Understanding elemental anomalies in Globular Clusters: Experimental study of the $^{30}Si(p,\gamma)^{31}P$ reaction

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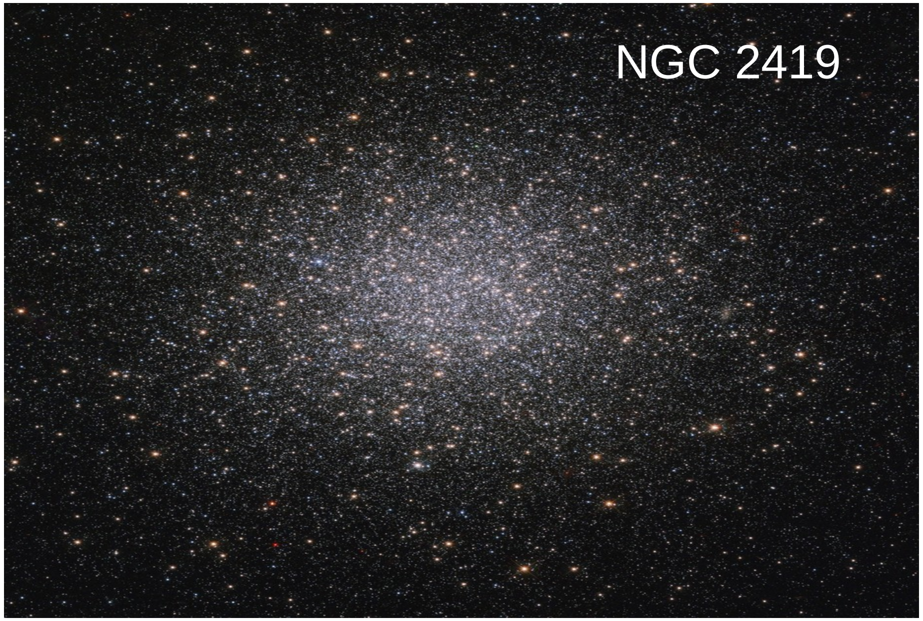
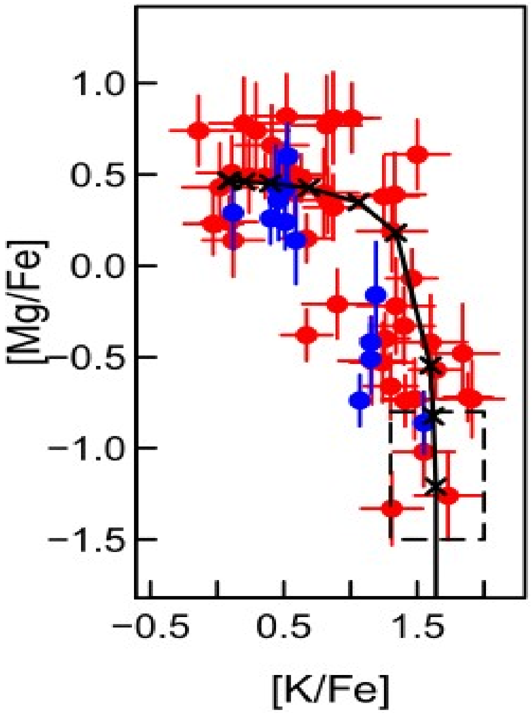
Globular Clusters

- Dense collection of stars (10^5-10^7) orbiting around the center of the Galaxy.
- Independent probes of the age and early chemical history of the Universe.
- Previleged sites for understanding stellar formation. Paradigm: unique stellar population (generation)



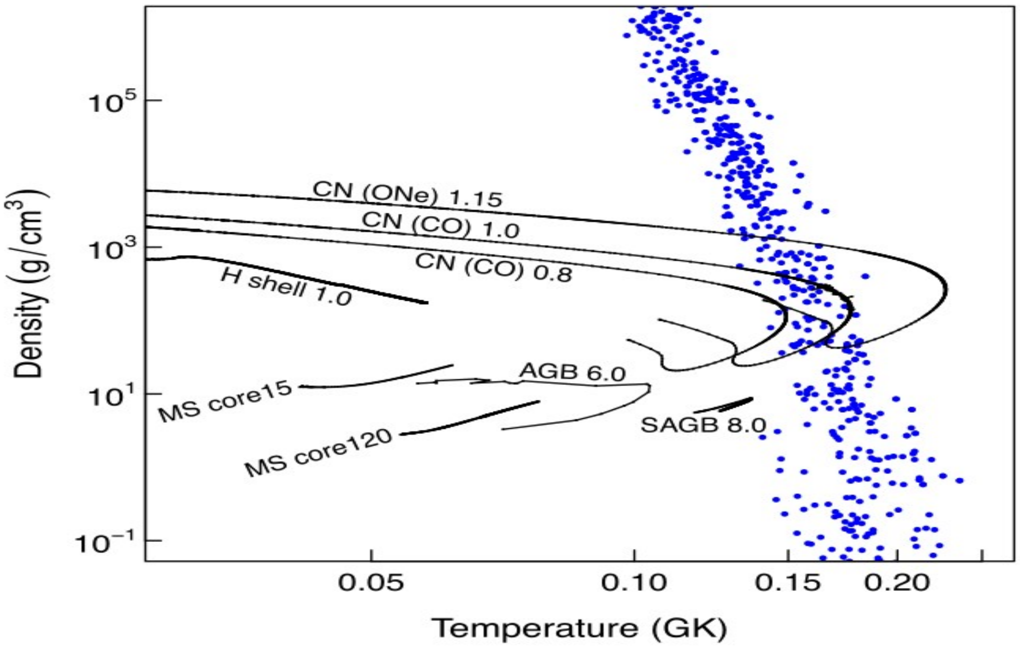


Iliadis *et al.* 2016

Observation : anticorrelation between pairs of chemical species, inconsitent with the current temperature of the stars → Shift in the paradigm: Globular clusters may have host **different generations of stars**.

What are the types of stars that were the site of nuclear reactions that engendred these anticorrelations → Polluter candidates ?

