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

Djamila Sarah HARROUZ

Supervisors:
Nicolas de Séréville
Faïrouz Hammache

XXIInd Colloque Ganil
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université PARIS-SACLAY

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Globular Clusters

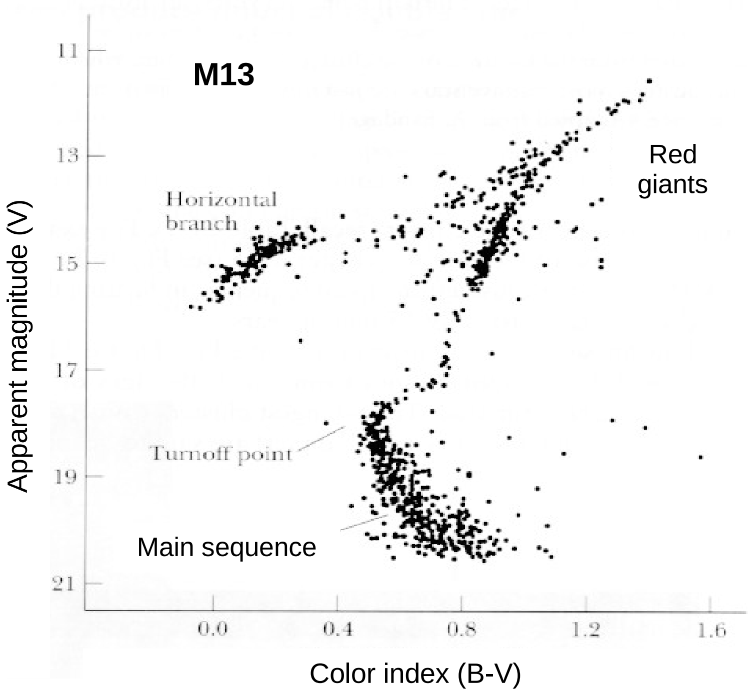
- Gravitationally bound systems of 10^5 to 10^7 stars, located in halo of spiral galaxies.
- Among the oldest structures in the Universe (age > 10 Gyr).

- Globular Clusters are important for:
  - Cosmology (age of the Universe)
  - Galactic physics (formation and early evolution of galaxies)

- Low mass stars mainly on the **Main Sequence** and **Red Giant** branch**.**

  → Hydrogen-burning

- Paradigm: **Single stellar population**: same age and chemical composition.

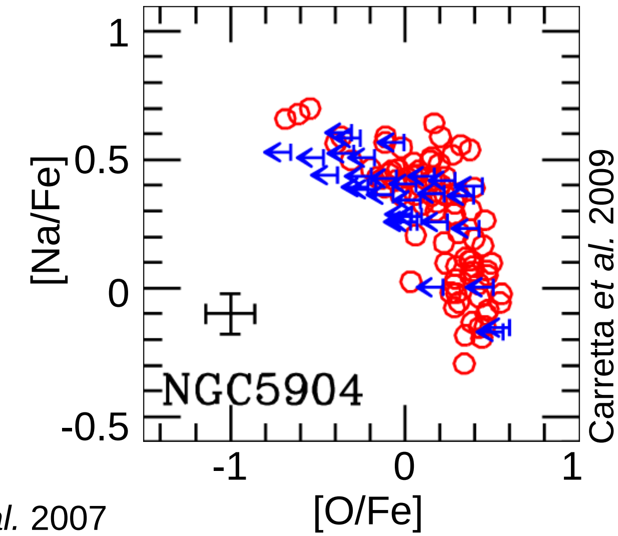


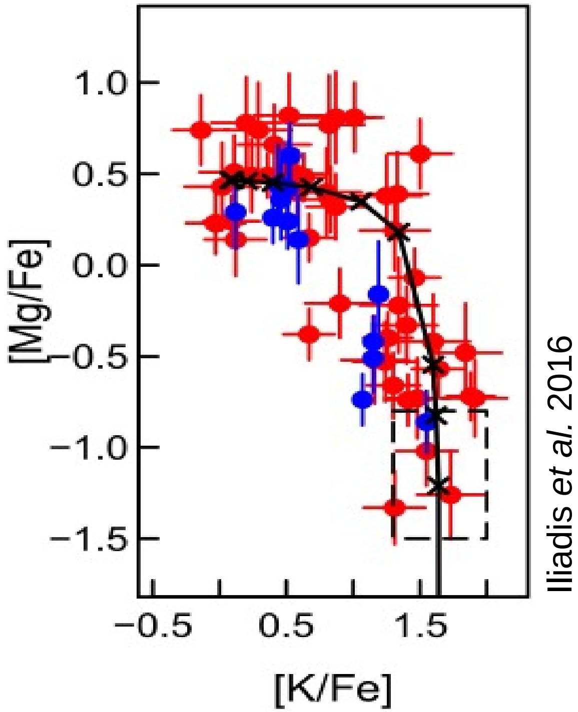
Abundance anomalies in Globular Clusters

- Spectroscopic observations in Red Giant stars:
  - Abundance anticorrelation for **C-N, O-Na, Mg-Al**
  - Abundances vary from star-to-star
- Red giant stars temperature too low to alter abundances

  ⟶ Abundances partially inherited from **unknown stars from previous generation, called polluters.**

  Polluters must burn Hydrogen at T ~ 75 MK (Prantzos *et al.* 2007 & 2017)



