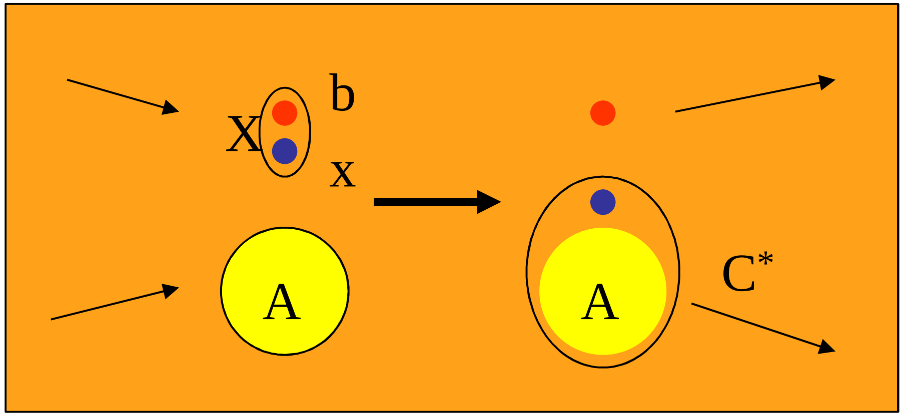
The 6th European Summer School on Experimental Nuclear Astrophysics

Transfer reactions as a tool for nuclear astrophysics

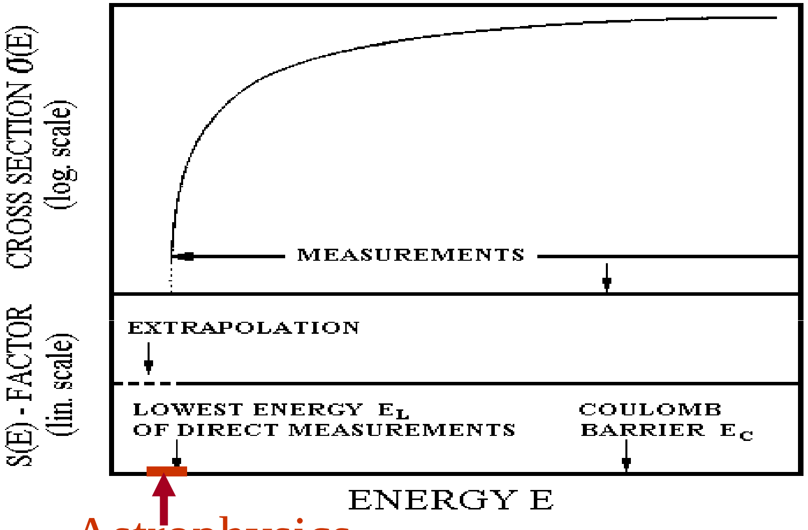


F. Hammache, IPN-Orsay

Santa-Tecla, Sicily , 18-25 September 2011

Characteristics of cross sections of astrophysics reactions

- Very week cross sections (fbarn-nbarn) at stellar energies (0.01-qqs MeV)
- Typical problem: the presence of Coulomb Barrier between the interacting nuclei



Astrophysics energies

The cross section decays exponentially

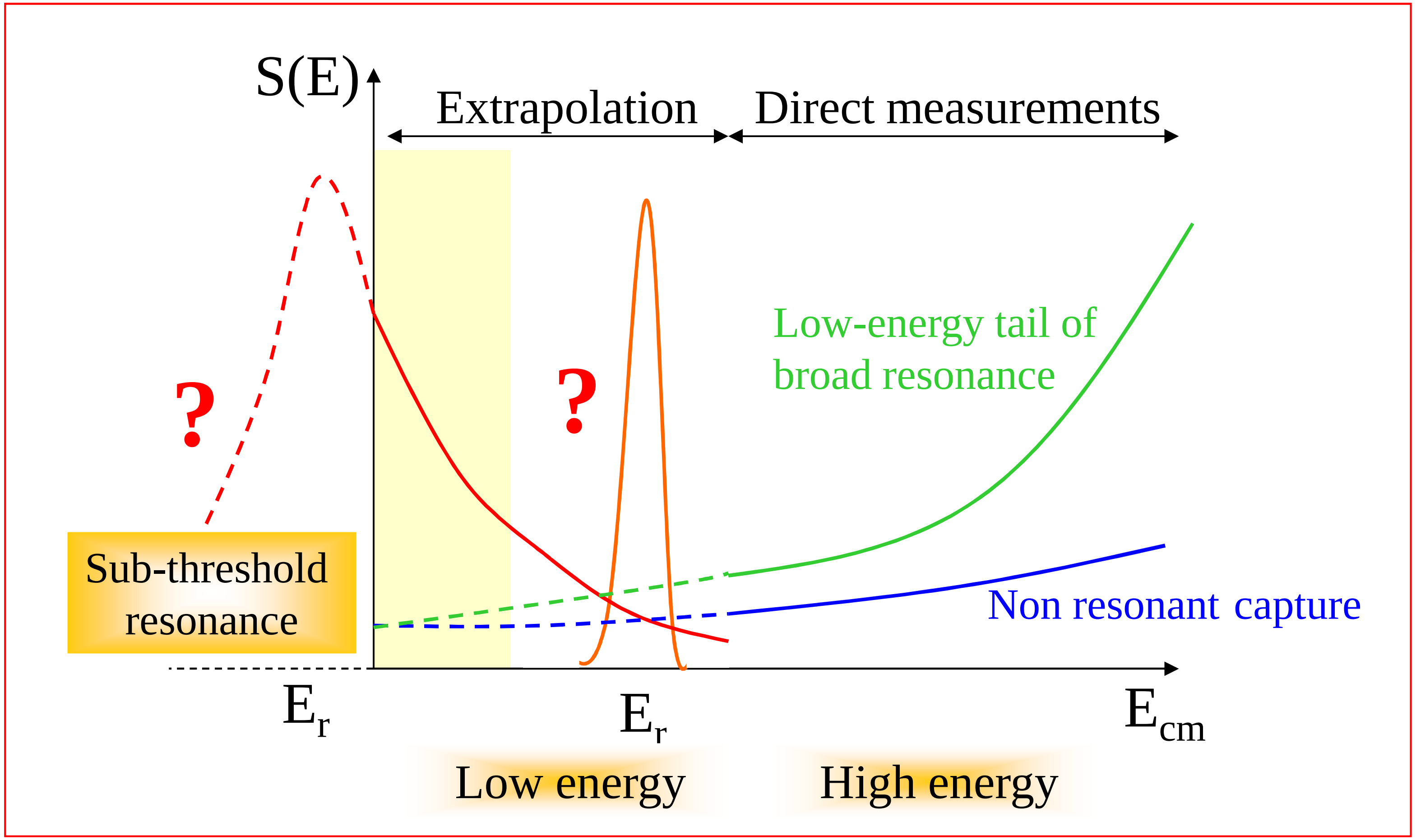
The astrophysical S-factor varies slowly

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

- The extrapolation to the energy of interest is often necessary

Problems with extrapolation

What about resonances @ low energy & subthreshold resonances?



Other difficulties

- Radioactive nuclei : low beam intensity(~10^5 p/s) or targets with few atomes/cm^2

↳ e.g novae nucleosynthesis eg: ^{18}F(p,α)^{15}O, ^{30}P(p,γ)^{31}S, …

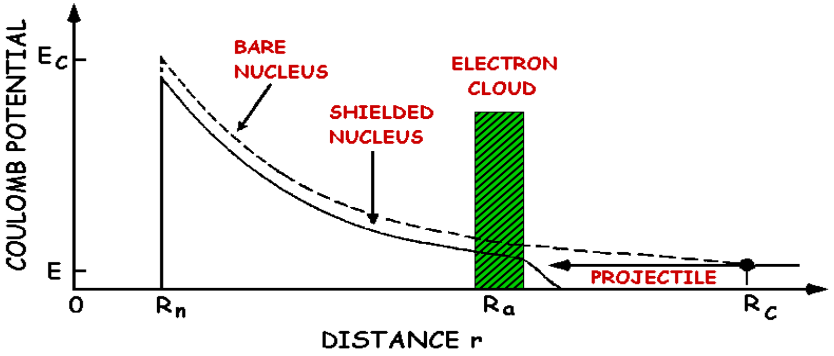
↳ direct measurement are very difficult

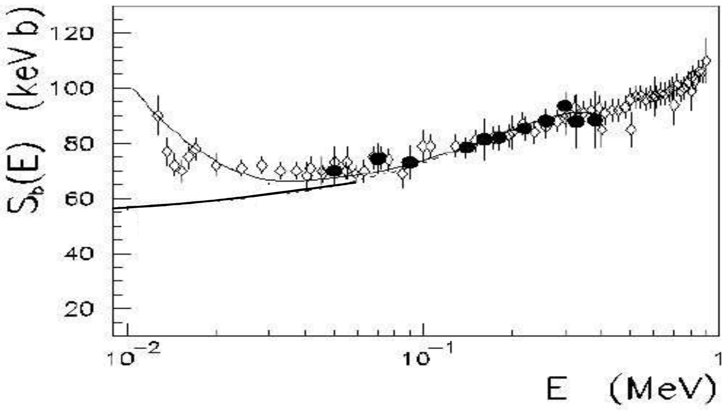
↳e.g (n,γ) captures in r-process → direct measurements are impossible

- Electron screening→ cross section enhancement at low energies

Lab. The cross sections are measured with targets → atoms

In astrophysical models, the required cross sections are those of interacting bare nuclei





S.Engstler et al : PLB 279,20,(1992)

What is the cross section without screening?

Talk: Gianluca Pizzone

Alternatives: Indirect Methods

☺ Experiments with high energies implying higher cross sections .

☺ The experimental conditions are relatively less rigorous.

☹ They are model dependent.

☹ They depend on the uncertainties relative to the different parameters used in the models ⇒ 2 sources of errors.

