Indirect techniques for astrophysical reaction rates determinations

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Why indirect techniques ?

Astrophysics reactions → Weak energies : few keV to few MeV<< E_C → σ(E) very weak (fb-pb)

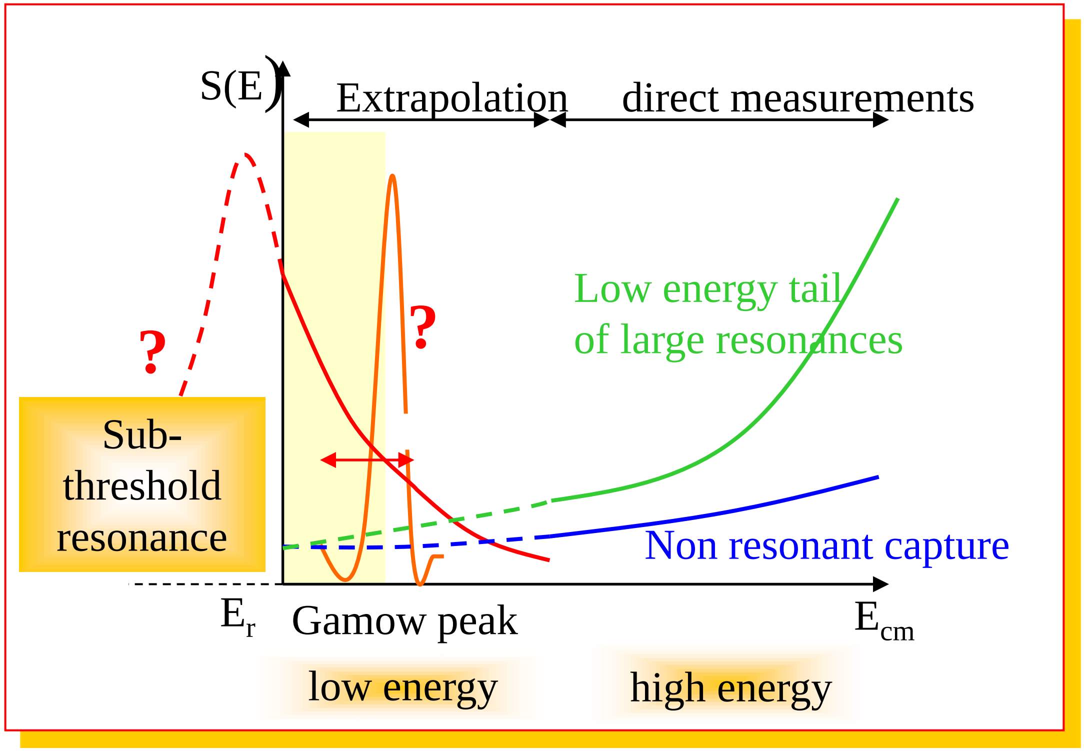
→ σ(E) ➘ (exponential) when E ➘

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

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

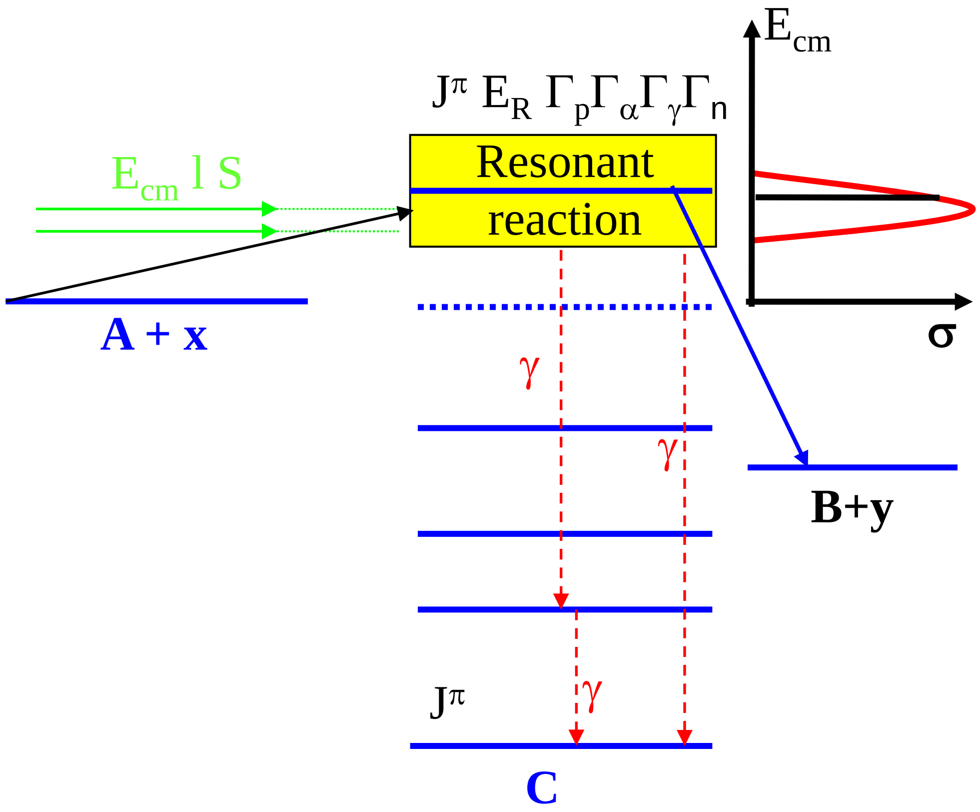
- Problems with extrapolation: sub-threshold resonances, resonances at very low energy

- Radioactive nuclei (novae, r or s-process…): low intensities (~10^5 p/s) or targets with few atoms/cm^2 ⇒ direct measurements difficult or impossible



Ingredients needed to evaluate σ & $N_A<\sigma v>$

Resonant reactions: A+x→C*→B+y or A+x→C*→C+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 reaction rates can be calculated if the resonant parameters (**E_R, J^π, Γ_i ,Γ_i /Γ_{tot}** ,...) are known

⬇

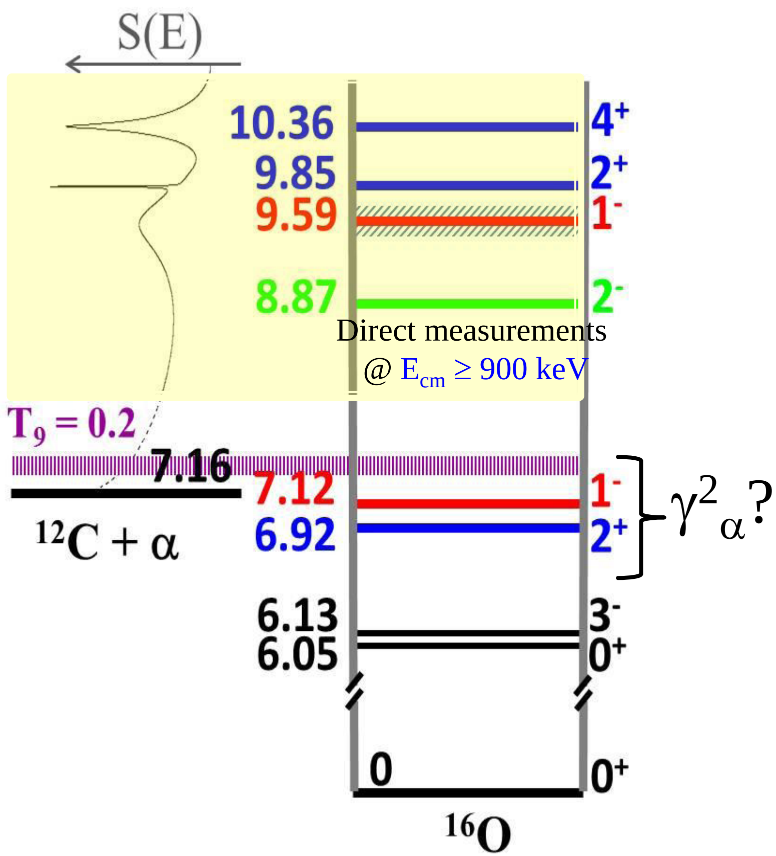
Indirect techniques & reactions can be used to extract these spectroscopic information:
Transfer, THM, Coulomb dissociation, ANC, inelastic scattering, charge exchange reactions …

