Study of stellar nucleosynthesis using indirect techniques

Faïrouz Hammache (IPN-Orsay)

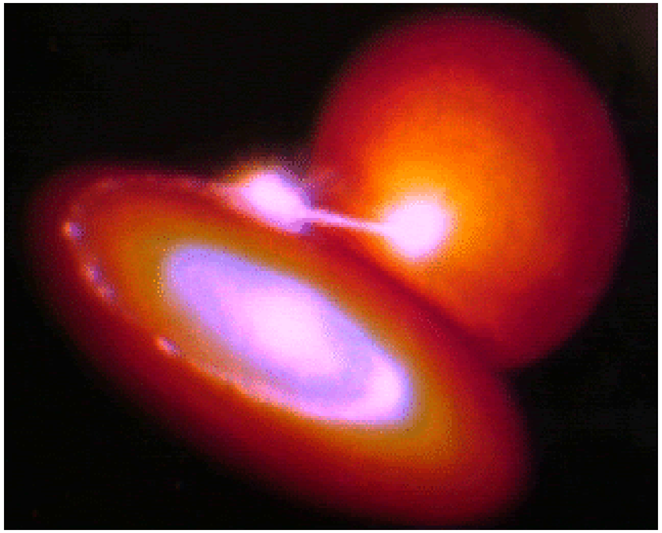
Why indirect techniques ?

- Many important reactions involve radioactive isotopes

- (n,γ) captures in s-process on waiting points: **$^{60}Fe(n,\gamma)^{61}Fe$**,…
- (n,p) & (n,α) reactions in massive stars:
- **$^{18}F(n,p)$, $^{18}F(n,\alpha)$, $^{26}Al(n,p)$, …**
- $^{30}P(p,\gamma)^{31}S$, $^{18}F(p,\alpha)^{15}O$,… in Novae
- (n,γ) captures in r-process
- …

→ Long-lived isotopes can be made into targets
but ~ few atoms/cm^2

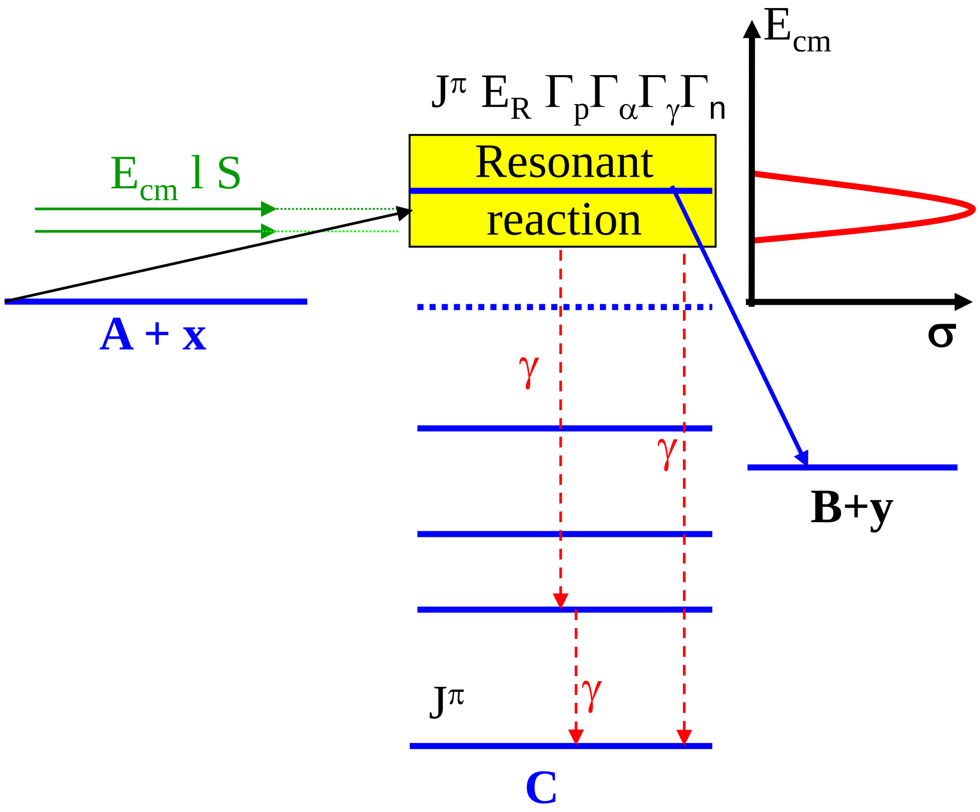
→ Short lived nuclei : beams
but the available intensities **~10^5 pps** are too low for direct measurements



- Indirect techniques require much lower intensities or use stable beams

Ingredients needed to evaluate σ & $N_A\langle\sigma v\rangle$

Resonant reactions: $A+x \rightarrow C^* \rightarrow B+y$ or $A+x \rightarrow C^* \rightarrow C+\gamma$



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

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

- Resonant reaction rates can be calculated if the resonant parameters (**E_R, J^π, Γ_i, Γ_i/Γ_{tot}**, ...) are known

↓

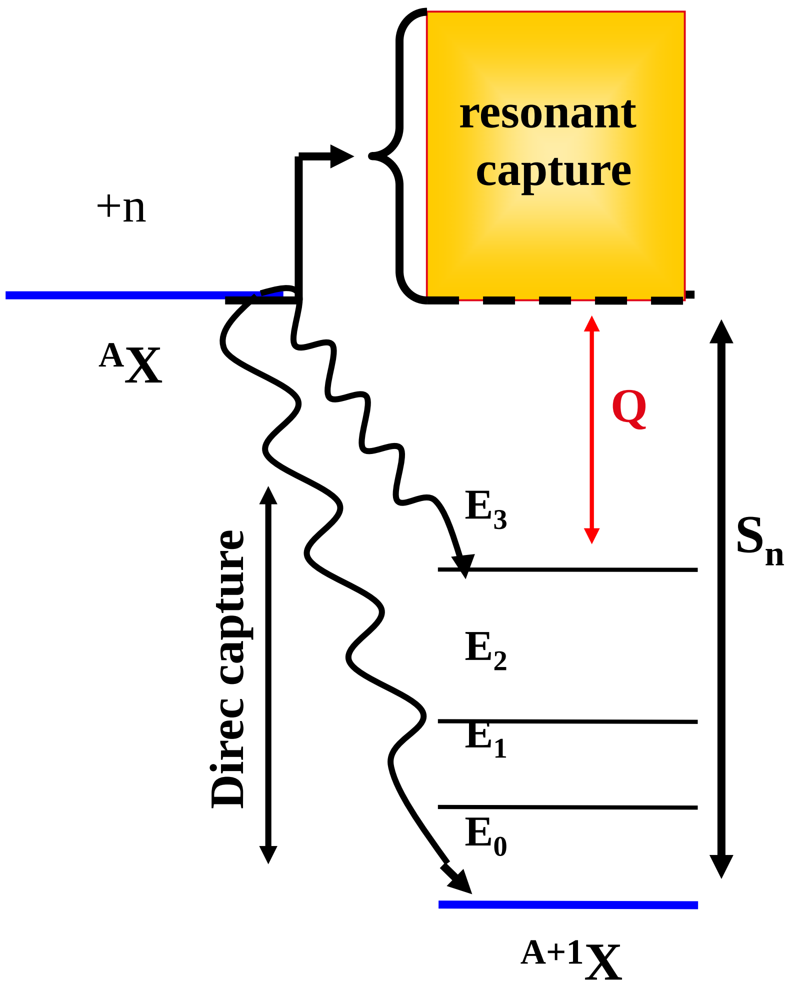
Indirect techniques & reactions can be used to extract these spectroscopic information:

Transfer, ANC, THM, **inelastic scattering**, …

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

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

Non resonant reactions: e.g Direct (n,γ) captures



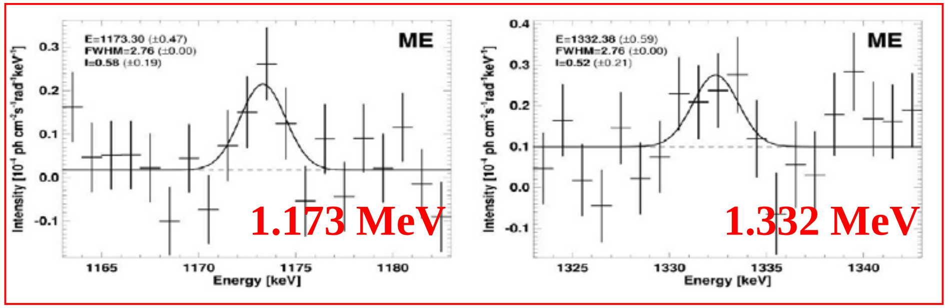
$$\sigma_{(n,\gamma)} = \sum_i C_i^2 S_i \sigma_i^{DC} = \sum_i C_i^2 S_i \left| \int_{r=0}^{\infty} \phi_f \theta_{em} \phi_i d\vec{r} \right|^2$$

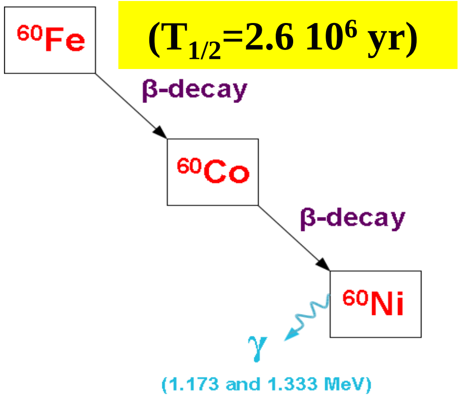
TEDCA code: H. Krauss

- Spectroscopic information on the low energy bound states, E_x, l, C^2S, are accessible via (d,p) **transfer** reactions.

