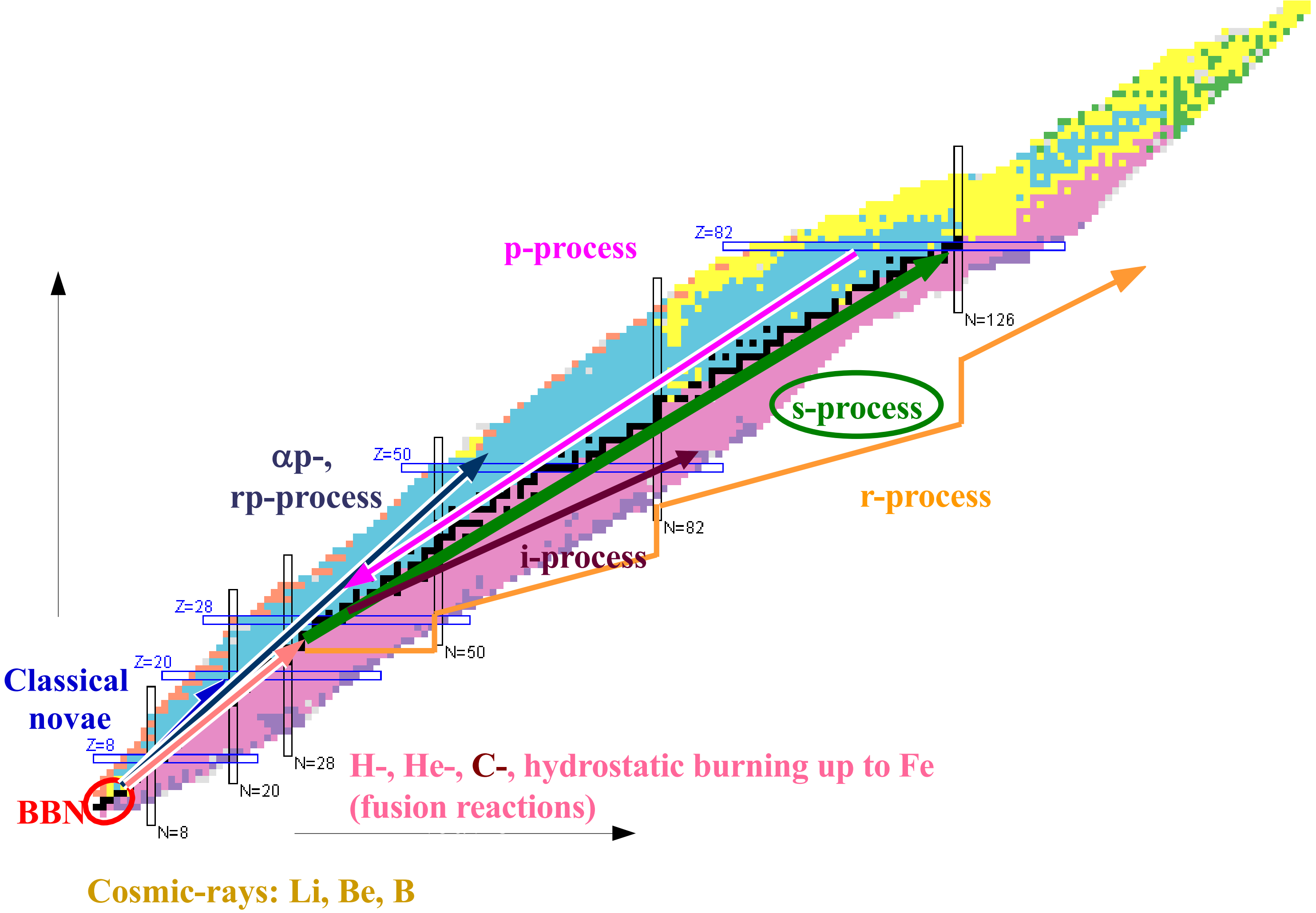
s-process (s = slow neutron capture process) → production of half of the abundance of heavy elements

$\tau_\beta \ll \tau_n \quad \Leftrightarrow N_n \sim 10^8$ n/cm^3



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

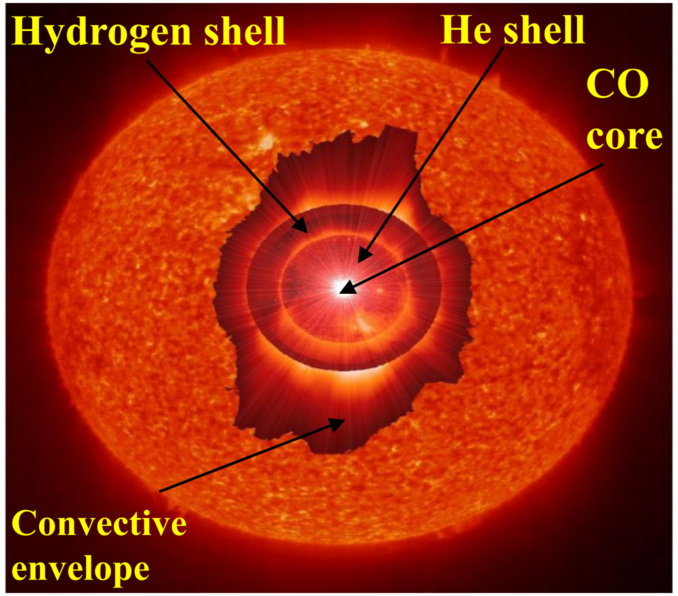
➢ **Weak** component
→ production of 56<A<90 elements in intermediate-mass AGB star (T~0.3 GK) & massive stars (T~0.2-1GK)



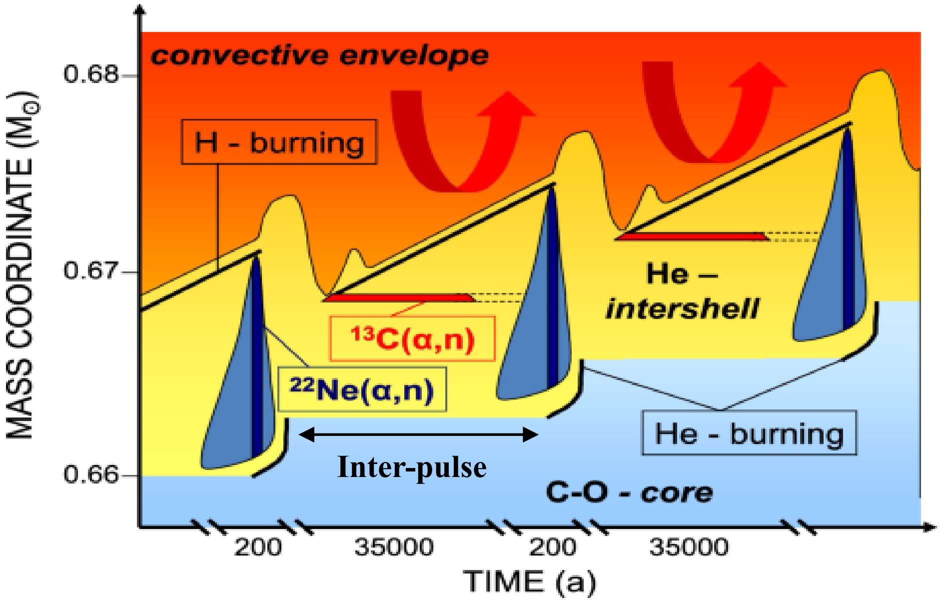
s-process in AGB stars

- **Main s-process :** production of 90<A<209 elements in **low-mass AGB** stars 1-4 $M_\odot$

- **main neutron source** in He intershell: $^{13}C(\alpha,n)^{16}O$
- Temperature ~ 10^8 K
- Neutron density: 10^6 -7.10^7 cm^{-3}
- Duration: 20000 years
- Contribution: **95%** to the total neutron flux in AGB stars



- $^{22}Ne(\alpha,n)^{25}Mg$: another neutron source
- Temperature @ base of the convective zone > 2.7×10^8 K
- Thermal pulses are maximum
- Neutron density ~ 10^{10} cm^{-3}
- Duration: only few years
- ~**5%** contribution to the total neutron flux



s-process in massive stars

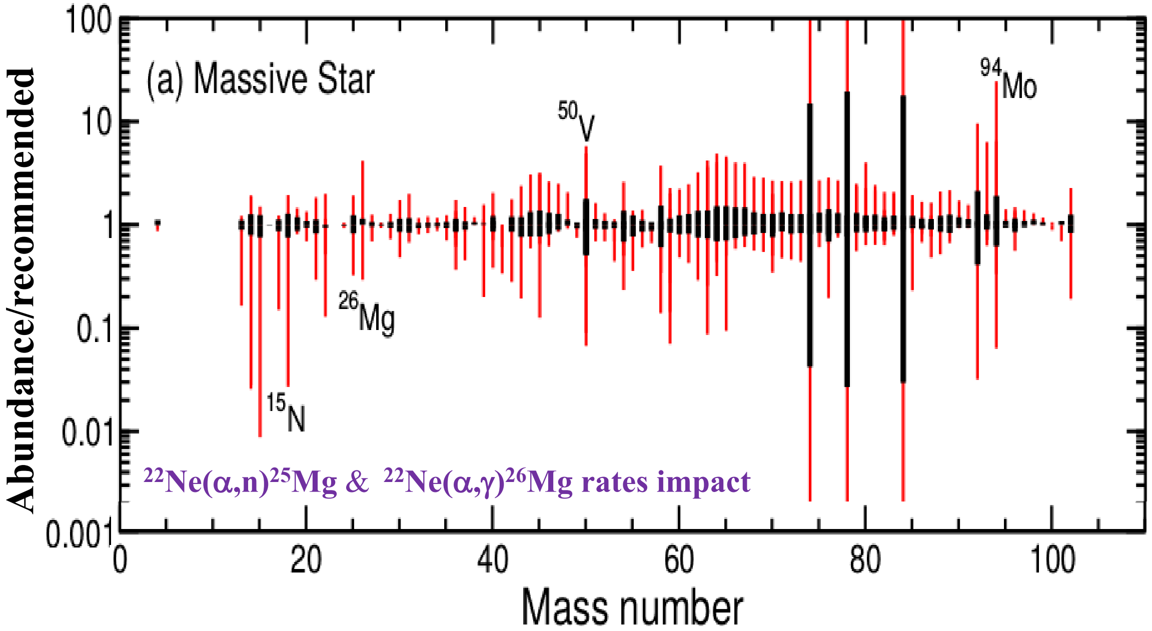
- **Weak s-process** → 56<A<90 in **massive stars** M>8M$_\odot$

➢ End of core He burning (T ~3·10^8 K, N_n =$\mathbf{10^6}$ cm^{-3}) ⟶ **Main neutron source: ^{22}Ne(α,n)^{25}Mg**

→ Starting with ^{14}N in the He core: ^{14}N(α,γ)^{18}F($\beta^+\nu$)^{18}O(α,γ)^{22}Ne ⟶ ^{22}Ne(α,n)^{25}Mg

➢ Not all ^{22}Ne are consumed when He in the core is exhausted

→ **^{22}Ne(α,n)^{25}Mg** reactivated during C-shell burning ^{12}C(^{12}C,α)^{20}Ne @ T~1 GK → N_n =$\mathbf{10^{11}}$ cm^{-3}



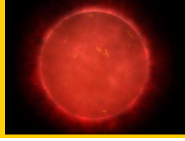
R. Longland, A. Karakas 2012

- Most important reactions affecting s-abundances with large uncertainties :

→ **^{22}Ne(α,n)^{25}Mg & ^{22}Ne(α,γ)^{26}Mg**

→**^{17}O(α,n)^{20}Ne & ^{17}O(α,γ)^{20}Ne** in low Z rotating stars **A. Choplin+18**

s-process in rotating metal-poor massive stars



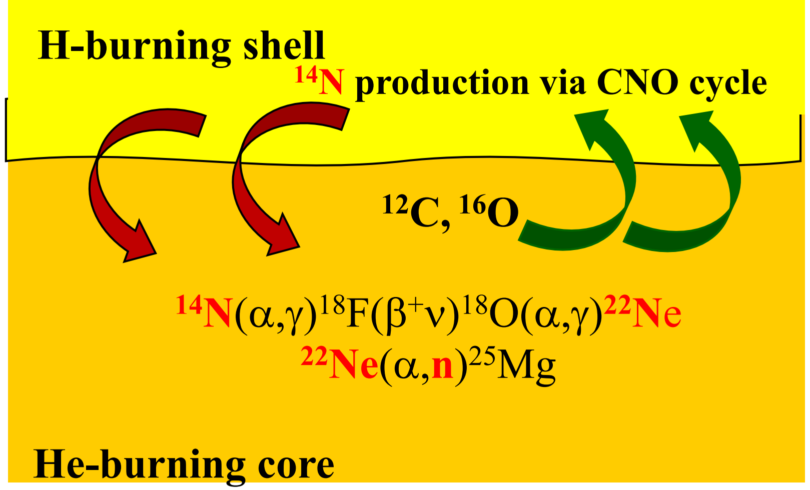
- Metal-poor massive stars → negligible *s*-process production (low ^{22}Ne & Fe seed abundance)
- With fast rotation induced mixing ➡ ^{22}Ne production in He core strongly enhanced **Nishimura+16, Choplin+18**