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

Massive stars & $^{12}C(\alpha,\gamma)^{16}O$ reaction

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

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

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

&

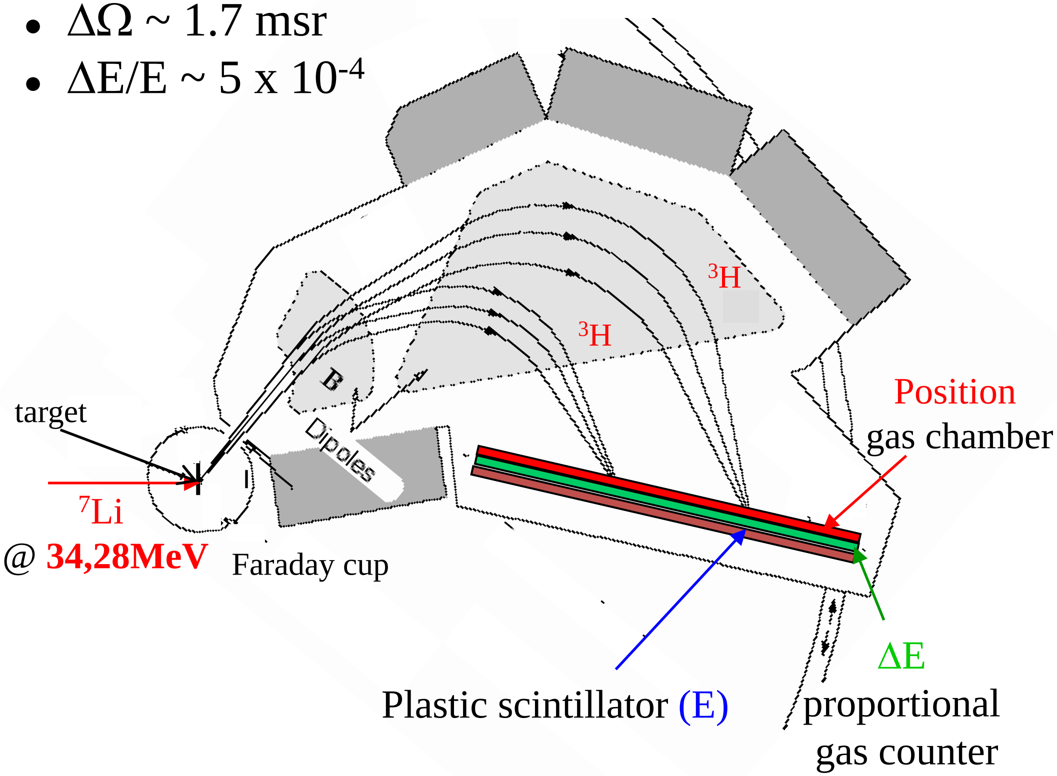
Interference effect & cascades ?

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

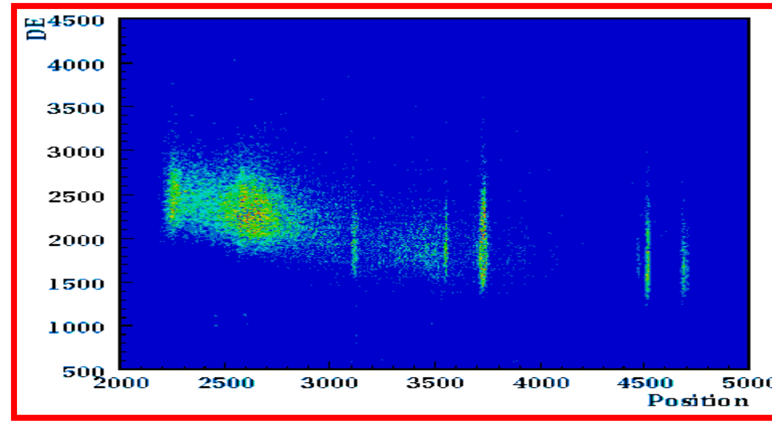
Experimental Set-up

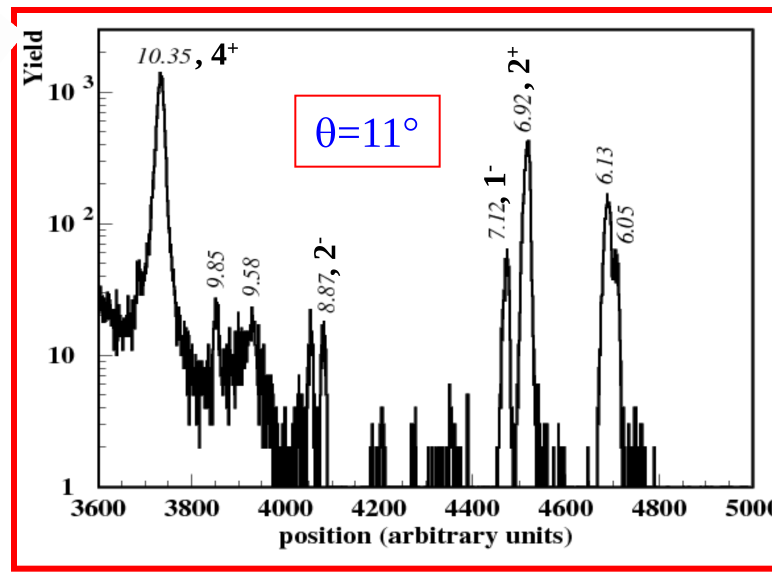
Split-Pole spectrometer (Tandem/ALTO)

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



- dσ/dΩ measurements up to 45°



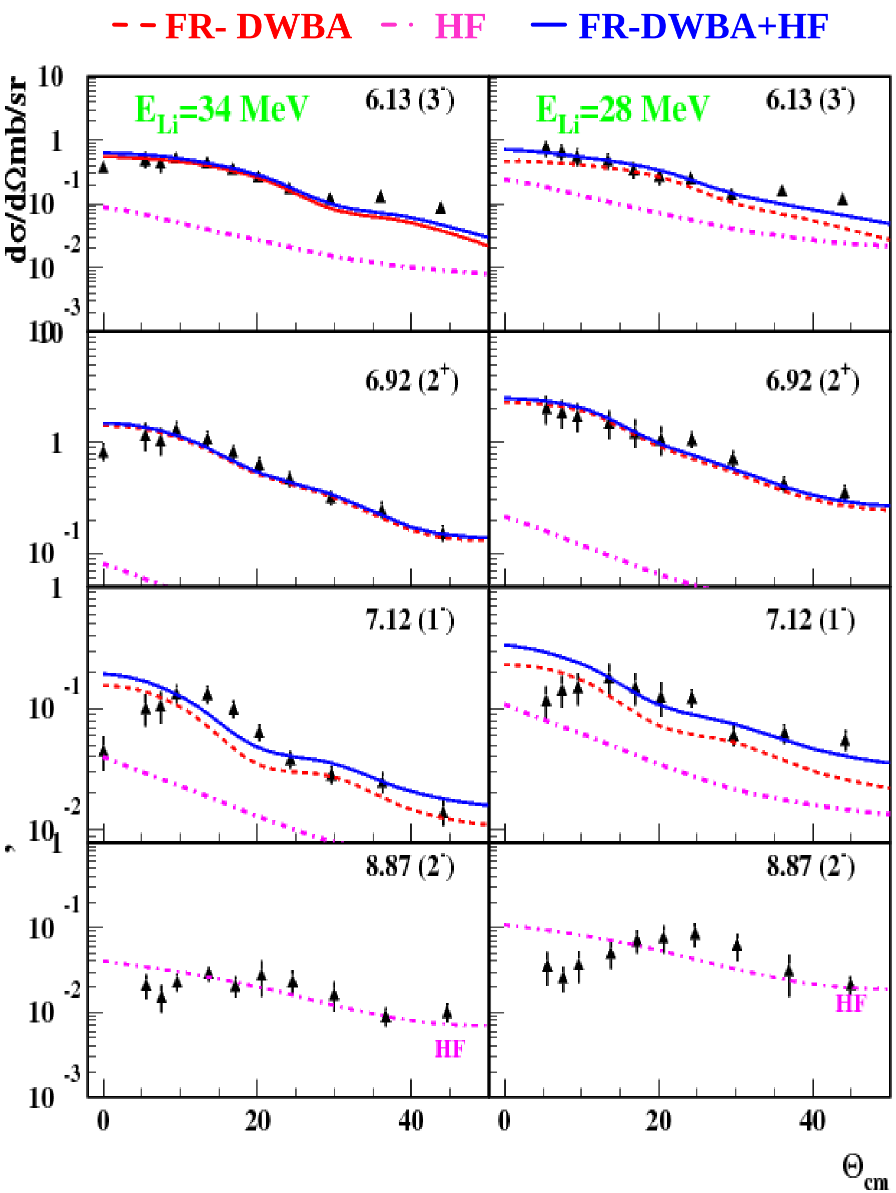


- Strong population of the α cluster 2^+ & 4^+state → direct transfer mechanism

- 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)