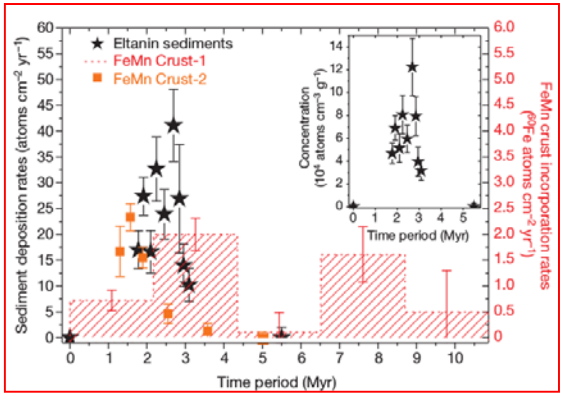
^{60}Fe observations in the galaxy & solar system

- ^{60}F γ-ray emission in the galaxy seen by RHESSI 04 & INTEGRAL 07
  Smith et al. 04 & Wang et al. 07



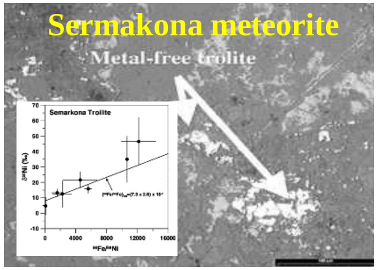


- ^{60}Fe in galactic cosmic rays CRIS/ACE **Binns et al. 2016**



- ^{60}Fe excess in deep ocean ferro-manganese crusts & marine sediments **Knie et al. 04, Wallner et al. 2016**
- ^{60}Fe in lunar sample **Fimiani et al. 2016**

Evidence of recent (~**2.2 Myr**) nearby supernovae explosions @ a distance < 1 kpc



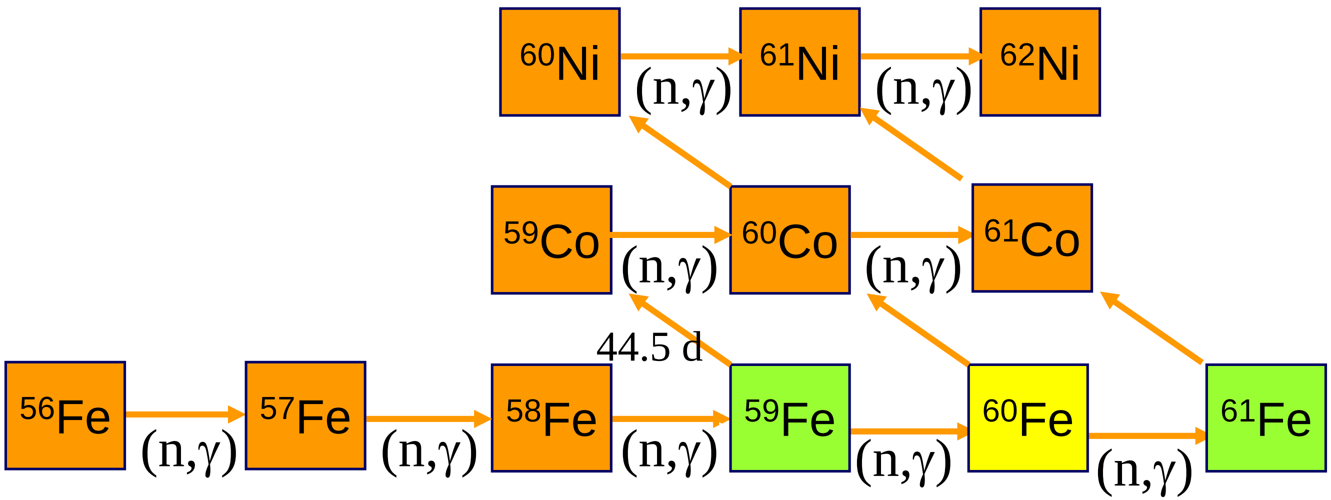
- Observed in solar grains as ^{60}Ni excess **Mostefaoui et al.04, Tang et al. 12**

^{60}Fe nucleosynthesis

- ^{60}Fe mainly produced in massive stars through weak s-process component & released in ISM by subsequent Core Collapse supernovae **Limongi et al. ApJ 06**

  → Convective He-shell burning ($T \geq 4 \cdot 10^8$ K, $N_n \sim 10^{11}$ cm^{-3})
  → Convective C-shell burning ($T \geq 10^9$ K, $N_n \sim 10^{12}$ cm^{-3})
  → Very small contribution from explosive phase

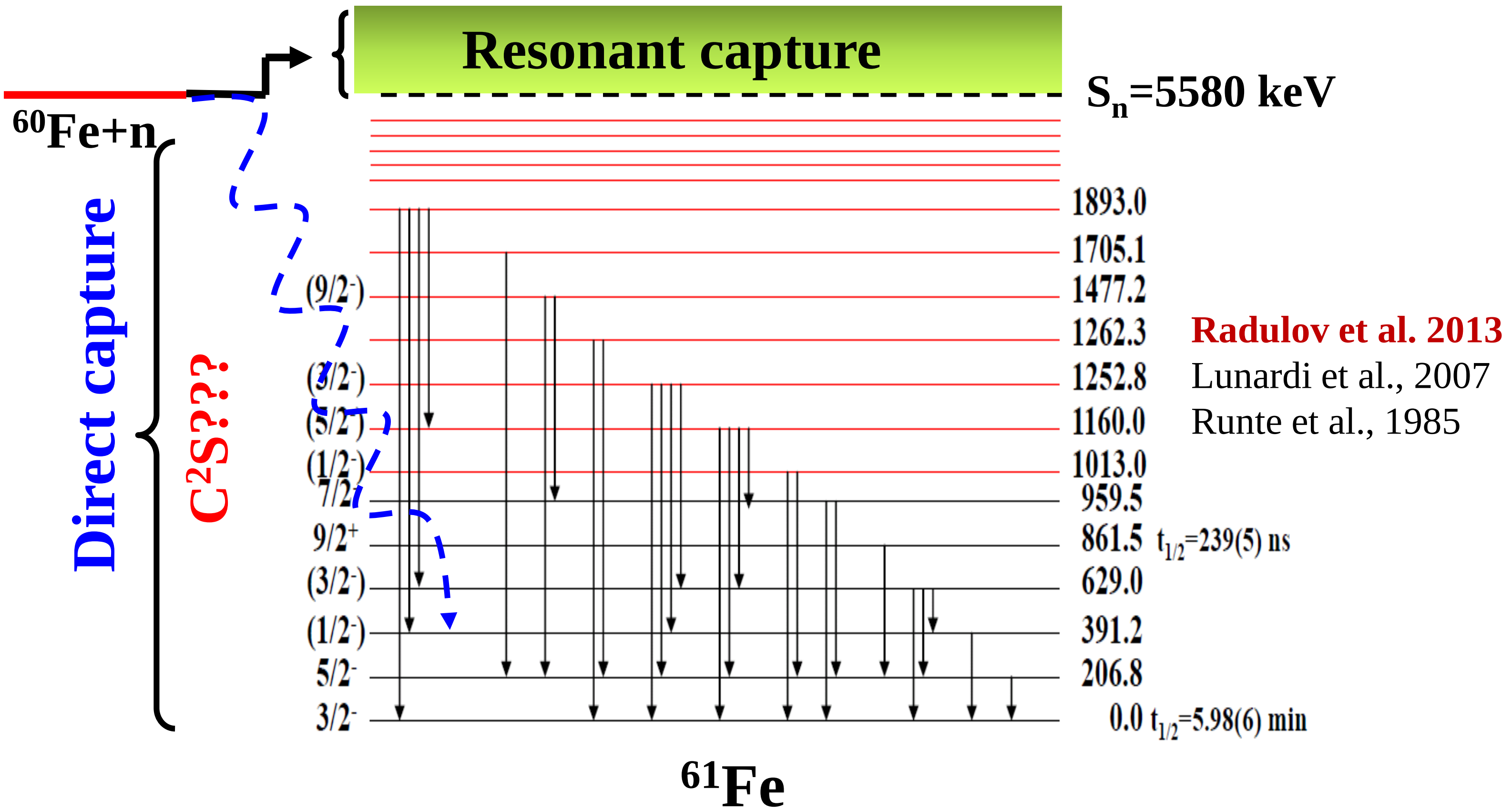
  } ^{22}Ne(α,n)^{25}Mg



- Production of **^{60}Fe** in core-collapse supernovae depends strongly on ^{59}Fe(n,γ)^{60}Fe & **^{60}Fe(n,γ)^{61}Fe** cross sections

^{60}Fe(n,γ)^{61}Fe status

- Reaction rate: HF calculations (resonant capture) + shell-model (direct capture)



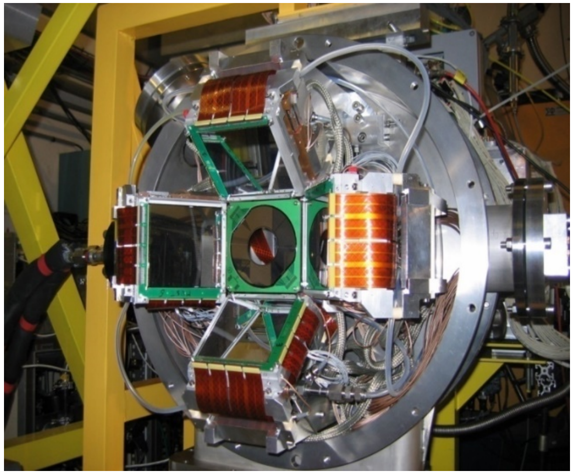
- ^{60}Fe(n,γ)^{61}Fe activation measurement: **Uberseder et al. 09**

Are the **shell model** calculations reliable in this mass region?