The global uncertainty can be reduced by combining different approaches

Indirect Methods

- **Transfer reactions**

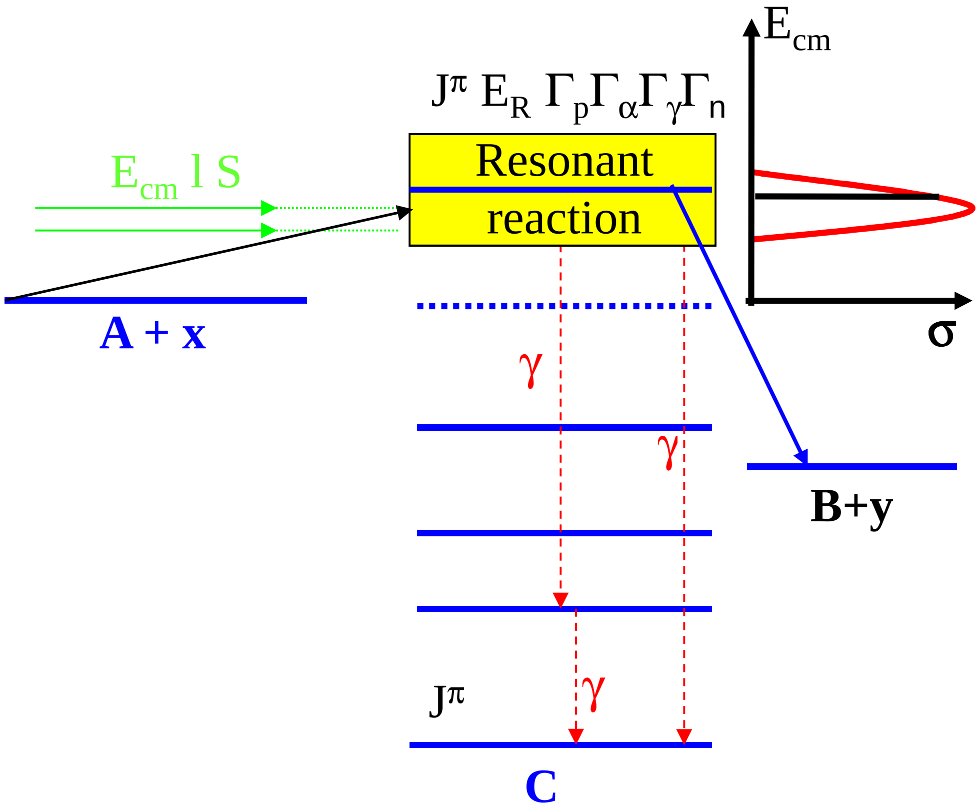
Resonant reactions: need of spectroscopic information: Resonance energy, spins, partial widths, branching ratios …

Direct captures like (n,γ) : need for Ex, spins, parities, spectroscopic factors

- Coulomb dissociation and radiative capture reactions (Bertulani & Motobayashi talks)
- Assymptotc Normalization coefficient and radiative capture reactions (Trache talk)
- Resonant elastic and non-elastic scattering
- Trojan Horse method (Spitaleri talk)

Resonant reactions

$A+x \rightarrow C^* \rightarrow B+y$ ou $A+x \rightarrow C^* \rightarrow C+\gamma$



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

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

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

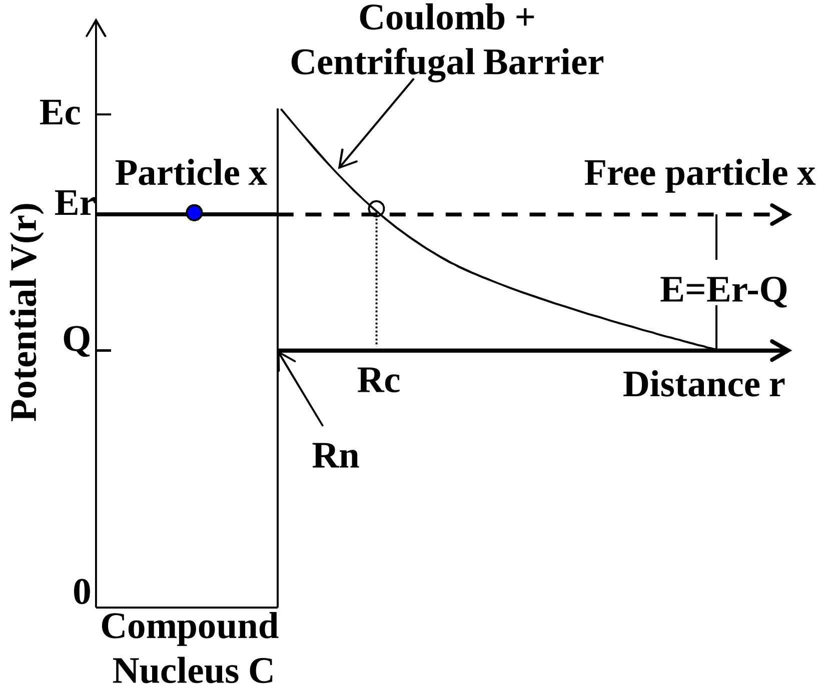
⬇

experiments 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 $\Psi = |A \oplus x>$



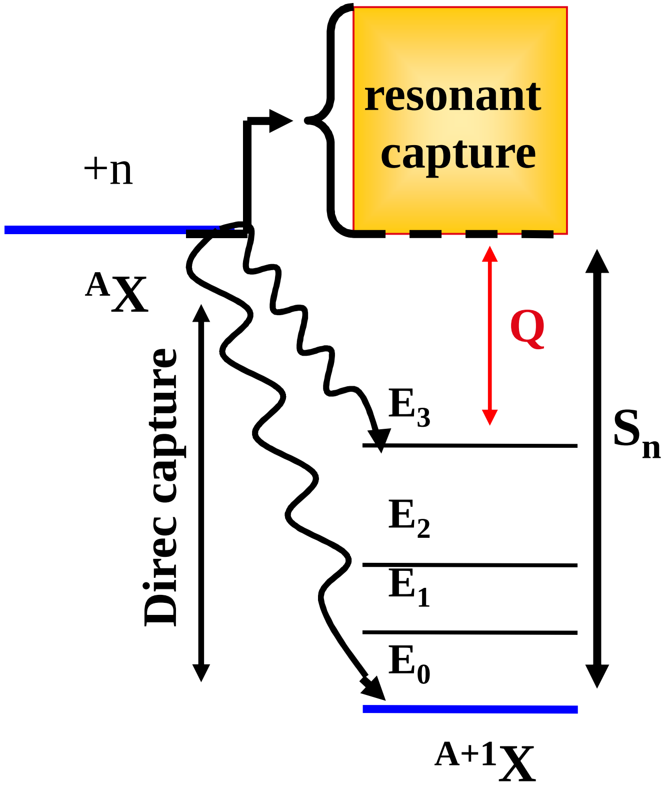
The decay partial width of C into A+x is given by
(See. Illiadis: Nuclear physics of stars)

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

P_l = penetrability factor
$\varphi(R_n)$ radial wave function of the particle x.

For a state with a pure core-particle configuration, $\Gamma_x^{s.p}$ can be calculated
In most of cases Ψ is a mixture of configurations and we have $\Gamma_x = S\, \Gamma_x^{s.p}$.
By determining the spectroscopic factor $S = <C^*|A \otimes x>^2$ via transfer reactions,
we can calculate Γ_x .

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



Direct capture mechanism can sometimes play an important role
e.g: $^{48}Ca(n,\gamma)^{49}Ca$ case
E. Krausmann et al. , Phys Rev. C. 53, 469 (1996)

- Capture on **bound** states of final nucleus.
- Captures possible for all neutron energies
- Smooth variation of the $\sigma_{(n,\gamma)}$ cross-section with the neutron energy

Direct neutron capture

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

TEDCA code: K.Krauss

Φ_i ,Φ_f : scattering & bound state wave functions in entrance and exit channels

↳ Schrödinger’s equation solution with a potential obtained by double folding

θ_{em}: multipole transition operator

S_i : Spectroscopic factor of the final state

$$\boxed{V = \lambda \iint \rho_n(\vec{r}_n)\rho_A(\vec{r}_A)\, \mathrm{v}_{eff}\,(E_n, \rho_n, \rho_A, |\vec{R} - \vec{r}|)\, d\vec{r}_n d\vec{r}_A}$$

V_{eff} : nucleon-nucleon interaction, ρ_n : neutron density, ρ_A : nucleus target density

λ : → adjusted to reproduce elastic scattering data for the entrance channel

↳ adjusted to reproduce the bound states energies in the exit channel

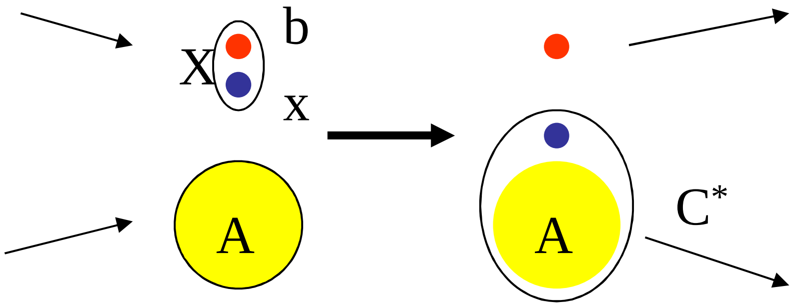
Spectroscopic infomations on the low energy bound states (E_x, l, C^2S) are accessible via (d,p) transfer reactions.