$S_\alpha(2^+) = 0.15 \pm 0.05 \rightarrow \gamma_\alpha^2 = 27 \pm 10$ keV

$S_\alpha(1^-) = 0.08 \pm 0.03 \rightarrow \gamma_\alpha^2 = 8 \pm 3$ keV

r=6.5fm

$$\tilde{C}^2(2^+) = (2.07 \pm 0.80) \times 10^{10} \text{ fm}^{-1}$$

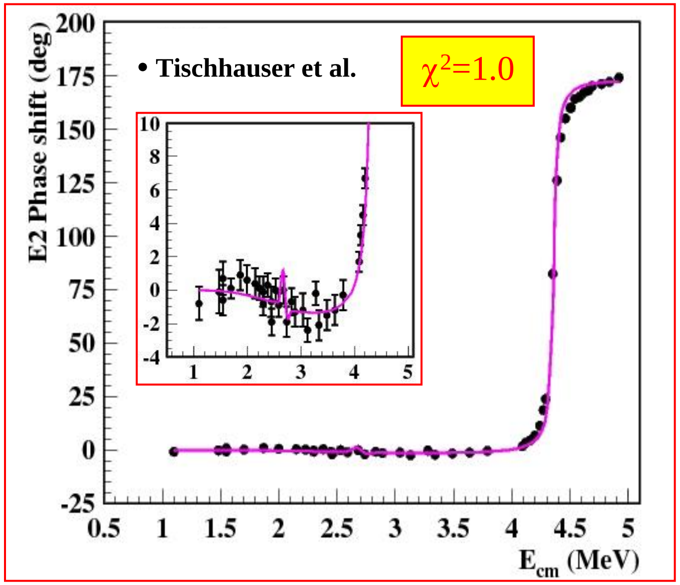
$$\tilde{C}^2(1^-) = (4.00 \pm 1.38) \times 10^{28} \text{ fm}^{-1}$$

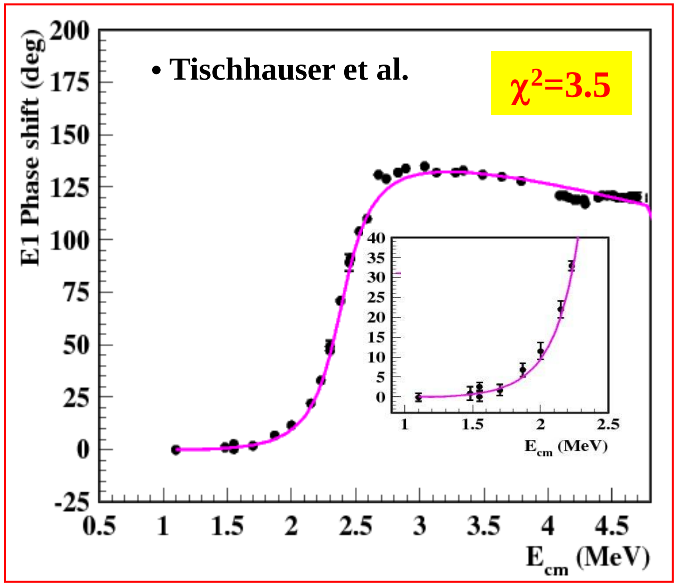
In agreement with ANC experiments
Brune et al. 2001
Avila et al. 2014

R-matrix calculations – E2 & E1 components

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

γ_α^2 of the 2^+ & 1^- sub-threshold states are fixed parameters





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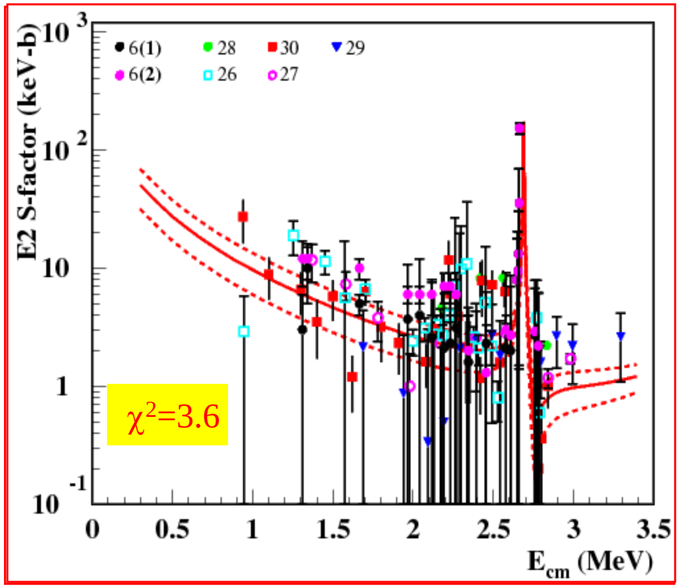
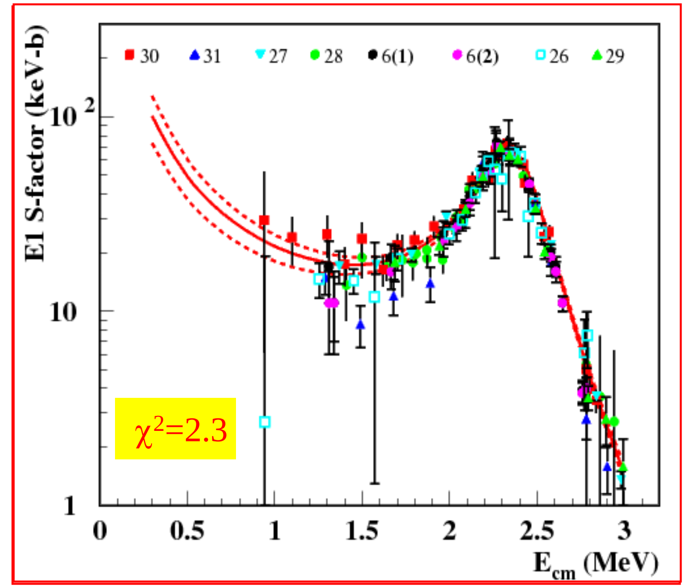




S_{E2}(300 keV)=50±19 keV-barn

S_{E1}(300 keV)=100±28 keV-barn

- In excellent agreement with ANC results of Brune et al. 2001 **($\gamma_\alpha^2(2^+)$ & $\gamma_\alpha^2(1^-)$ fixed)**
- In agreement with other works ($\gamma_\alpha^2(2^+)$ & $\gamma_\alpha^2(1^-)$ free parameters) within error bars but central values $\geq 20\%$ (E1) & $\leq 30\%$ (E2)

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

Big-Bang Nucleosynthesis & ^{7}Li problem

➢ Primordial nucleosynthesis (**BBN**) of light elements is one of the three observational pillars of the Big Bang model together with the expansion of the Universe & the Cosmic Microwave Background radiation

When $T \leq 10^9$ K → BBN begins :

- D, ^{4}He, ^{3}He, ^{7}Li synthesized via nuclear reactions
- Abundances depend on $\Omega_B h^2$