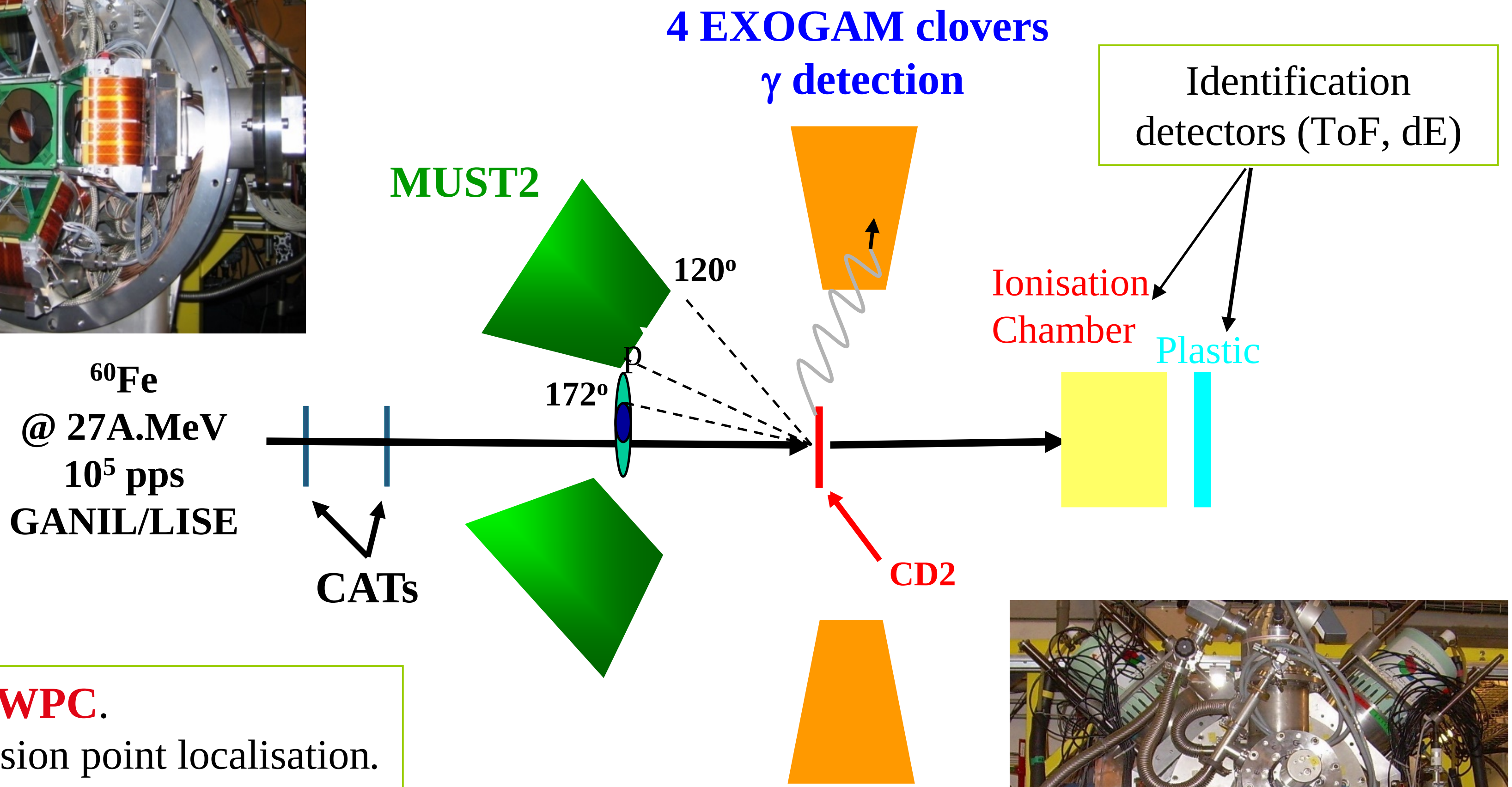
Does the direct component plays an **important role** as in ^{48}Ca(n,γ)^{49}Ca case **?** **Krausmann et al. 96**

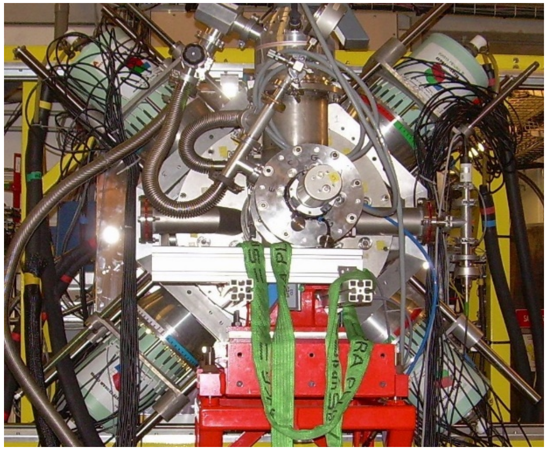
→ Direct $\sigma_{60Fe(n,\gamma)61Fe}$: E_x, l & C^2S of ^{61}Fe → **(d,p)** transfer reaction

Study of the direct component $^{60}Fe(n,\gamma)^{61}Fe$ via $^{2}H(^{60}Fe,p\gamma)^{61}Fe$ transfer reaction @ LISE/GANIL



(Collaboration IPNO/GANIL/IRFU/IPHC/LPC/CSNSM/RIKEN/GSI/LISBOA)



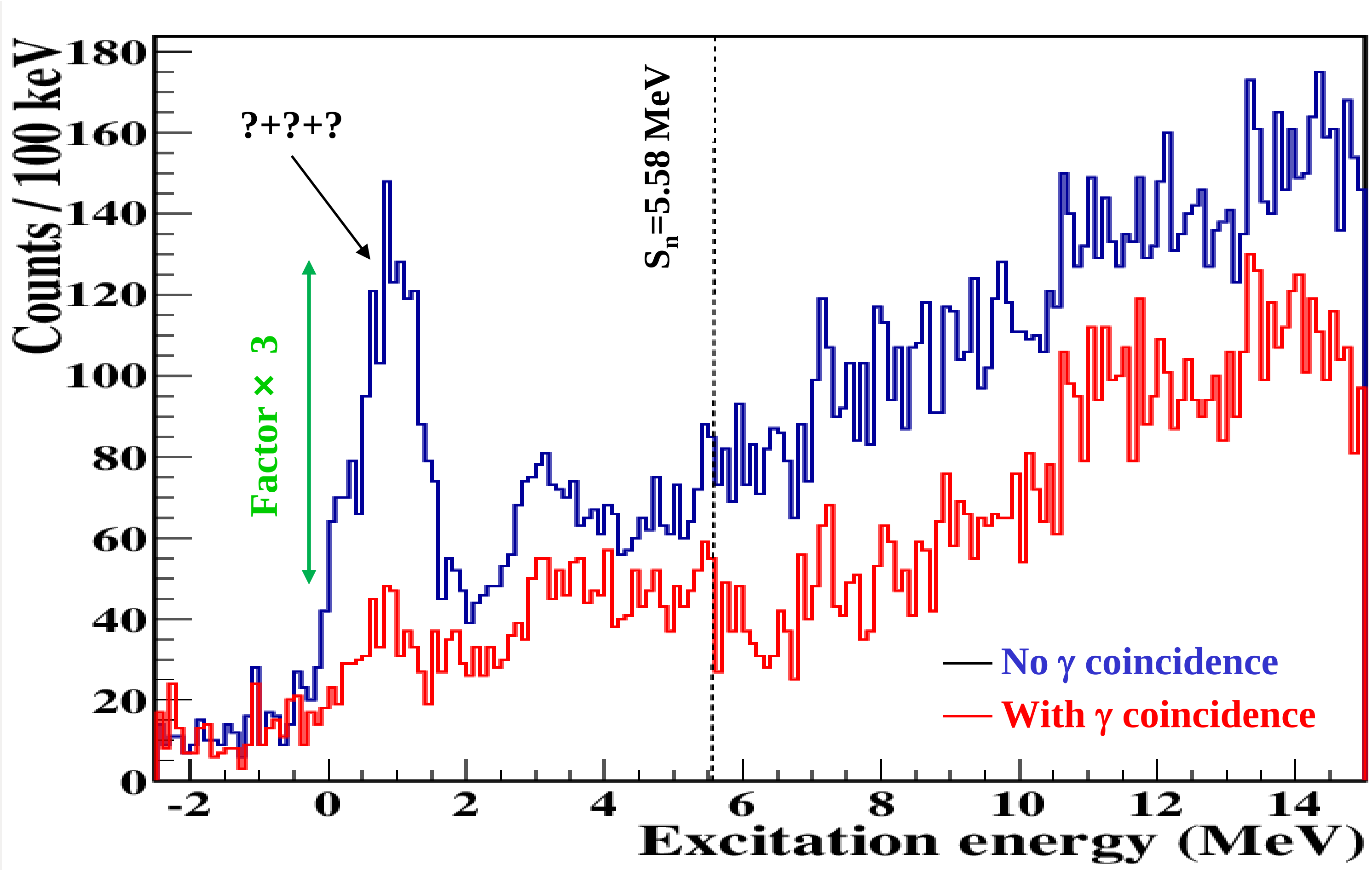


CATS: - **MWPC**.
-Proton emission point localisation.

MUST2 : -**DSSSD** **(300μm)** + **SiLi** (4.5 mm) detectors.
- Proton **impact localisation.**
- Proton **energy** measurement.