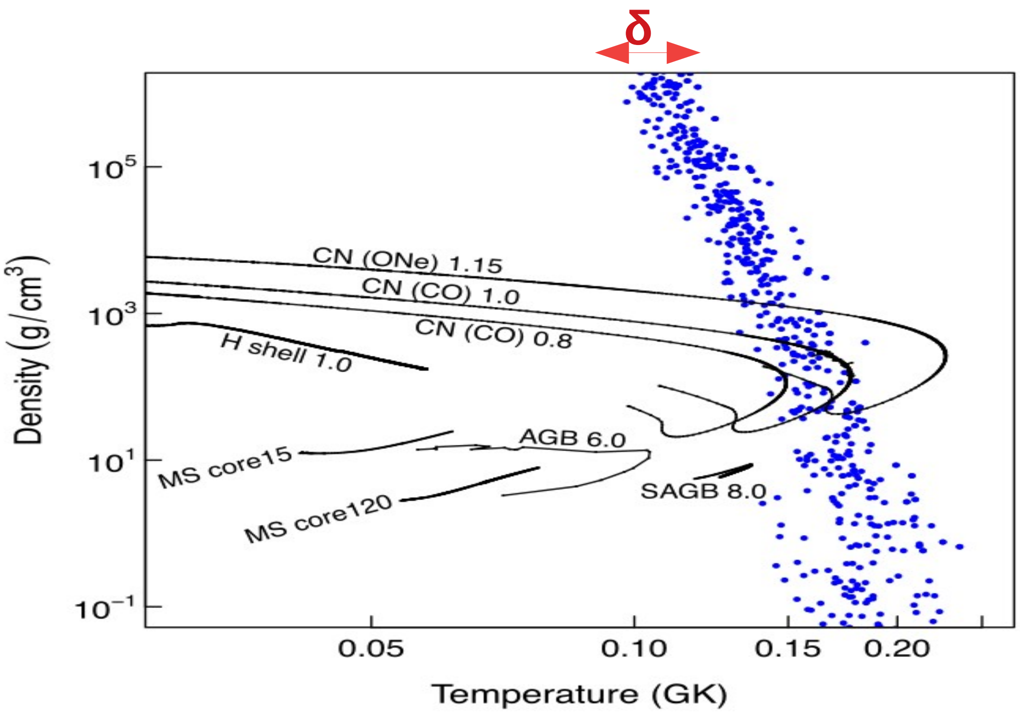


Extreme case of NGC2419

- Observed **Mg-K** anticorrelation
- Requires much higher temperature in polluter site (between 100 MK and 200 MK) to overcome Coulomb barrier in proton capture reactions.

What is the nature and type of polluter stars? (T,ρ)?

NGC2419 Abundances



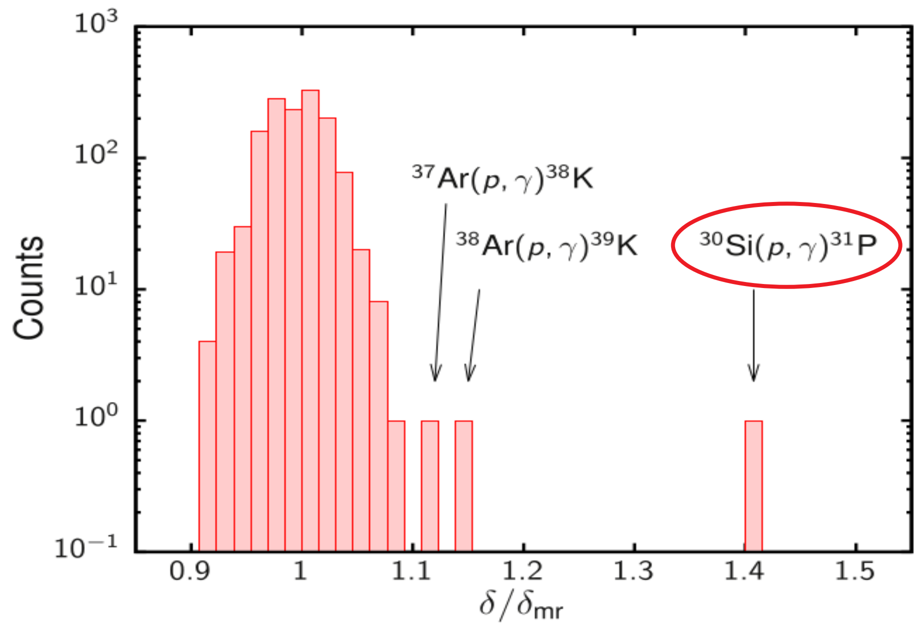
Iliadis *et al.* 2016

Sensitivity Studies

- Simulate nucleosynthesis reaction network in **H-burning conditions** (with Monte Carlo calculation) for uniform **T** and **ρ** distributions, and varying reaction rates within uncertainties.
- Uncertainty on reaction rates → T spread increased by 70%.