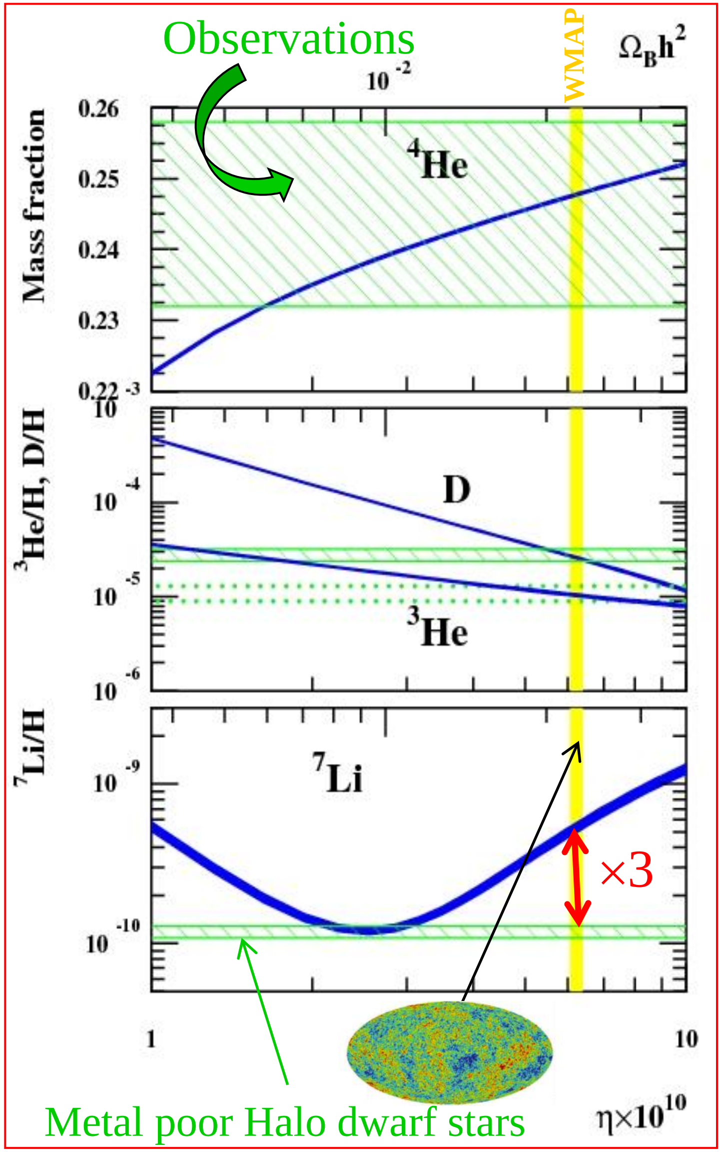
$\Omega_B h^2 = 0.02249 \pm 0.00062$ (WMAP) (Komatsu et al. 2011)

↓

(BBN+CMB) predictions (D, ^{3}He, ^{4}He) ≅ observations

But: $(^{7}\text{Li/H})_{BBN} / (^{7}\text{Li/H})_{obs} \approx$ **3 !!!** (Coc et al. 2013)

→ **^{7}Li problem.**



Nuclear solution to ^{7}Li problem ?

➢ ^{7}Li production via EC of ^{7}Be:

^{7}Be production:

^{3}He(^{4}He,γ)^{7}Be → known better than 8%
(Adelberger et al. 2010, Di Leva et al. 2013)

^{7}Be destruction:

^{7}Be(n,p)^{7}Li(p,α)α → very well known
(Descouvemont et al. 2004)

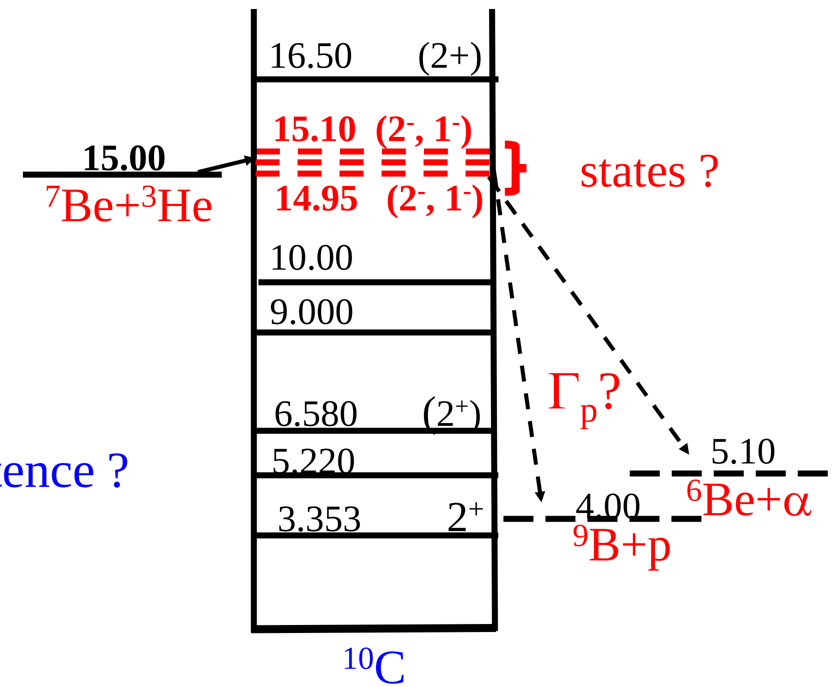
➢ **Missing ^{7}Be destruction channels ?**
Chakraborty et al. 2011, Civitarese et al. 2013

- ^{7}Be+d→**^{9}B*** → 16.71 MeV (5/2$^+$) state
  Angulo et al. 2005, O'Malley et al. 2011, Scholl et al. 2011

- ^{7}Be+^{3}He→**^{10}C***
  → hypothetical state at ~ 15 MeV (1$^-$, 2$^-$)

- ^{7}Be+^{4}He→**^{11}C***
  → hypothetical state at ~ 7.8 MeV

Existence ?

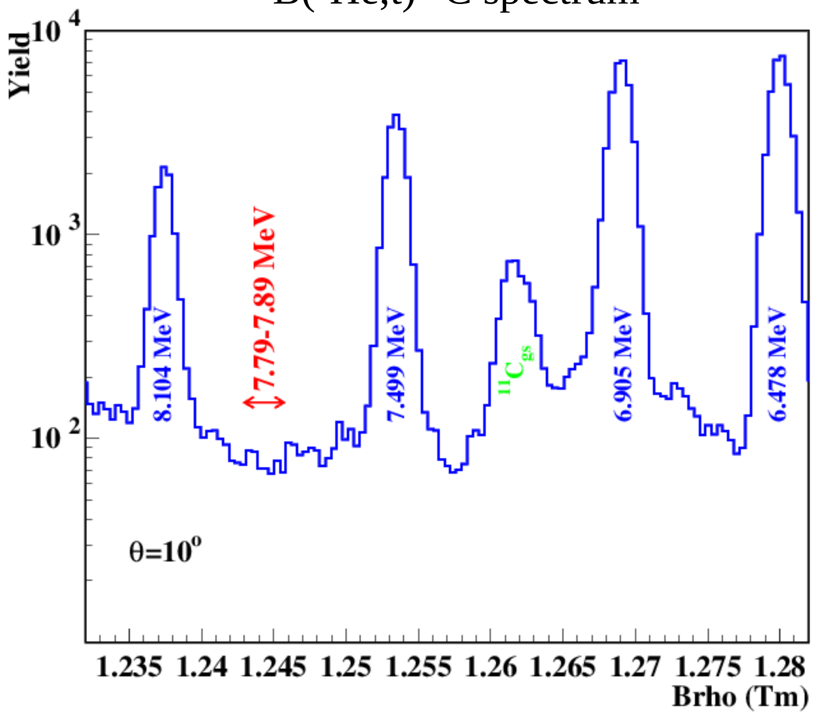


Search for missing ^{10}C & ^{11}C states & Experimental Results

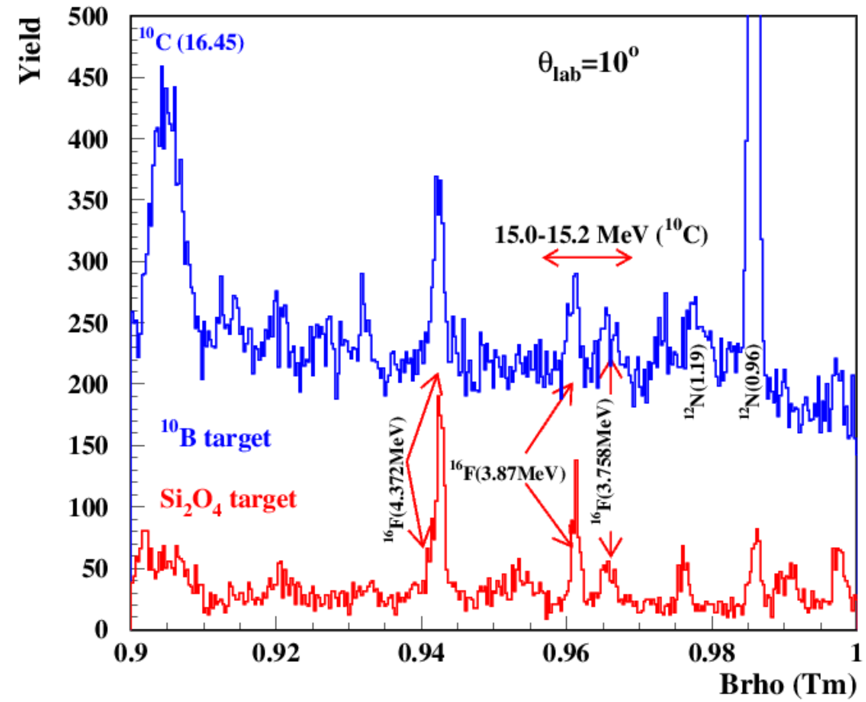
$^{10}B(^3He,t)^{10}C$ & $^{11}B(^3He,t)^{11}C$ **charge-exchange** reactions @ 35 MeV → Split-Pole @ Tandem-ALTO