↳ 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**



H-burning shell

^{14}N production via CNO cycle

^{12}C, ^{16}O

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

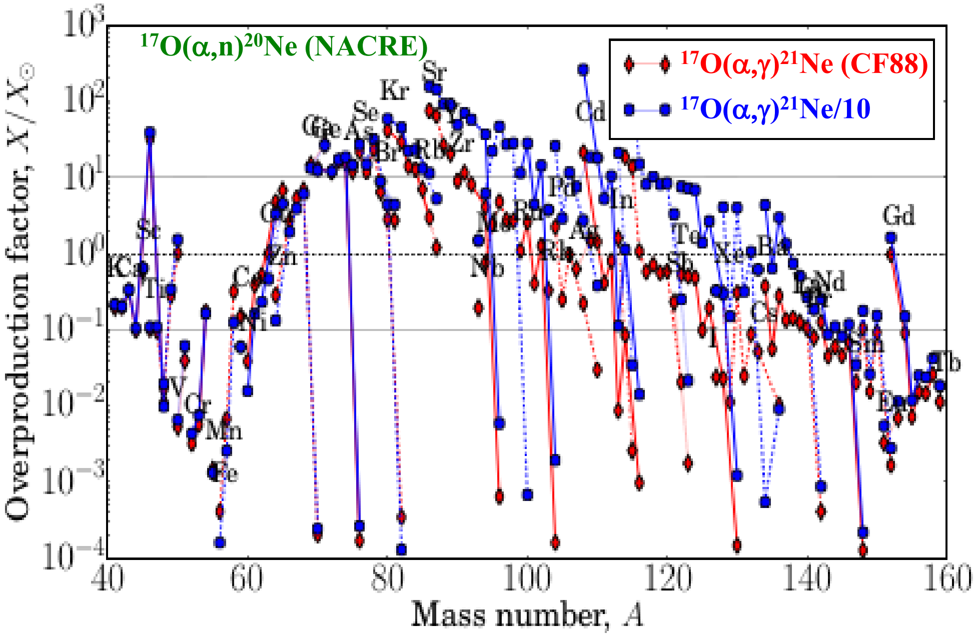
$^{22}Ne(\alpha,n)^{25}Mg$

He-burning core

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



Hirschi et al. MNRAS-2017

(α,n) & (α,γ) cross-sections: Characteristics & challenges

- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$, $^{22}Ne(\alpha,\gamma)^{25}Mg$
- $^{17}O(\alpha,n)^{20}Ne$, $^{17}O(\alpha,\gamma)^{21}Ne$

T=0.09-0.3 GK → few hundreds keV << $E_{Coulomb}$

→ σ(E) very weak (≤ 100 pb)

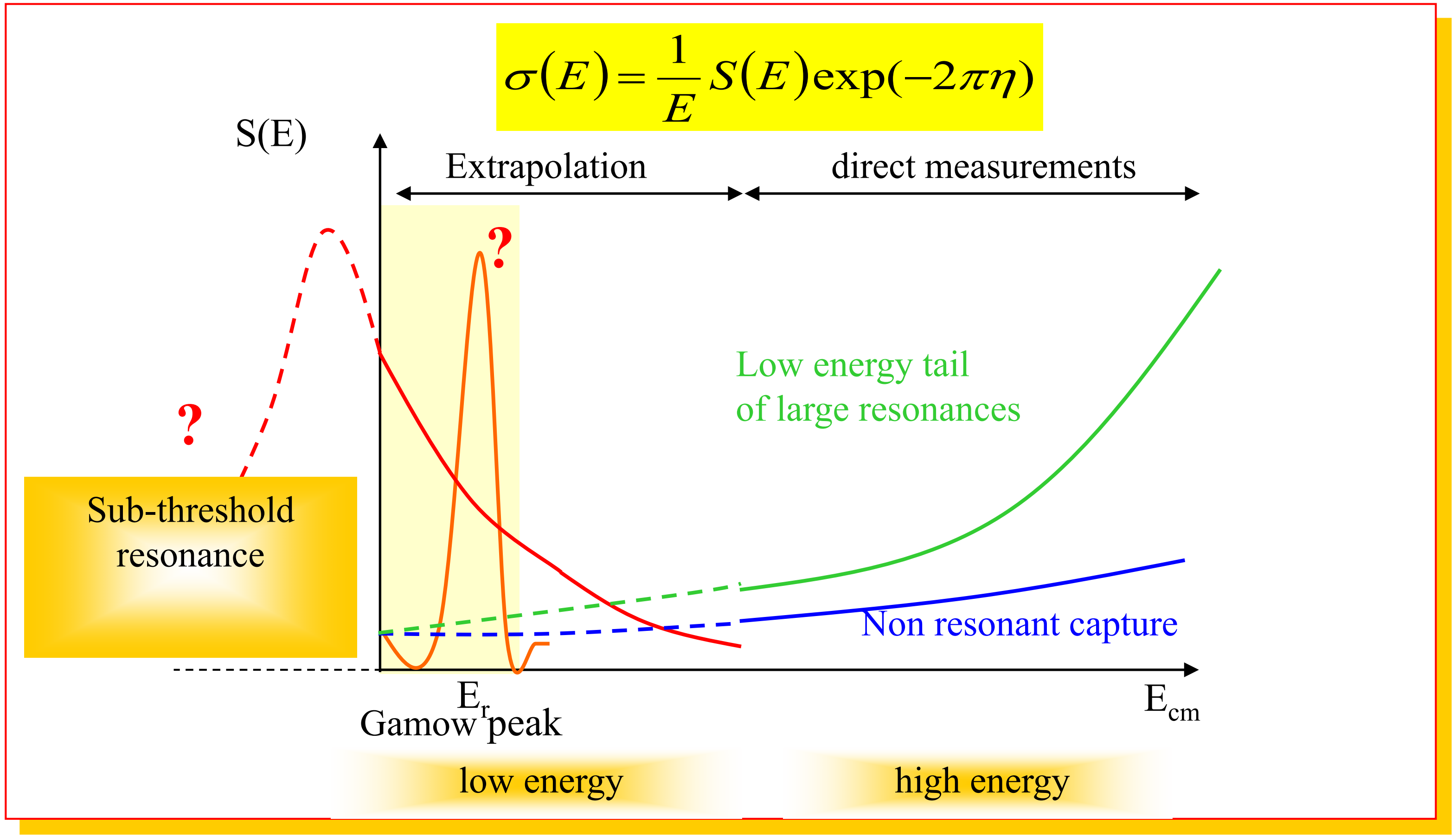
→ Direct measurements are very challenging

→ Neutron detection: large background

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



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

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

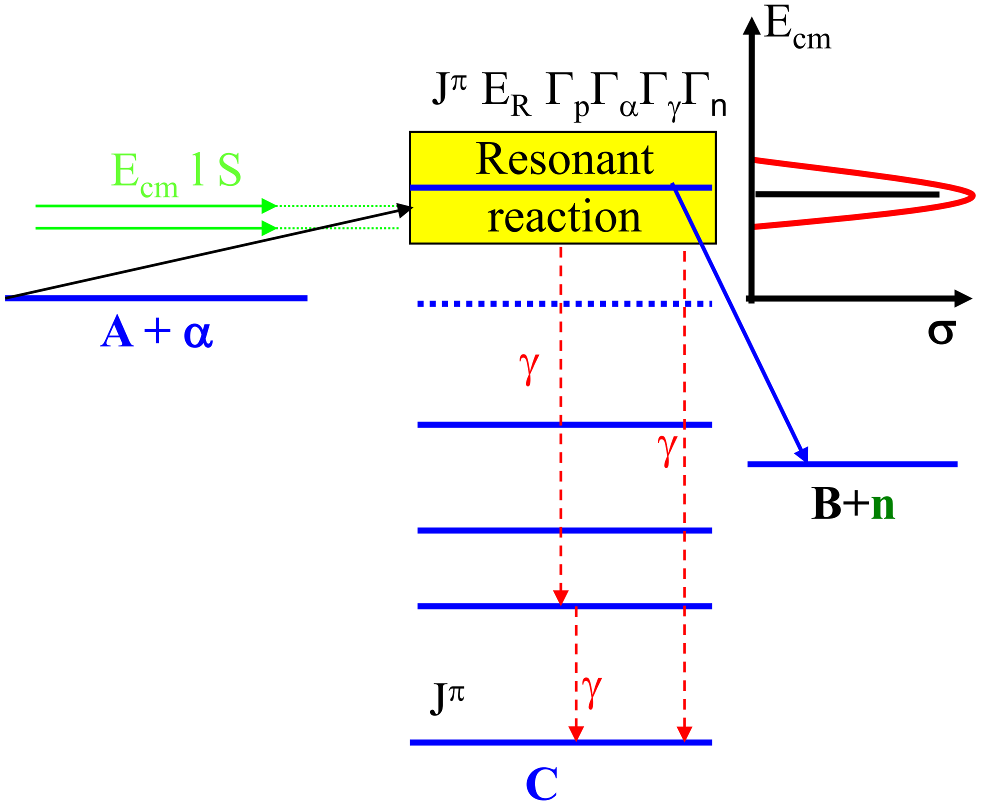
Reaction rate: $\langle \sigma v \rangle = \left(\frac{8}{\pi\mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{-E/kT} dE$

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

$x = \alpha$, $y = n$
or γ

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

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



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

🡇

Indirect techniques (transfer &/or resonant elastic scattering reactions,…) can be performed to extract these spectroscopic information

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

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 $\Psi = |A \oplus x>$ (ex: $x = \alpha$)

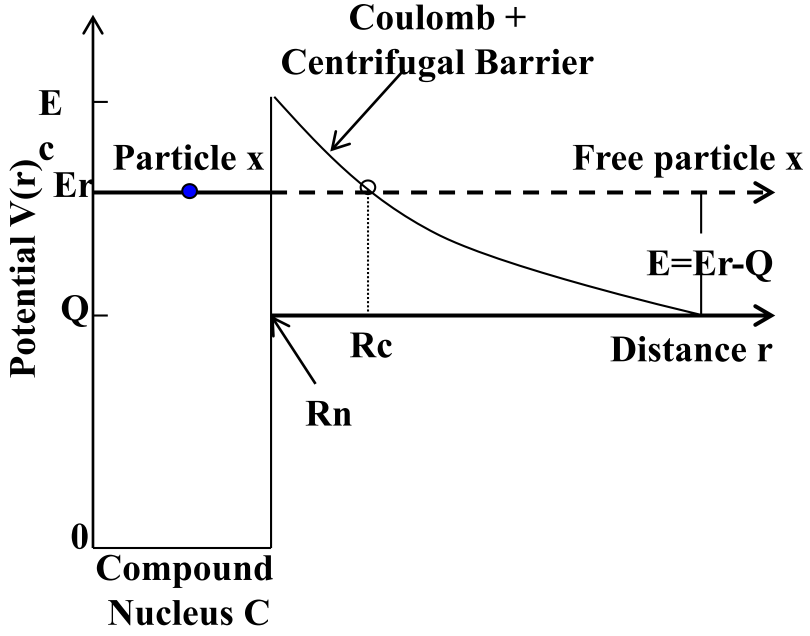
The single-particle decay partial width of C into A+α is given by

(See. Illiadis: Nuclear physics of stars)

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

P_l = penetrability factor

$\varphi(R_n)$ radial wave function of the particle *x* (ex: $x = \alpha$).



- 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 $\Gamma_\alpha = S_\alpha \Gamma_\alpha^{s.p}$
- S_α is a measure of the overlap between the initial and final state
- Transfer reaction → **Spectroscopic factor** $S_\alpha = <C^*|A \otimes \alpha>^2$

  → α-decay reduced width γ_α^2 & α-decay partial width Γ_α

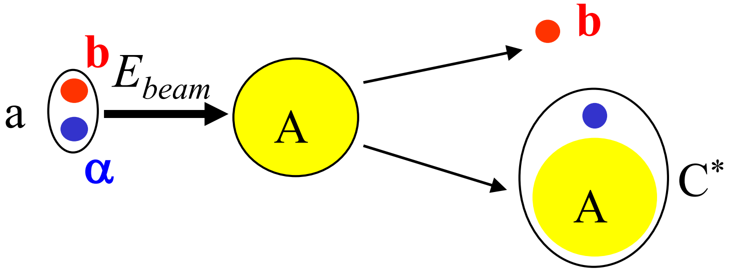
$$S_\alpha \Rightarrow \gamma_\alpha^2 = \frac{\hbar^2 r}{2\mu} S_\alpha |\varphi(r)|^2$$

$$\Gamma_\alpha = 2 P_l \gamma_\alpha^2$$

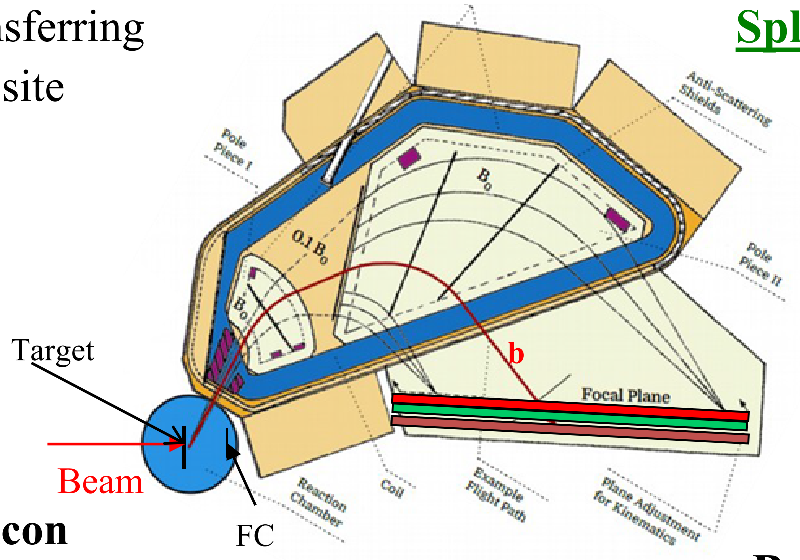
Transfer reactions: $a(=\alpha+b)+A \longrightarrow C^{*}(\alpha+A)+b \longleftrightarrow \alpha+A \longrightarrow C^{*} \to C+\gamma,\ B+n$

- Populate the states of interest in the compound nucleus C* formed by α+A by transferring the particle **α** from a high-energy projectile **a** (^{6}Li or ^{7}Li,...) assumed to be composite (**a=α+b (d or t)**) (typical E ~ few tens of MeV >> V_{coul}) to the target nucleus A

What do we measure by detecting b?