Transfer reactions

The DWBA (Distorded Wave Born Approximation) cross section for a transfer reaction

$$\mathbf{X(=x+b)+A \longrightarrow C(x+A)+b \longleftrightarrow x+A \longrightarrow C^{*} \longrightarrow B+y}$$

Can be writen as:



$$\sigma_{tra} \propto \left| \left\langle \chi_f I_{xA}^{C} \middle| \hat{V} \middle| I_{bx}^{X} \chi_i \right\rangle \right|^2$$

$\chi_{i,f}$	The distorded wave functions of the initial and final state
$\hat{V}$	Transition operator
$I_{\beta\gamma}^{\alpha}(r_{\beta\gamma})$	The overlaping function of the bound state α formed by β and γ

The radial part $I_{\beta\gamma}^{\alpha}$ is: $I_{\beta\gamma}^{\alpha}(r_{\beta\gamma}) = S^{1/2}\varphi_{\beta\gamma}(r_{\beta\gamma})$

$\varphi_{\beta\gamma}$ Is the radial wave function of the bound state α formed by β and γ

S is the spectroscopic factor

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} \propto S_x^{C} S_x^{X} \left(\frac{d\sigma}{d\Omega}\right)_{DW}$$

From spectroscopic factors to decay reduced widths

$$S_x^C$$

Decay reduced width calculation

$$\gamma_x^2 = \frac{\hbar^2 R}{2\mu} S_x^C \left|\phi(R)\right|^2 \Rightarrow \Gamma_x = 2P_l\gamma_x^2$$

ANC calculation

$$\tilde{C}^2 = S_x^C \frac{R^2\left|\phi(R)\right|^2}{W(R)^2})$$

The calculation has to be done @ a radius R where *ϕ(R)* reaches its Coulomb asymptotic behavior

Which parameters do we need to do **DWBA** (Distorded Wave Born Approximation) calculations?

$X+A \rightarrow C+b$ with $X=a+b$

$$\left(\frac{\partial\sigma}{\partial\Omega}\right)_{DWBA} = \sum \left| \int_{r=0}^{\infty} dr \Psi_f^{(-)} \frac{u(r)}{r} Y_{lm} \Psi_i^{(+)} \right|^2$$

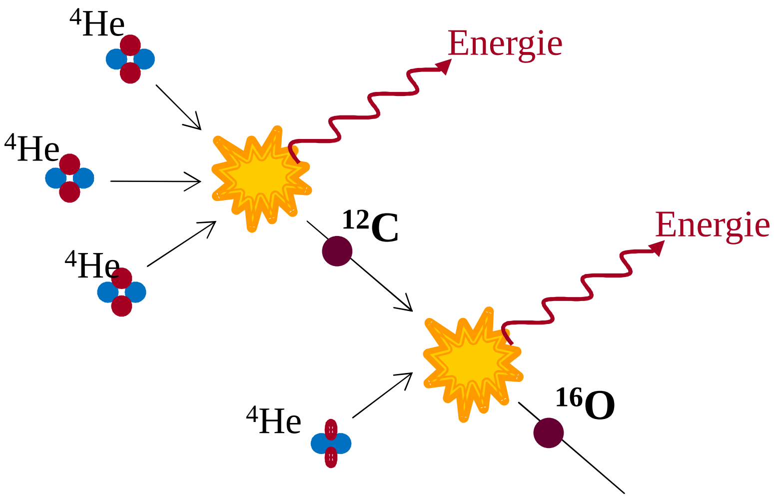
- Optical potential parameters (Wood-Saxon:V_1, r_1, a_1) of the entrance channel
  - Elastic diffusion measurements → X(A,A)X
- Optical potential parameters (Wood-Saxon:V_2, r_2, a_2) of the exit channel
  - Elastic diffusion measurements → C*(b,b)C* ?
- Potential parameters (Wood-Saxon: V, r, a) describing the interaction

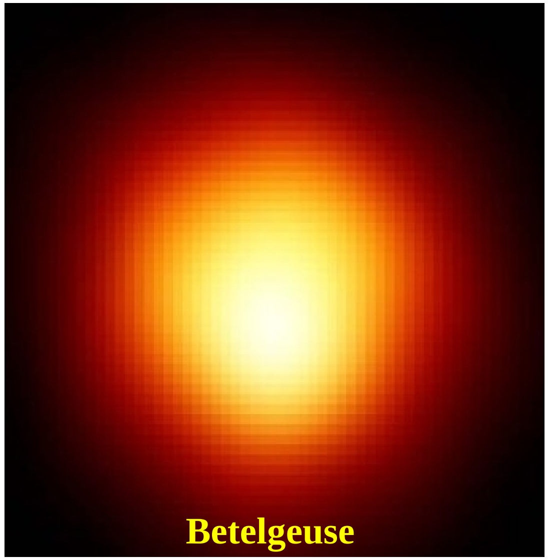
Case of resonant reaction: Indirect study of the astrophysical reaction $^{12}C(\alpha,\gamma)^{16}O$ via the transfer reaction $^{12}C(^{7}Li,t)^{16}O$

Helium burning
in red giants

→ triggered on ^{4}He ashes of hydrogen burning (pp et CNO)

→ Main reactions :
$3\alpha \rightarrow {}^{12}C$ & $^{12}C(\alpha,\gamma)^{16}O$





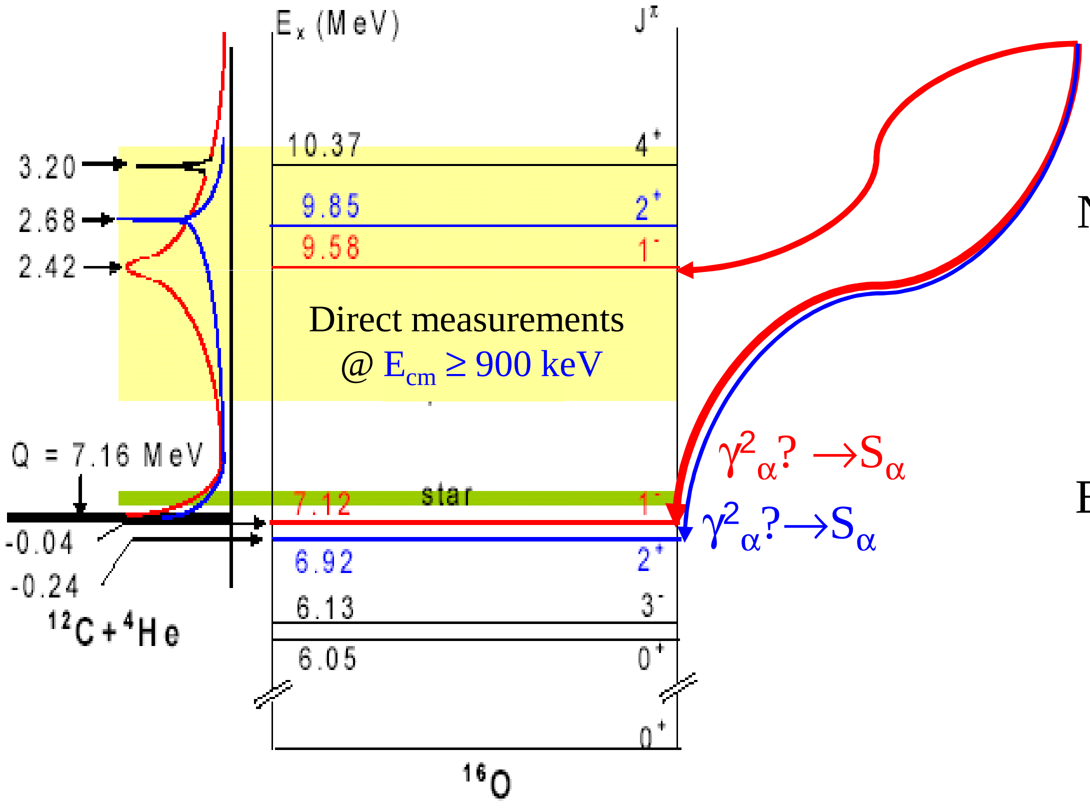
$^{12}C/^{16}O$ abundance rate

- Nucleosynthesis of elementss A>12
  In massive stars
- Subsequent stellar evolution of
  massive stars
  (black holes, neutron stars..)

Status of $^{12}C(\alpha,\gamma)^{16}O$ reaction

- The cross section of $3\alpha \rightarrow {}^{12}C$: 10% uncertainty

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



Direct measurements
@ $E_{cm} \geq 900$ keV

γ^2_α? → S_α

γ^2_α?→S_α

$S(E_0)$ is dominated by E1 & E2 transitions

Need of precise data at high energies & extrapolation at 300 keV

BUT

Effect of the high energy tail of the subthreshold resonances?

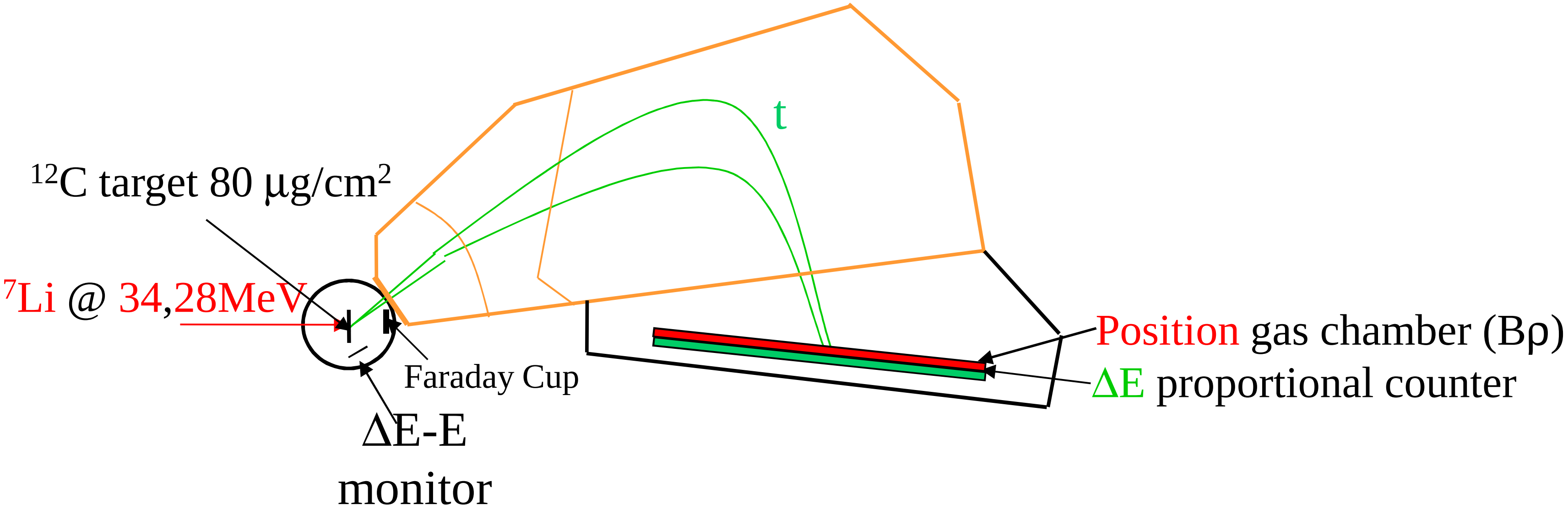
$S_\alpha(1^-) \rightarrow$ 0.02-1.08 !?