θ_{SP}=7°,10, 15°

$^{11}B(^3He,t)^{11}C$ spectrum



$^{10}B(^3He,t)^{10}C$ spectrum



No additional state in ^{11}C at ~ 7.8 MeV

- Only statistical fluctuations

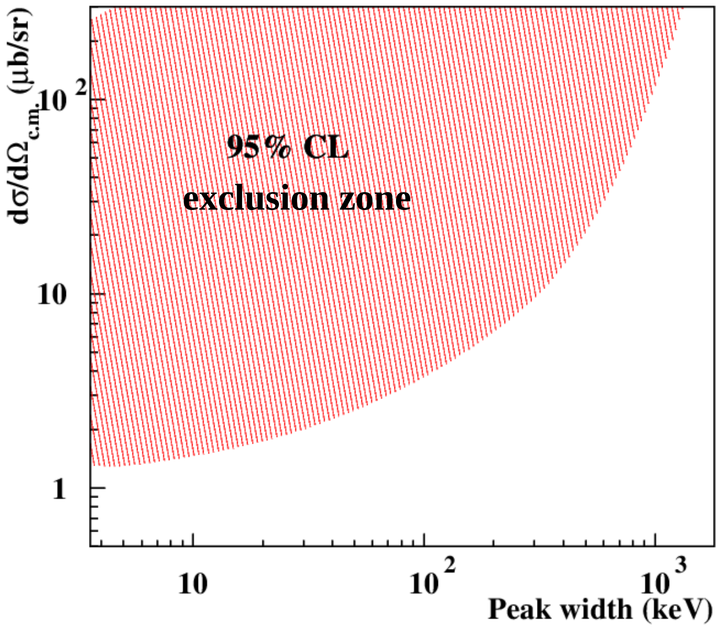
→ All known ^{11}B mirror nucleus states below E_x = 9 MeV have their counterpart in ^{11}C

No obvious additional state in ^{10}C at ~ 15 MeV

- Contamination peaks due to ^{16}O
- Same results at other angles (7° and 15°)

^{10}C state observation @ 95% confidence level

- Simulation of a state in the region of interest with various Γ_{tot} & $d\sigma/d\Omega(^3He,t)$ & same target thickness, number of incident ^3He ions & energy resolution as experiment

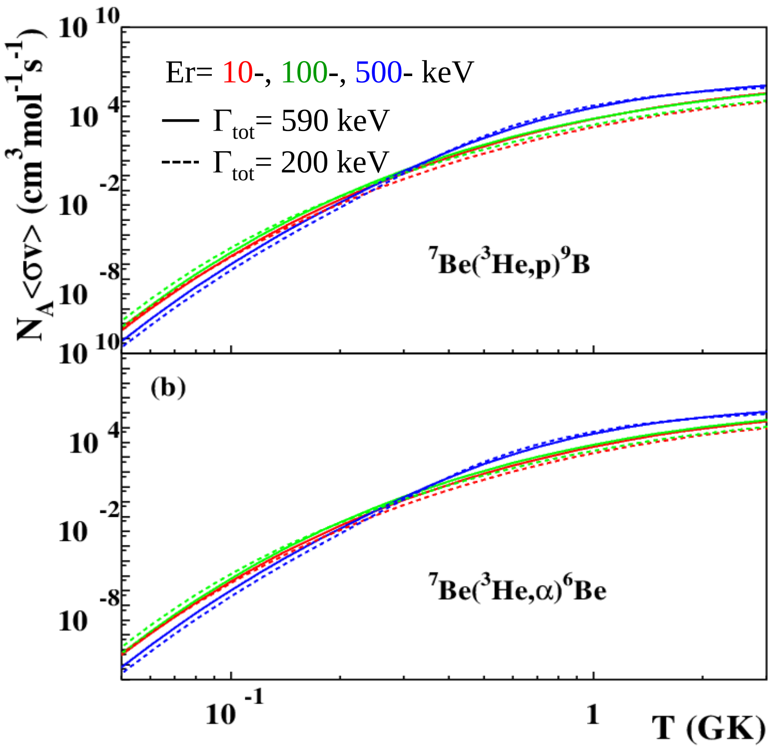


Typical $(^3He,t)$ cross-sections to 1^-, 2^- states @ 10°
→ $d\sigma/d\Omega > 25$ μb/sr

If present → $\Gamma_{total} \geq 590$ keV (95% CL)

F. Hammache, A. Coc et al. PRC 88, 062802 (R) 2013

$^7Be+^3He$ reaction rates & impact on ^7Li



Γ_{3He} from Wigner limit ($\gamma^2_W = 1.842$ MeV)
→ in all cases $\Gamma(^3He) << \Gamma_{tot}$
→ $\Gamma_{tot} = \Gamma_p$ or Γ_α

BBN calculations: → no impact on ^7Li

→ ^7Li problem not due to resonant states in ^{10}C & ^{11}C

^{10}C state observation @ 95% confidence level

^{7}Be+^{3}He reaction rates & impact on ^{7}Li

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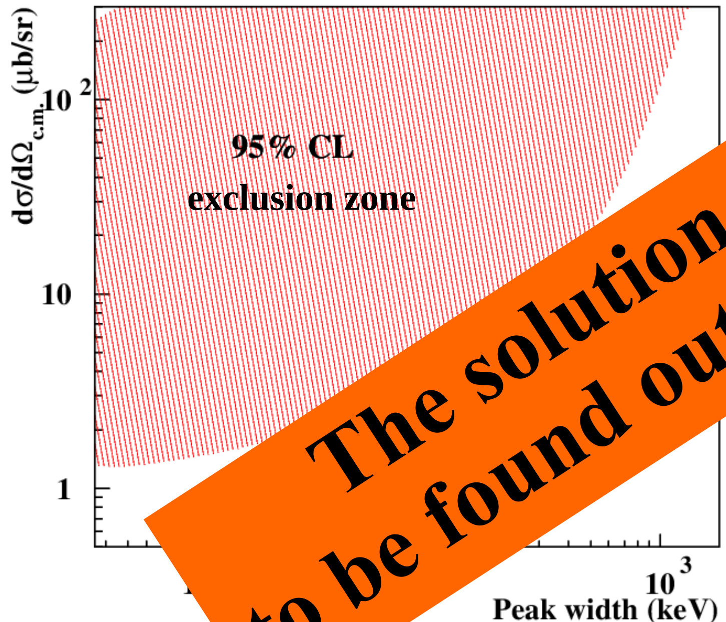

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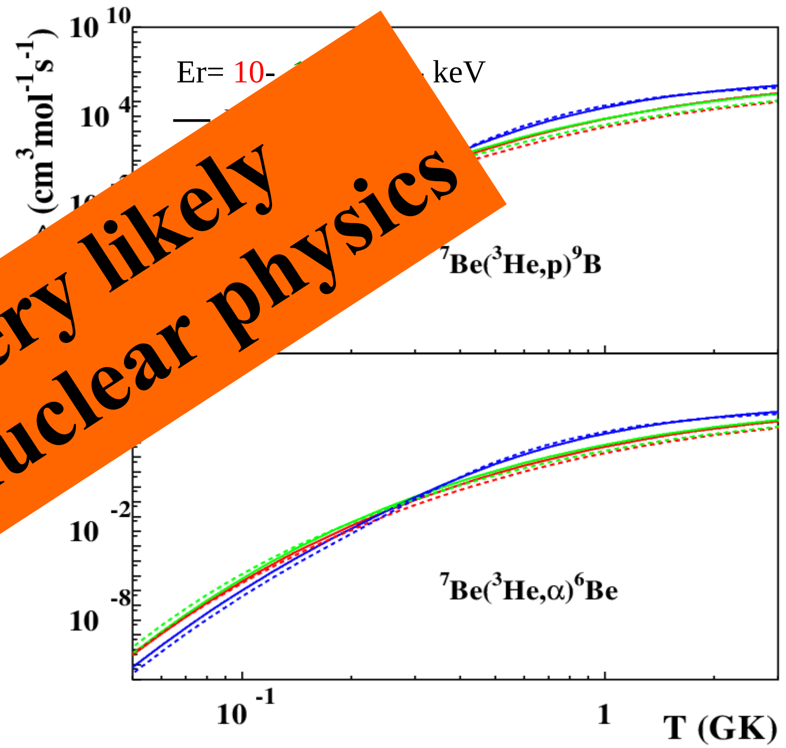