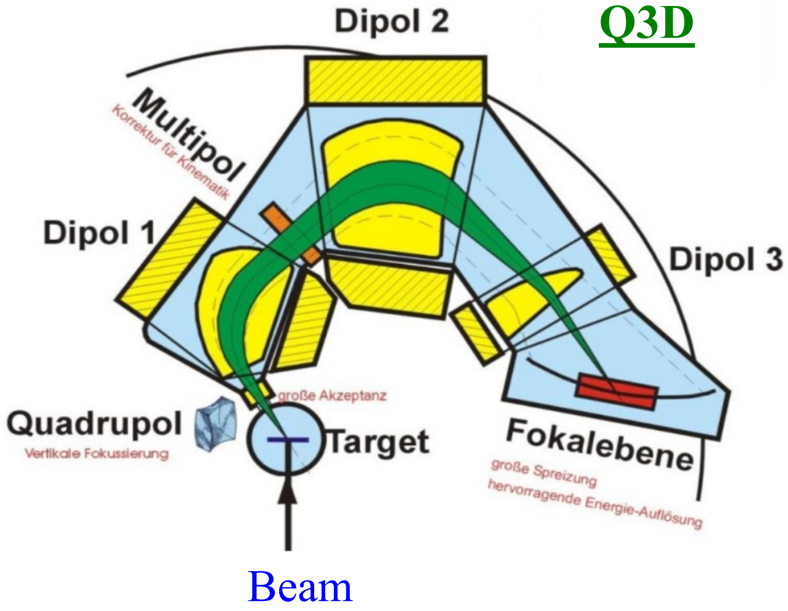
Split-Pole



- Particle **b** can be detected in a focal plane of a **magnetic spectrometer** or in **silicon detectors**. **BUT**: **Better energy resolution** with magnetic spectrometers

Bρ=mv/q

Q3D



E_b, $\theta_b \to$ Excitation Level energies of C^{*}: $\mathbf{E_x}$ (kinematics)

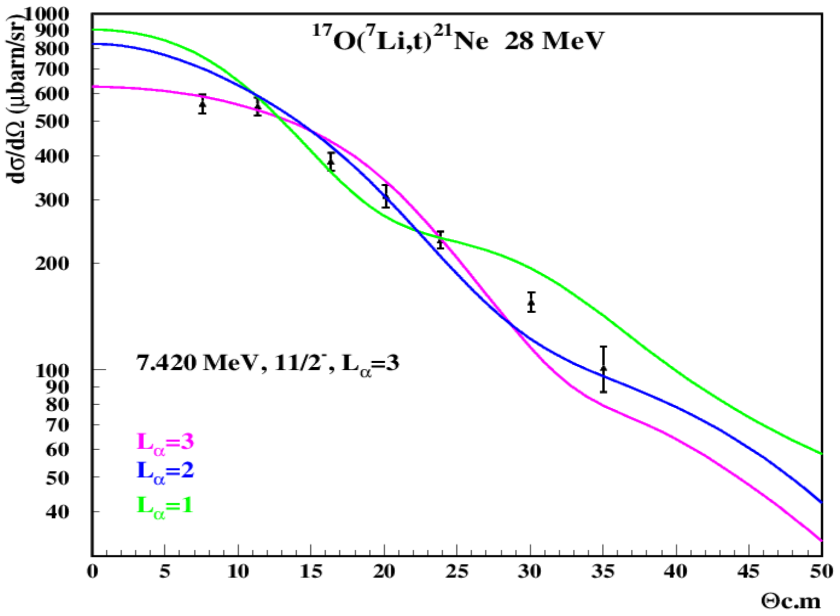
$\text{Yield}_b(\theta) \to$ Differential cross-sections of each state: $\mathbf{d\sigma/d\Omega}$

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

- *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: $a(=\alpha+b)+A \longrightarrow C^{*}(\alpha+A)+b \longleftrightarrow \alpha+A \longrightarrow C^{*}\begin{array}{l}\nearrow C+\gamma \\ \searrow B+n\end{array}$

- From the shape of the angular distribution → 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

→ Spectroscopic factor

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

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

$S_\alpha = \langle C \,|\, A \otimes \alpha \rangle \rightarrow \gamma^2_\alpha \rightarrow \Gamma_\alpha = 2P_l\, \gamma^2_\alpha$

Detailed and elaborate finite-range Distorded Wave Born Approximation (DWBA) analysis of the data is needed

$^{17}O(\alpha,n)^{20}Ne$ & $^{17}O(\alpha,\gamma)^{21}Ne$ experimental status & recent studies

^{17}O(α,n)^{20}Ne and ^{17}O(α,γ)^{21}Ne case: experimental status

- 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(α,n)^{20}Ne & ^{17}O(α,γ)^{21}Ne direct measurements:

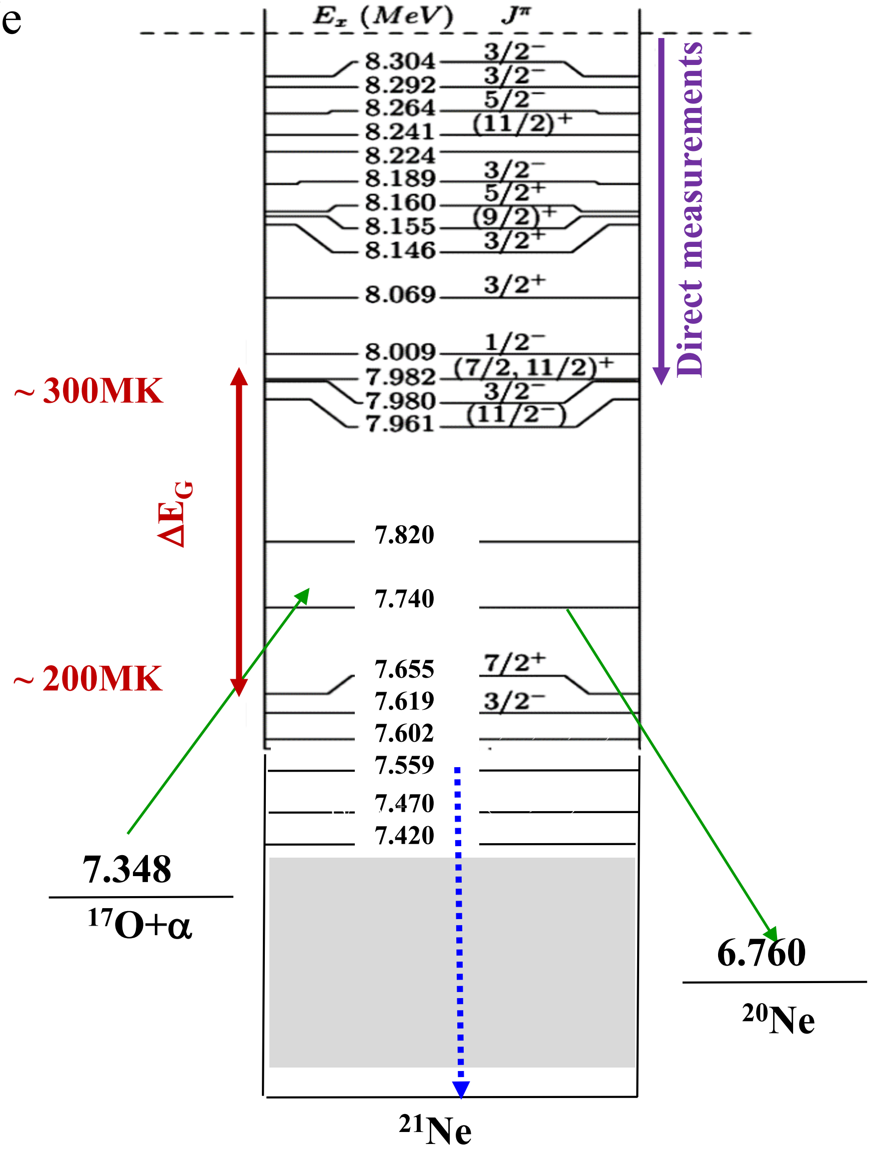
- **Denker+1994, Best+2013 → $0.63 \leq E_{cm} \leq 1.8$MeV**
- **Best +2011, Taggart+2019**
- **Williams+2022**

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

- 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(α,n) and ^{17}O(α,γ) rates (core He burning)

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



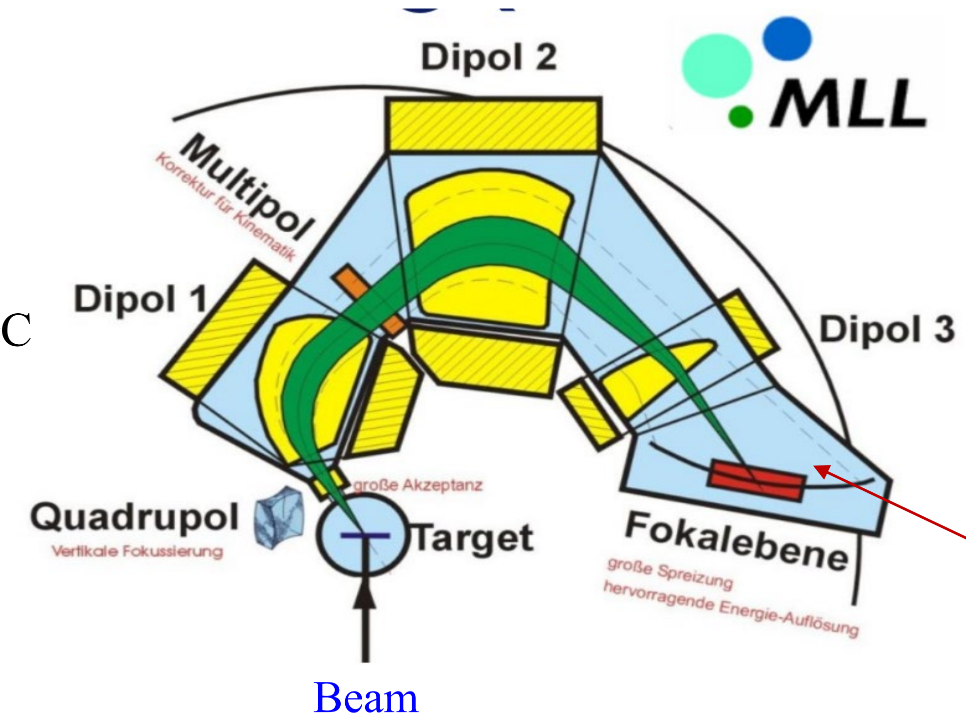
- Neutron transfer reaction → S_n→ Γ_n **Frost-Schenk+MNRAS2022**
- α-transfer reaction → S_α→ Γ_α **F. H+PRL 2024**

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

Q3D spectrometer (MLL)

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

- **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}



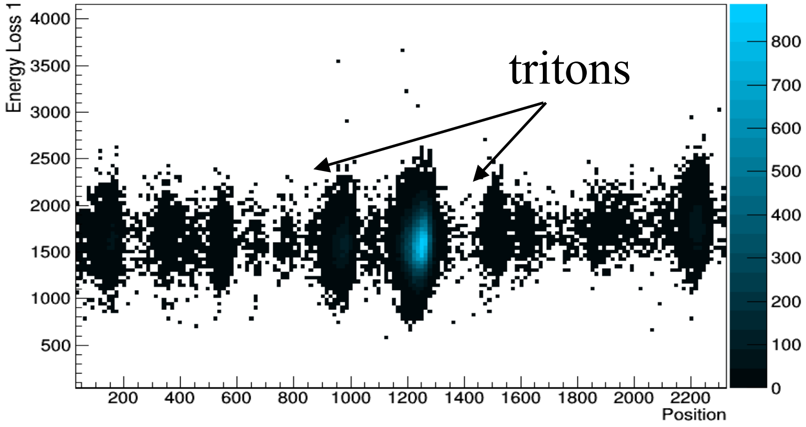
- 2 proportional gas counters: **Pos, ΔE$_1$, ΔE$_2$**
- plastic scintillator: **E**

dσ/dΩ measurements:

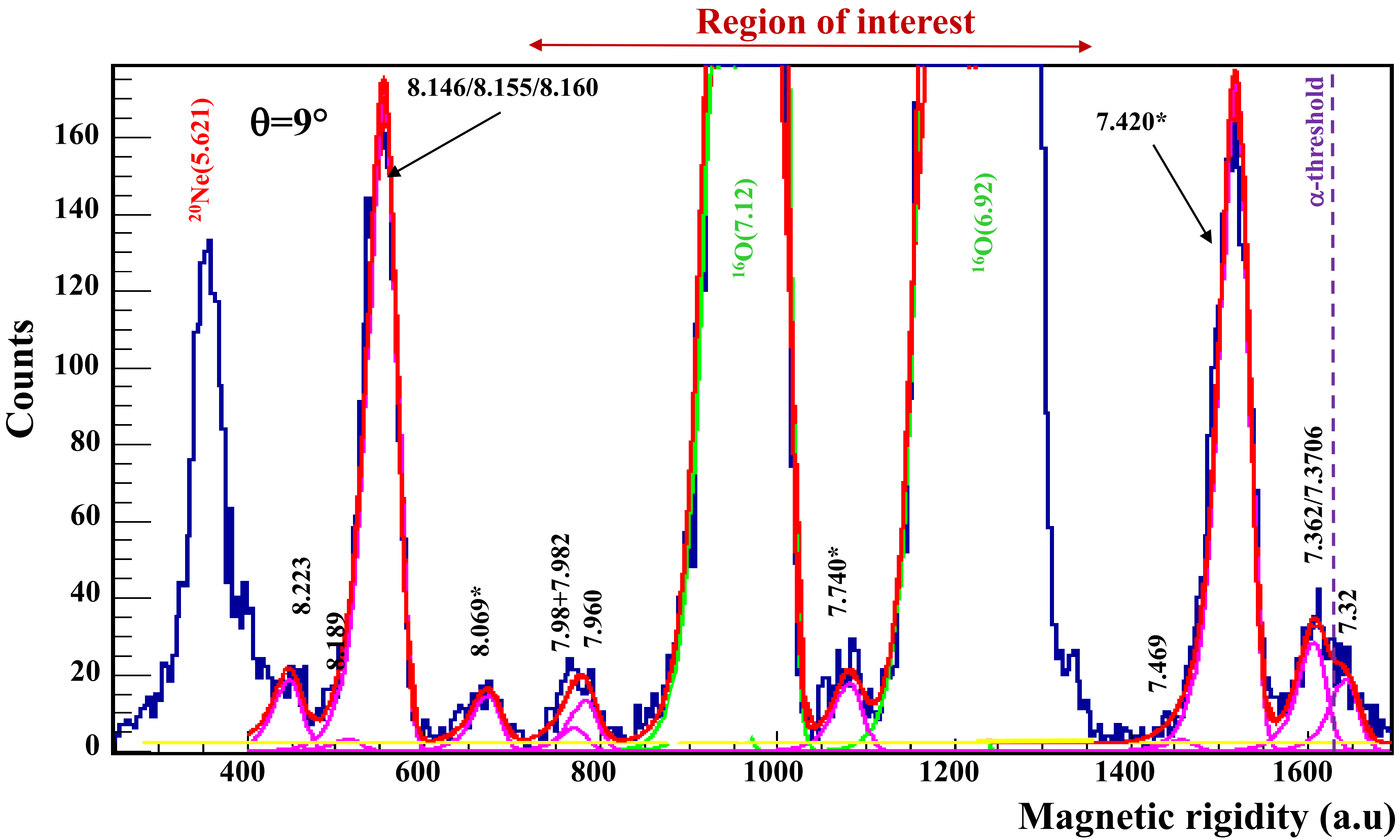
- 9 angles θ_{lab}= 6°-36° ⇒ θ_{cm} → 7.5°- 45°

- 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



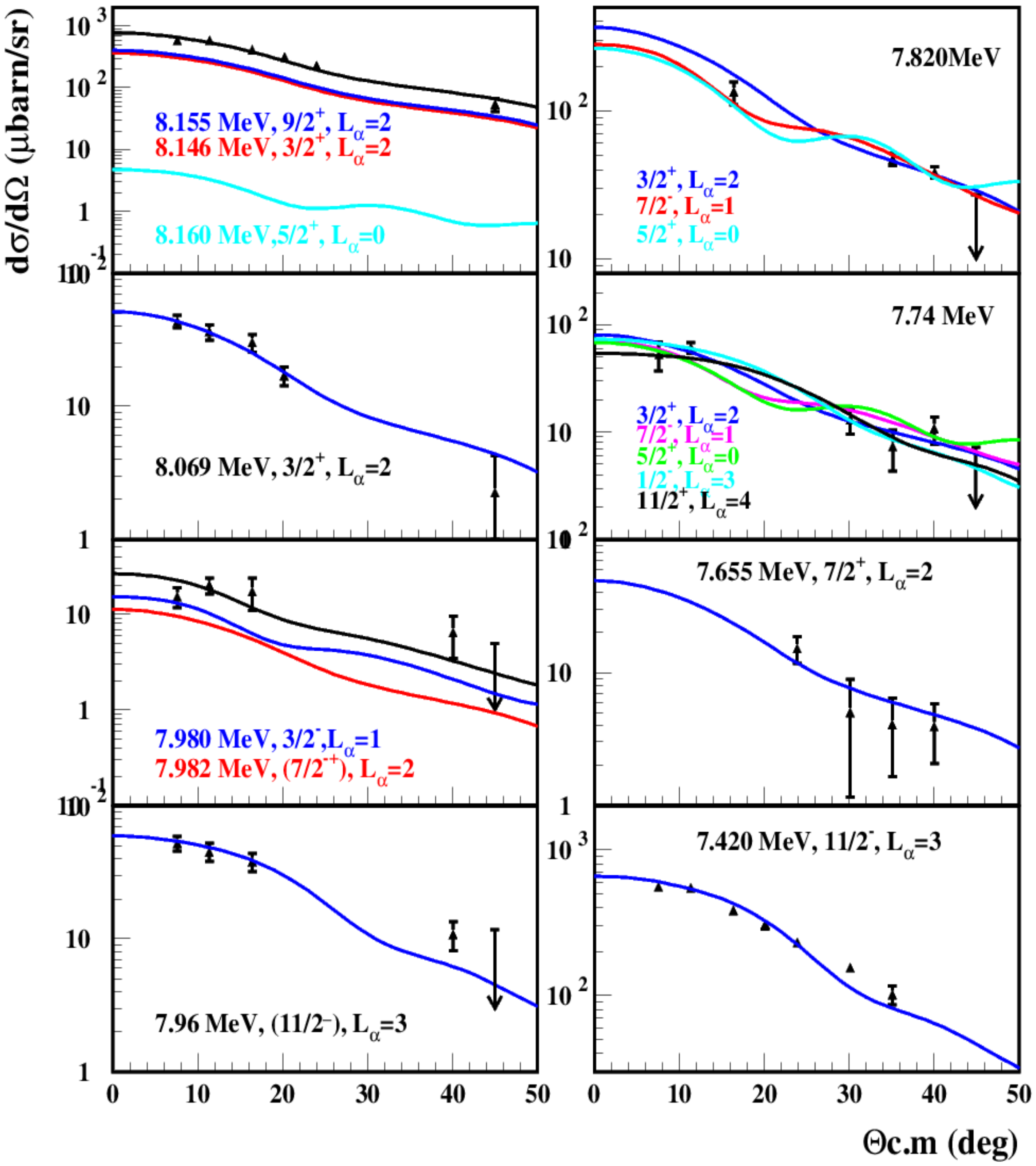
Excitation energy spectrum of ^{21}Ne



- 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)

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

@ R=7.5 fm

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

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

Rates calculations:

RateMC code **Longland+2013**

☐ For Er < 721 keV & Er=807 keV:

→ Γ_α (**present work**)

Γ_α (7.81MeV) 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)

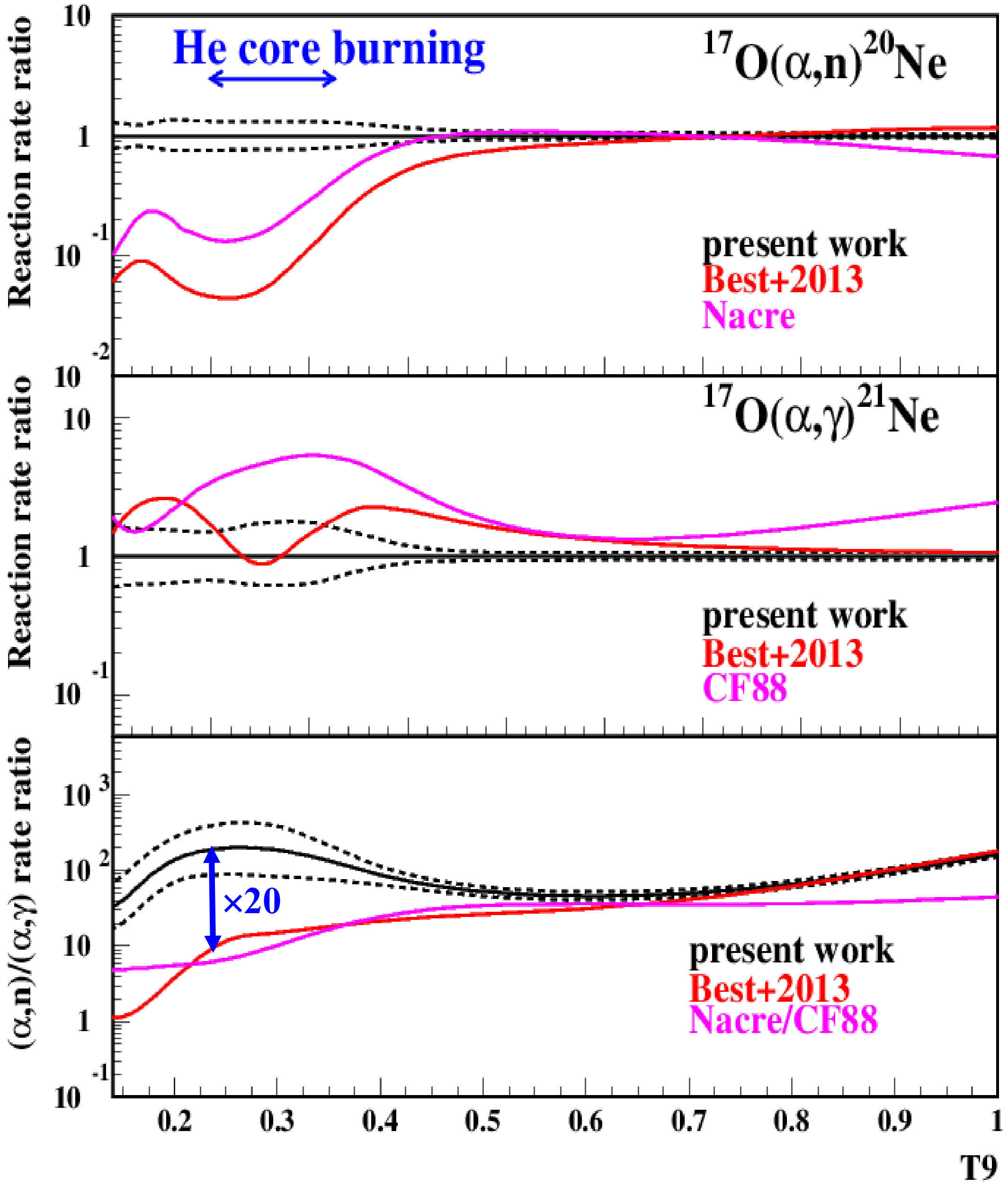
☐ Γ_γ from:

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

→ ωγ(α,γ) **Williams+2022** combined with present Γ_α & Γ_n **(Frost Schenk+22)**