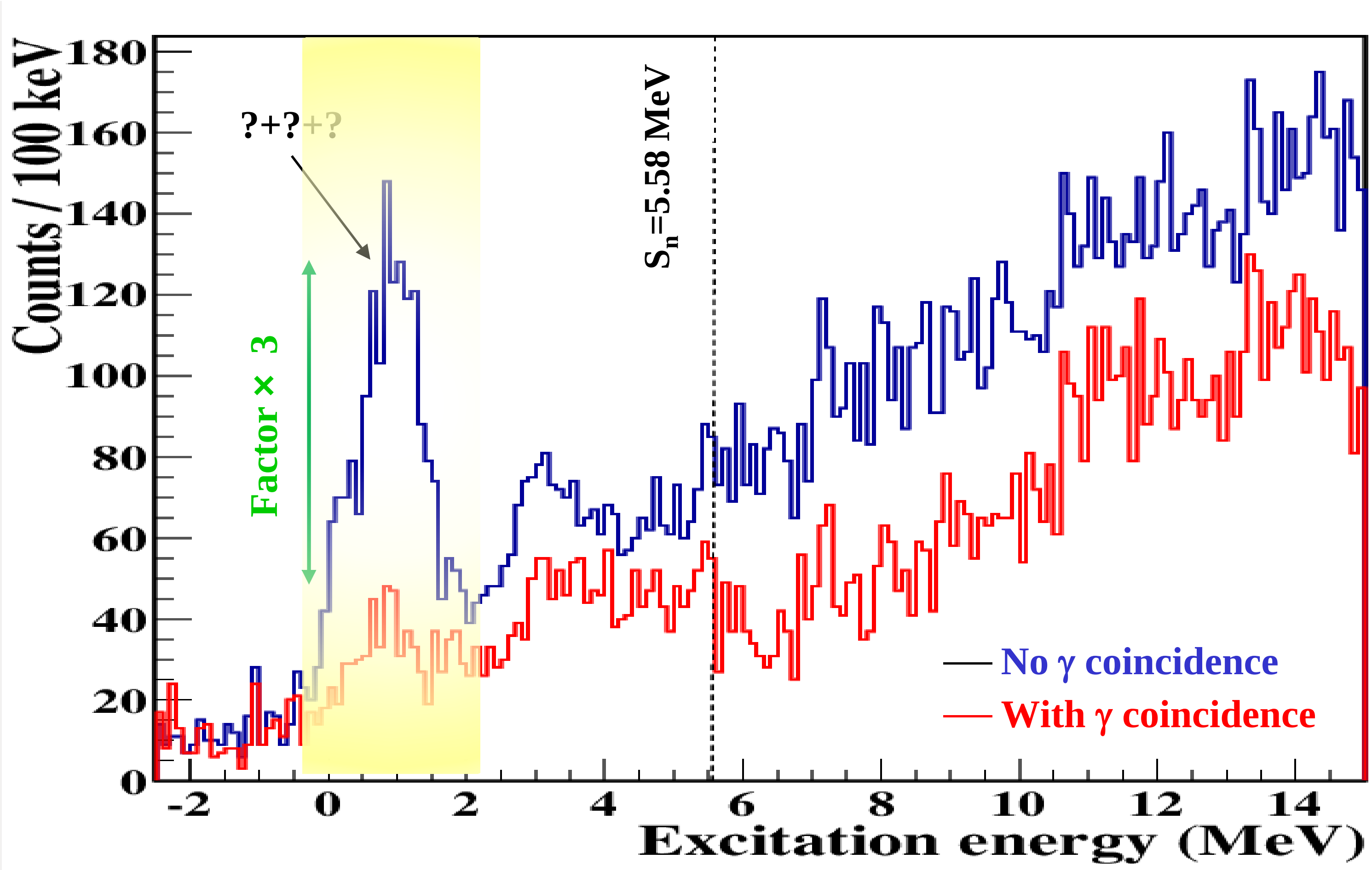
S1: Si annular detector (500 μm, 64 strips in Θ and 16 in Φ)

Experimental Results: ^{61}Fe excitation energy spectrum



- FWHM(peak) > 800 keV (expected energy resolution) ➔ population of 2-3 states
- Population of the 861 keV (J^{π}=9/2+) isomeric state (τ=239 ns)

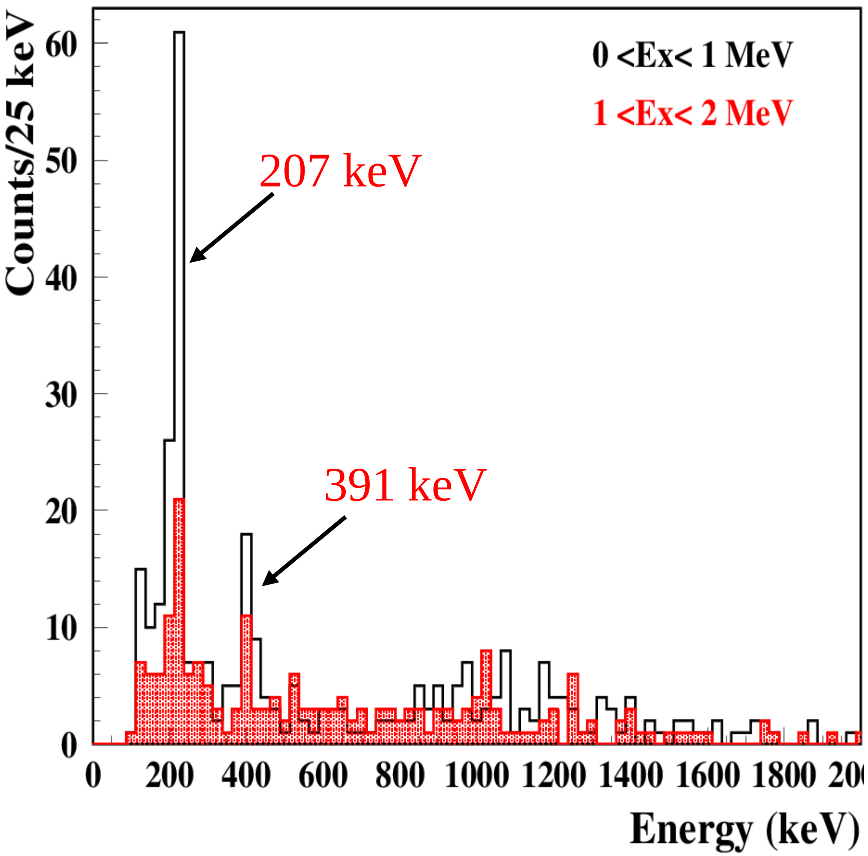
Experimental Results: ^{61}Fe excitation energy spectrum



- FWHM(peak) > 800 keV (expected energy resolution) ➔ population of 2-3 states
- Population of the 861 keV (J^{π}=9/2+) isomeric state (τ=239 ns)

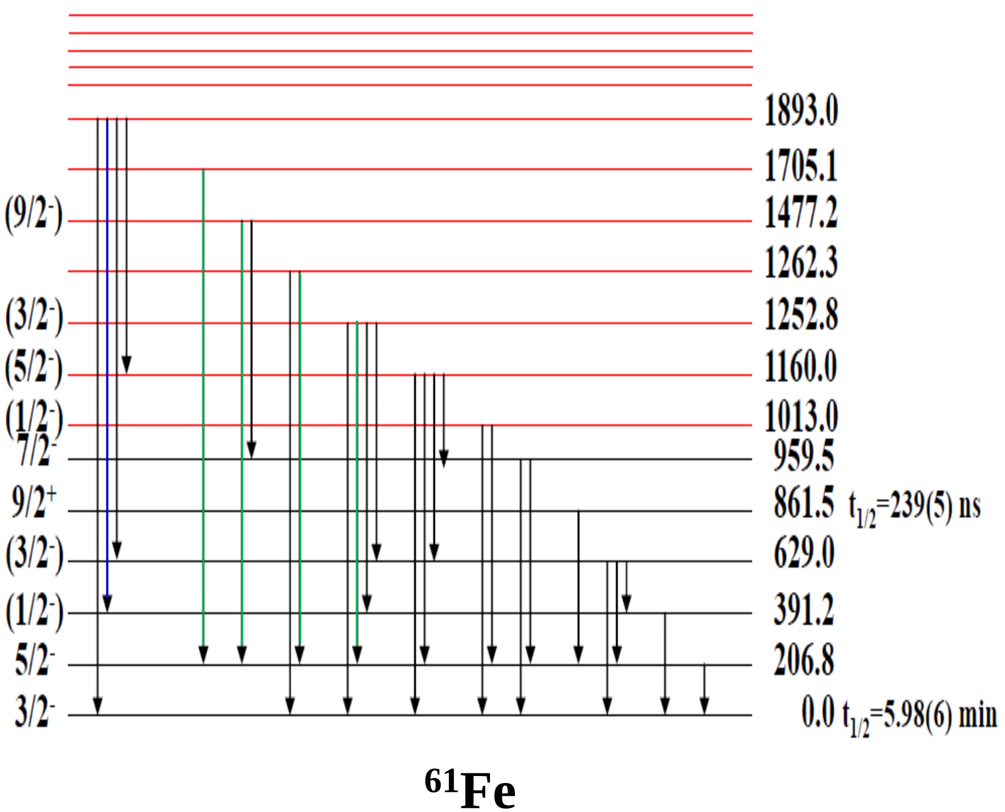
Experimental Results : γ-ray spectra (1st peak)

γ-ray spectra



Results of β decay of ^{61}Mn to ^{61}Fe levels

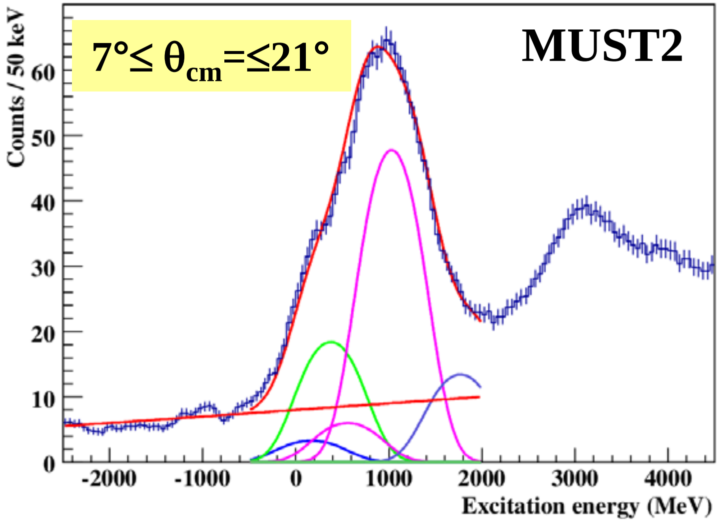
Radulov et al. PRC88, 014307 (2013)

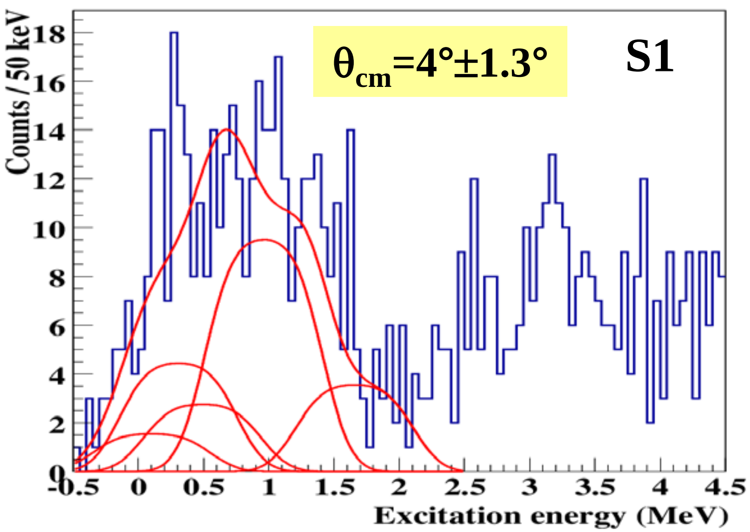


- Population of **207 & 391 keV** states in the 1st peak
- No clear identification of the γ-ray partners of the 207 & 391 keV transitions in the range 1 MeV <Ex<2 MeV → large background, low statistics (low cross sections, efficiency ↘)