Key Reactions

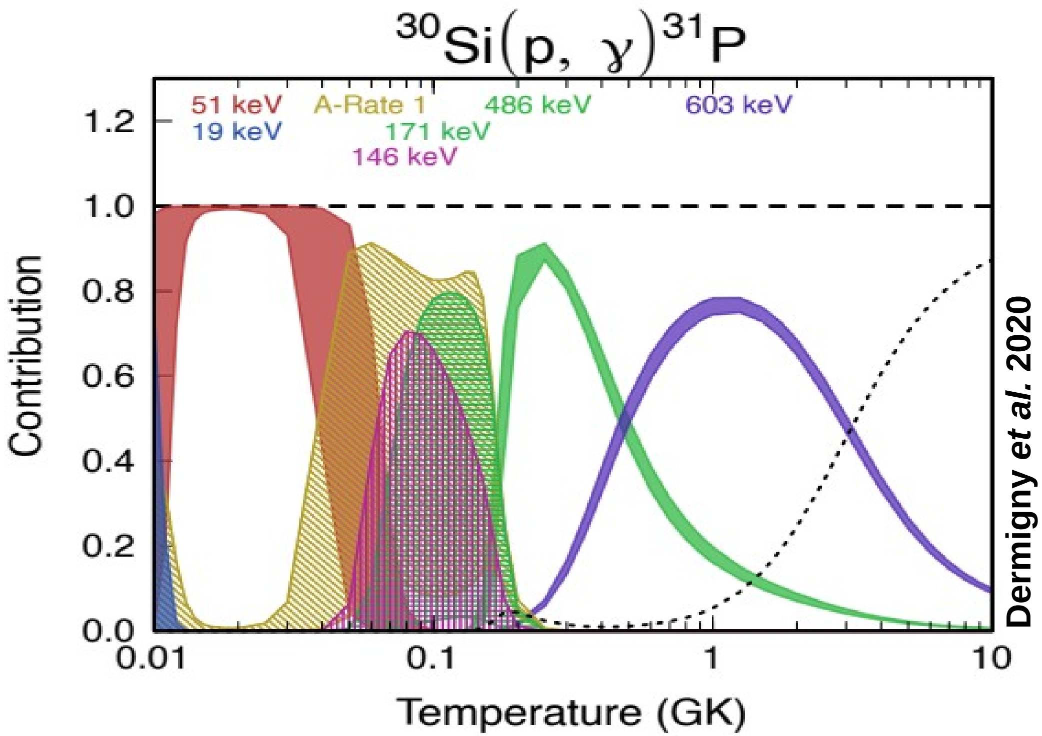
- Individual variation of reaction rates within their uncertainties.
- Impact of a few (p,γ) reactions.
- **^{30}Si(p,γ)^{31}P reaction contributes the most to the spread of the (T, ρ) locus for 100 MK < T < 200 MK**

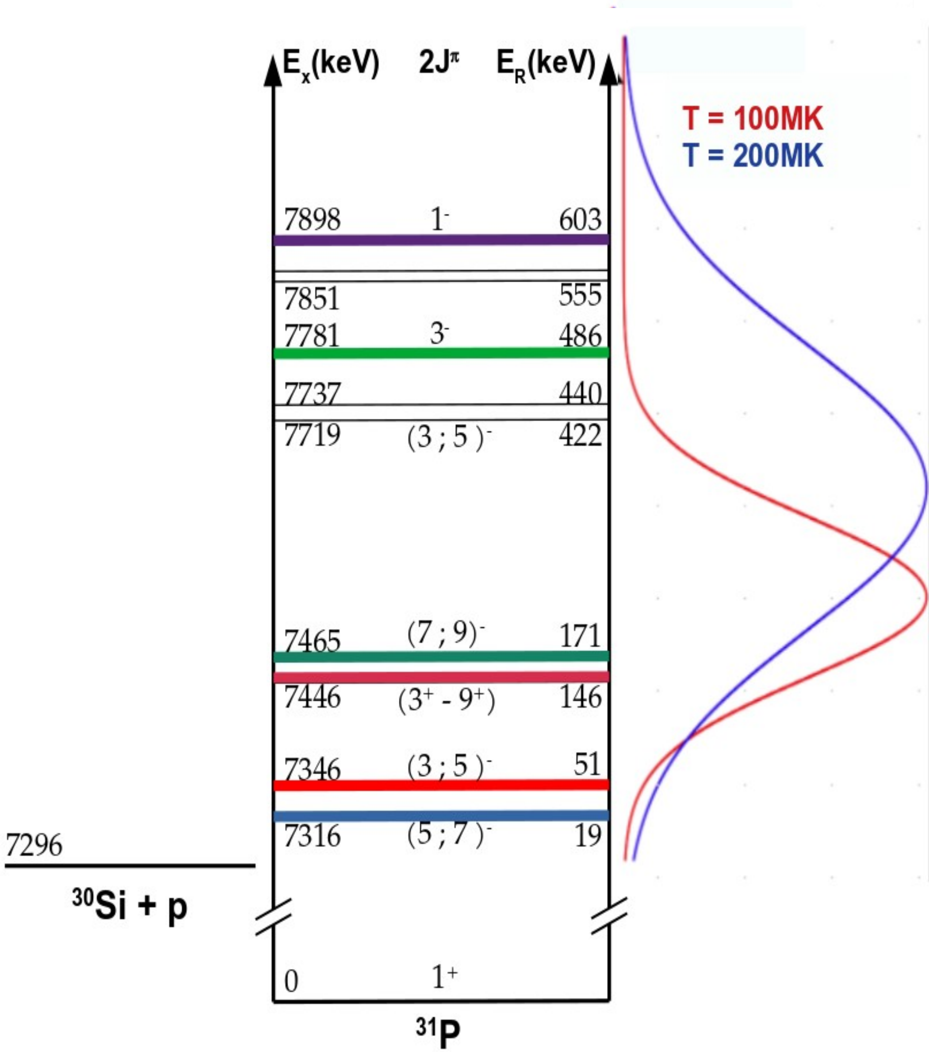


Dermigny *et al.* 2017

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

- Energies known with uncertainty better than 4 keV
- Spins and parities constrained but mostly unknown