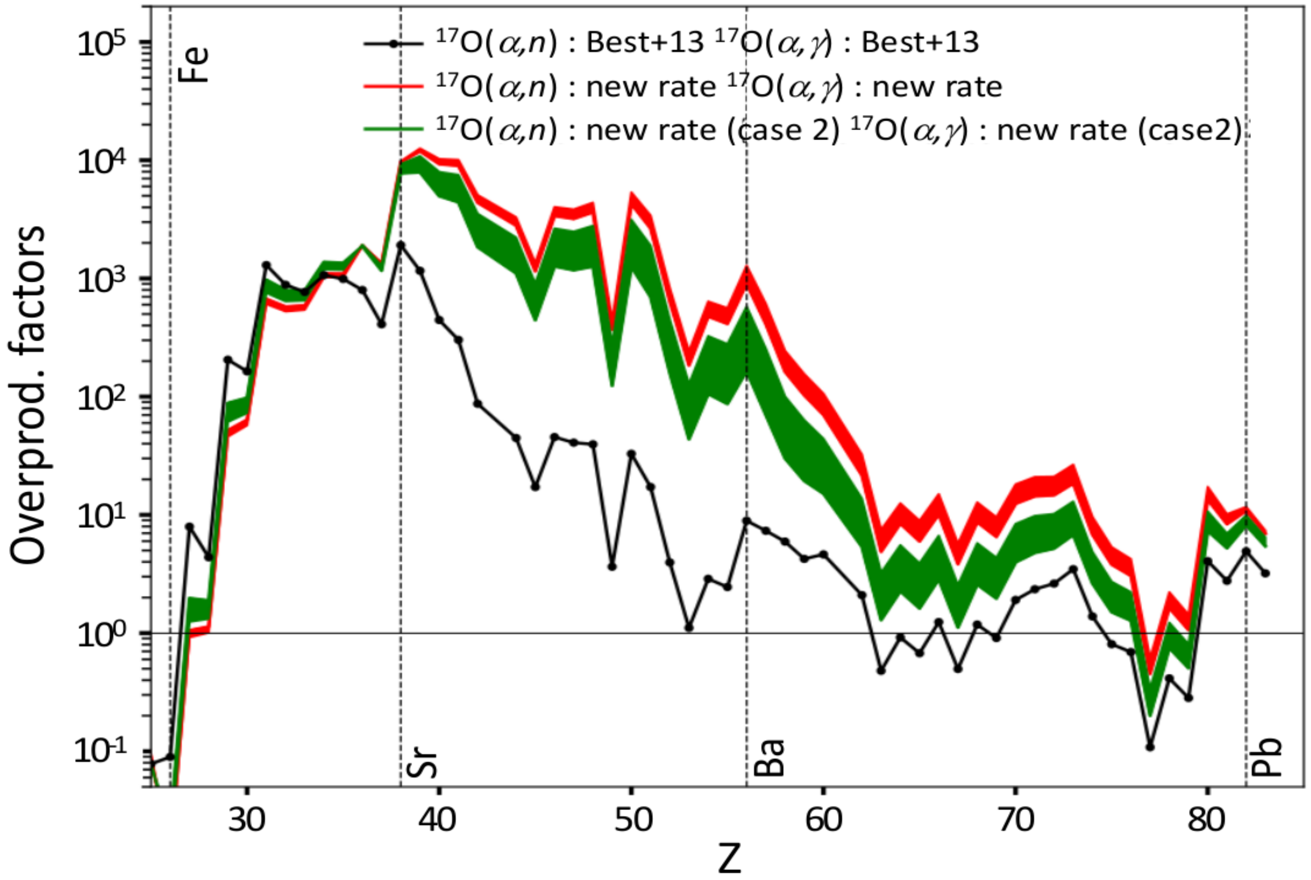
→ when no Γ_n → Γ_γ/Γ_n **Best+2013**

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



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 ($Z=0.001$, $M=25\ M_\odot$)



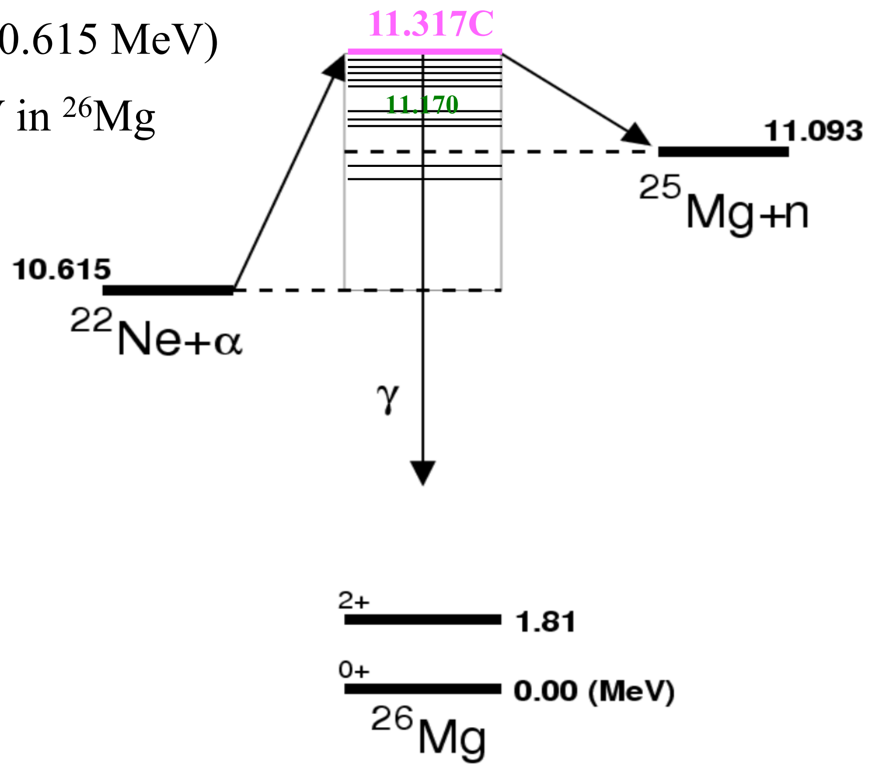
→ **Large enhancement** (>1.5 dex (>1.3 dex)) of elements $40 < Z < 60$ with the present **new rates** in comparison to **Best+13** rates

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

F. H+PRL 2024

^{22}Ne(α,n)^{25}Mg & ^{22}Ne(α,γ)^{26}Mg experimental status

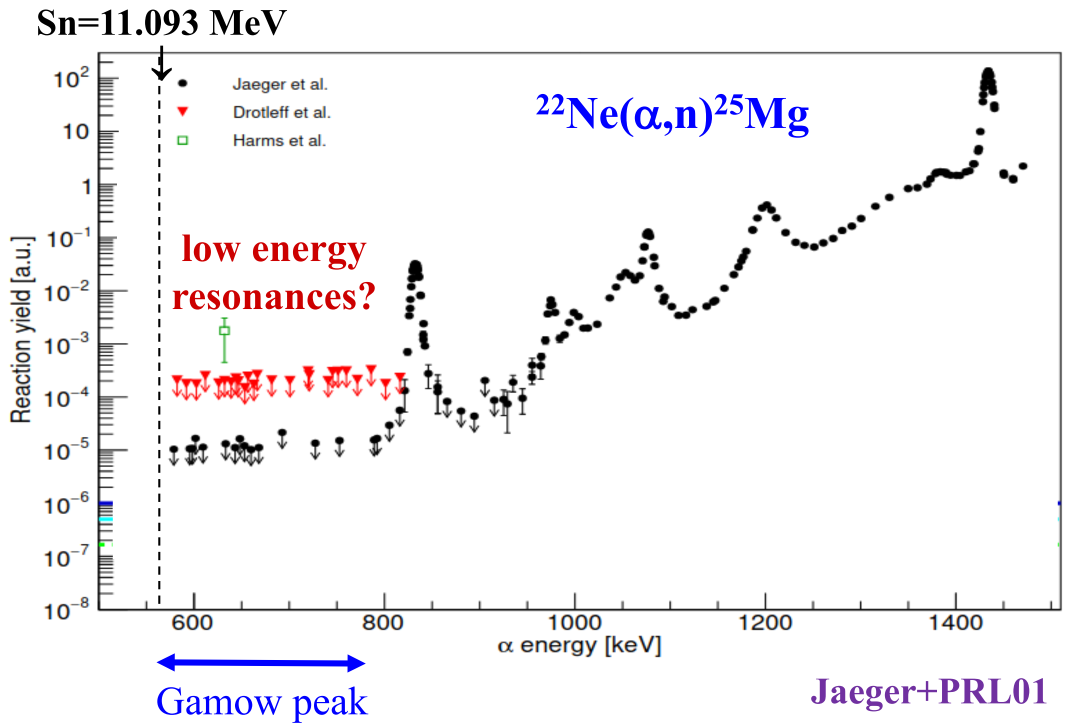
$^{22}Ne(\alpha,n)^{25}Mg$ & $^{22}Ne(\alpha,\gamma)^{26}Mg$: Experimental status & direct studies



- ➢ $^{22}Ne(\alpha,n)^{25}Mg$ (Q=-0.478 MeV) → competition with $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction (Q=10.615 MeV)
  - Core He burning: T ~0.2-0.3 GK → $E_{c.m}$~358-748 keV → E_x=10.973-11.363 MeV in ^{26}Mg

Direct measurements: $^{22}Ne(\alpha,n)^{25}Mg$ **Haas+73, Harms+91, Drotleff+93, Jaeger+01**

Jaeger+PRL01→ He^+ beams on windowless gas target with enriched ^{22}Ne (99.9%)
→ 4π neutron detectors: 12 proportional counters surrounding a cylindrical polyethylene moderator (Eff=50%)
→ Plastic scintillator (veto to suppress cosmic-ray-induced background)



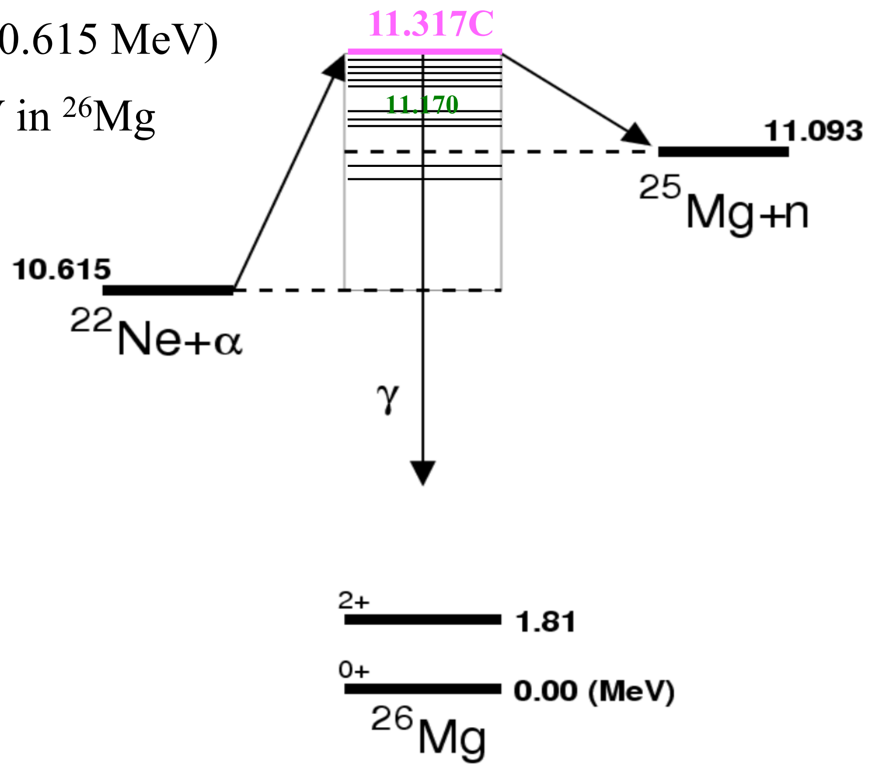
Jaeger+PRL01

→ Down to S_n: E_{cm}= 477 keV (E_α(lab)=564 keV)

But: Only upper limits @ E_α(lab) < 830 keV (High background in the neutron detectors due to cosmic rays)

→ Contribution of the low energy resonances?

^{22}Ne(α,n)^{25}Mg & ^{22}Ne(α,γ)^{26}Mg: Experimental status & direct studies



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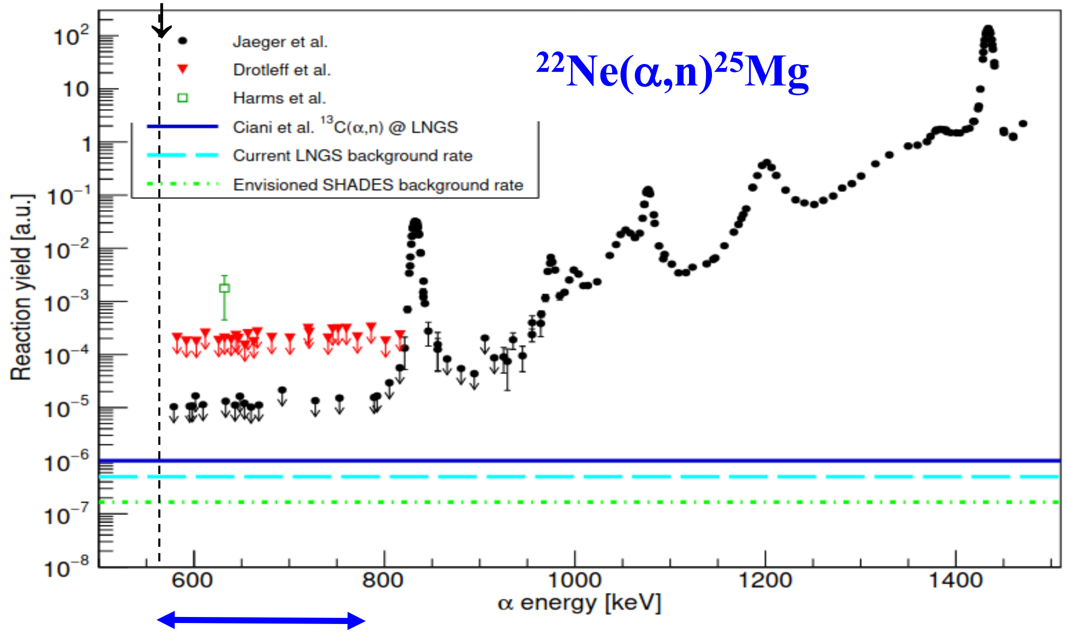
Sn=11.093 MeV



Gamow peak

Jaeger+PRL01

→ Down to S_n: E_{cm}= 477 keV (E_α(lab)=564 keV)

But: Only upper limits @ E_α(lab) < 830 keV (High background in the neutron detectors due to cosmic rays)

→ Contribution of the low energy resonances?