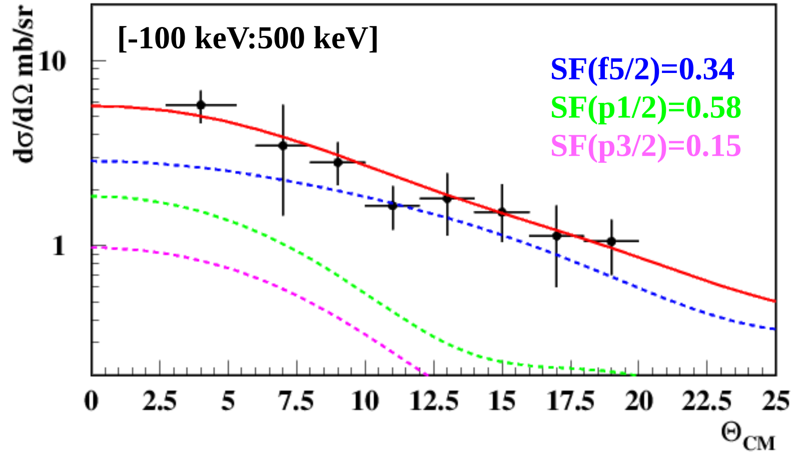
Experimental Results: Spectroscopic factors

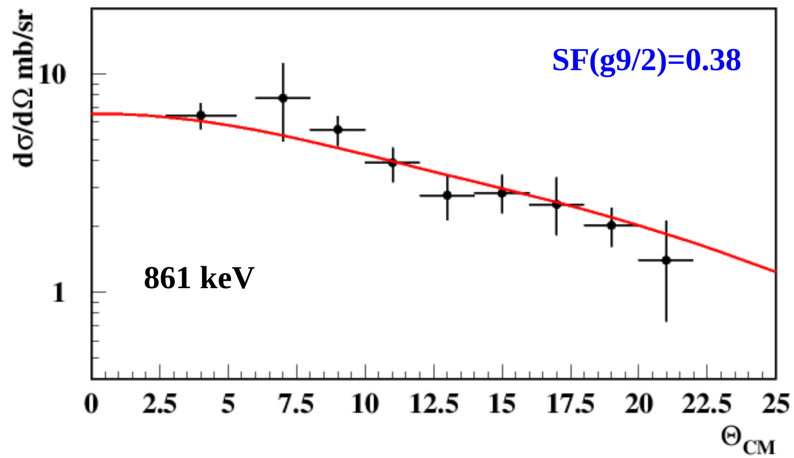
Deconvolution with: **gs, 207, 391, 861 keV** & a higher level ~ ’’1600 keV’’





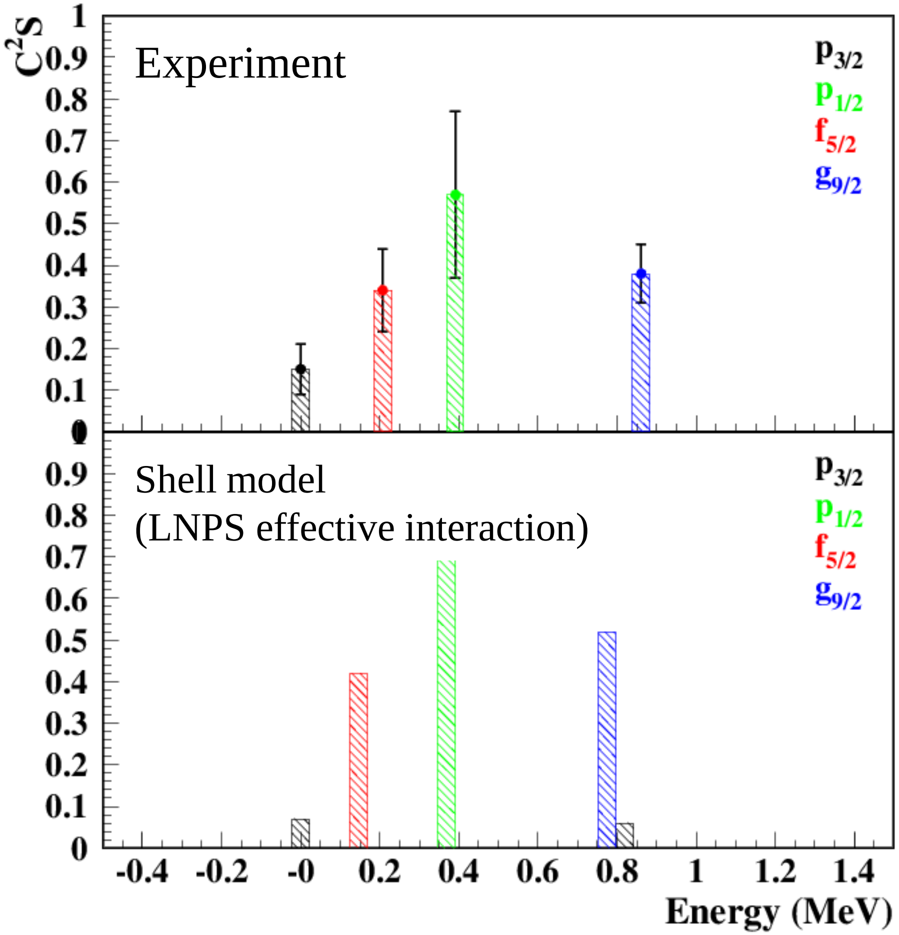
Zero-range ADWA calculations





S = **0.15±0.06** (p3/2 gs)
S = **0.34±0.10** (f5/2 207 keV)
S = **0.58±0.20** (p1/2 391 keV)
S = **0.38±0.07** (g9/2 861 keV)

Comparison with shell model calculations

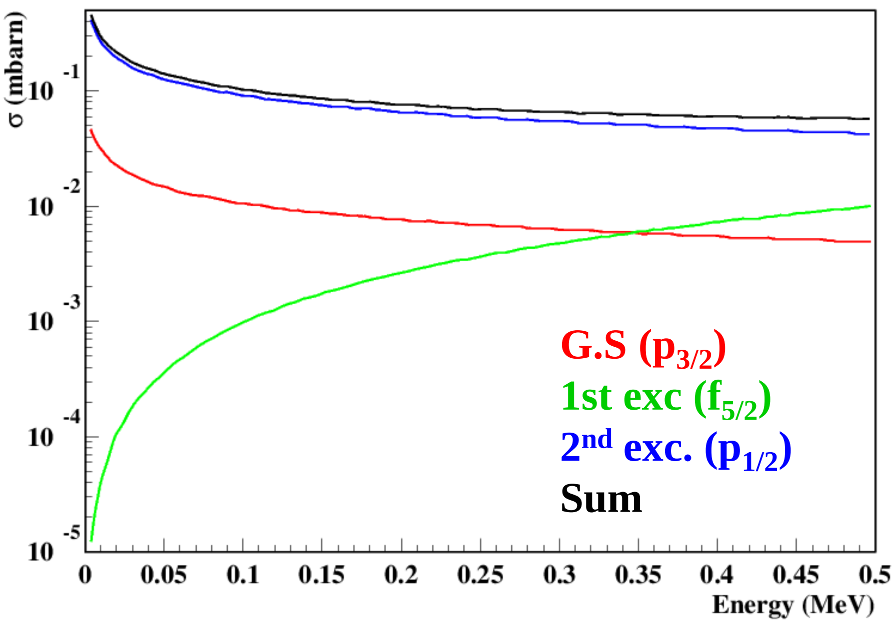


Very good agreement between SM predictions (**S.M.Lenzi et al. 2010**) & experimental results → **SM calculations are reliable in this mass region**

Direct $\sigma_{60Fe(n,\gamma)61Fe}$

$$\sigma_{(n,\gamma)} = \sum_i C_i^2 S_i \sigma_i^{DC} = \sum_i C_i^2 S_i \left| \int_{r=0}^{\infty} \phi_f \theta_{em} \phi_i d\vec{r} \right|^2$$

TEDCA code: H.Krauss



S. Giron, F. Hammache, N. de Séréville et al. 2017

@ 25 keV:

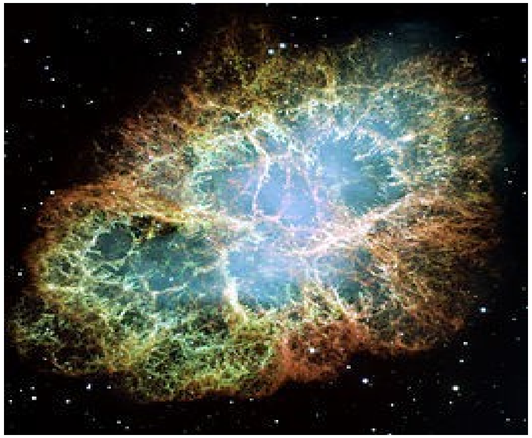
σ_{total}=10 mbarn **Uberseder et al. 09**

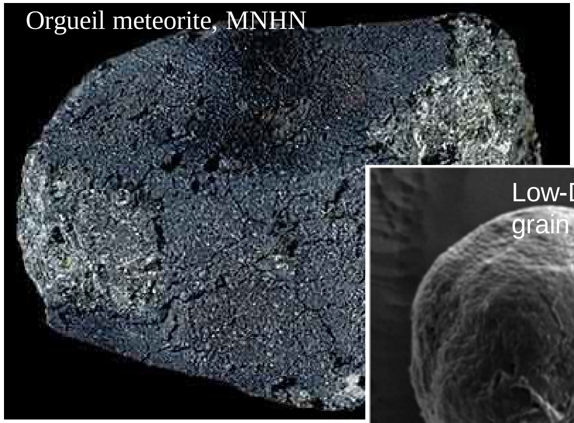
This work: σ_{direct} =0.2 mbarn → **2%** (total)

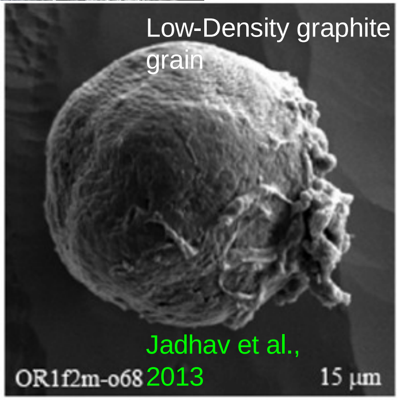
→Resonant capture dominates

^{15}N Nucleosynthesis in massive stars

- Massive stars ($M > 8\ M_{\odot}$) play a key role in the chemical & dynamical evolution of our galaxy
- Material from these stars is brought to earth in presolar grains embedded in meteorites







- Low-Density graphite grains carry isotopic anomalies typical from massive stars

→ Which layer is at the origin of these anomalies?