- E_r= 19 keV: C^2S = 0.002 *(Vernotte et al. 1990)*
- E_r= 51 and 146 keV: Mean reduced widths, systematic study $\langle\theta^2\rangle = 0.0003$
- E_r= 171 keV: Upper limit C^2S < 0.003 *(Dermigny et al. 2020)*

- E_r= 422, 486 keV sole direct measurements using $\gamma\gamma$ coincidences *(Dermigny et al. 2020)*
- E_r= 603 keV: several direct measurements, reference resonance

Experimental Strategy

Thermonuclear reaction rate for single and isolated narrow resonance :

$$\langle \sigma \nu \rangle \propto (\omega\gamma) e^{(-E_R/kT)}$$

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

High energy

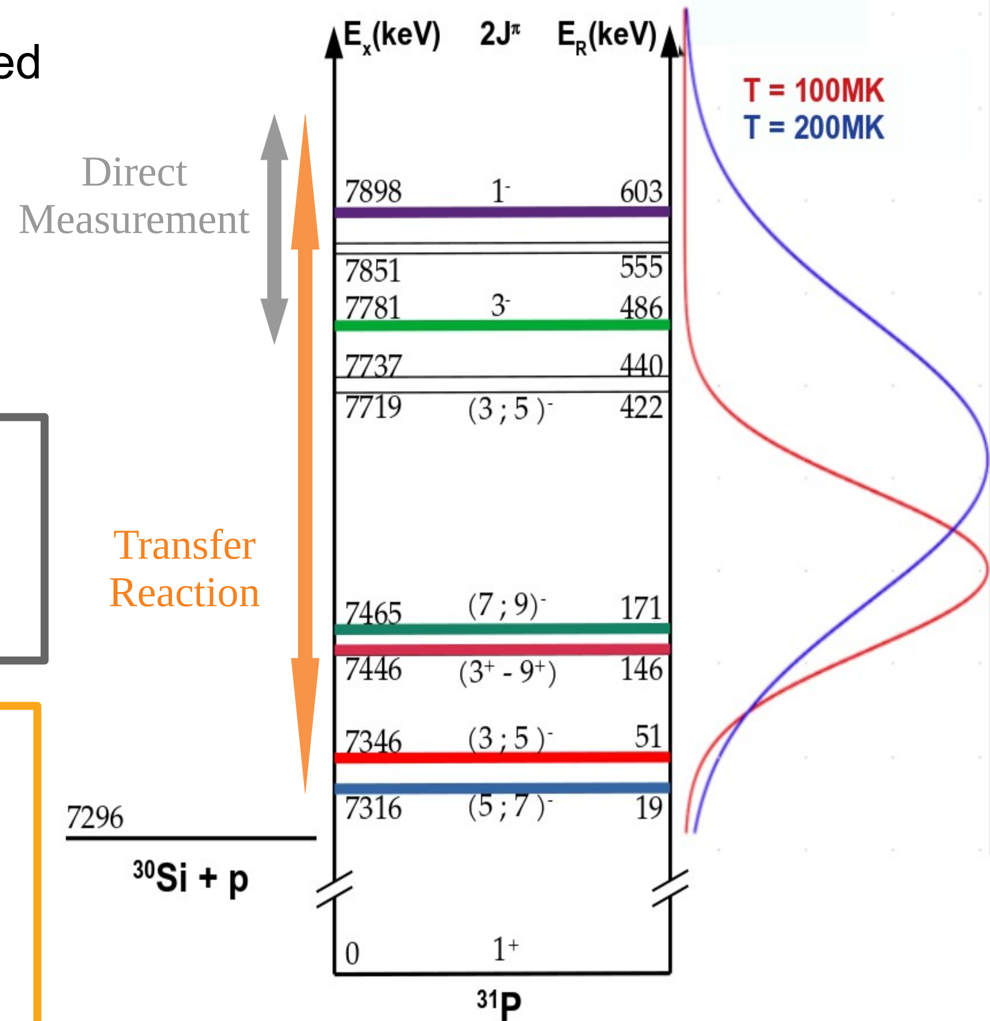
- Direct measurement of resonance strength $\omega\gamma$ **@DRAGON** (Triumf)
- Independent strength determination of the 484 keV resonance.

Low energy

$$\begin{cases} \Gamma = \Gamma_p + \Gamma_\gamma \\ \Gamma_p \ll \Gamma_\gamma \end{cases} \Longrightarrow \omega\gamma \simeq \omega\Gamma_p$$

$^{30}Si(^{3}He,d)^{31}P$ transfer reaction

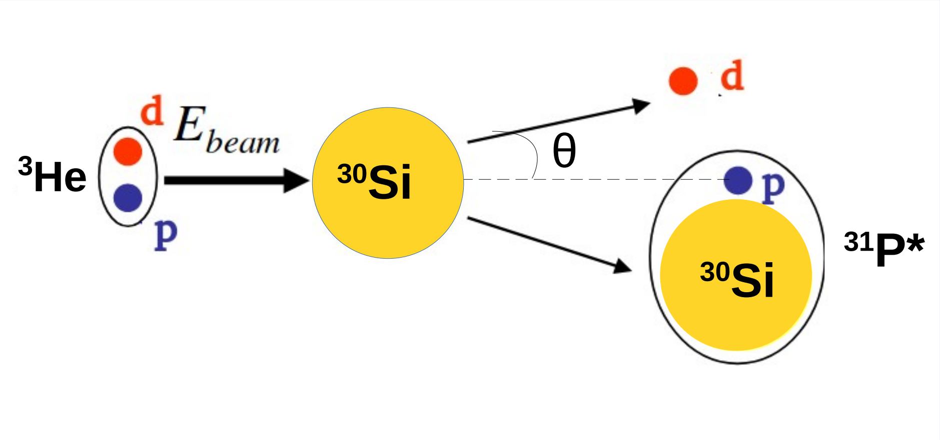
- Experiment by Vernotte in 1990 at Orsay's SplitPole: low statistics, limited resolution and contaminations.
- → new measurements **@Q3D** (MLL) with improved energy resolution and sensitivity.