More (α,n) measurements with less background are needed
→ Ongoing project @ underground lab LUNA-MV (SHADES)

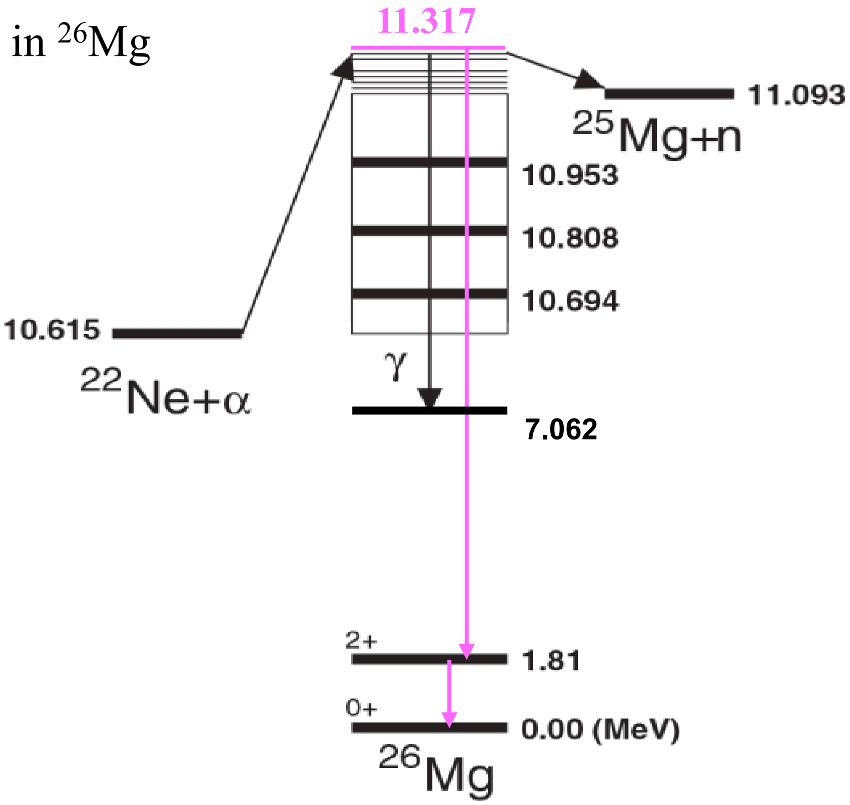
^{22}Ne(α,n)^{25}Mg & ^{22}Ne(α,γ)^{26}Mg: Experimental status & direct studies

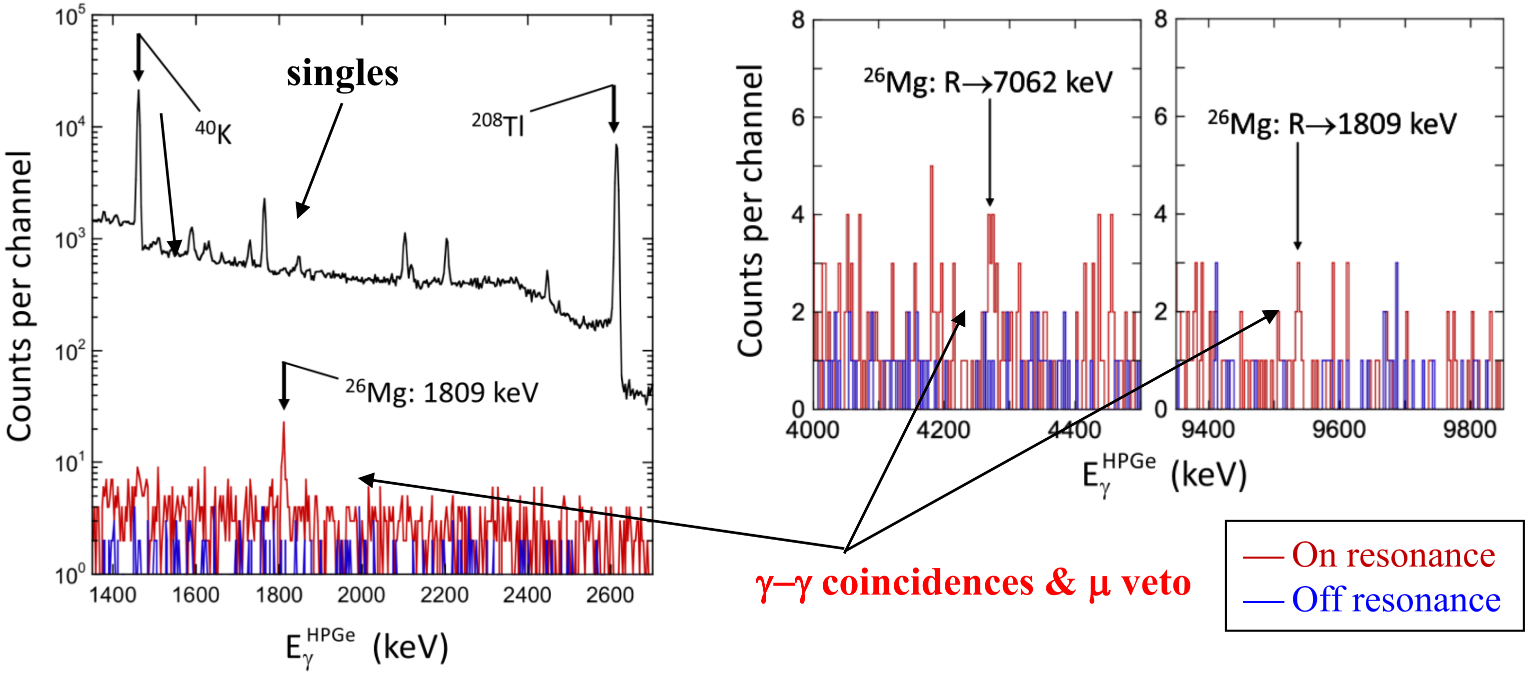
- **^{22}Ne(α,n)^{25}Mg** (Q=-0.478 MeV) → competition with ^{22}Ne(α,γ)^{26}Mg reaction (Q=10.615 MeV)
  - Core He burning: T ~0.2-0.3 GK → $E_{c.m}$~358-750 keV → E_x=10.973-11.365 MeV in ^{26}Mg

Direct measurements: **^{22}Ne(α,γ)^{26}Mg** **Wolk+89, Hunt+19**

→ ωγ(α,γ) of E_{cm}=702 keV (Ex=11.317 MeV) resonance ($E_α$=830 keV)

Hunt+PRC19→ He$^+$ beams on ^{22}Ne-implanted Ti backing
→γ rays detected in LENA's γ γ -coincidence spectrometer: high-purity germanium (HPGe) detector @ 1.1 cm from target surrounded by an NaI
→Plastic scintillator (veto to suppress cosmic-ray-induced background)





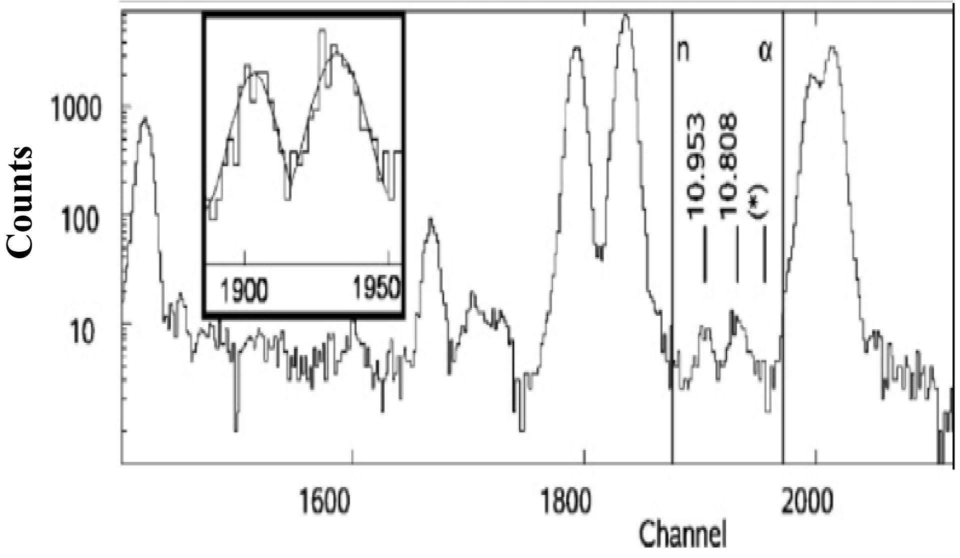
γ–γ coincidences & μ veto

Data at lower energies are needed
→ EASγ new project @ underground lab LUNA-MV

^{22}Ne(α,n)^{25}Mg & ^{22}Ne(α,γ)^{26}Mg: Transfer reaction measurements

- Various **α-transfer** (**^{6}Li,d**) & (**^{7}Li,t**) reactions
  → S_{α} ⇒ Γ_{α} → ωγ(α,n) of 10.614-11.365MeV states in ^{26}Mg.

Ugalde+07→ Implanted ^{22}Ne 7μg/cm^{2} into 40 μg/cm^{2} of carbon



→ High Background due to C ☹

→ Too low ^{22}Ne density ☹

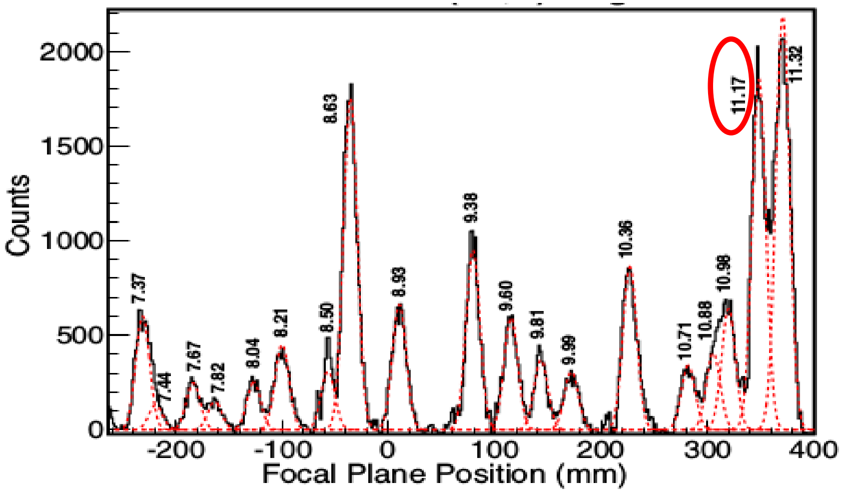
Challenging needs:

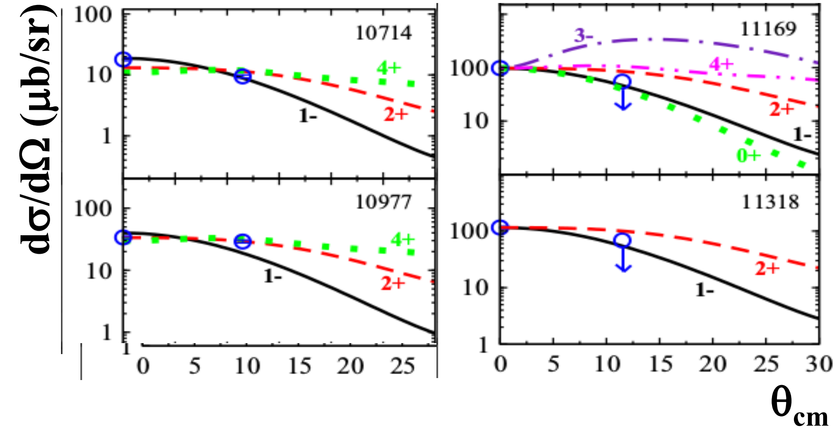
→ ^{22}Ne implanted targets with high densities on high Z material (Ni, …)

or

→ ^{22}Ne gas cells with thin (< 1 μm) High Z windows (Ni) for incident ^{6}Li or ^{7}Li beam energies ~ 28-38 MeV (good momentum matching)

Talwar+16→ (^{6}Li,d), ^{22}Ne gas target & high resolution spectrometer: ΔE~ 100 keV no background but very poor momentum matching (14***h*** @ E_{6Li}=82.3 MeV)

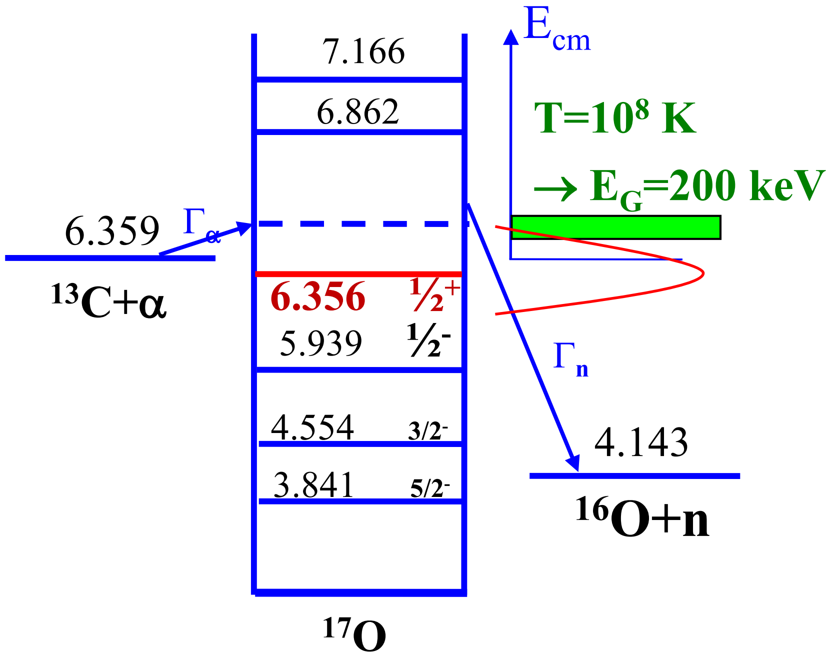




only 2 angles!