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

⇒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 by ^{12}C(^{7}Li,t)^{16}O α-transfer reaction

SPLIT-POLE spectrometer (Orsay-Tandem)



^{12}C target 80 µg/cm^{2}

^{7}Li @ 34,28MeV

t

Faraday Cup

ΔE-E monitor

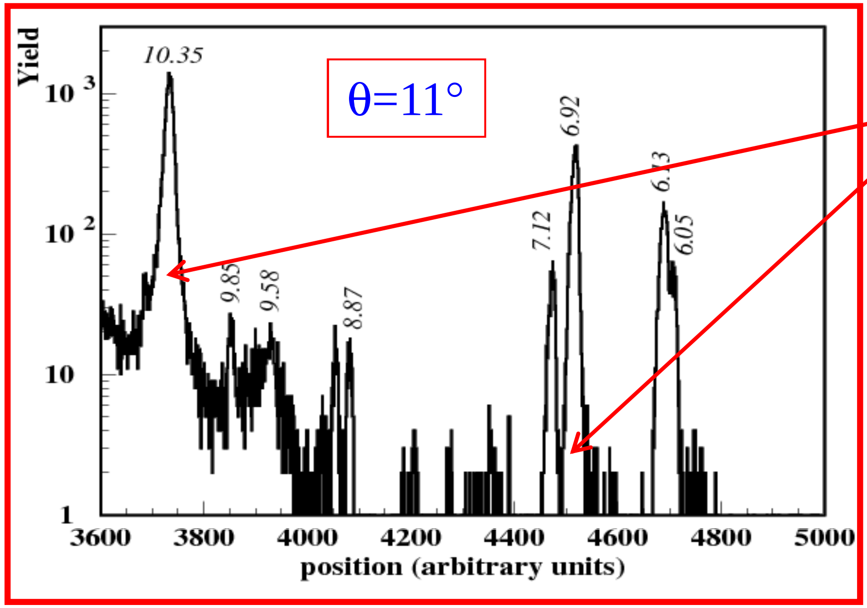
Position gas chamber (Bρ)

ΔE proportional counter

☐ **E_{7Li} = 28 MeV, 34 MeV**

- Transfer $\frac{d\sigma}{d\Omega}$ measurements on ^{12}C targets **[0°-32°]**
- ^{12}C(^{7}Li,^{7}Li)^{12}C elastic measurements @ 28 MeV
- ^{12}C(^{7}Li,^{7}Li)^{12}C data @ 34 MeV from Schumacher et al. *NPA 212 (1973) 573*

Excitation energy spectrum of ^{16}O @ 11°



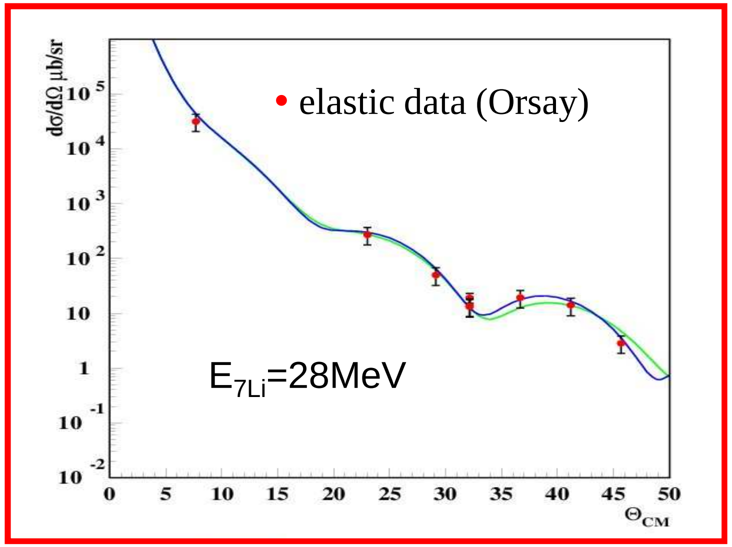
➢Strong population of the α cluster states
⇘ Transfer direct mechanism

➢Population (weak) of the non natural parity 2^-, the 8.87 MeV

🡻

Non direct transfer: compound nucleus?

⇒ Finite Range-DWBA analysis
& Hauser-Feshbach calculations



- (V_1, r_1, a_1) of the entrance chanel:

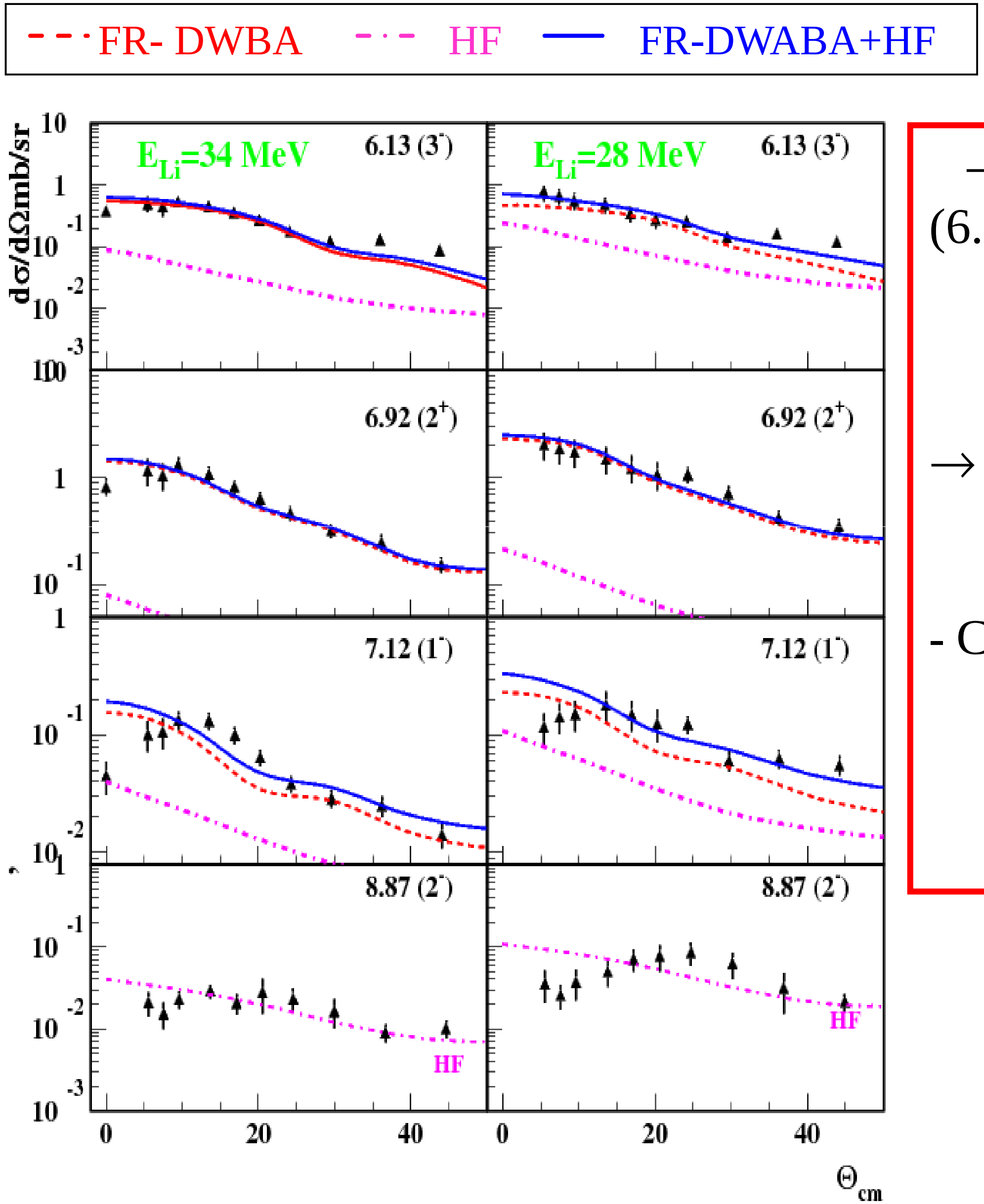
^{12}C(^{7}Li,^{7}Li) ^{12}C measurements @ 28 MeV

- (V_2, r_2, a_2) of the exit chanel:

From ^{20}Ne(t,t) ^{20}Ne measurements @ 15 MeV
Garret et al. (1970)

N. Oulebsir PhD thesis

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 θ <10° for the 7.12 (observed → Becchetti et al (1978))

↓

- Coherent interference between the direct component & the CN component

⇘ $\frac{d\sigma}{d\Omega}$ ↘ ???