One proton Transfer Reaction

(p,γ) can be studied through one proton (^3He,d) transfer reaction

Experimental method



Theoretical model for direct transfer

Distorted Wave Born Approximation:

- Elastic scattering dominates entrance and exit channels (described by optical models)
- Transfer 1st order perturbation
- No configuration rearrangement

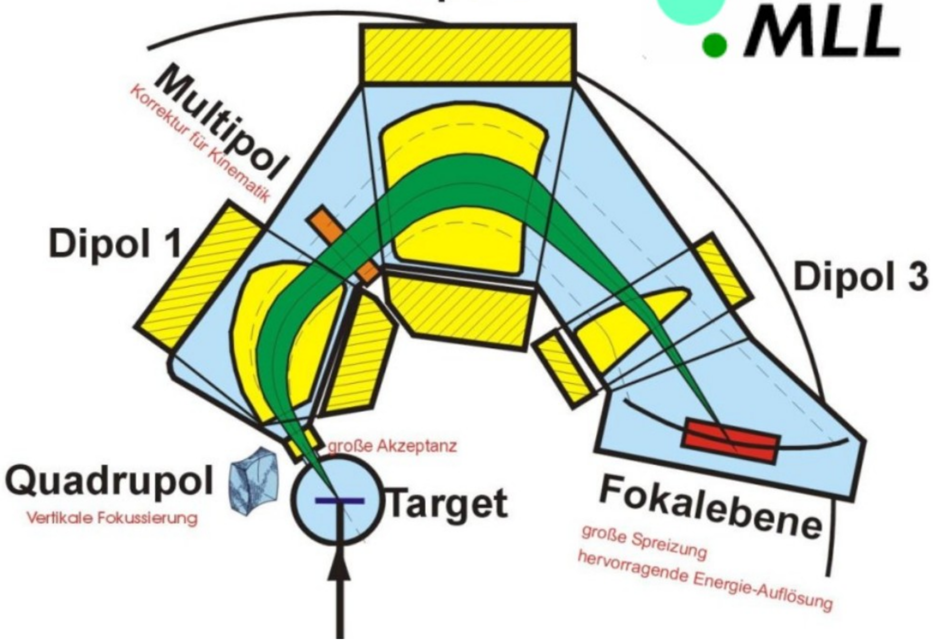
- Excitation energies
- Angular distribution

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

$$\Gamma_p = C^2S\ \Gamma_p^{s.p}(E_r,\ell)$$

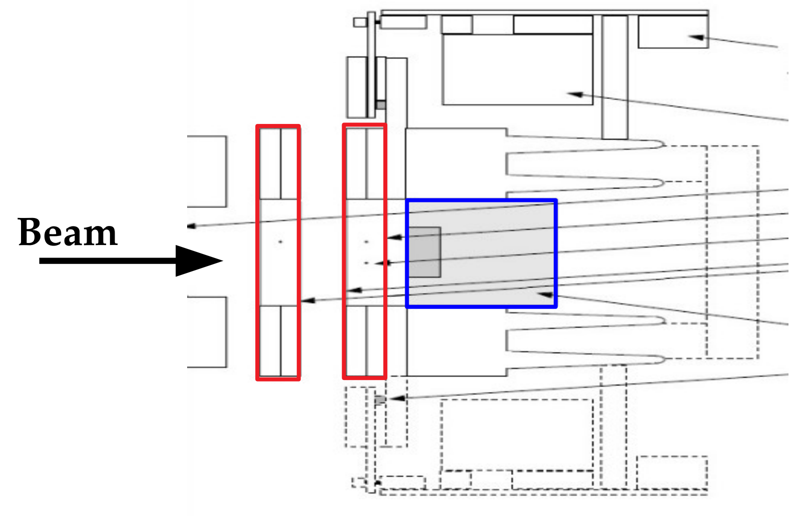
Shape of the distribution
$\rightarrow$ transferred angular orbital momentum ℓ