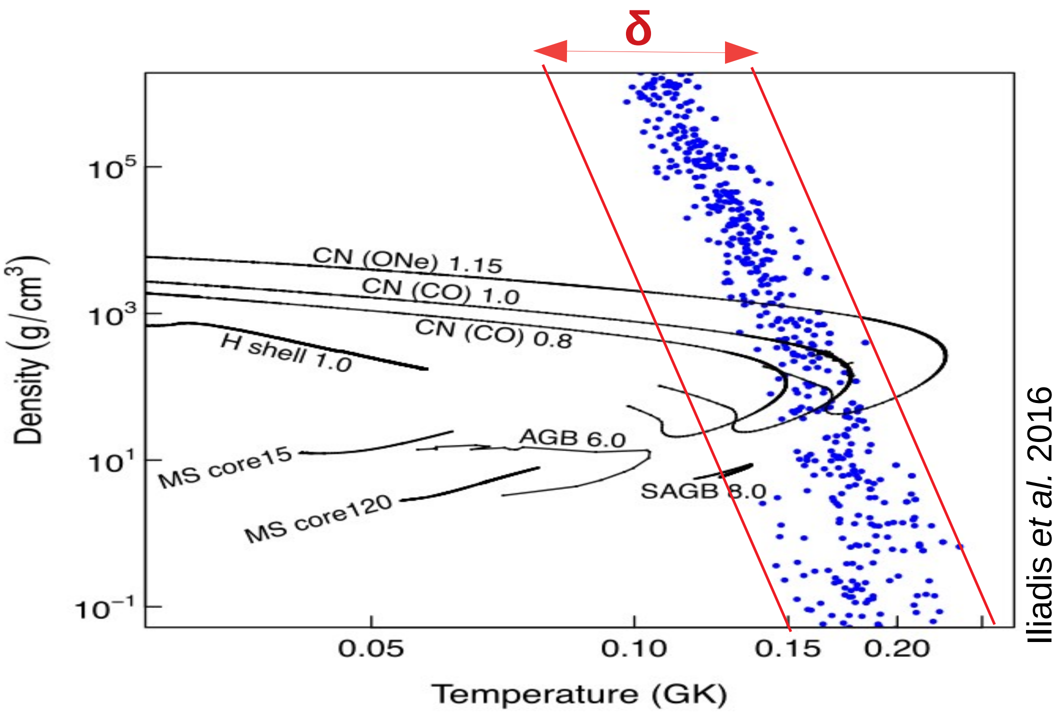
Reactions of interest



Iliadis *et al.* 2016

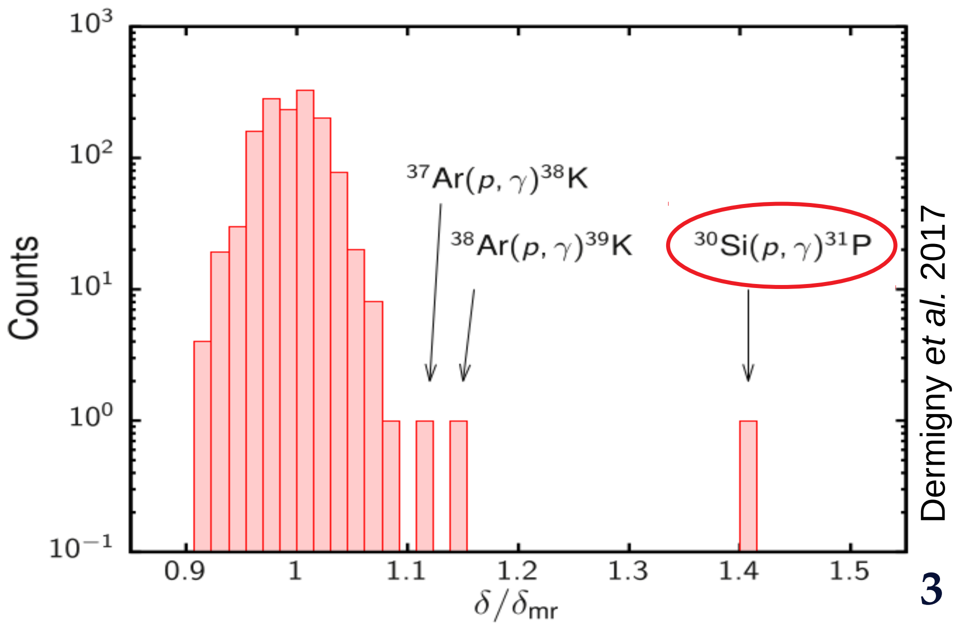
- Each (T, ρ) point reproduces the observed abundances in Globular Clusters.
- The abundances are estimated by simulating a network of nuclear reactions occuring at a given (T, ρ) set.
- Conditions corresponding to Hydrogen burning stage.

Reactions of interest



- Each (T, ρ) point reproduces the observed abundances in Globular Clusters.
- The abundances are estimated by simulating a network of nuclear reactions occuring at a given (T, ρ) set.
- Conditions corresponding to Hydrogen burning stage.

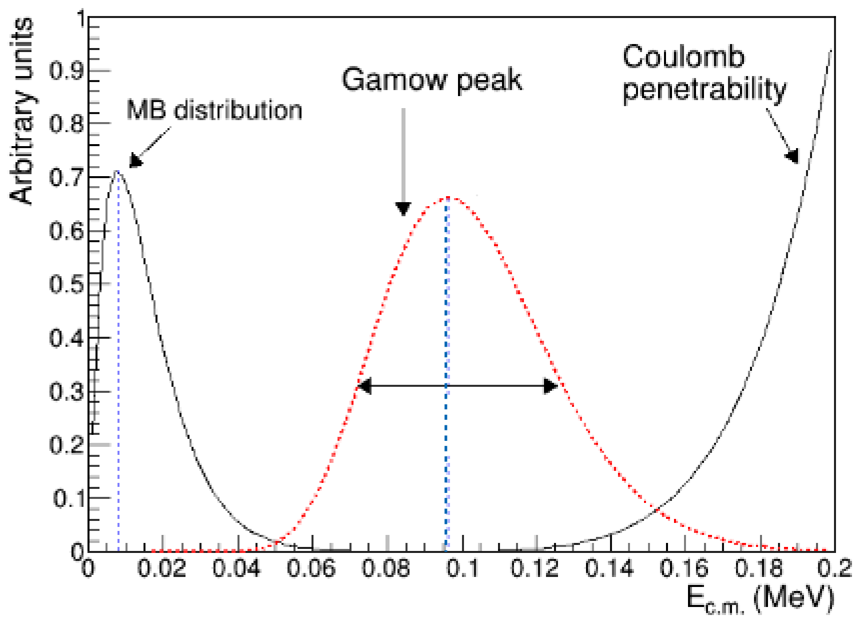
- Impact of the reactions and their uncertainty is identified with a Monte Carlo sensitivity study.
- Si reaction contributes the most to the spread of the (T, ρ) locus.

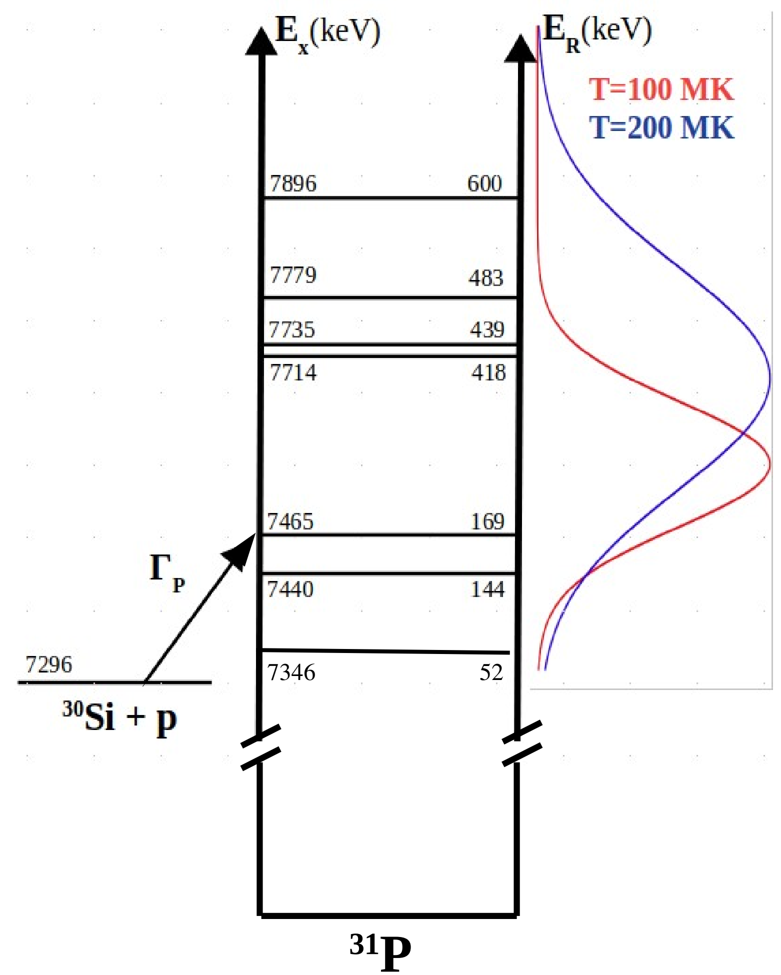


Thermonuclear reaction rate

The thermonuclear reaction rate is defined as :

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





Narrow resonances $\langle \sigma v \rangle \propto \sum_i \omega\gamma_i\, e^{\frac{-E_{Ri}}{kT}}$

Resonance strength $\omega\gamma = \frac{2J_R+1}{(2J_p+1)(2J_{30Si}+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$