$S_\alpha(6.92)=0.15\pm0.05$

$S_\alpha(7.12)=0.08\pm0.03$

R matrix calculations– E2 & E1 components

$S_\alpha(6.92)=0.15\pm0.05 \rightarrow$ $\gamma_\alpha^2 = 27 \pm 10$ keV

$S_\alpha(7.12)=0.08\pm0.03 \rightarrow$ $\gamma_\alpha^2 = 8 \pm 3$ keV

r=6.5fm

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

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

In agreement with Brune's et al. results

(ANC experiment)

Multi-level R-matrix analysis

P. Descouvemont Code

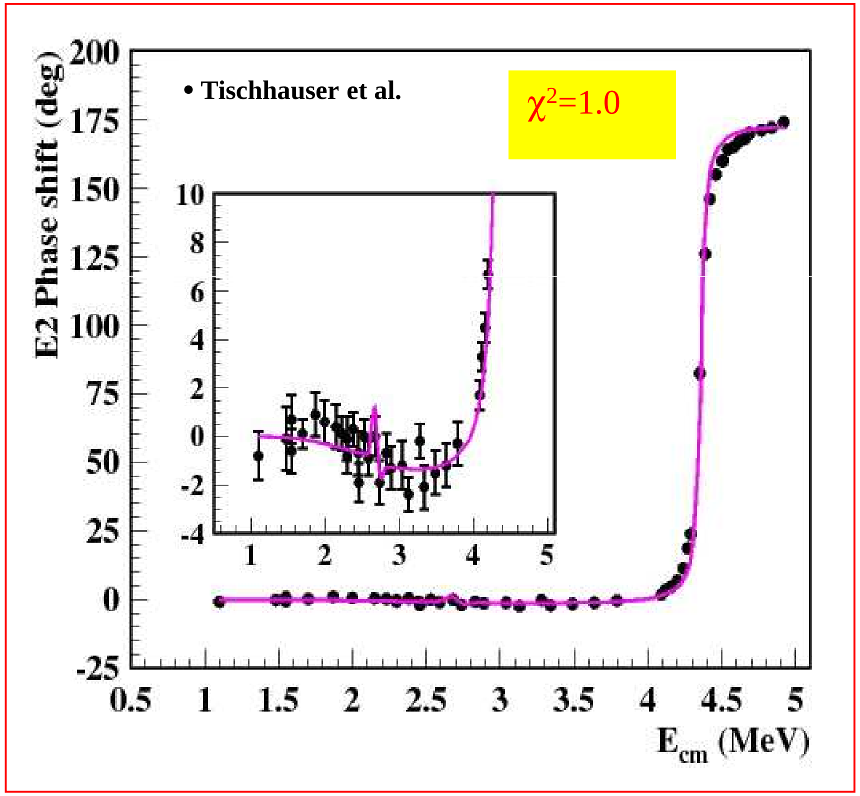
$$R_{CC'} = \sum_\lambda \frac{\gamma_{\lambda C}\gamma_{\lambda C'}}{E_\lambda - E}$$

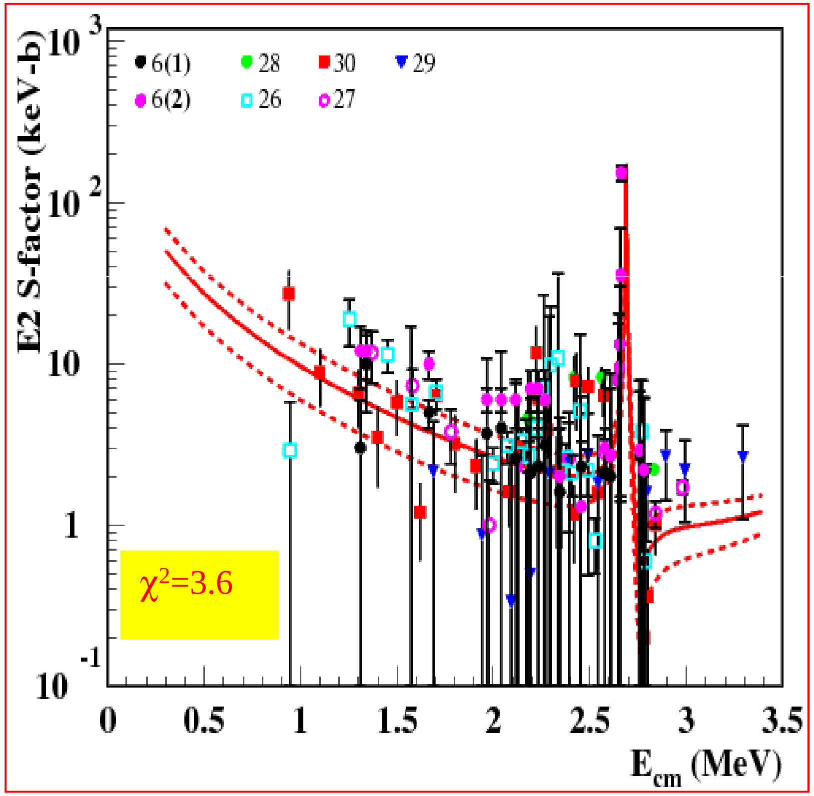
- Fit
  - $^{12}C(\alpha,\gamma)^{16}O$ astrophysical S-factors (direct data)
  - phase shifts data → $^{12}C(\alpha,\alpha)^{12}C$ measurements
- Fit E2 & E1 components separately

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, $\Gamma_{\alpha4}$, $\Gamma_{\gamma4}$)





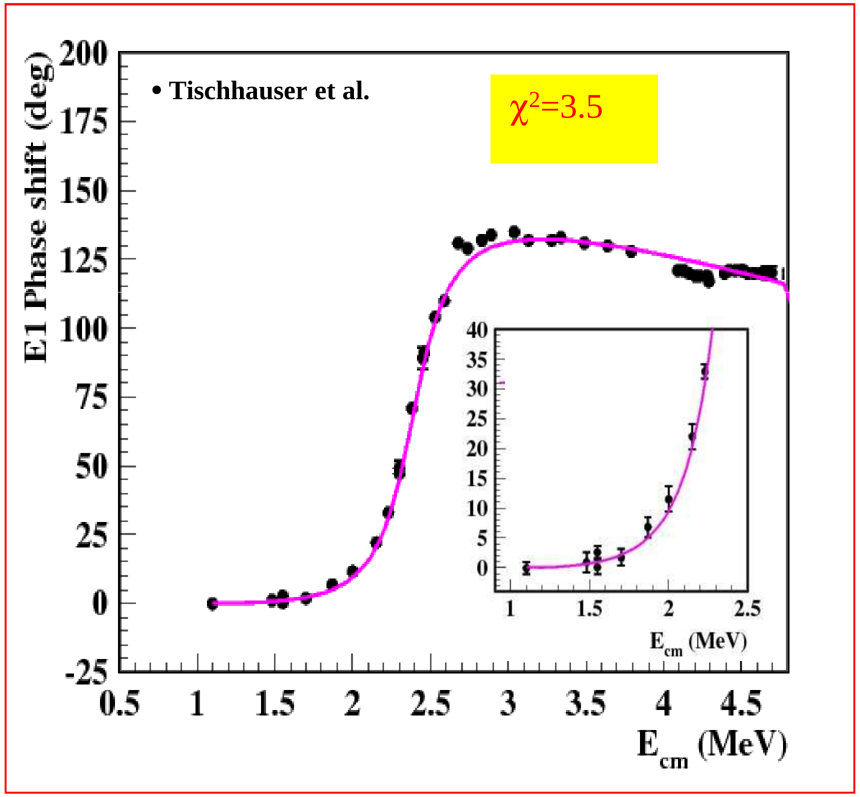
S_{E2}(300 keV)=50±19 keV-barn

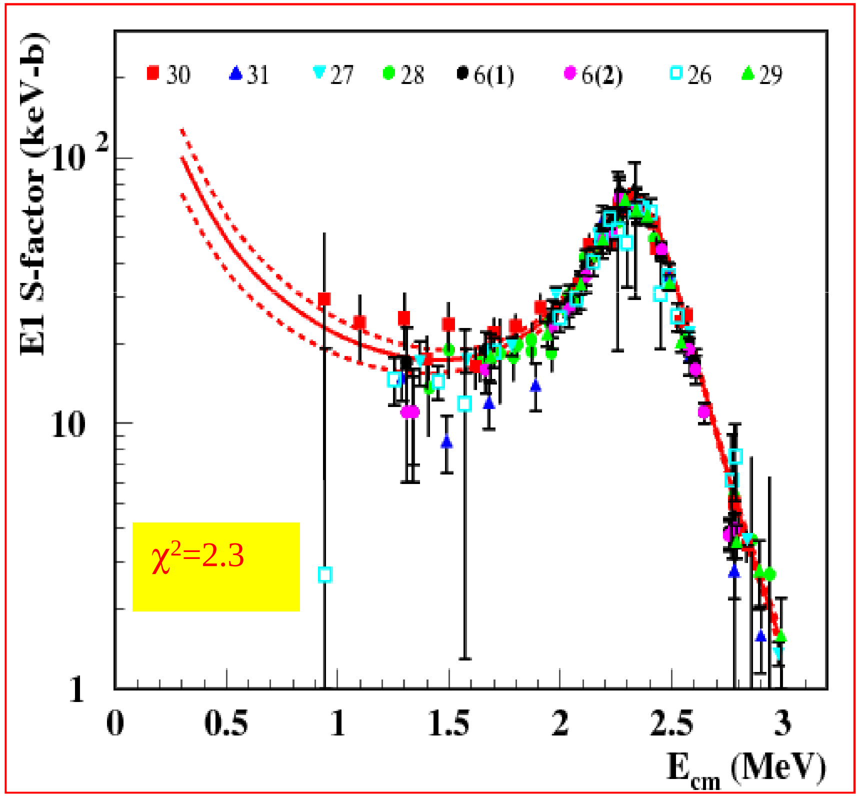
R matrix calculations– E1 component

- E1 Component calculation→ 3 states

\- 7.12, 9.58 → fixed resonance parameters

-Background equivalent state (Er_3, $\Gamma_{\alpha 3}$, $\Gamma_{\gamma 3}$)