$^{30}Si(^{3}He,d)^{31}P$ reaction @Q3D

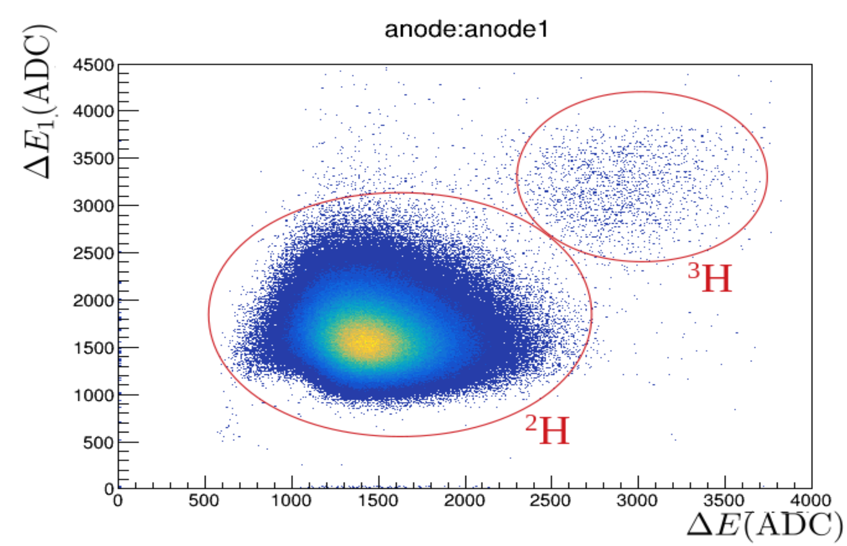


- Beam ^{3}He : E = 25 MeV
  I = 200nAe
- Targets: $^{30}SiO_2$ (40 µg/cm²) enriched at 95% on ^{nat}C
  $^{nat}SiO_2$ (20 µg/cm²) on ^{nat}C
- Solid Angle : 4 to 12 msr
- Energy resolution $\frac{\Delta E}{E} \sim 2.10^{-4}$

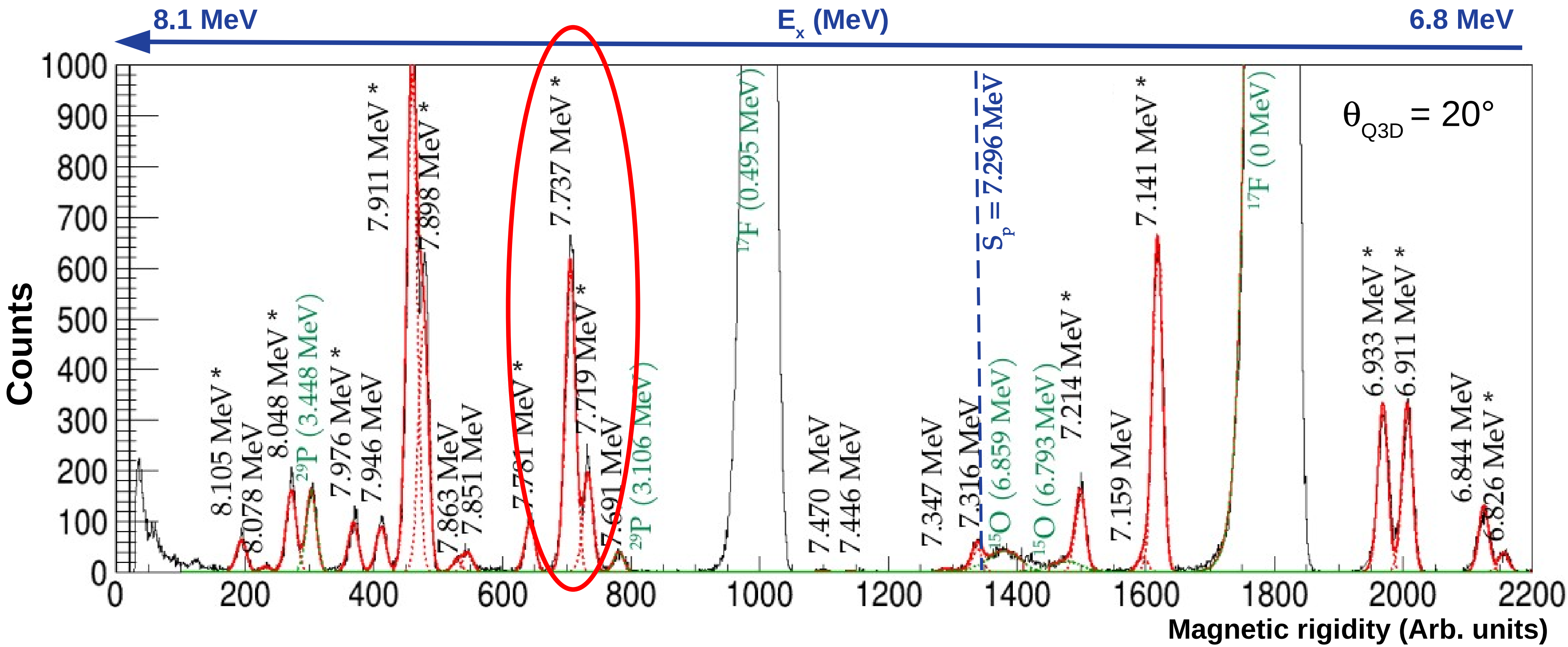
Focal plane detectors :



- Single-wire proportional counters → position on the focal plane and energy loss.
- Plastic scintillator → residual energy.