- Recent measurements show spatially well correlated hot spots of excesses in ^{15}N and ^{18}O

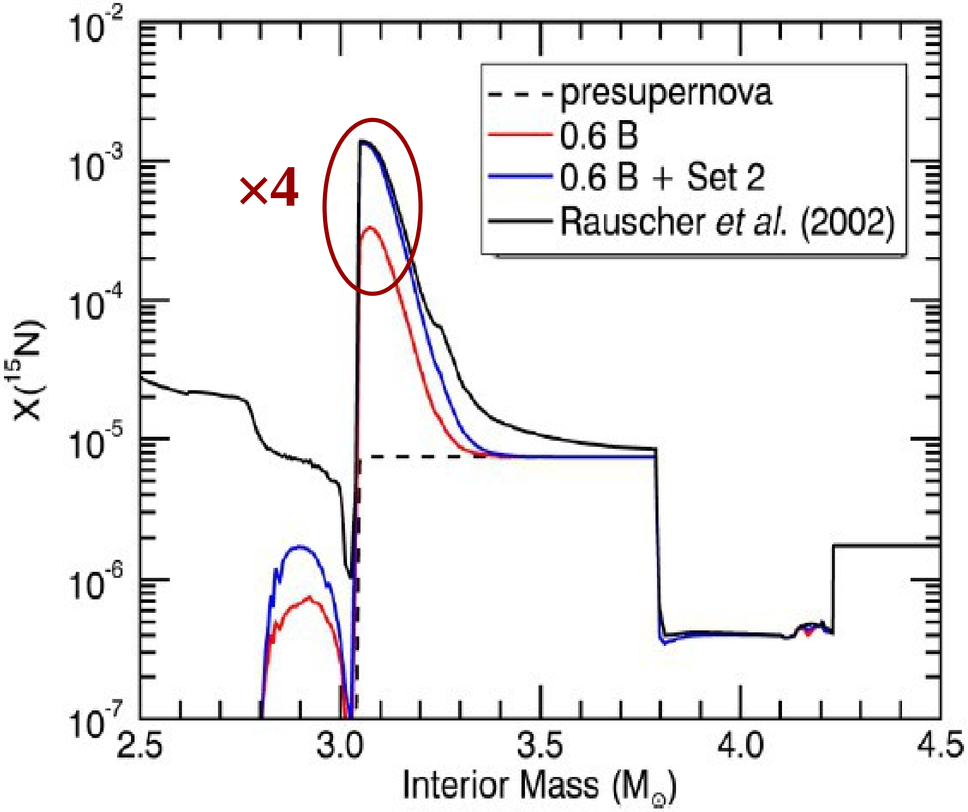
→ This points toward the He layer **Groopman et al. 12**

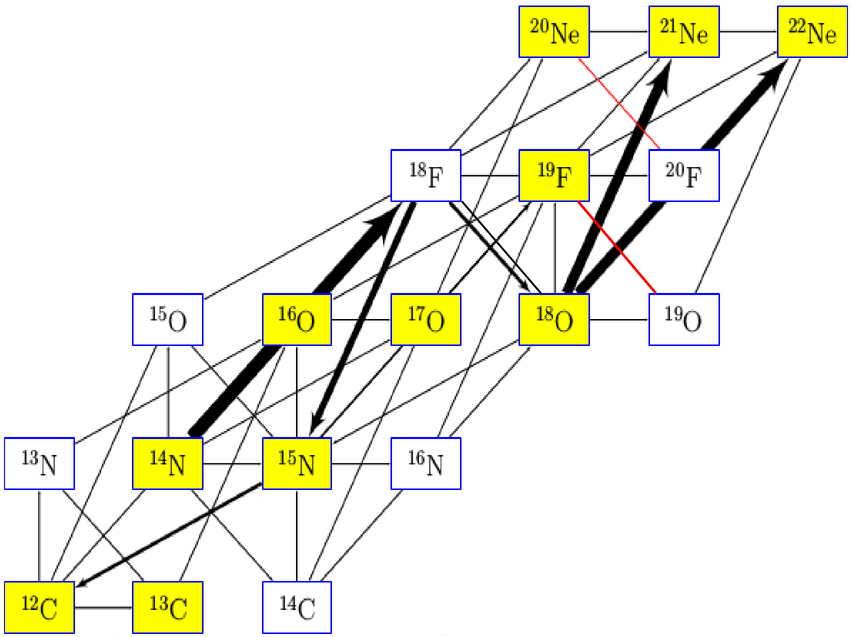
- Rauscher et al. → Stellar explosion affects slightly ^{18}O mass fraction in the inner part of He layer but strongly ^{15}N

→ The observation of ^{15}N is an important probe to explain the origin of supernova graphite grains & constrain their formation scenario

^{15}N Nucleosynthesis in massive stars

Sensitivity study for ^{15}N production in case of explosion of a 15 $M_\odot$ star **J. Bojazi & B. Meyer 2014**

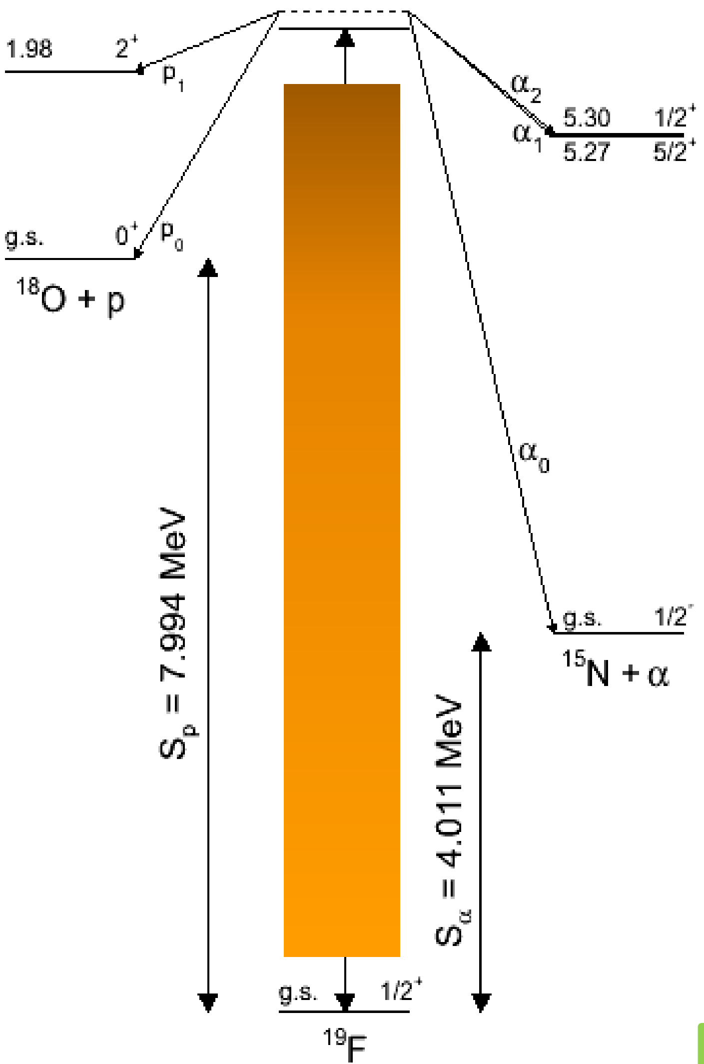




→ Mainly due to uncertainty of 5 in the ^{18}F(n,p)^{18}O & ^{18}F(n,α)^{15}N reaction rates (Hauser-Feschbach calc.)

Lack of spectroscopic information in ^{19}F nucleus above neutron threshold

^{19}F experimental status



- **Region of interest:** $S_n < E_x < S_n + 150$ keV (T_9=0.7GK)
  - o s-wave neutron capture: J^{π} = 1/2+, 3/2+
  - o p-wave neutron capture: J^{π} = 1/2-, 3/2-, 5/2-
- **8 known states with measured Γ_{tot}** **(Tilley et al. 95)**

Ex (MeV± keV)	**J^{π}**	**$\Gamma_{c.m}$ keV**	**Γ_p keV**	**Γ_α keV**
10.469±4		11.0±1.2		
10.488±4		4.8±0.8		
10.496±1.3	3/2+	5.7±0.6	2.4	(1.0)
10.521±4		14±2		
10.542±11		2.5±0.2		
10.555±3.0	3/2+	4.0±1.2		
10.564±2.0		4.6±0.7		
10.581±4	(5/2+)	22±3		

Reaction rate : $\omega\gamma = \omega\Gamma_n \Gamma_{p,\alpha}/\Gamma_{tot}$ and $\Gamma_{tot}=\Gamma_n+\Gamma_p+\Gamma_\alpha$

Experimental Method & Set-up

→ Populate ^{19}F above the neutron threshold via inelastic proton scattering => less selectivity