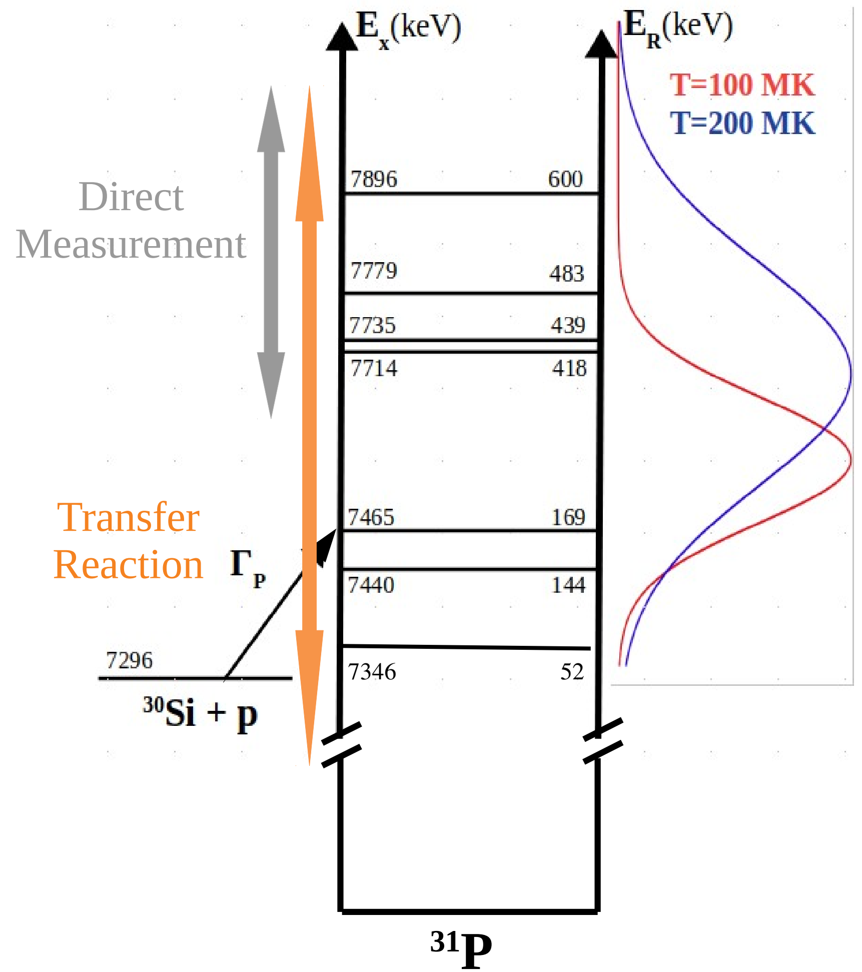
In our case $\begin{cases} \Gamma = \Gamma_p + \Gamma_\gamma \\ \Gamma_p \ll \Gamma_\gamma \end{cases} \Longrightarrow \omega\gamma \propto \Gamma_p$

State of the art for $^{30}Si(p,\gamma)^{31}P$ reaction

Several measurements performed for E_r > 600 keV
Last one published by **Dermigny *et al*. 2020**, resonance strengths measured through gamma spectroscopy.

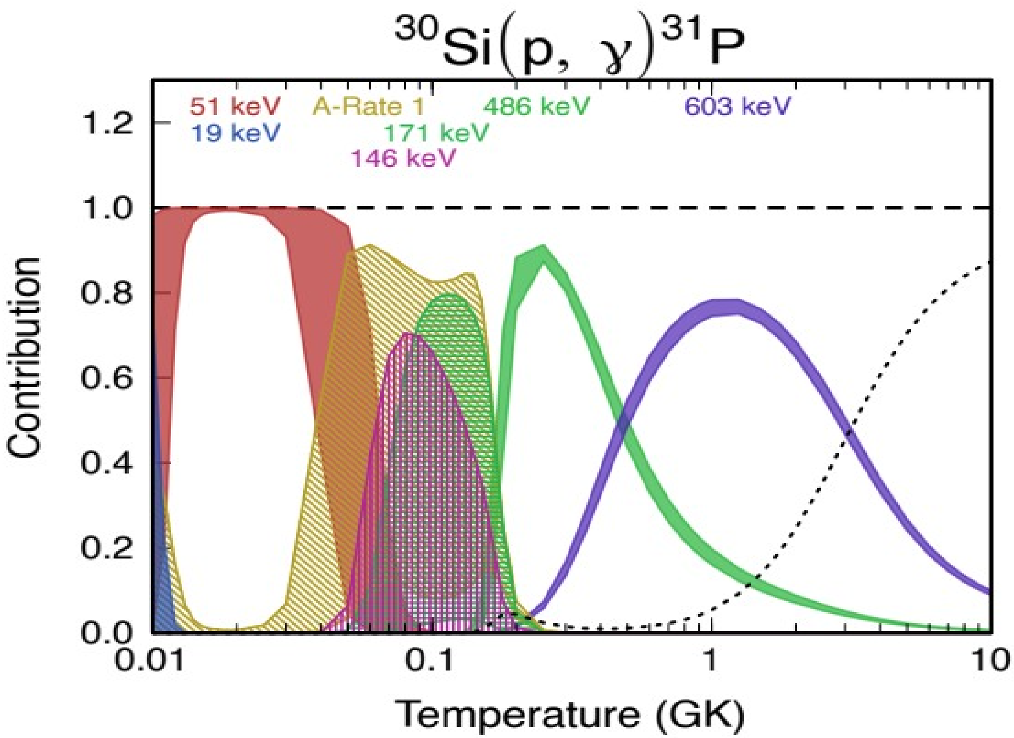
Experiment performed by **J.Vernotte in 1990** at Orsay's SplitPole: $^{30}Si(^{3}He,d)^{31}P$

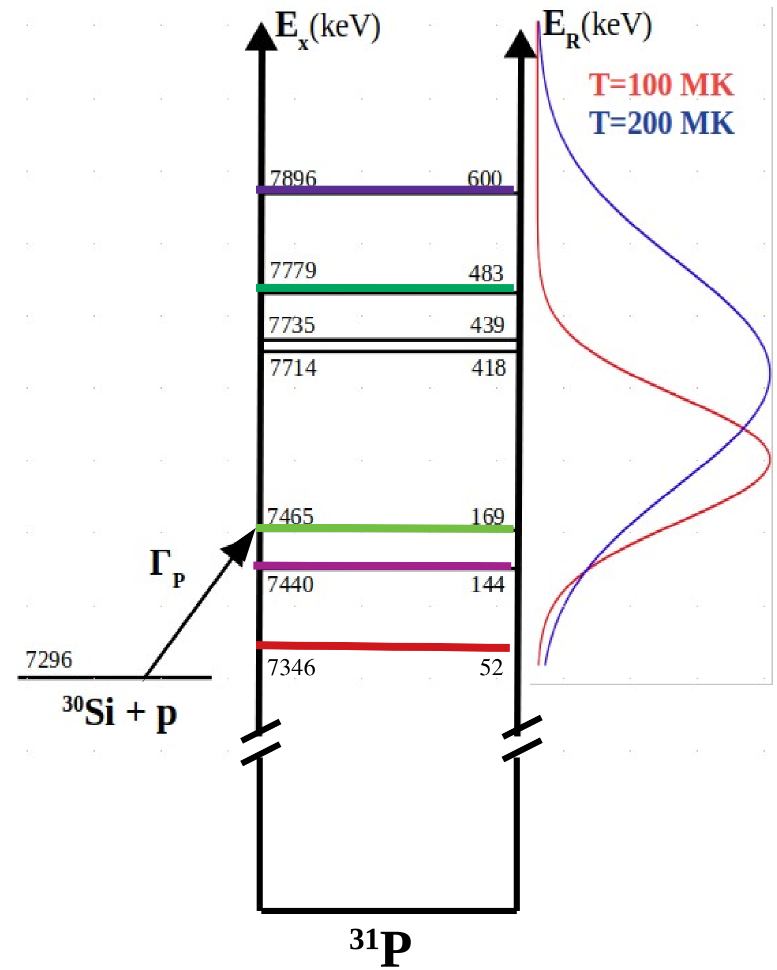
- No astrophysical motivations: did not observe the states at 7.440 and 7.465 MeV.
- The resolution did not allow the separation of the 7.714 - 7.735 MeV doublet.



State of the art for $^{30}Si(p,\gamma)^{31}P$ reaction

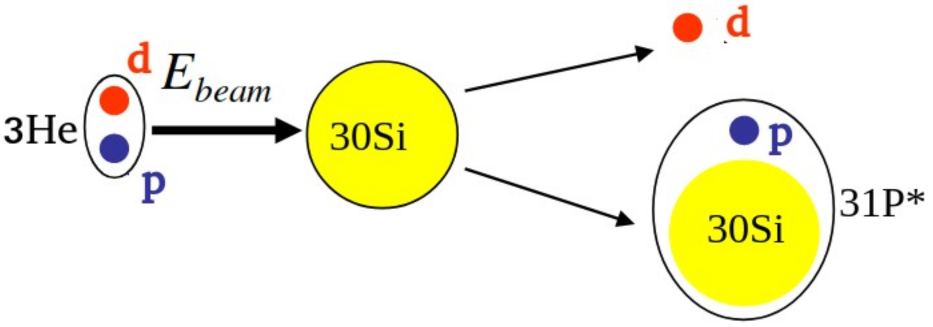
Dermigny *et al.* 2020





Transfer Reaction

Compare the experimental angular distribution to the one obtained from a model describing the direct transfer process:



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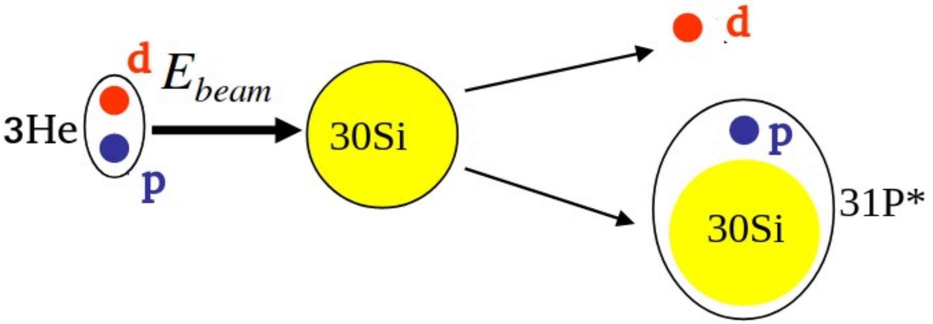


Compare the experimental angular distribution to the one obtained from a model describing the direct transfer process:

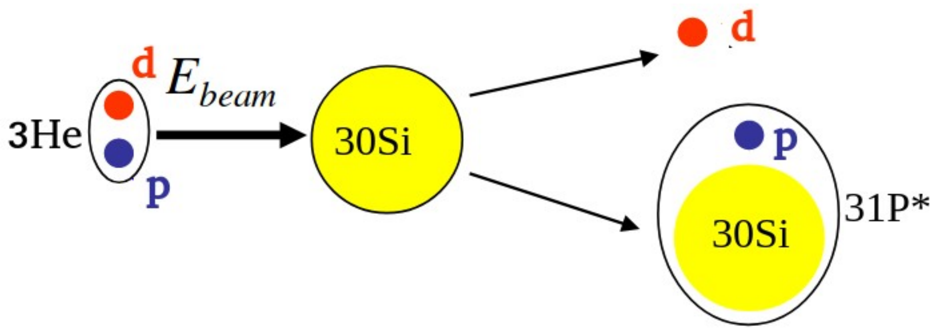
- Normalisation:

$$\frac{d\sigma}{d\Omega}(\theta)_{\exp} = C^2 S_{lj} \frac{d\sigma}{d\Omega}(\theta)_{DWBA}$$

$$\Gamma_p = C^2 S_{lj} \Gamma_p^{single\ particle}(E_r, l)$$

- Shape of the distribution → transferred angular orbital momentum l

Transfer Reaction



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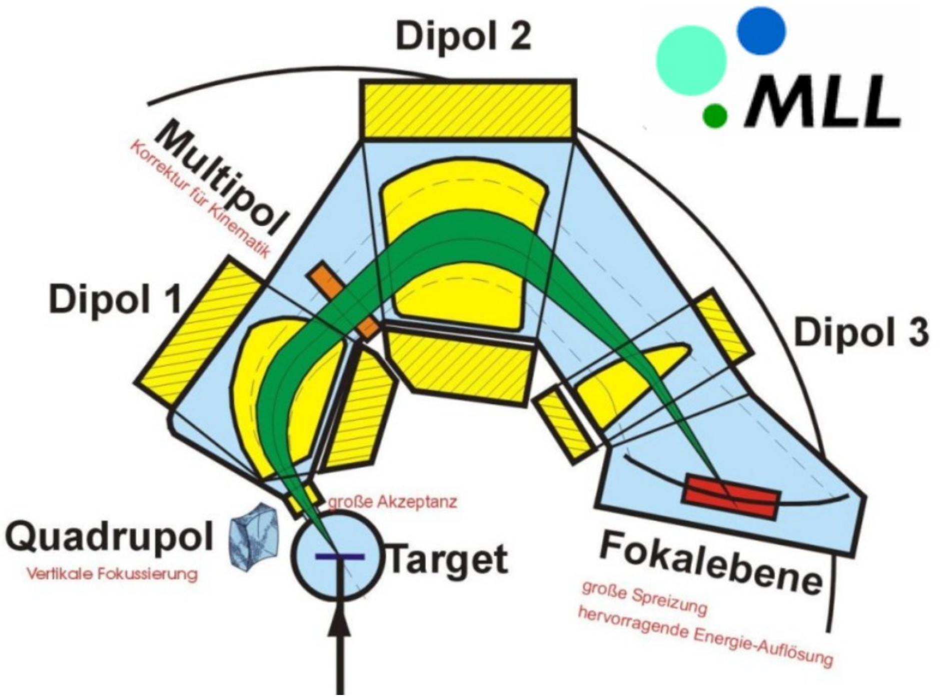
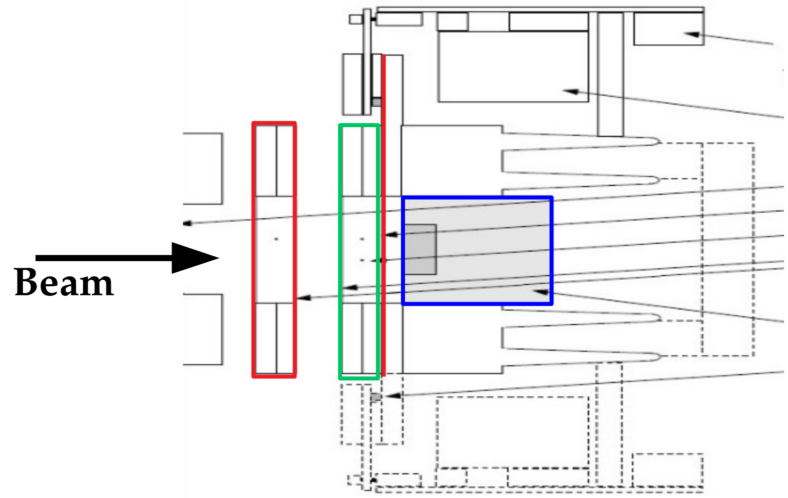
Distorted Wave Born Approximation :

- Entrance and exit channels are dominated by elastic scattering.
- The transfer of the nucleon is a first order perturbation.
- No configuration rearrangement in the composite nucleus.

Main ingredients: optical potentials describing elastic channels.

Q3D experiment





Focal plan detectors :

- Gaz detector & strips → position on the focal plane.
- Ionisation chamber → energy loss.
- Plastic scintillator → residual energy.

- Beam ^{3}He : $E = 25\, MeV$
  $I = 200\, nAe$
- Targets: $^{30}SiO_2$ (40 µg/cm²) enriched at 95% on ^{nat}C
  $^{nat}SiO_2$ (20 µg/cm²) on ^{nat}C
- Solid Angle : $4 - 12\, msr$
- Energy resolution $\Delta E/E \sim 2.10^{-4}$

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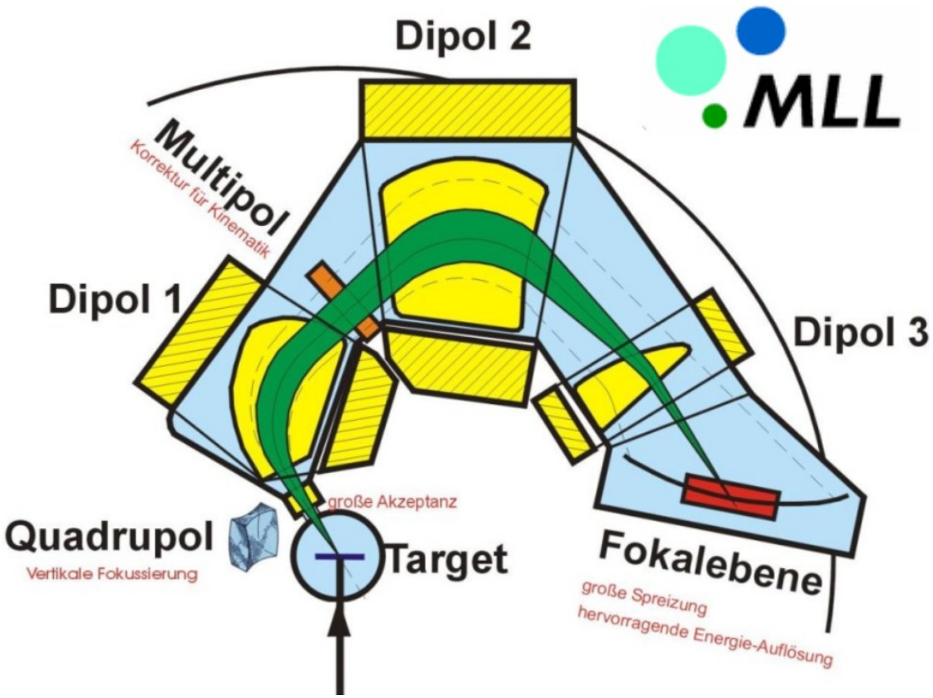