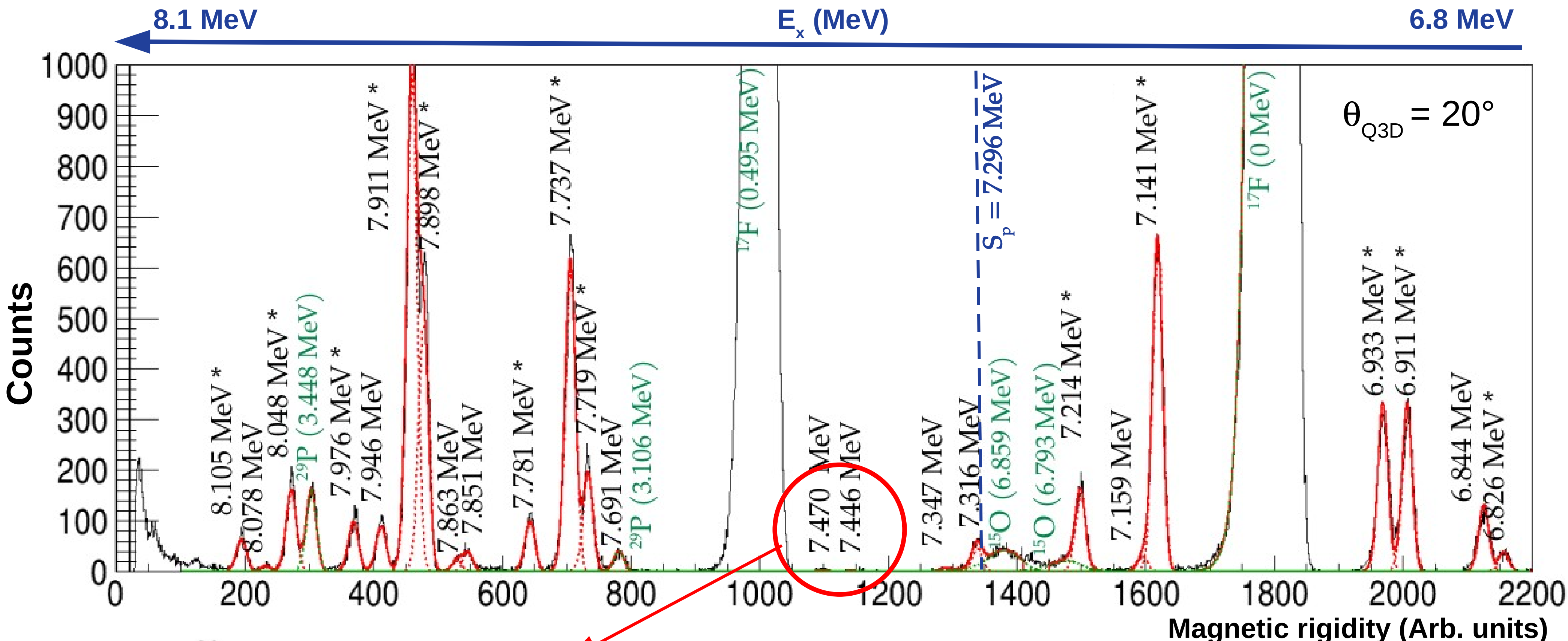
Magnetic rigidity spectrum

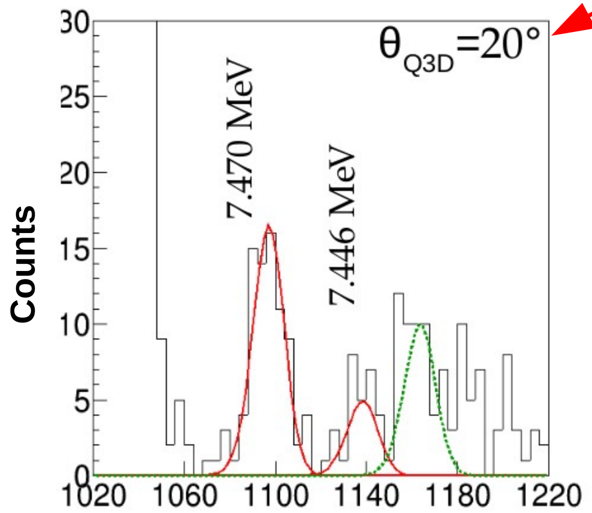


- Spectra for 7 lab angles : 6°, 10°, 12°, 16°, 20°, 23°, 32°
- Fit with multiple skewed gaussians with common width.
- Experimental resolution **FWHM ~ 7 keV**
  Vernotte (1990) ~25 keV

- Doublet at E_x = 7719 - 7737 keV separated.