$^{19}F + p \rightarrow {}^{19}F^* + p'$ → Ex

Sp = 7.994 MeV

S_α = 4.011 MeV

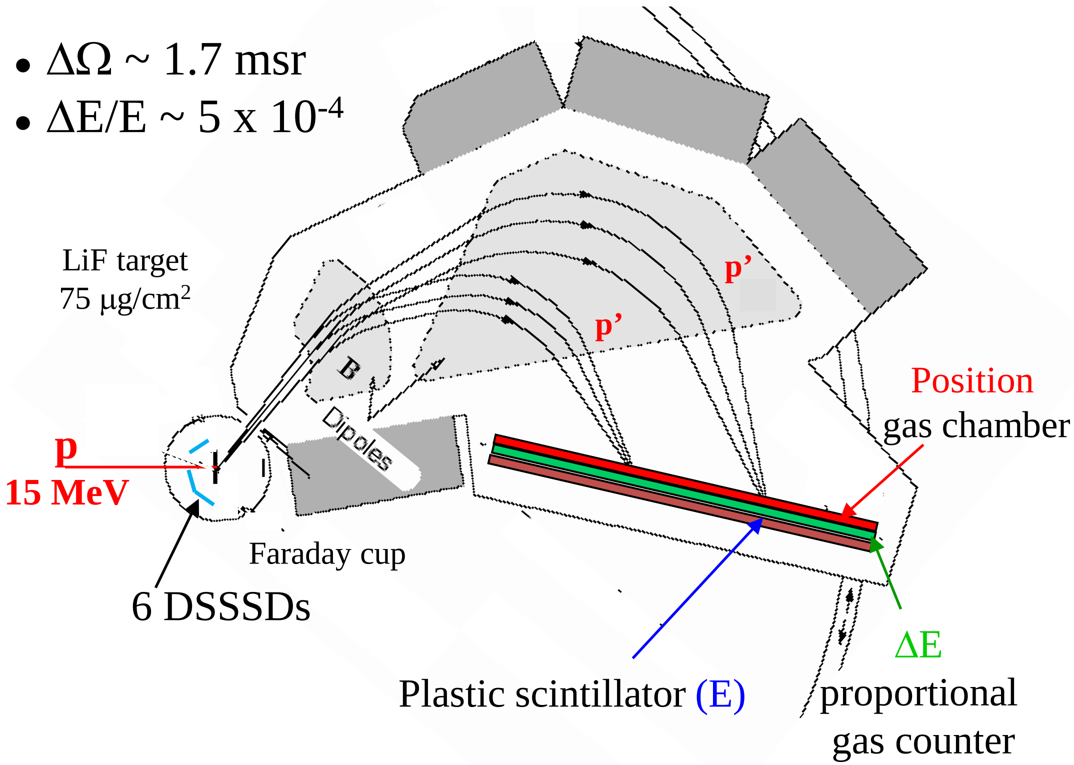
→ p'' + ^{18}O

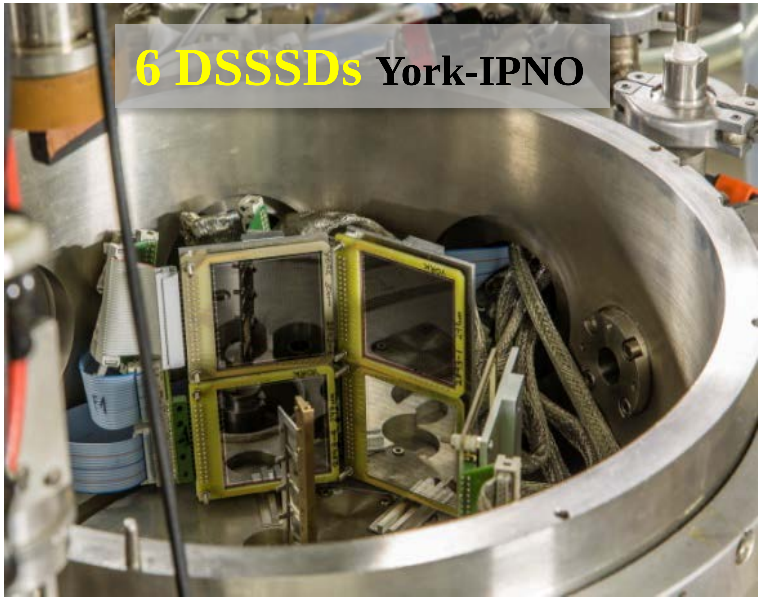
→ α + ^{15}N

- Decay branching ratio: Γ_p / Γ_{tot} & $\Gamma_\alpha / \Gamma_{tot}$
- Angular correlations: J

Split-Pole spectrometer (Tandem/ALTO)

- ΔΩ ~ 1.7 msr
- ΔE/E ~ 5 x 10^{-4}





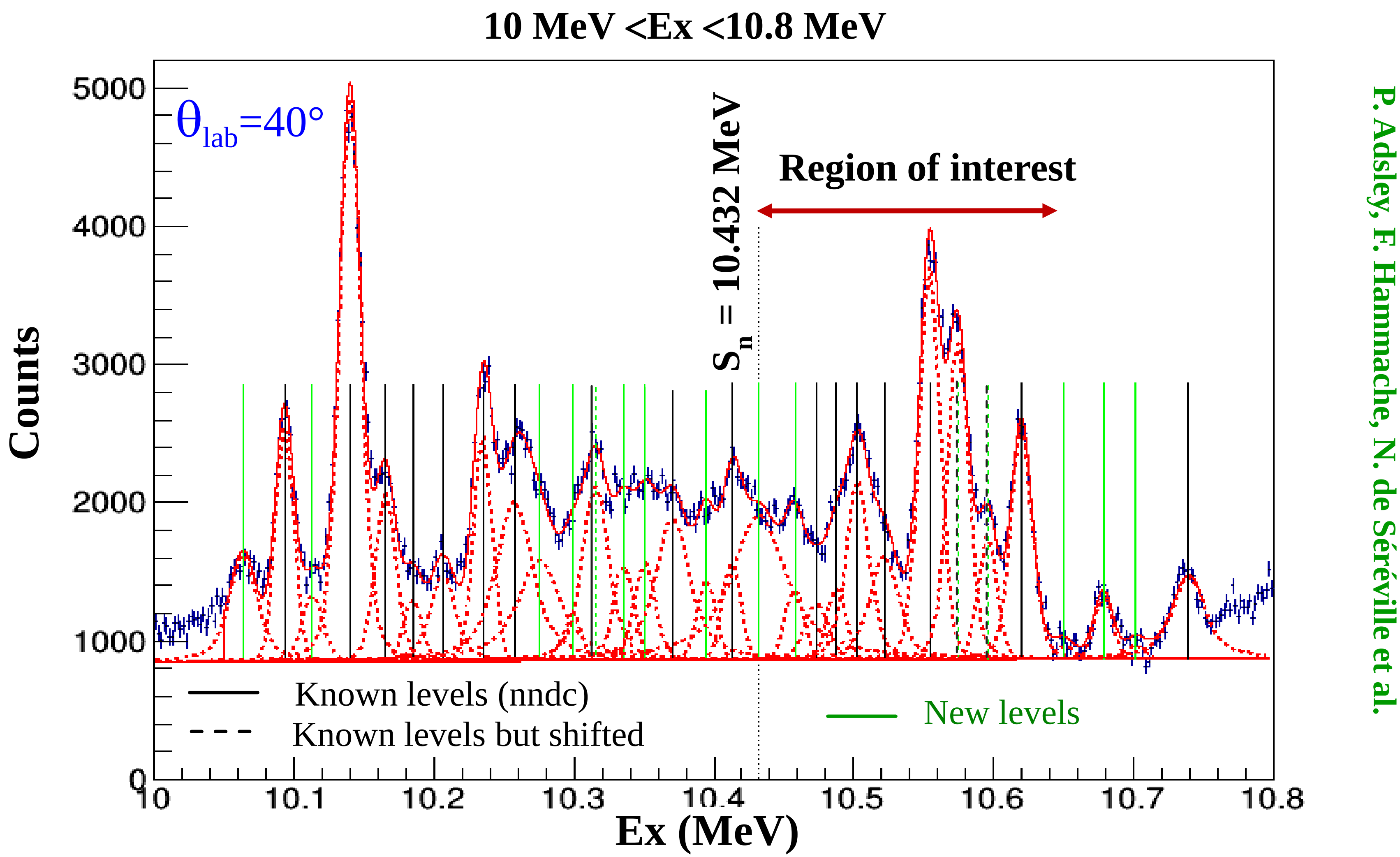
6 W1 detectors (300 μm)

5 x 5 cm², 16+16 strips, ΔE = 18 keV

d ~ 10 cm, ε ~ 10% of 4π

θlab= 110° – 165°→ θcm= 60° – 170°

Experimental results: ^{19}F excitation energy spectrum & deconvolution



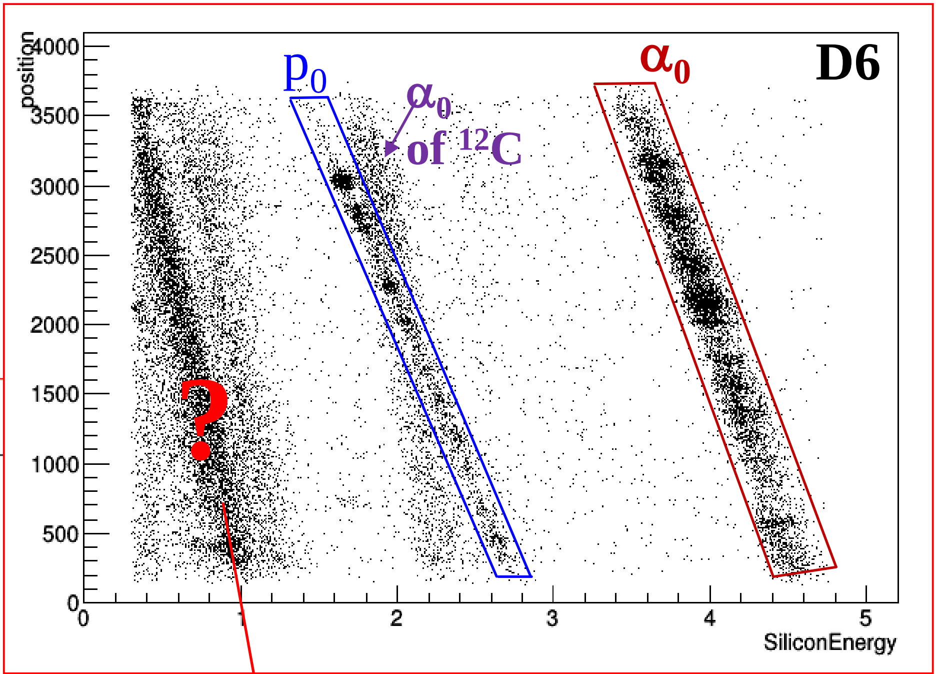
- Energy resolution : **16 keV**
- Good agreement with the known states except with Ex=10.564 & 10.581 MeV (off by 10 keV)
- 2 new states in the region of interest at Ex= **10.432 MeV** & Ex= **10.458 MeV**