S_{E1}(300 keV)=100±28 keV-barn

R matrix calculations– Results

S_{E2}(300 keV)=50±19 keV-barn

S_{E1}(300 keV)=100±28 keV-barn

- with $S_{cascade}$=25 ±16 keV-b (matei et al. 2006) → **S_{total}(0.3)=175 ±63 keV-b** (Orsay)

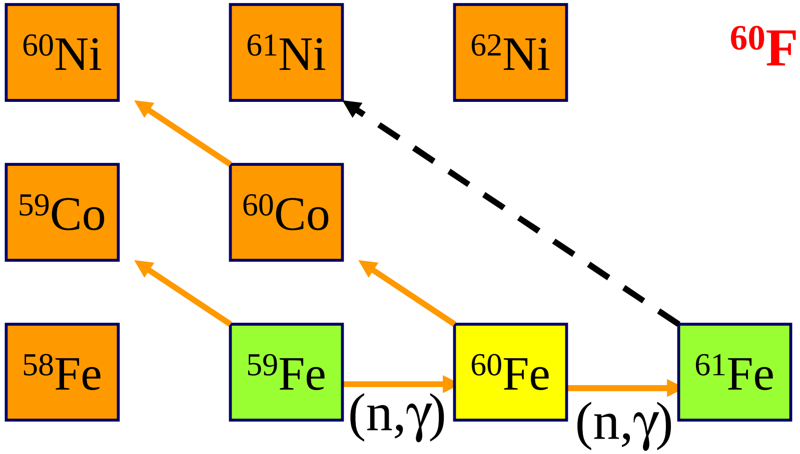
Brune et al. (2006) → 170±52 keV-b ; NACRE (1999)→ 224 ±97 keV-b
Kunz et al. (2001) → 186±66 keV-b, …

Orsay & Brune's et al. results → fixed γ_{α}^{2} for the 6.92 and 7.12 MeV sub-threshold states

T.A.Weaver & S. E. Woosley (1993) calculations → **170±50 keV-b**
From the comparison of solar abundances of elements
16≤ A ≤32 with nucleosynthesis calculations in massive stars of 12 to 40 $M_{\odot}$

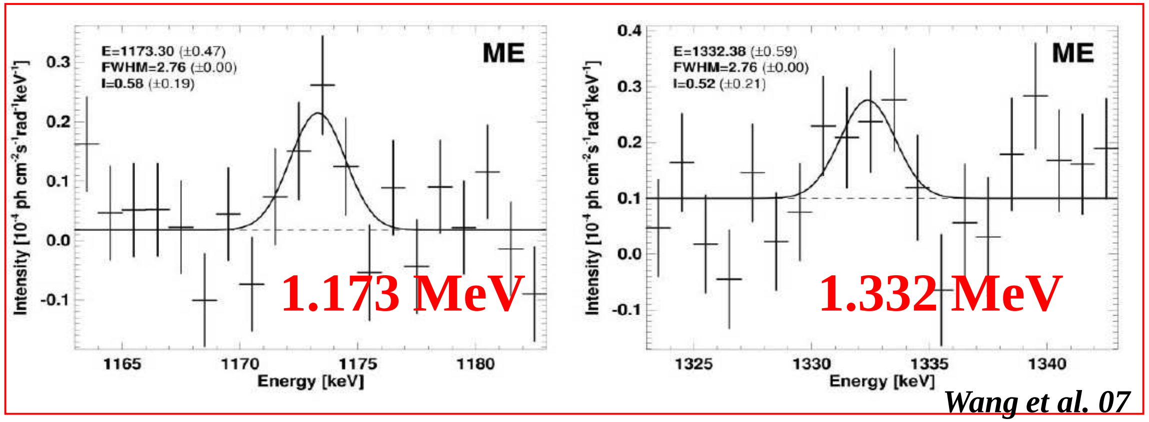
N. Oulebsir, F. Hammache et al. submitted to PRC

Case of (n,γ) capture: Indirect study of the astrophysical reaction **^{60}Fe(n,γ)^{61}Fe** via the transfer reaction **d(^{60}Fe,p)^{61}Fe**



^{60}Fe (T$_{1/2}$=2.6 10^{6} yr)

Detection of ^{60}Fe
by
RHESSI & INTEGRAL ➡

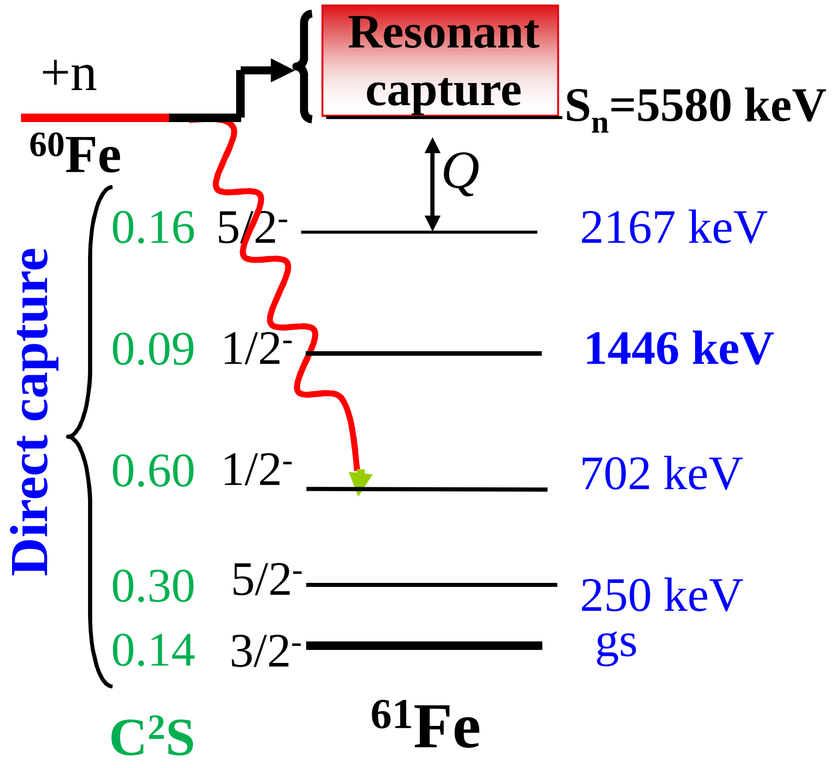


Wang et al. 07

Production of **^{60}Fe** in core-collapse supernovae type II depends strongly on the uncertain ^{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)



+n

^{60}Fe

Resonant capture

S_n=5580 keV

Q

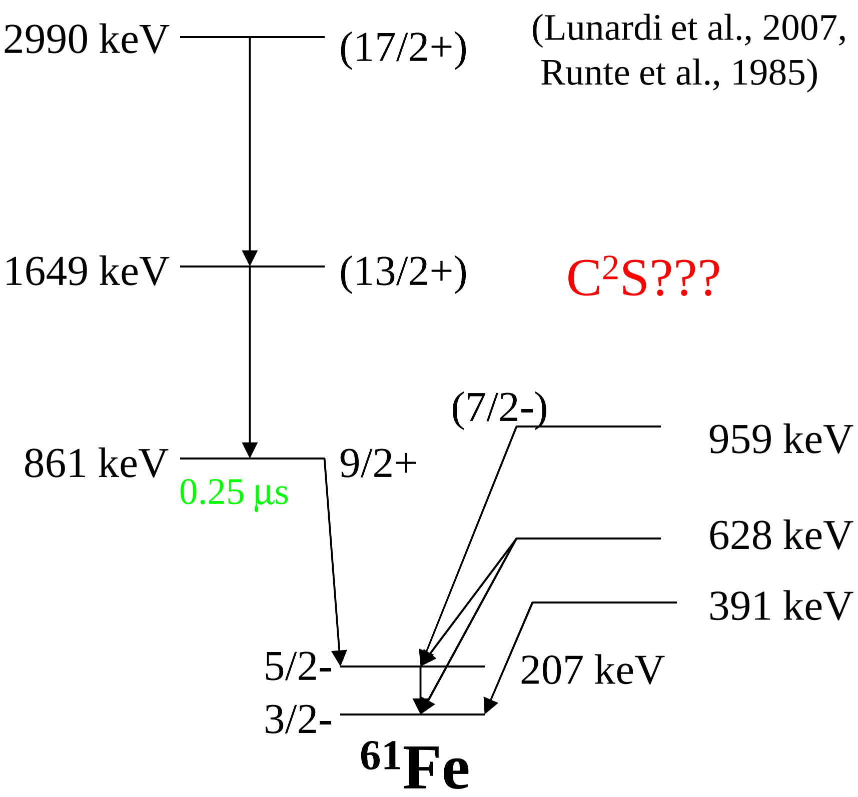
Direct capture

C²S			
0.16	5/2⁻	2167 keV	
0.09	1/2⁻	**1446 keV**	
0.60	1/2⁻	702 keV	
0.30	5/2⁻	250 keV	
0.14	3/2⁻	gs	

^{61}Fe

Monte Carlo Shell Model calculations
G. Martinez-Pinedo

Experiments



2990 keV (17/2+)

(Lunardi et al., 2007, Runte et al., 1985)

1649 keV (13/2+)

C²S???