Γ_{3He} from Wigner limit (γ^{2}_{W} = 1.842 MeV)
→ in all cases $\Gamma(^{3}He) \ll \Gamma_{tot}$
→ $\Gamma_{tot} = \Gamma_{p}$ or Γ_{α}

BBN calculations: → no impact on ^{7}Li

→ ^{7}Li problem not due to resonant states in ^{10}C & ^{11}C

The solution has very likely to be found outside nuclear physics

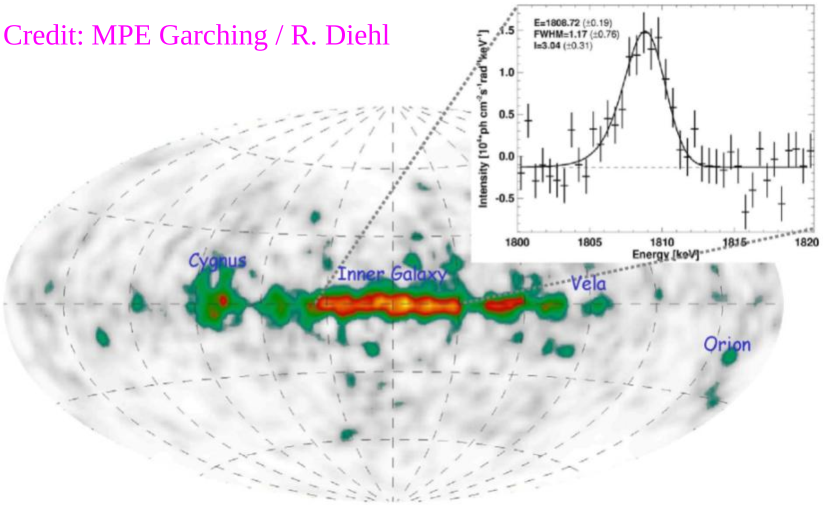
^{26}Al observations & Nucleosynthesis

- Massive stars: (> 8 $M_\odot$) → Wolf-Rayet phase and ccSNe

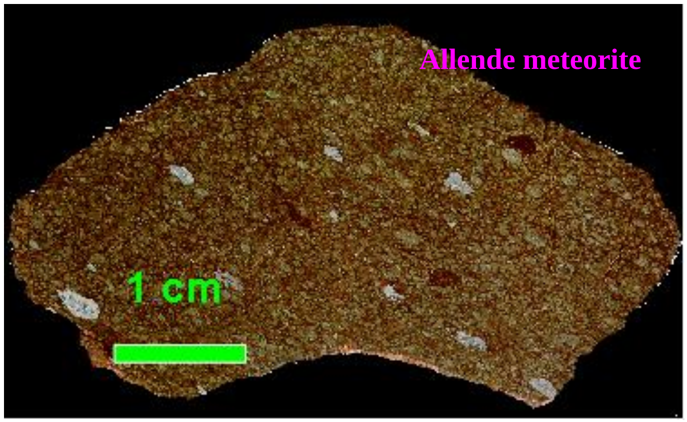
Observations of ^{26}Al ($T_{1/2}$=7.4 10^5 y)

$^{26}Al \xrightarrow{\beta^+} {}^{26}Mg^* \xrightarrow[1.809\ MeV]{\gamma} {}^{26}Mg$

Credit: MPE Garching / R. Diehl



Source of ^{26}Al ?



Astrophysical context of Solar System formation

Cameron et al., 1977 Tatischeff et al., 2010

^{26}Al nucleosynthesis in massive stars:

- Core H burning
- Ne/C convective shell burning
- explosive Ne burning

Limongi et al., 2006 & Woosley et al., 2007, Iliadis et al. 2001

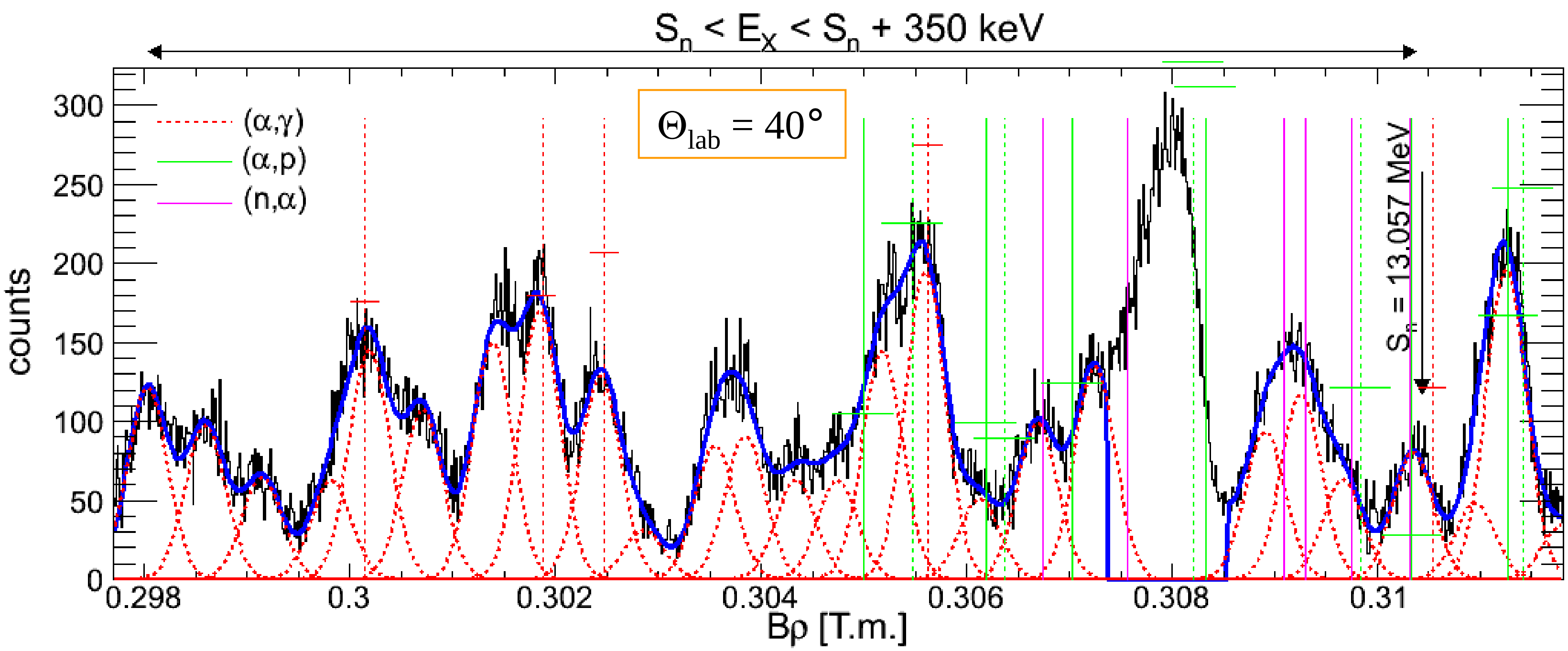
^{26}Al yield depends crucially on ^{26}Al(n,p) and ^{26}Al(n,α) reactions

Rates x2 → ^{26}Al yield/2

^{27}Al levels above neutron threshold

^{27}Al(p,p')^{27}Al* inelastic scattering @ 18 MeV
→ Split-Pole @ TANDEM-ALTO
θ_{SP} = 10°, 25°, 40°, 45°

Deconvolution above neutron threshold (S_n = 13.05 MeV):
→ energy resolution 14 keV



Comparison with known levels:

- Very good agreement with ^{23}Na(α,γ)^{27}Al and ^{26}Al(n,α)^{23}Na

(de Voigt et al. 1971, de Smet et al. 2007, Whitmire et al. 1974)

→ about 30 new resonances above S_n!

Resonance's spins?