$^{13}C(\alpha,n)^{16}O$ experimental status

^{13}C(α,n)^{16}O case: experimental status

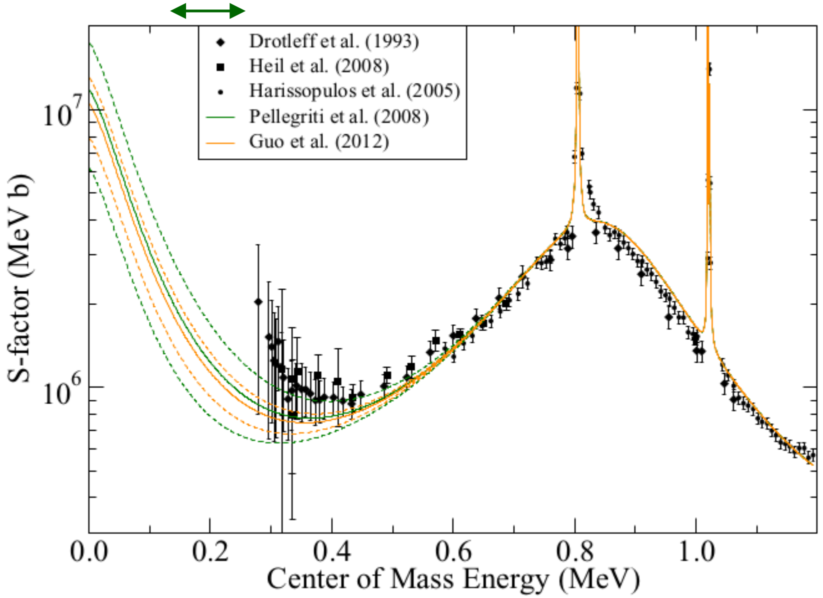


Direct measurements: Before JUNA & LUNA recent experiments **(Drottlef+93, Harissopulos+05, Heil+08)**

→ Down to E$_{cm}$= 300 keV

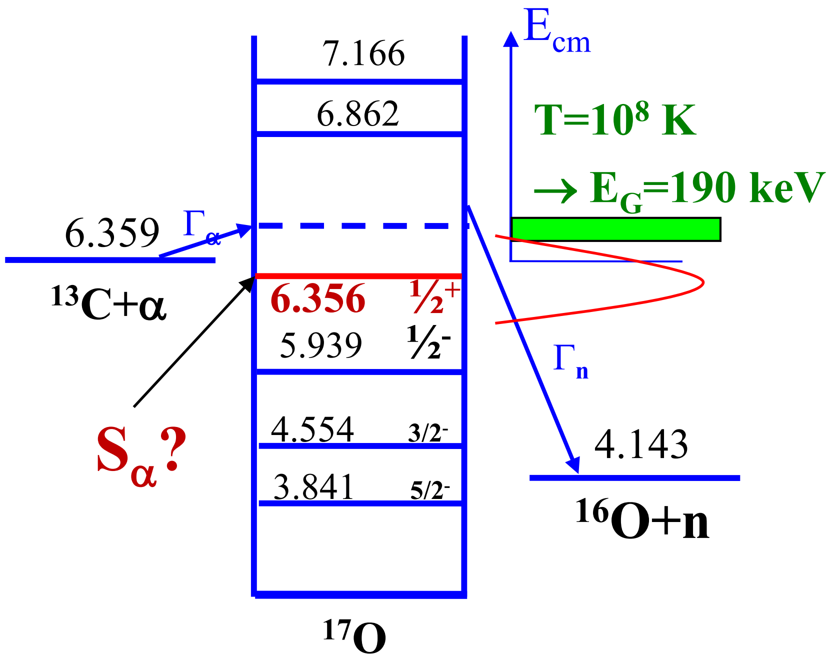
→ Lowest data points: Large error bars

Gamow peak ~200 keV →σ ≈100 pb



De Boer+20

^{13}C(α,n)^{16}O case: experimental status & studies



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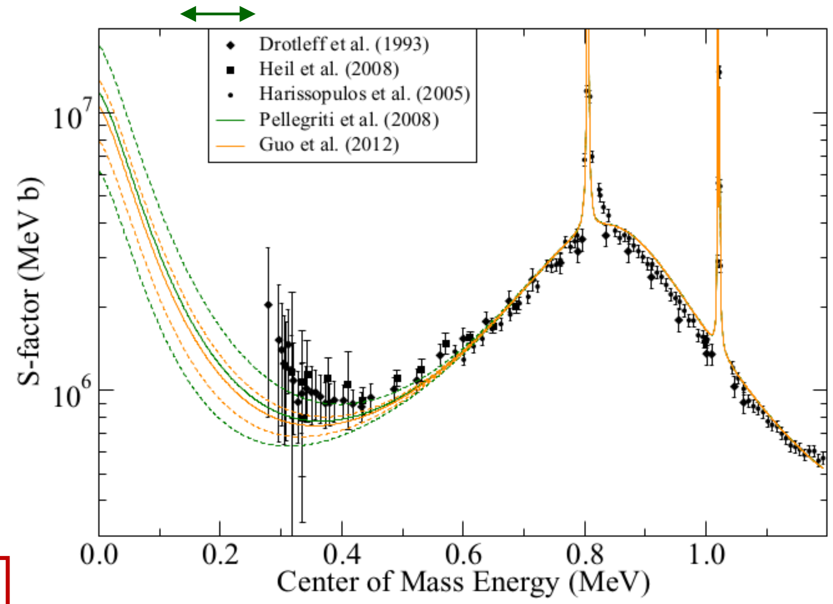


De Boer+20

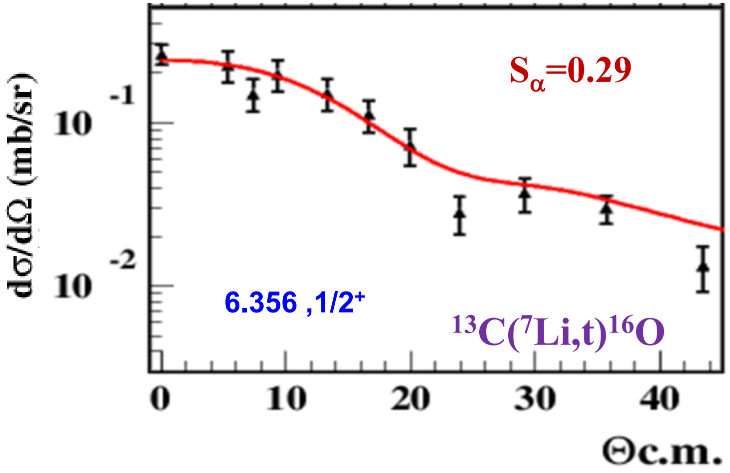
- Effect of the sub-threshold state @ 6.356 MeV?

➢ **Various α-transfer reactions (Kubono+06, Johnson+06,Pellegriti+08, Guo+12, Avila+15):**

(^{6}Li,d), (^{7}Li,t), (^{11}B,^{7}Li) → S$_\alpha$ ⇒ γ$^2_\alpha$ of the 6.356 MeV state

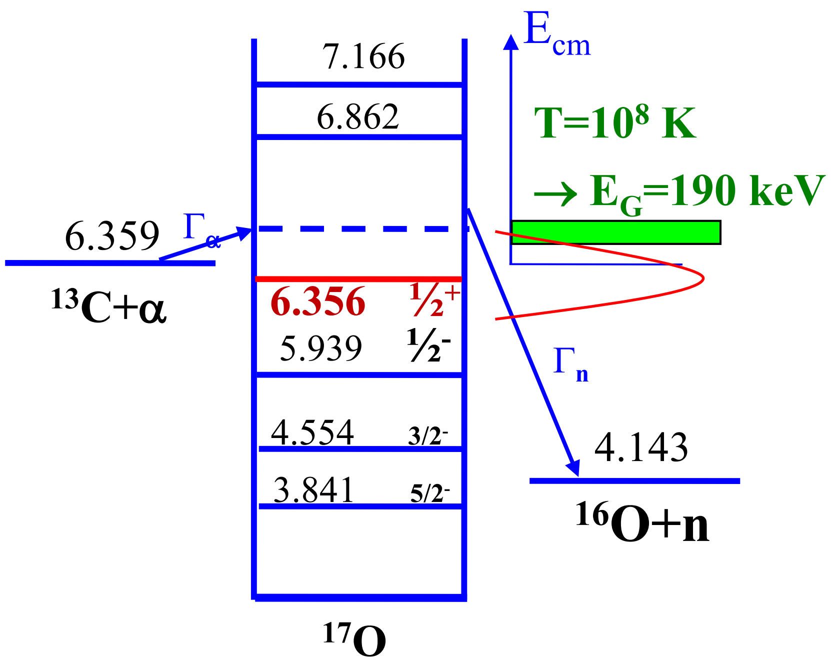
→R-matrix calculation of ^{13}C(α,n)^{16}O

→Except **Kubono+06, Johnson+06**, all the other measurements give consistent results



Pellegriti+PRC (R) 08

$^{13}C(\alpha,n)^{16}O$ case: experimental status & studies



Direct measurements: Before JUNA & LUNA recent experiments **(Drottlef+93, Harissopulos+05, Heil+08)**

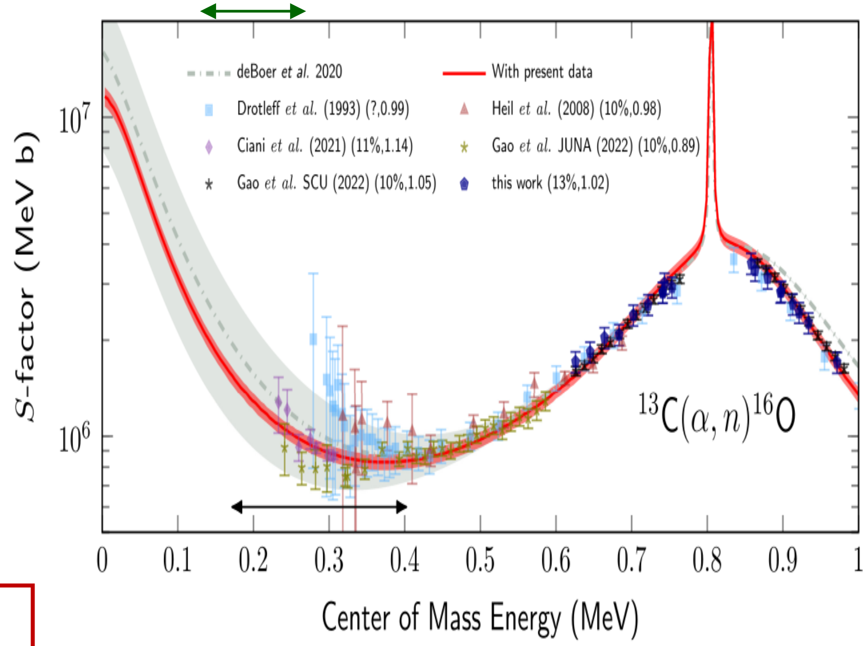
→ Down to E_{cm}= 300 keV

→ Lowest data points: Large error bars

- After LUNA **Ciani+21**, JUNA **Gao+22 & de Boer+24**

→ Down to E_{cm}= 233 keV

→ More precise data @ very low energies



De Boer+24

- Effect of the sub-threshold state @ 6.356 MeV?