Preliminary results: Coincidence spectra

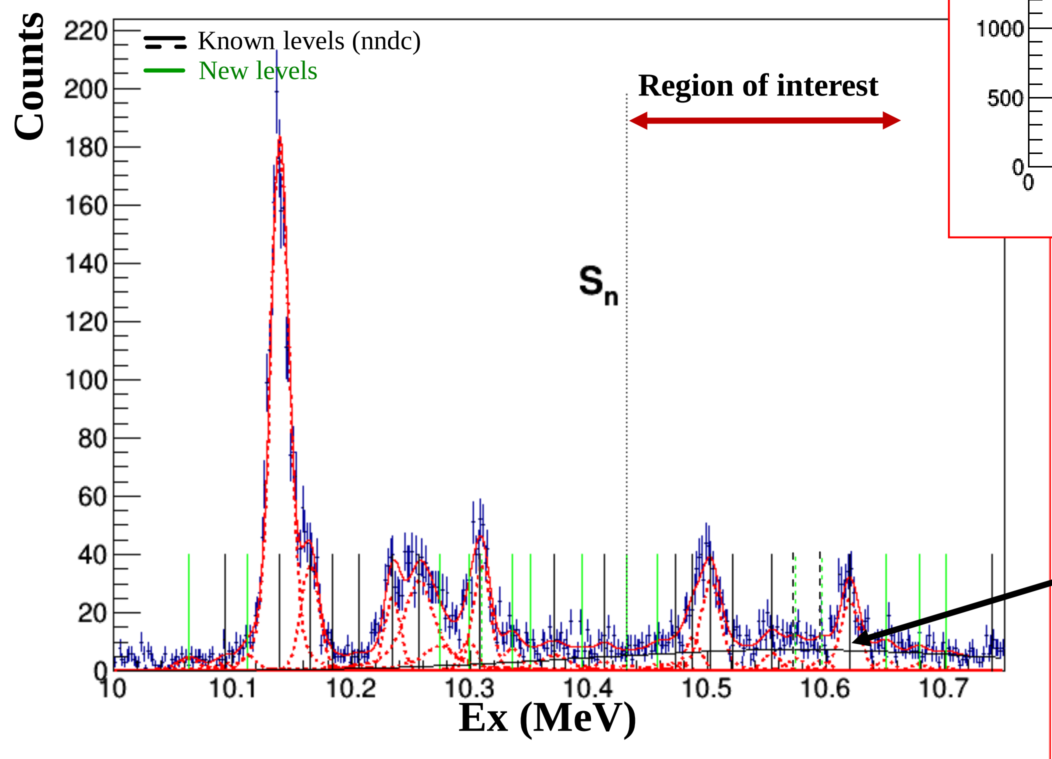
Split-Pole position vs Silicon energy spectrum:

→ α_0 locus is very clear

→ p_0 locus is very clear but has an overlap with ^{12}C α-decay locus. They are distinguished with ToF information for D5&6 only



p-p_0 coincidence spectrum



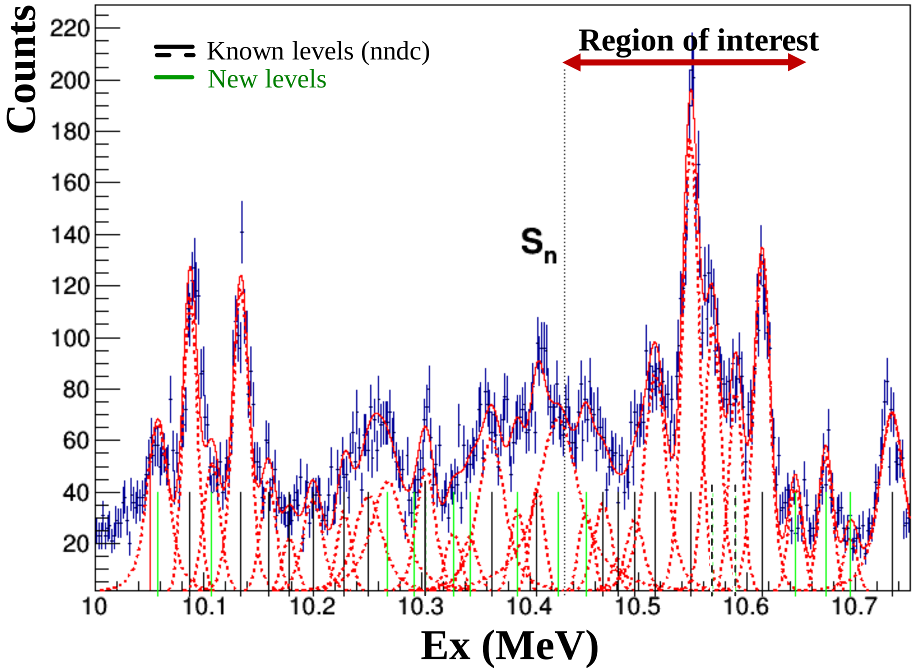
Not α_1. Other ^{12}C α-breakups?

(simulation in progress)

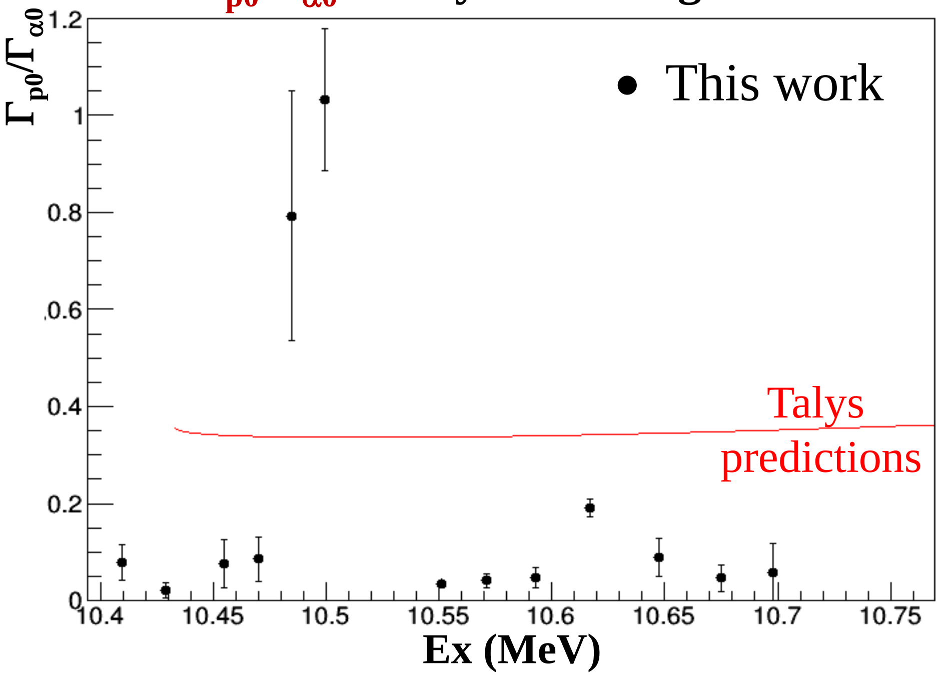
Black curve: **α_0 from ^{12}C breakup**

Preliminary results: α coincidence spectrum & relative branching ratios

p-α_0 coincidence spectrum



$\Gamma_{p0}/\Gamma_{\alpha0}$ decay branching ratios



In the region of interest

- For most of the states $\Gamma_{\alpha0}$ is larger than Γ_{p0} by ~ one order of magnitude
- $\Gamma_{p0}/\Gamma_{\alpha0}$ (this work) do not agree with $\Gamma_{p0}/\Gamma_{\alpha0}$ (Talys predictions) by a factor ~2 – 4
- $^{18}F(n,\alpha)^{15}N$ dominates over $^{18}F(n,p)^{18}O$

Next (Analysis in progress)

Extract the angular correlations ; Deduce the absolute values of Γ_{p0} , $\Gamma_{\alpha0}$ & Γ_n

→ Calculate $^{18}F(n,p)^{18}O$ and $^{18}F(n,\alpha)^{15}N$ reactions rates

Summary

- Various indirect techniques (transfer & inelastic scattering reactions,…), beams (stable and unstable) in small & large facilities can be used to investigate key reactions of astrophysical interests.

- The direct component of $^{60}Fe(n,\gamma)^{61}Fe$ reaction was investigated via $^{60}Fe(d,p)^{61}Fe$ reaction in inverse kinematics. It was found to be negligible.

- The measured spectroscopy of ^{61}Fe confirms the reliability of the LNSP shell model calculations in the N=34 region mass.

- $^{18}F(n,p)^{18}O$ & $^{18}F(n,\alpha)^{15}N$ reactions, which play a role in the ^{15}N nucleosynthesis in CC supernova, were investigated through the $^{19}F(p,p')^{19}F^*$ inelastic scattering reaction with the aim of determining the proton and alpha decay branching ratios.
  - $^{18}F(n,\alpha_0)^{15}N$ dominates over $^{18}F(n,p_0)^{18}O$
  - Experimental analysis is still ongoing : angular correlations, proton & alpha decay branching ratios, reactions rates

Collaborations

FRANCE **IPN (Orsay)**, CSNSM (Orsay), GANIL (Caen), CEA-IRFU (Saclay), LPC (Caen), IPHC (Strasbourg), ISMO (Orsay)

UK University of York

SPAIN University of Huelva, University of Santiago de Compostel, UPC of Barcelona

CZECH REPUBLIC ASCR, Rez

GERMANY GSI, Darmstadt

PORTUGAL CFNU, Lisboa

JAPAN RIKEN, Wako

ALGERIA University A. Mira, Béjaïa