861 keV 9/2+

0.25 μs

(7/2-) 959 keV

628 keV

391 keV

5/2- 207 keV

3/2-

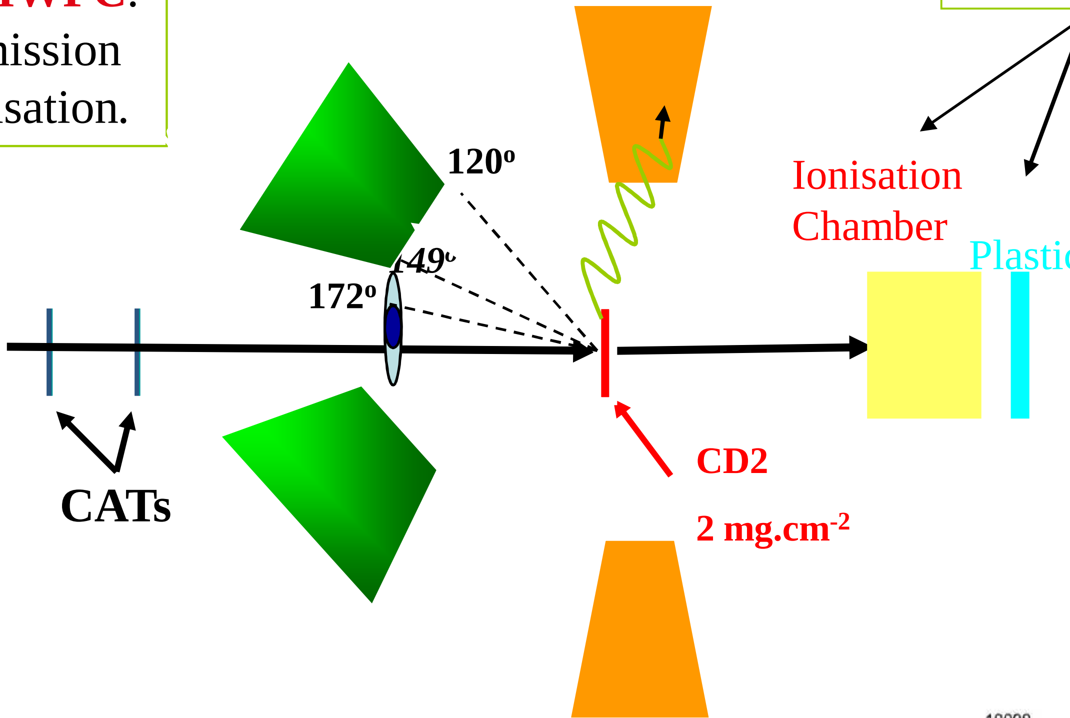
^{61}Fe

Direct $\sigma_{60Fe(n,\gamma)61Fe}$ → E_x, l & C²S of ^{61}F → (d,p) transfer reaction

Note: Recent ^{60}Fe(n,γ)^{61}Fe activation measurement (Uberseder et al, 2009)

d(^{60}Fe,pγ)^{61}Fe experiment

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



4 EXOGAM clovers
γ detection

Identification detectors (ToF, dE)

Ionisation Chamber

Plastic

^{60}Fe
@ 27A.MeV
10^5 pps
GANIL/LISE

CATs

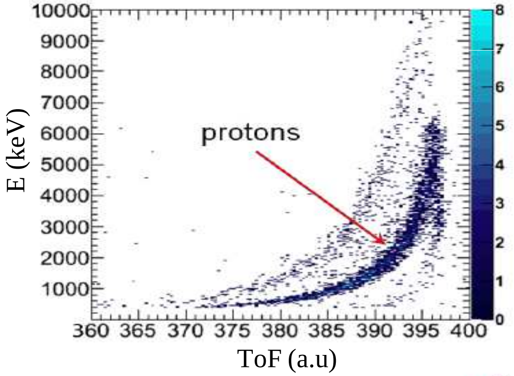
120º

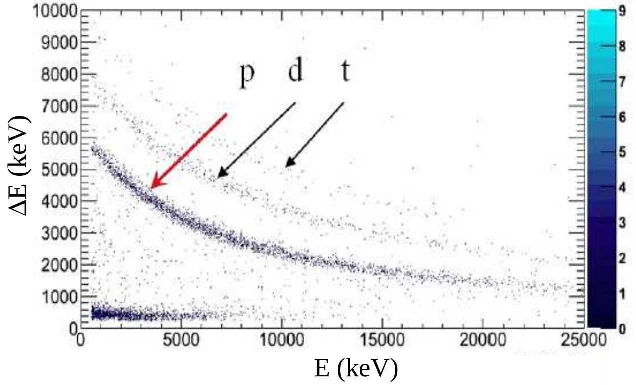
149º

172º

CD2

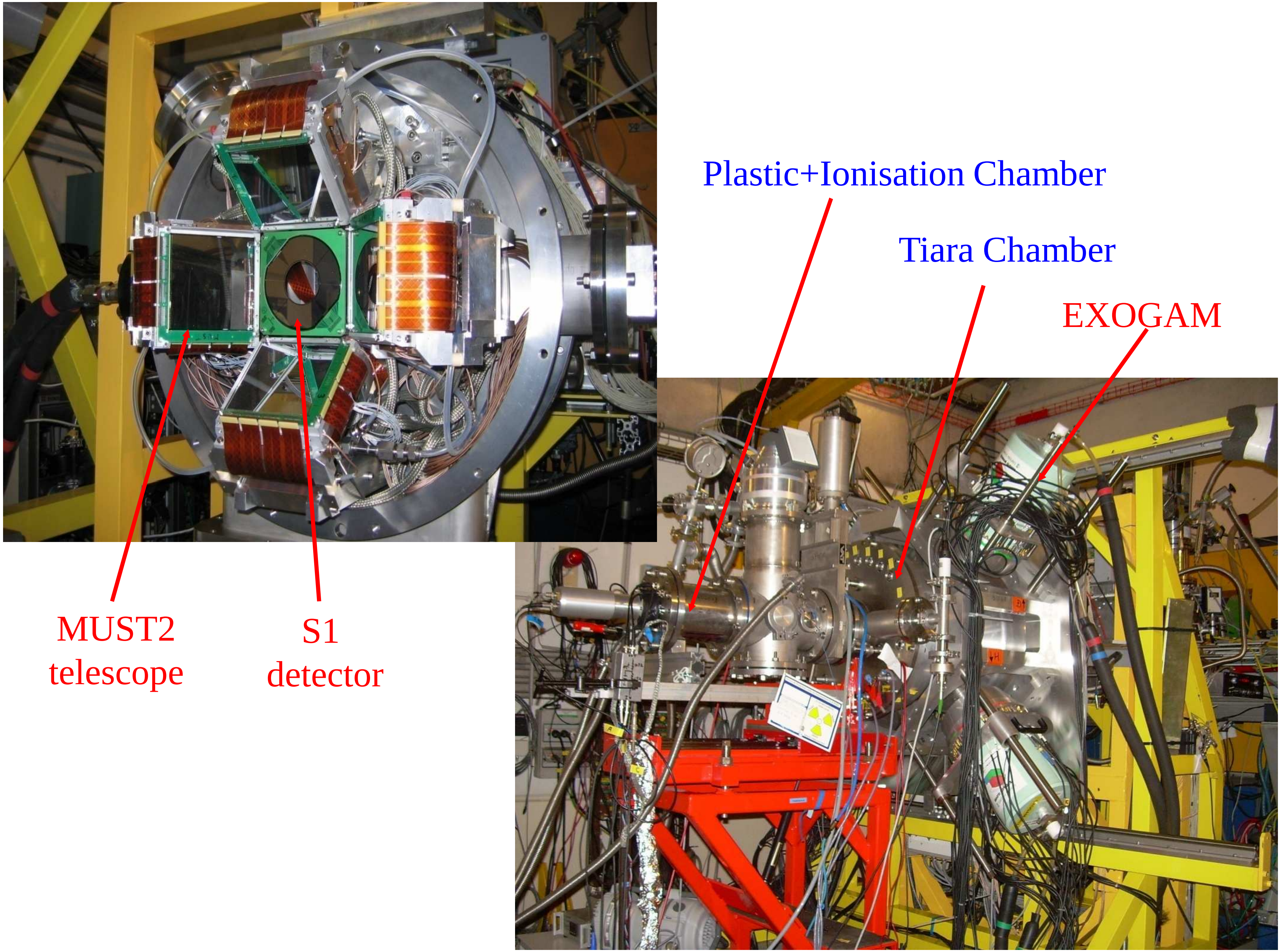
2 mg.cm^{-2}





MUST2 : -**Si Strip** **(300µm)** + **SiLi** (4.5 mm) detectors.
-Proton **impact localisation.**
- Proton **energy** measurement. (~ 35 keV resolution for ^{241}Am α-source)

S1: Si annular detector (500 µm, 64 strips in Θ and 16 in Φ)
(~ 50 keV resolution for ^{241}Am α-source)