- (α,γ) and (n,α) preferentially populate high-spins (J>7/2)

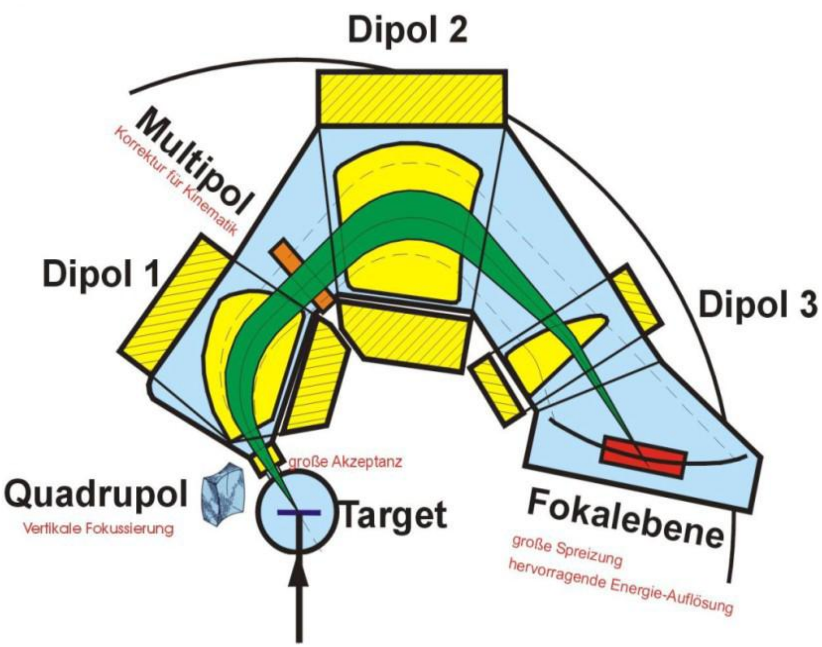
→ new resonances probably have low-spins

S. Benamara, N. de Séréville et al. PRC89, 065805 (2014)

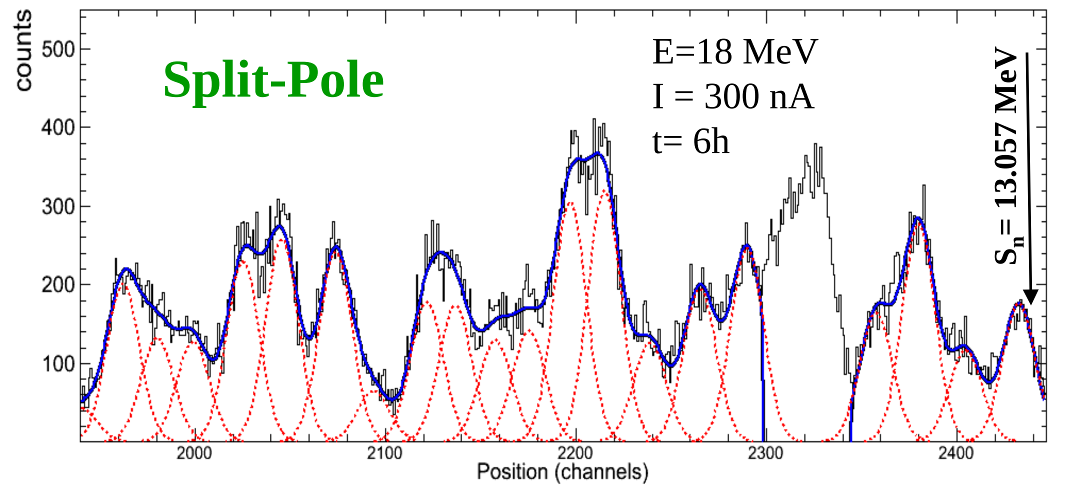
^{27}Al(p,p') measurements @ Q3D (MLL)

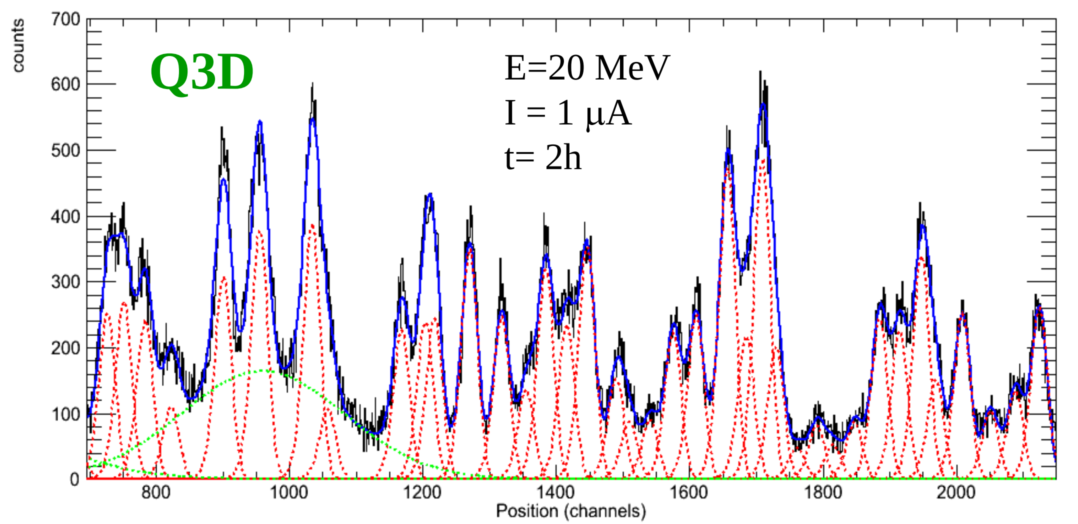
Q3D

- $\Delta E/E = 2 \times 10^{-4}$
- $\Delta\Omega = 14$ msr



$S_n + 350$ keV $< E_x < S_n$





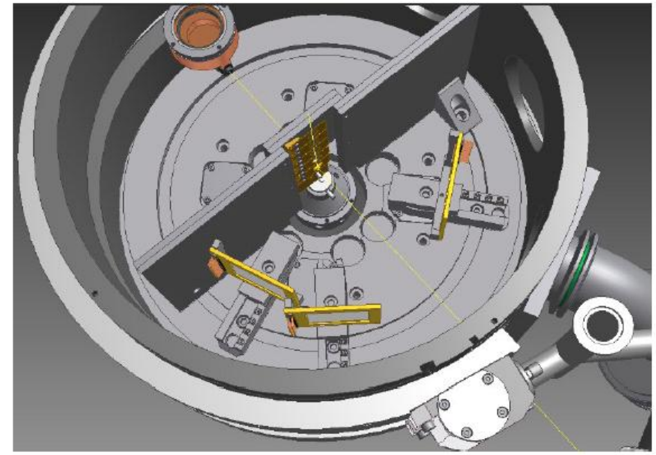
→ Confirmation of SP data with better energy resolution (~7 keV) & precision (~2 keV)