➢ **Various α-transfer reactions (Kubono+06, Johnson+06,Pellegriti+08, Guo+12, Avila+15):**

(^{6}Li,d), (^{7}Li,t), (^{11}B,^{7}Li) → $S_\alpha \Rightarrow \gamma^2_\alpha$ of the 6.356 MeV state

→R-matrix calculation of $^{13}C(\alpha,n)^{16}O$

→Except **Kubono+06, Johnson+06**, all the other measurements give consistent results

➢ Recent data have achieved consistency between direct measurements and transfer measurements

➢ Uncertainty decreased from 30% to 5%

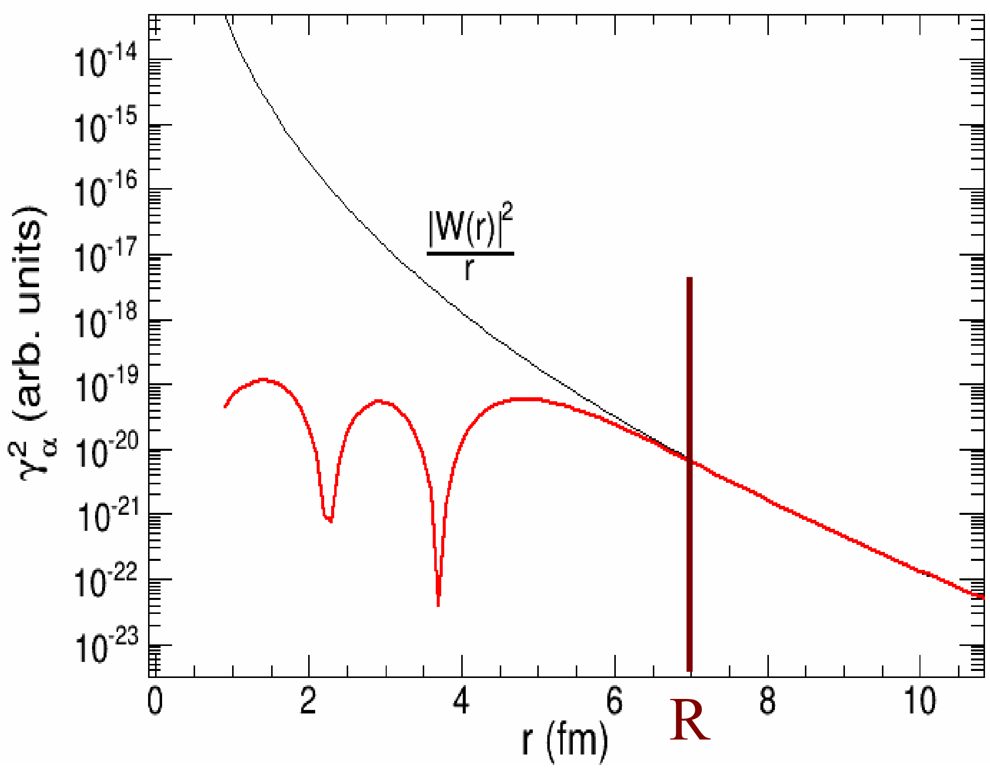
THANK YOU
FOR
YOUR ATTENTION

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

$$S_x^C \left\{ \begin{array}{l} \gamma_x^2 = \dfrac{\hbar^2 R}{2\mu} S_x^C |\phi(R)|^2 \Rightarrow \Gamma_x = 2P_l \gamma_x^2 \\ \\ \tilde{C}^2 = S_x^C \dfrac{R^2 |\phi(R)|^2}{W(R)^2}) \end{array} \right.$$

W(R): Whittaker function

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



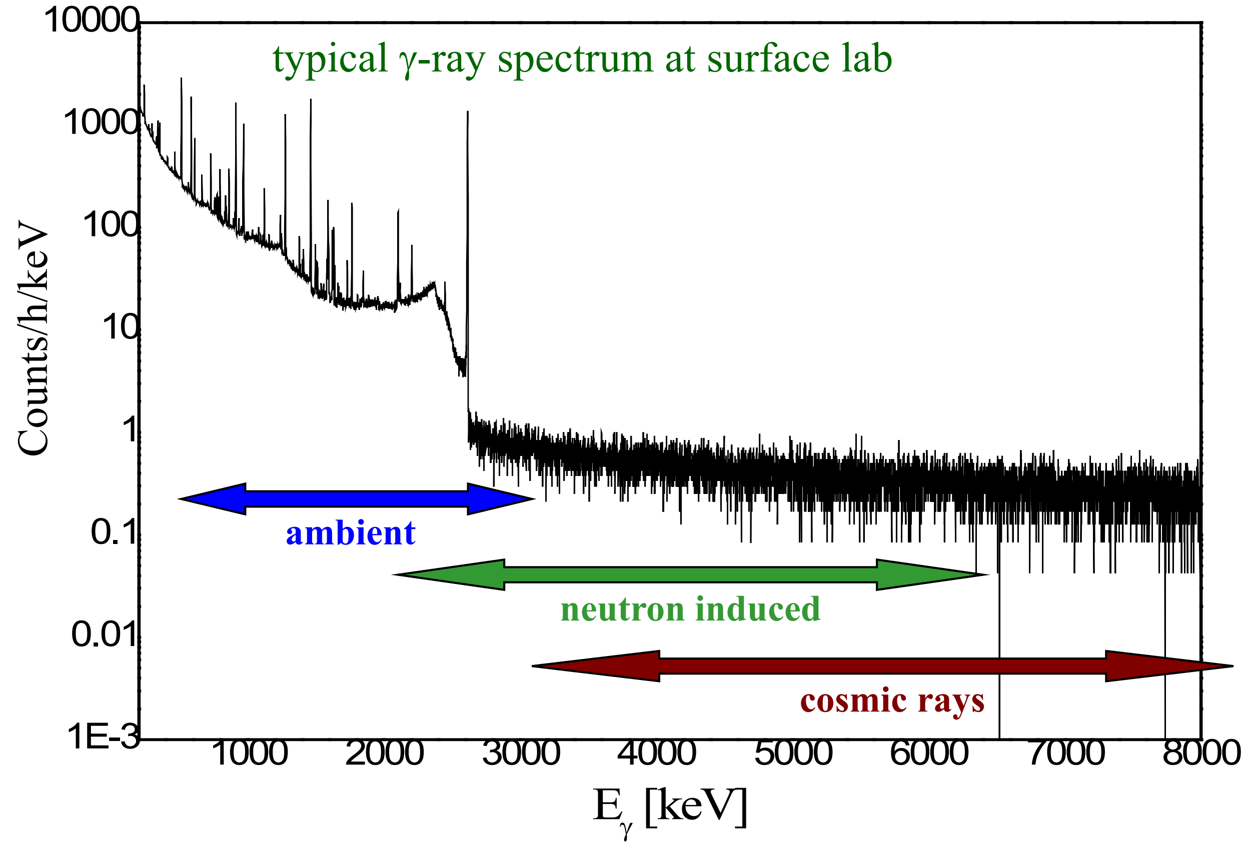
The LUNA (Laboratory Underground for Nuclear Astrophysics) facility

Main sources of background

- natural radioactivity (mainly from U and Th chains)
- cosmic rays (muons, $^{1,3}H$, ^{7}Be, ^{14}C, …)
- neutrons from (α,n) reactions and fission

} Go underground + low U and Th environments

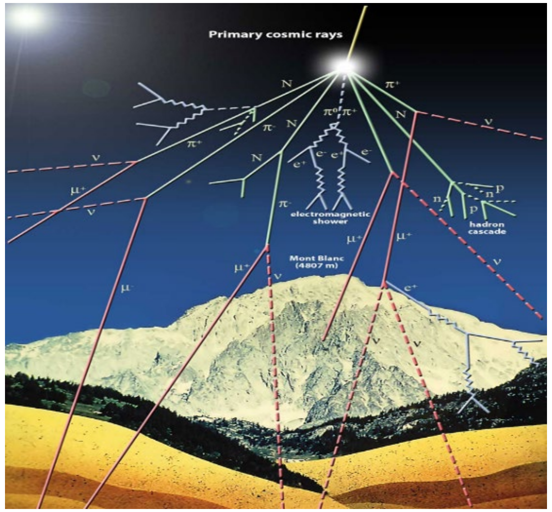
⬇



In cases where:

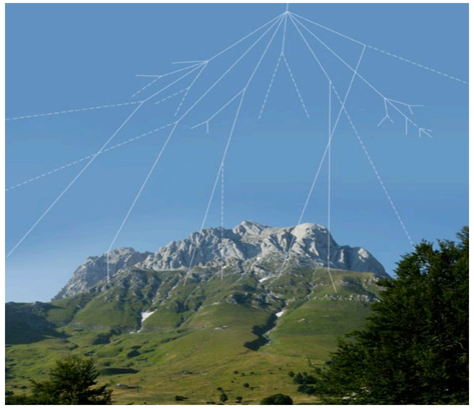
→ background is dominated by cosmic rays

→ poor signal-to-noise ratio at surface level

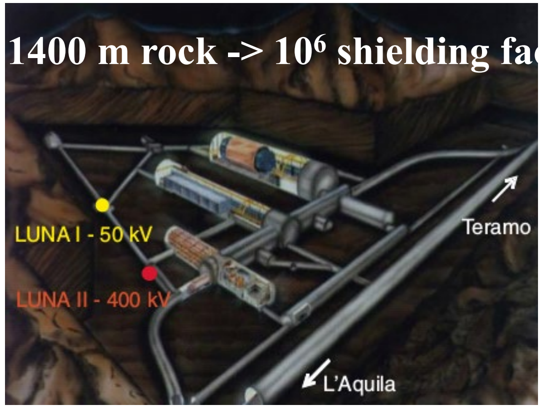


The LUNA (Laboratory Underground for Nuclear Astrophysics) facility

Gran Sasso - Italy



Laboratori Nazionali del Gran Sasso

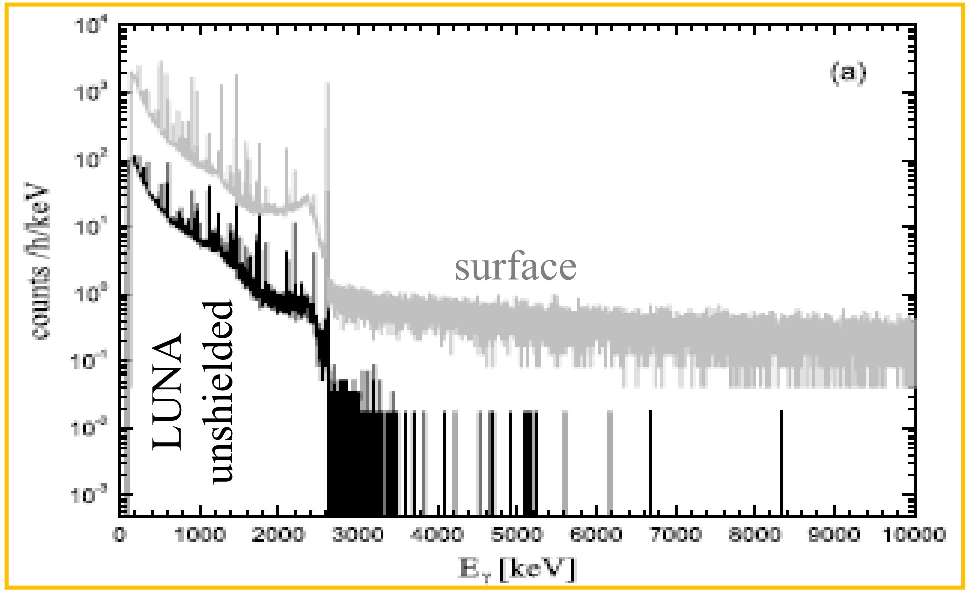


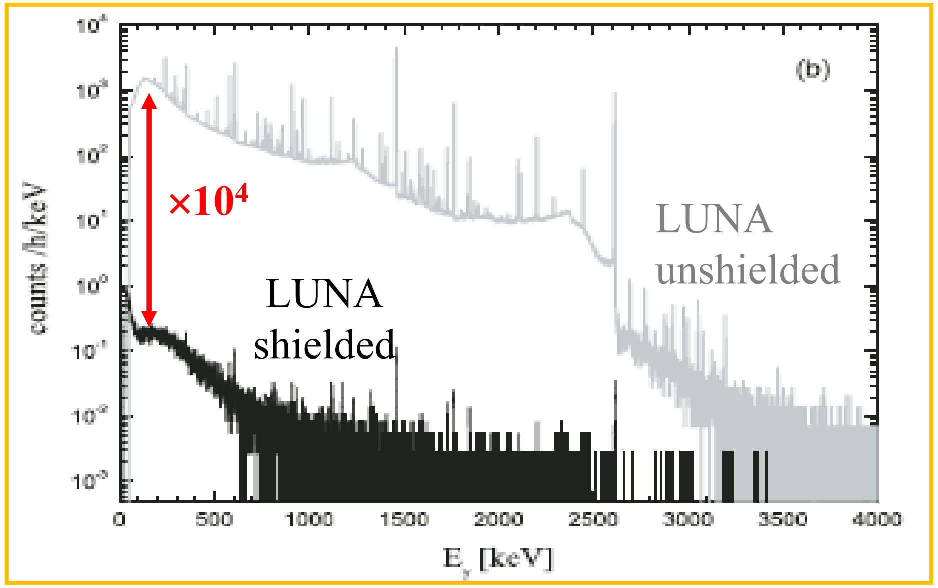
LUNA Collaboration:

Italy, Germany, Hungary,UK

Background reduction in LNGS

Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}
photons	10^{-1}





→ With lead shielding in underground : very high suppression factor