Plastic+Ionisation Chamber

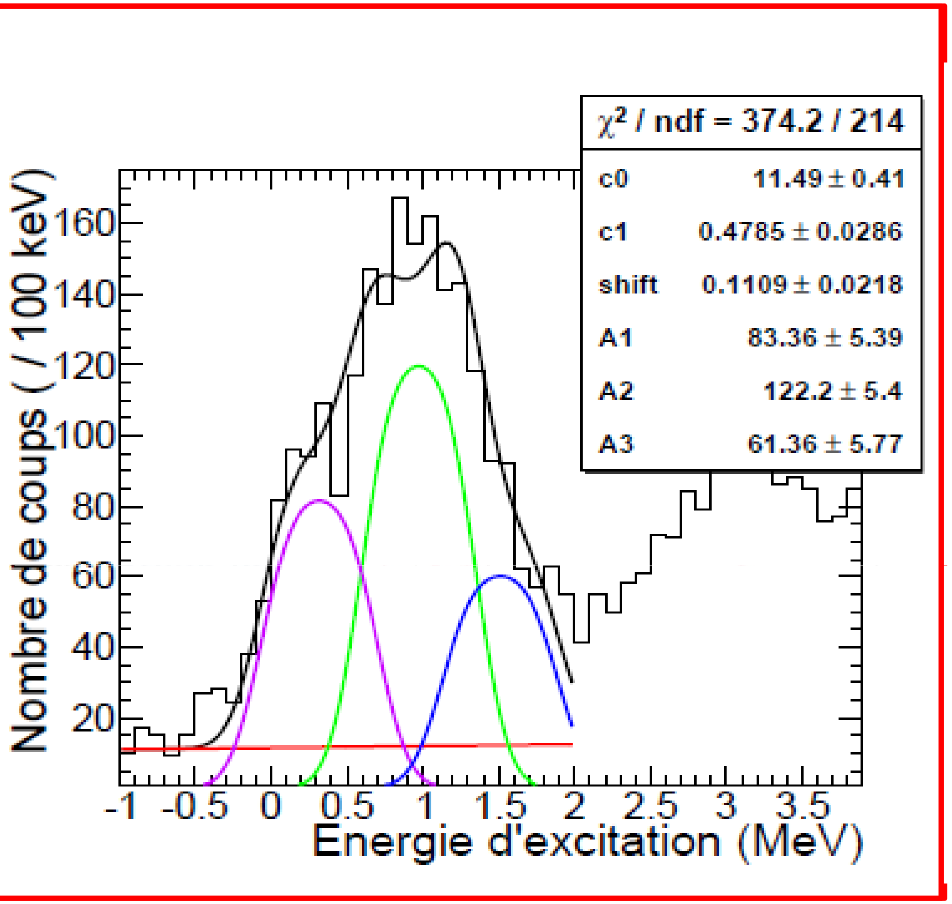
Tiara Chamber

EXOGAM

MUST2
telescope

S1
detector

^{61}Fe Excitation energy spectrum

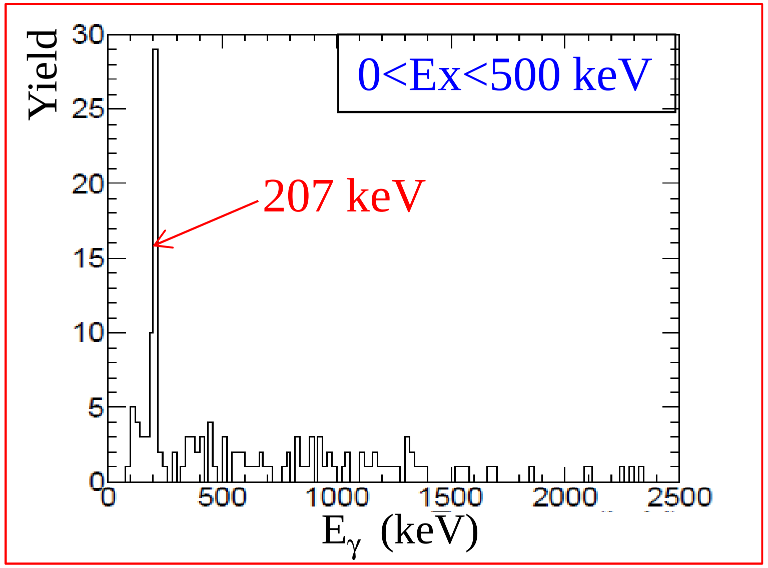


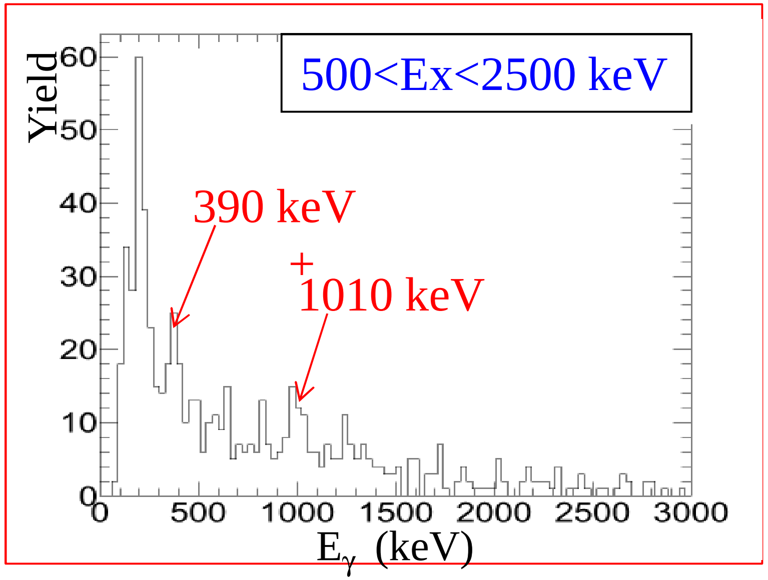
→Population of 207, 861 & 1400 keV states of ^{61}Fe in the 1st peak
→Difficulties to identify the states in the 2nd peak. Eγ>1400 keV → efficiency ↘

S. Giron PhD thesis

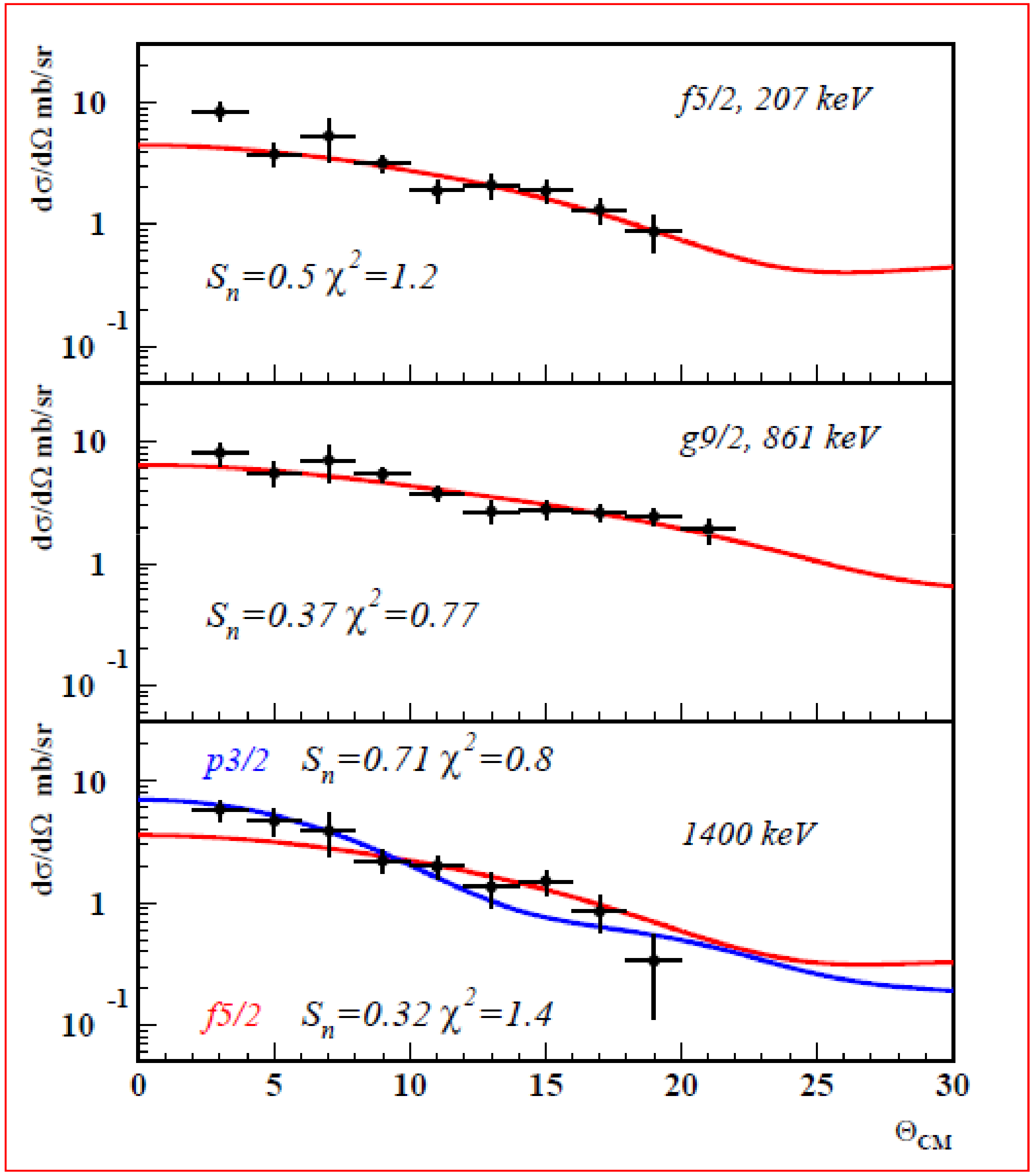
Gamma-ray spectra

Discrimination of the ≠ populated states





Preliminary results: Measurements & DWBA calculations



→ Zero range DWBA calculation

- (V_1, r_1, a_1) of the entrance chanel:

→ Adiabatic approximation to take into account the deuteron breakup

G.L.Wales and R.C. Johnson (1976)

- (V_2, r_2, a_2) of the exit chanel:

→Varner's et al. global nucleon optical model potential

Varner et al. (1991)

S_n =0.50±0.15 (f5/2 207 keV)
S_n =0.37±0.11 (g9/2 861 keV)
S_n =0.71±0.21 (2p3/2 1400 keV)

Analysis still in progress

Conclusions on transfer reactions

- Can be used to extract partial widths, spins and resonance energies involved in resonant reaction rates

- Can be used to extract excitation energies, spins and spectroscopic factors involved in direct capture reaction rates

- A reliable DWBA analysis needs elastic scattering measurements in the entrance and exit channel

- Sensitivity of the spectroscopic factors to the potential parameters

- The accuracy on the extraction of the spectroscopic factor can not ne better 30 %

References on transfer reactions

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