→ New states observed

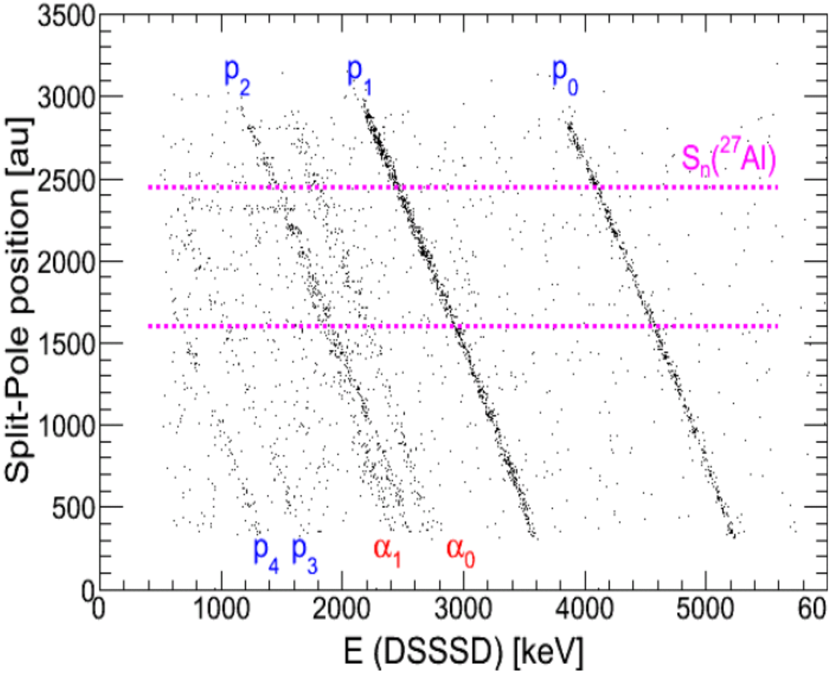
Coincidence measurements @ Orsay

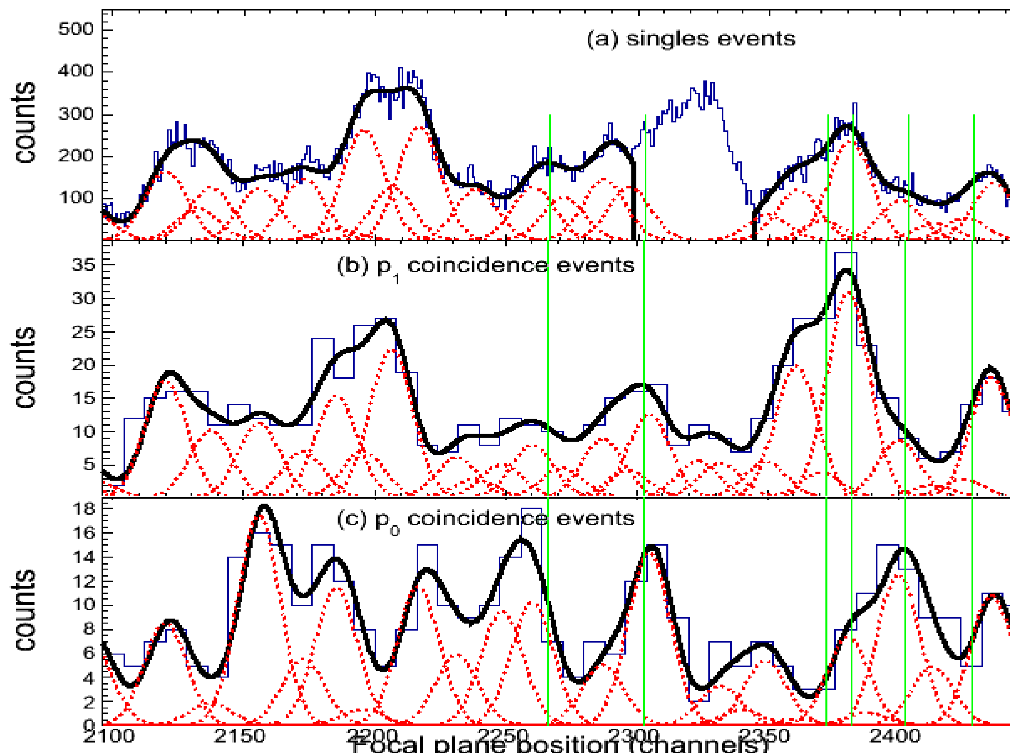
Experimental conditions:

- 3 W-type DSSSDs
  - → 16 + 16 strips (ΔE ~ 20 keV FWHM)
- close geometry around the target
  - → d ~ 11 cm, ε ~ 4%
- Low background environment
- Beam intensity ~ 100 nA !



Coincidence spectrum:





$^{26}Al(n,p)^{26}Mg$ dominated by (n,p_1) channel

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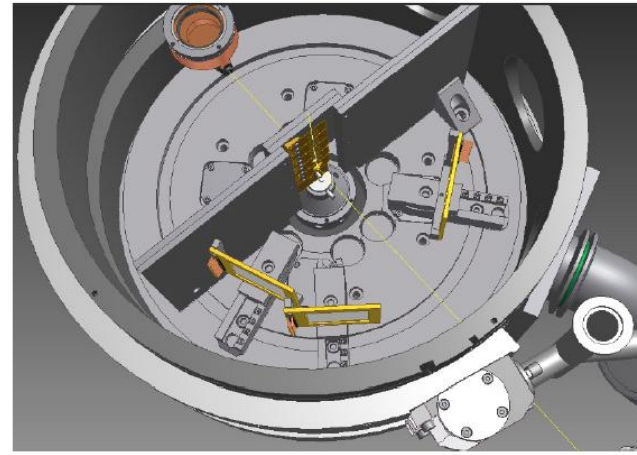

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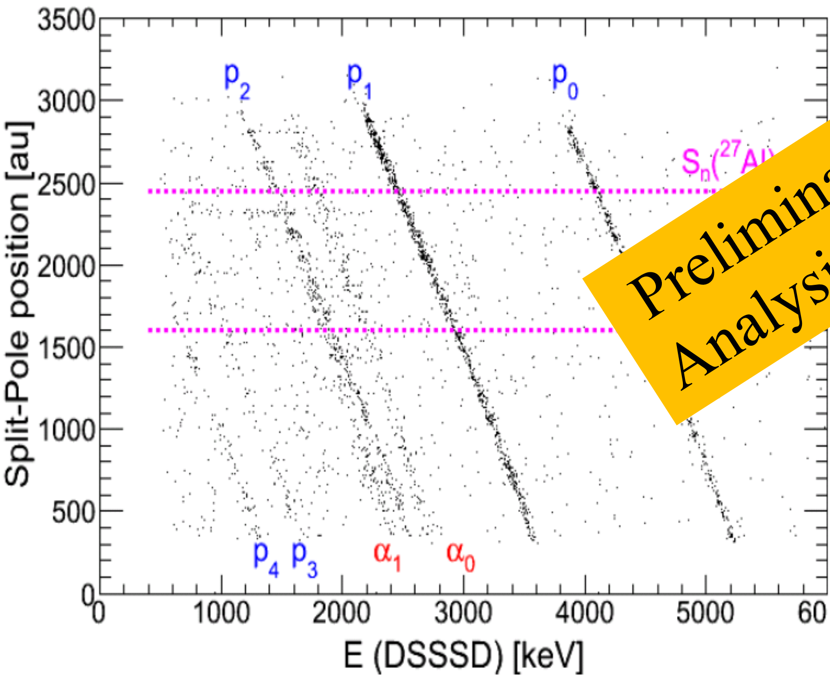
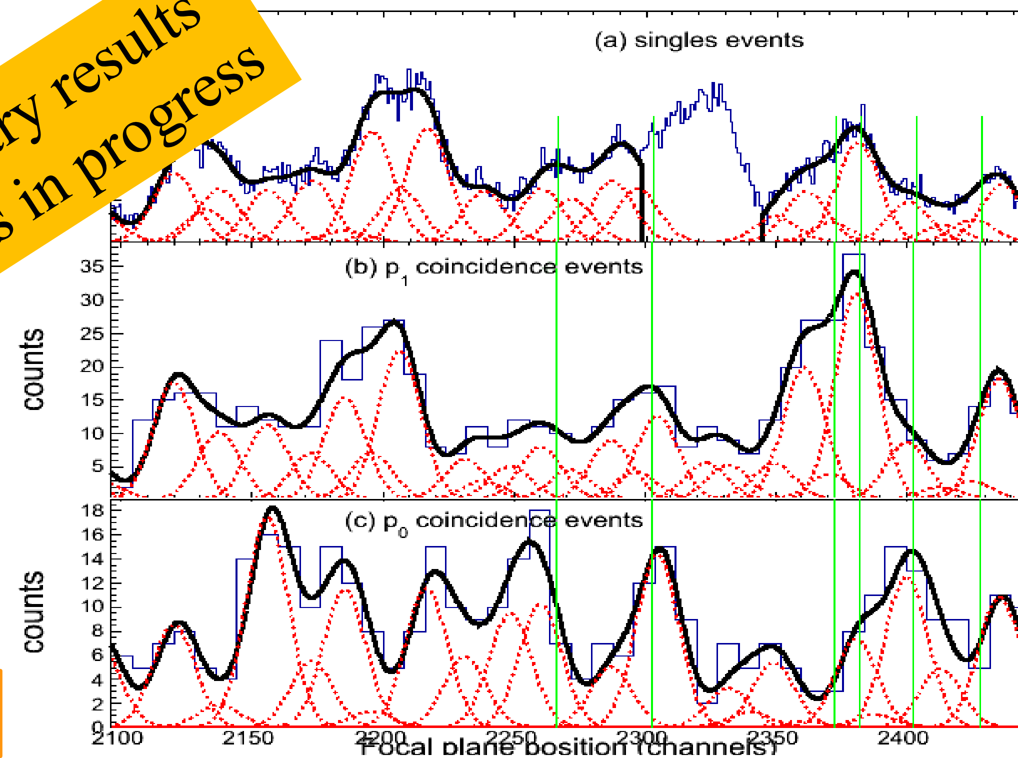


Preliminary results
Analysis in progress



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Collaborators

IPN-Orsay: F. Hammache, N. de Séréville, I. Stefan, P. Roussel, S. Ancelin, M. Assié, L. Audouin, D. Beaumel, S. Franchoo, B. Le Crom, L. Lefebvre, I. Matea, A. Matta, G. Mavilla, P. Morfouace, L. Perrot, D. Suzuki, M. Vandebrouck

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