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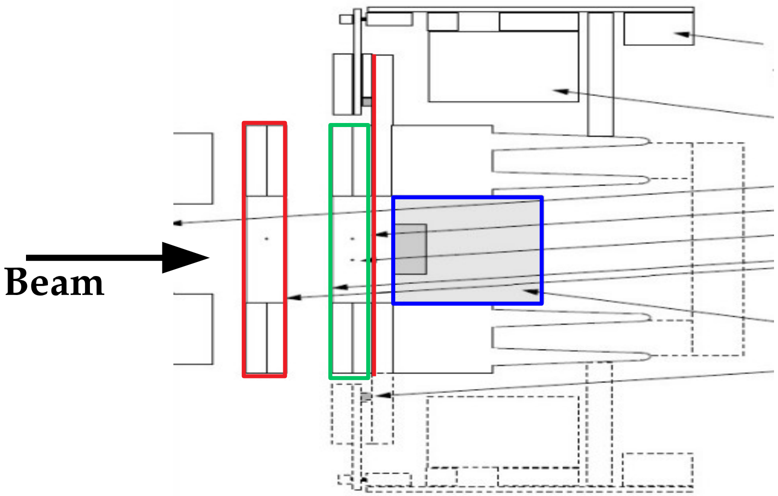

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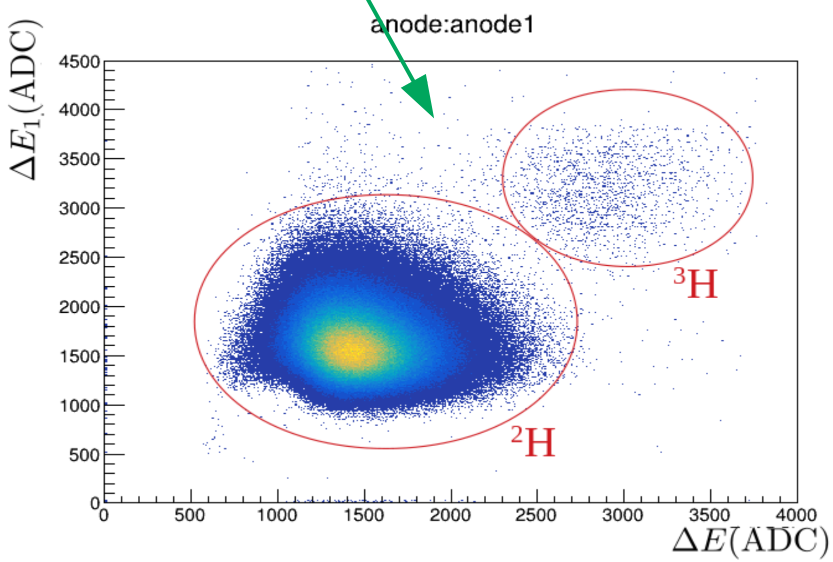
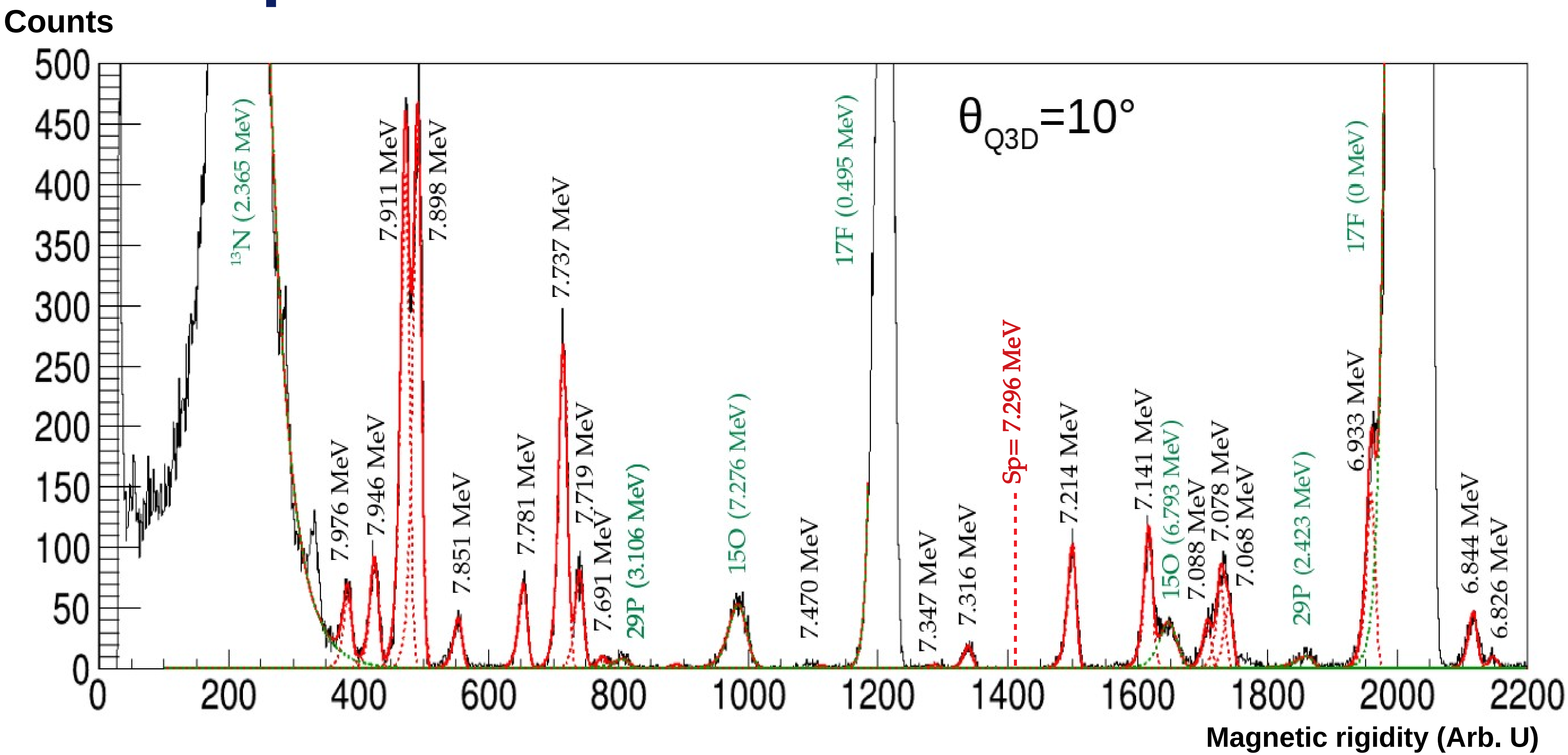


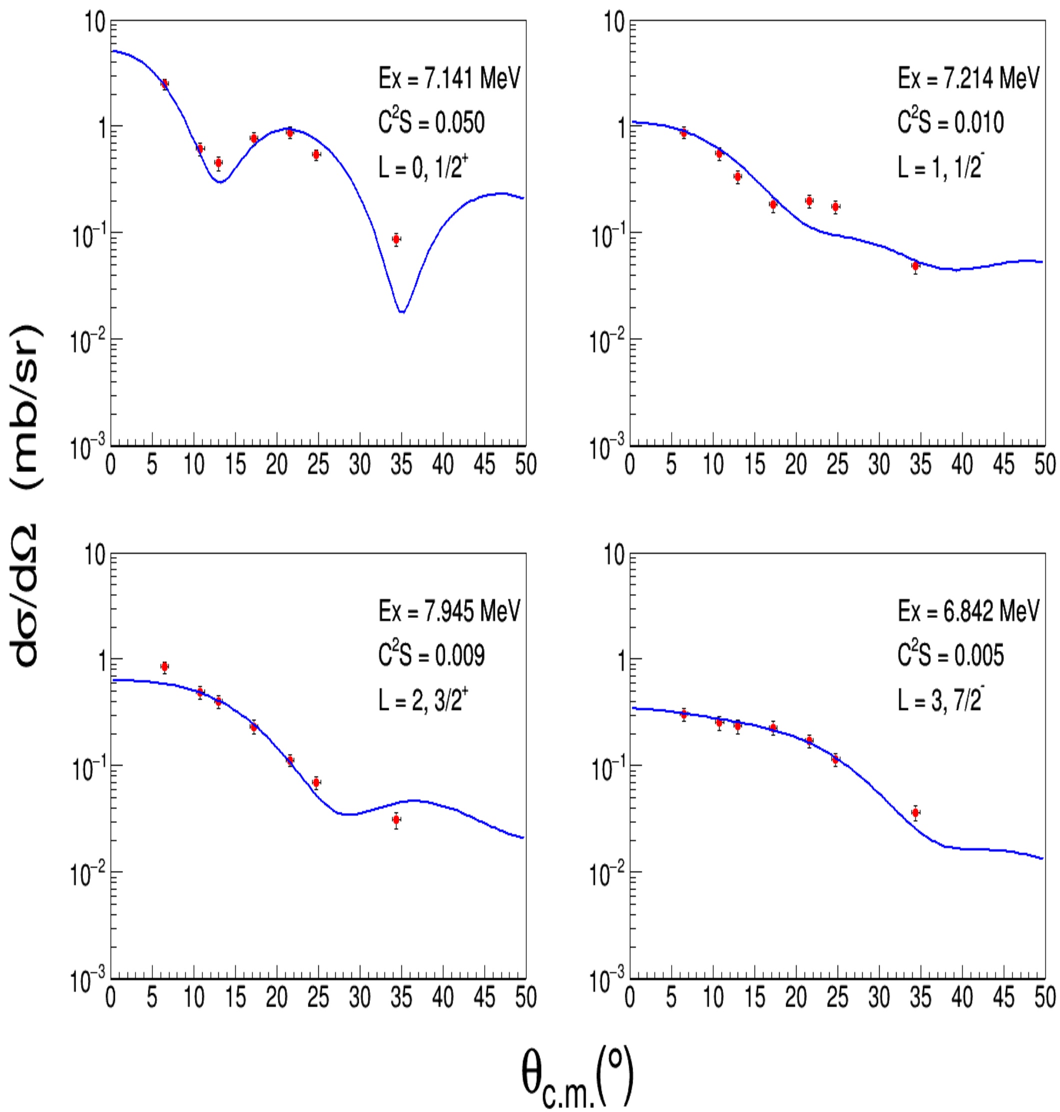
Spectrum



- Spectra for 7 lab angles : 6°, 10°, 12°, 16°, 20°, 23°, 32°
- Experimental resolution FWHM ~ **7 keV**
  Vernotte (1990) ~25 keV

- **Doublet at 7719 - 7737 keV separated**
- **Level at 7470 keV observed.**
- **Indications about the 7440 keV level.**

Angular distributions



Differential cross section

$$\frac{d\sigma}{d\Omega}(\theta)_{\exp} = \frac{N_{counts}}{N_{beam} \cdot N_{target} \cdot \Delta\Omega} = C^2 S_{lj} \frac{d\sigma}{d\Omega}(\theta)_{DWBA}$$

Finite-Range DWBA calculations performed with **FRESCO code.**

Once the spectroscopic factor is estimated from the transfer reaction, we can compute:

- the proton width: $\Gamma_p = C^2 S_{lj} \Gamma_p^{single\ particle}(E_r, l)$
- the resonances strengths:

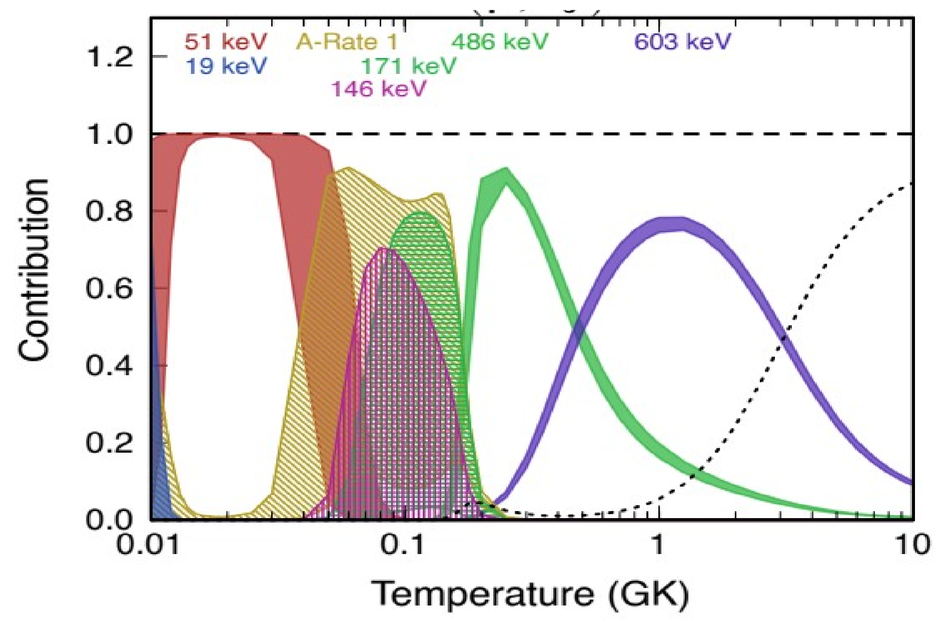
$$\omega\gamma = \frac{2J_R+1}{(2J_p+1)(2J_{30Si}+1)}\Gamma_p$$

- Uncertainties ~ 30% (optical potentials)

Results

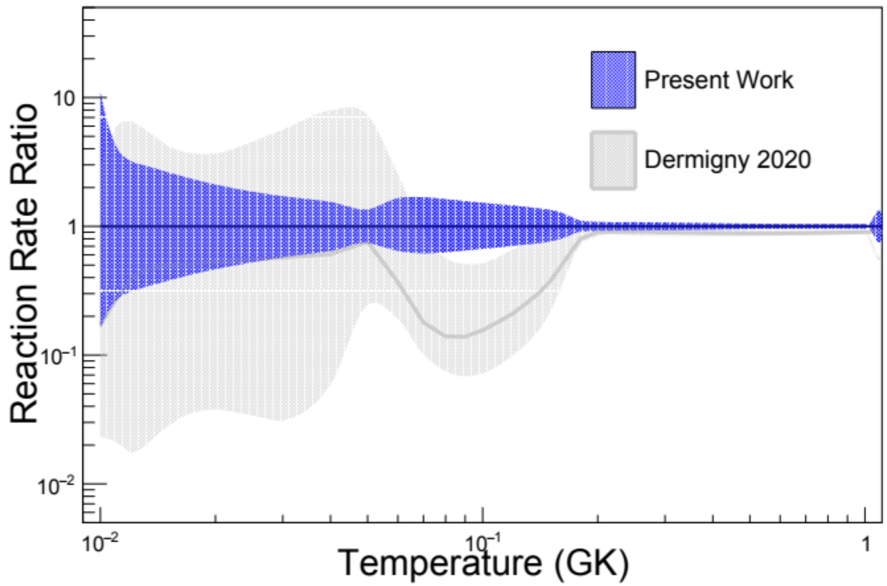
- Doublet separation → strong constraints on the spin of low component (E_r = 418 keV, l=3).
- Good agreement for strength values (within 50%) with direct measurements (E_r = 486 keV)

Dermigny *et al.* 2020

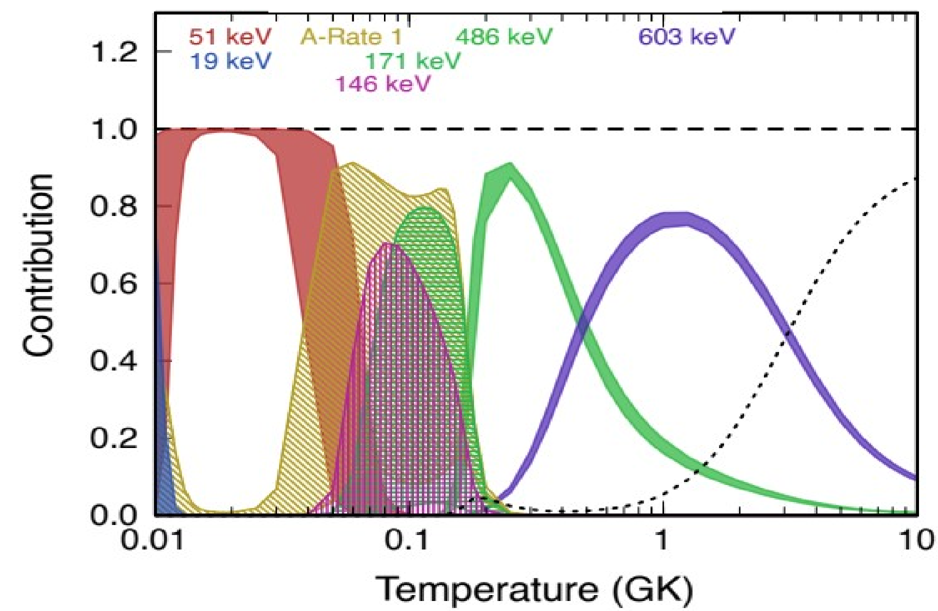


Results

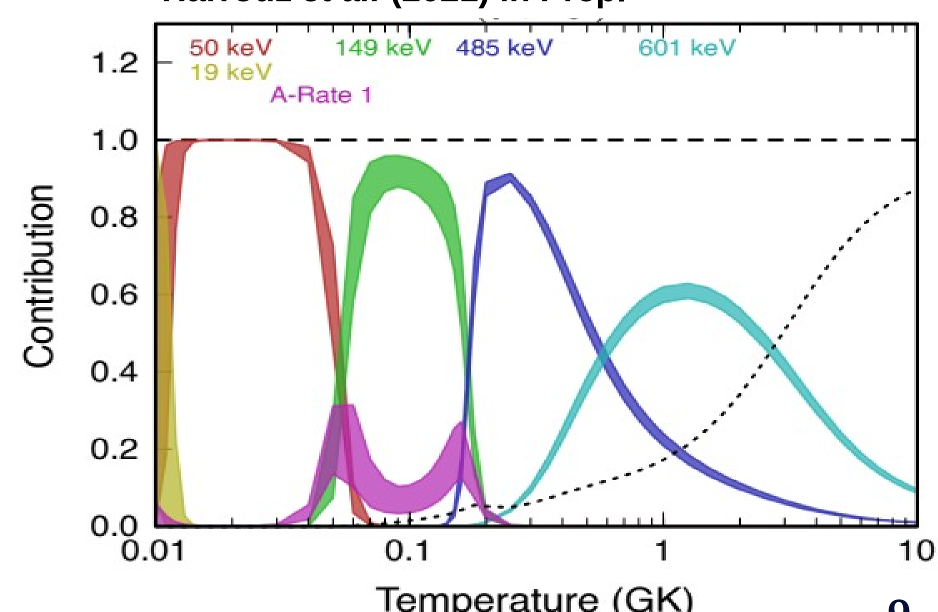
- Doublet separation → strong constraints on the spin of low component (E_r = 418 keV, l=3).
- Good agreement for strength values (within 50%) with direct measurements (E_r = 485 keV)
- Positive measurement of low energy resonances that were considered upper limits previously (E_r = 19 keV, E_r = 51 keV and E_r = 170 keV)
- Observation of the E_r = 149 keV which is a key resonance in the temprature range of interest (spin have to be better constrained).



Dermigny *et al.* 2020



Harrouz *et al.* (2021) in Prep.



Conclusions

- Extraction of spectroscopic information for the ^{31}P nucleus between E_x = 6800 – 8100 keV.
- Calculation of strengths for resonances up to E_r = 600 keV.
- Improved determination of the $^{30}Si(p,\gamma)^{31}P$ reaction rate.

Conclusions

- Extraction of spectroscopic information for the ^{31}P nucleus between E_x = 6800 – 8100 keV.
- Calculation of strengths for resonances up to E_r = 600 keV.
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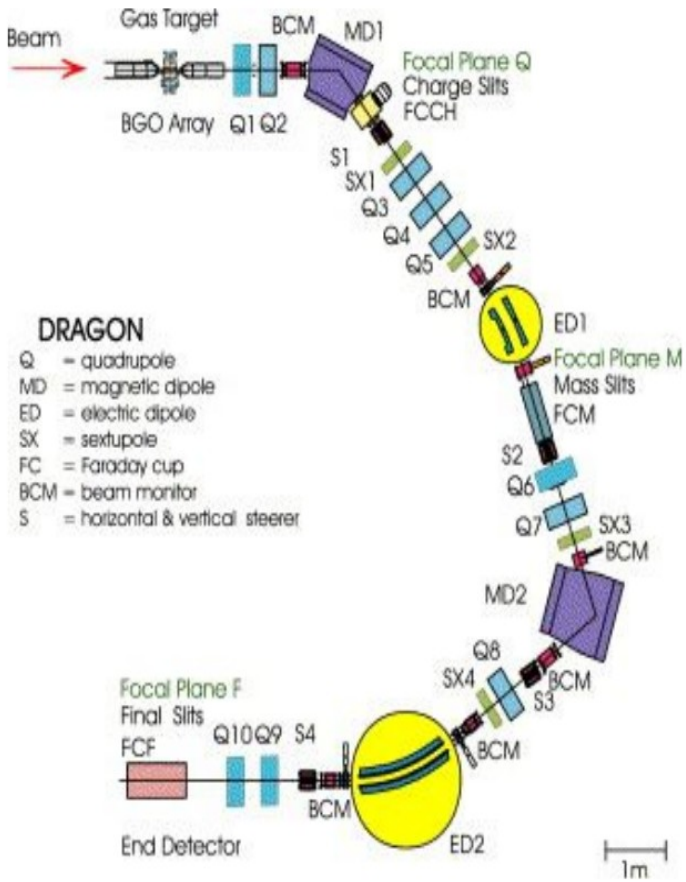
Perspectives

- Perform direct measurement of ^{30}Si(p,γ)^{31}P reaction rate with the Recoil spectrometer DRAGON (experiment rescheduled next August)
- Participation in the analysis of ^{39}K(p,γ)^{40}Ca reaction for the same research program concerning Globular Clusters.
- Impact of the new measurements on the temperature locus for constraining "the polluter" candidates.



Thank you for your attention

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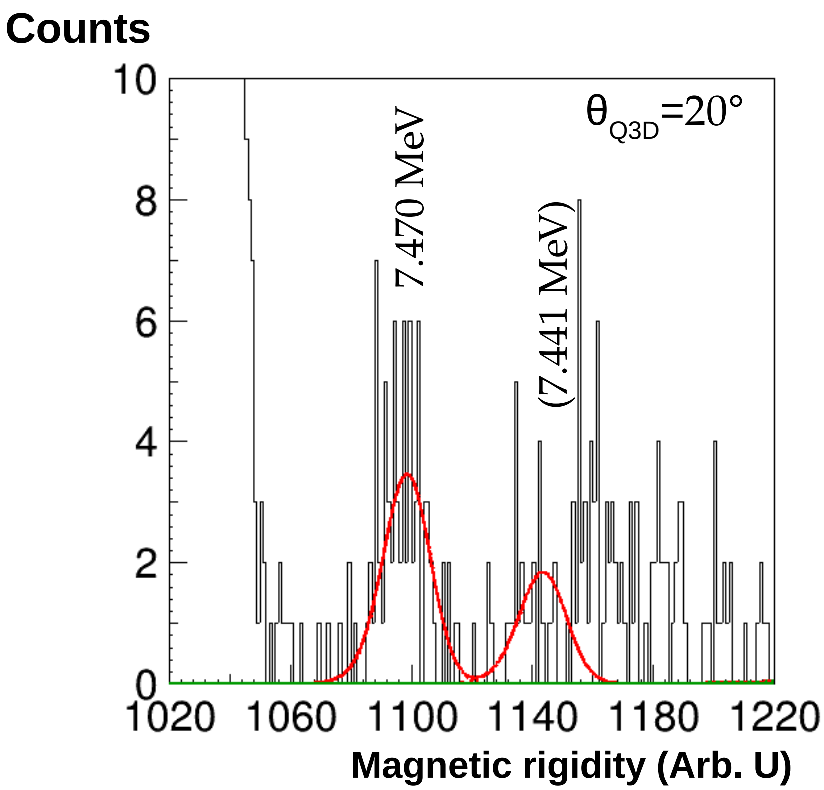
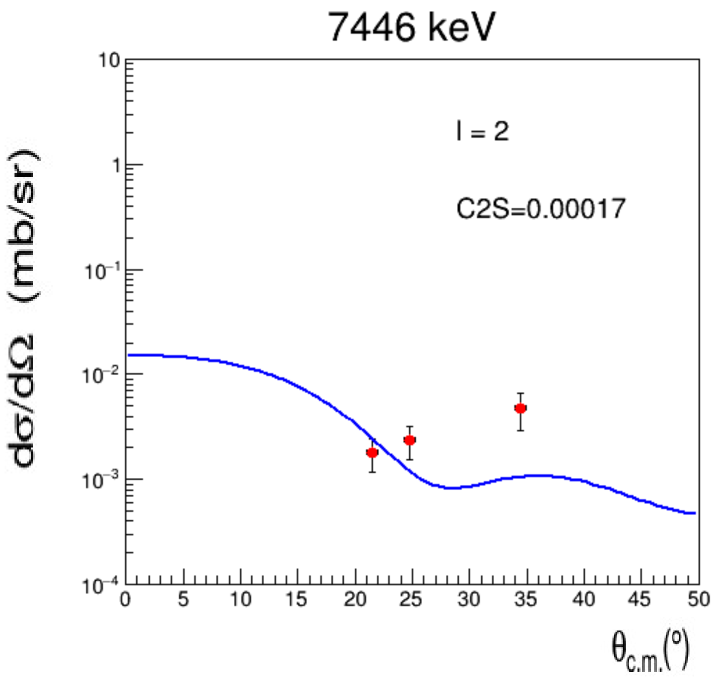
Aurora Tumino (LNS)
Hans-Friedrich Wirth (TUM)

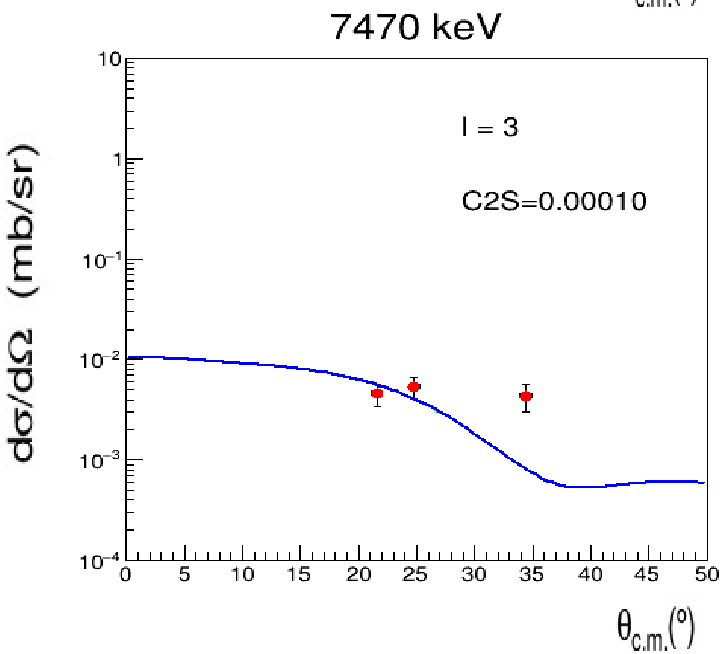
Back-up



Counts
θ_{Q3D}=20°
7.470 MeV
(7.441 MeV)
0
2
4
6
8
10
1020
1060
1100
1140
1180
1220
Magnetic rigidity (Arb. U)

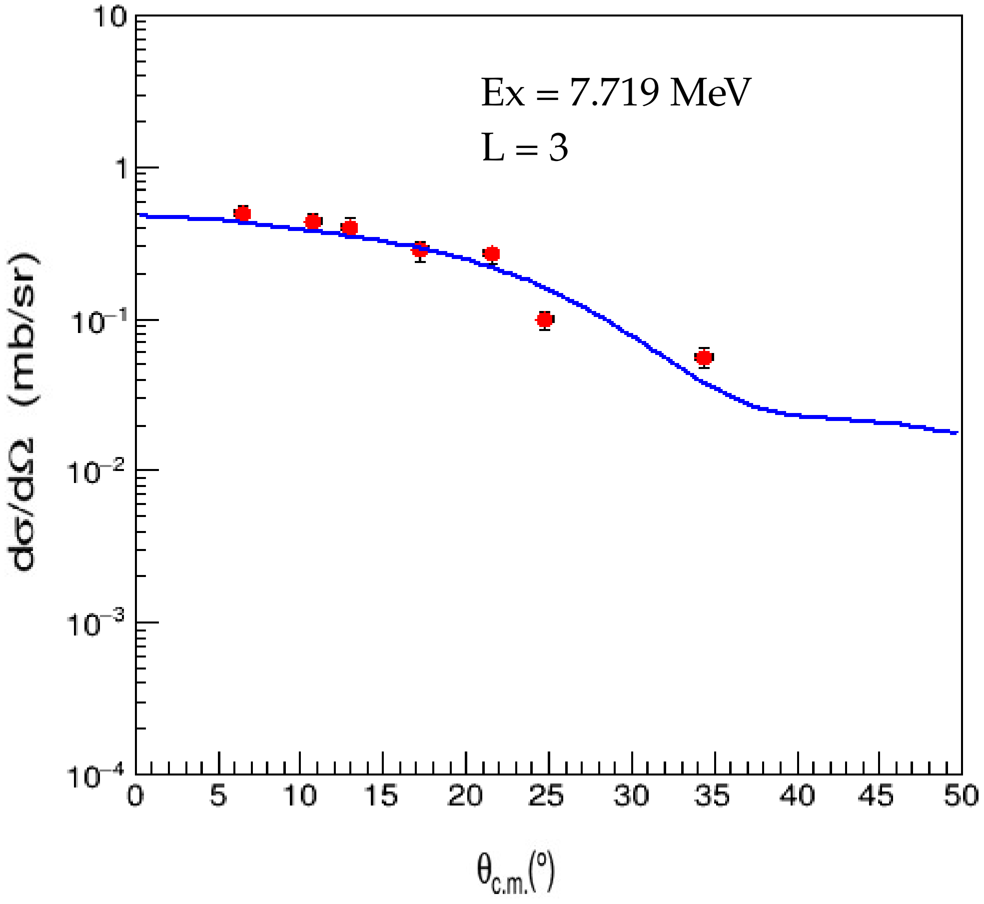


7446 keV
l = 2
C2S=0.00017
dσ/dΩ (mb/sr)
$\theta_{c.m.}$(°)

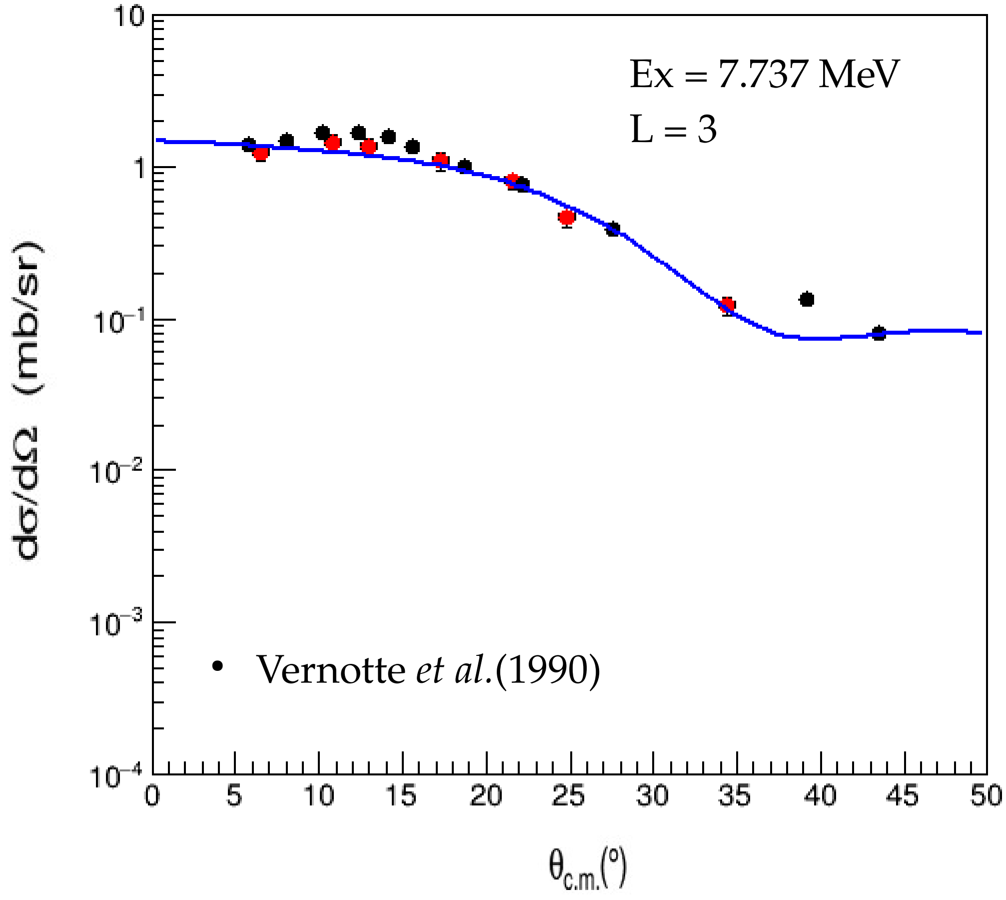


7470 keV
l = 3
C2S=0.00010
dσ/dΩ (mb/sr)
$\theta_{c.m.}$(°)

Back-up



Ex = 7.719 MeV
L = 3
dσ/dΩ (mb/sr)
θc.m.(°)



Ex = 7.737 MeV
L = 3
• Vernotte et al.(1990)
dσ/dΩ (mb/sr)
θc.m.(°)