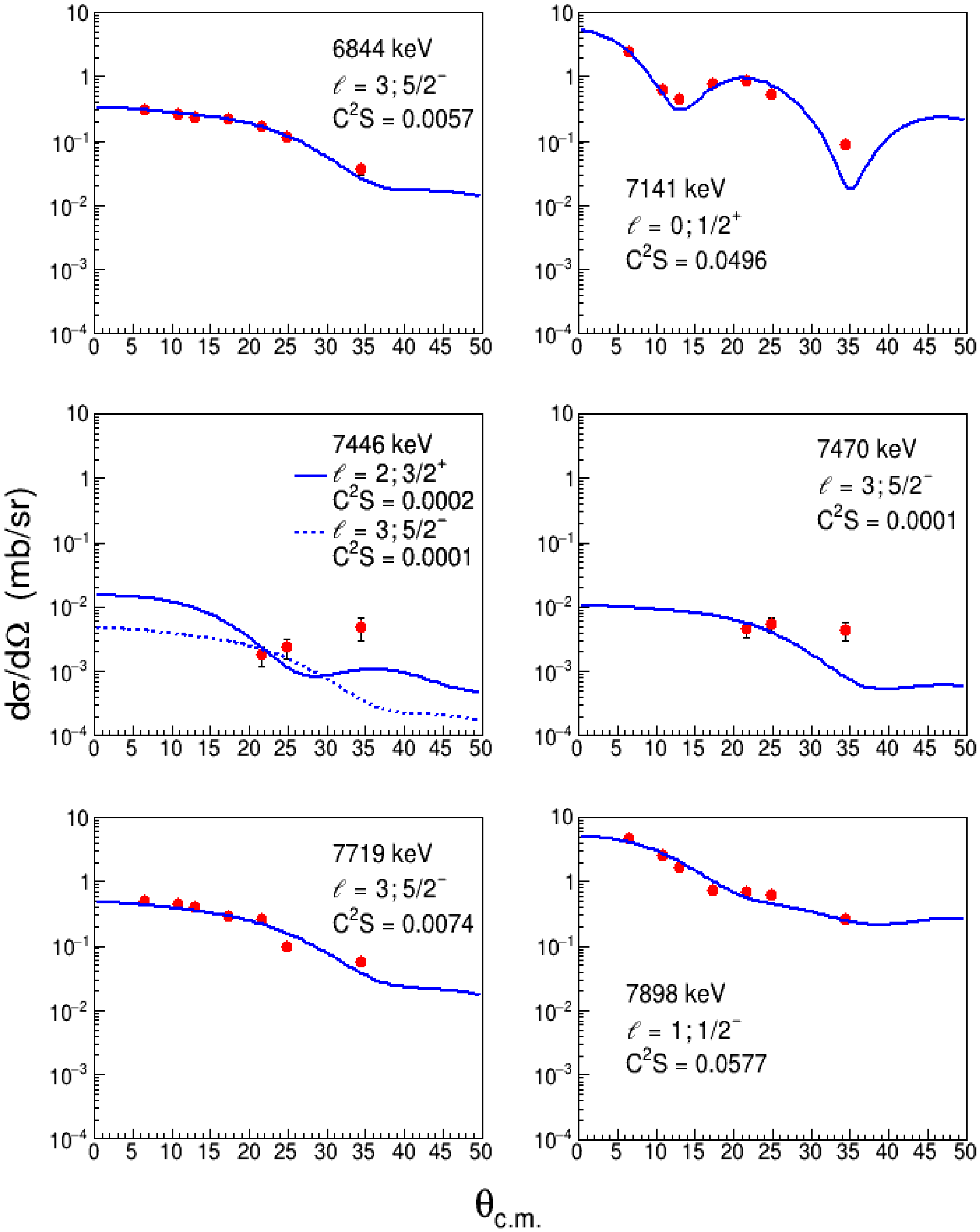
Magnetic rigidity spectrum





- Doublet at E_x = 7719 - 7737 keV separated.
- Levels at E_x = 7446 and 7470 keV observed for $\theta_{Q3D} \geq 20°$.

Angular distributions



Differential cross section

$$\frac{d\sigma}{d\Omega}(\theta_{c.m})_{exp} = \frac{N_d(\theta_{c.m})}{N_{beam}N_{target}\Delta\Omega_{c.m}} = C^2S\frac{d\sigma}{d\Omega}(\theta_{c.m})_{DWBA}$$

Finite-Range DWBA calculations

→ performed with **FRESCO code.**

Optical potentials

^{30}Si + ^{3}He: Vernotte et al (1982)

^{31}P + d : Daehnick, (1980)

Binding Potentials

^{30}Si + p: Wood-Saxon, volume + Spin-Orbit

<^{3}He|d+p> overlap: GFMC Brida (2011)

→C^2S extrapolated to correct unbound energy

$$\Gamma_p \propto C^2S \mid R(r) \mid^2 \qquad r = 7fm$$

Radial wave-function calculation

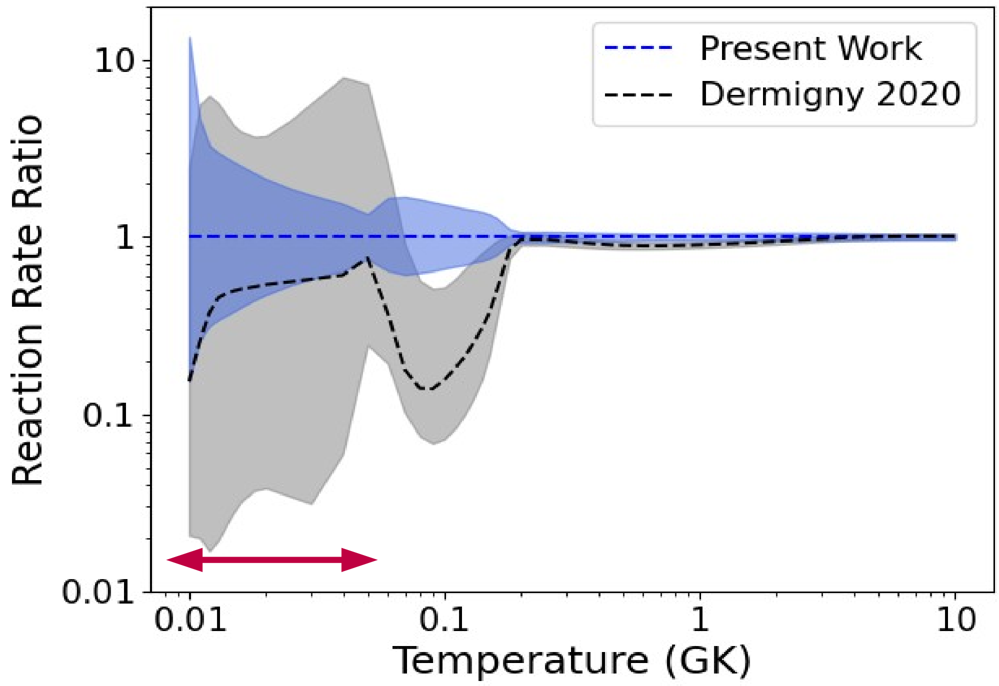
→ performed with **DWUCK4 code**

Vincent & Fortune (1970) procedure

- Γ_p uncertainties ~ 30% (from optical pot.)

$^{30}Si(p,\gamma)^{31}P$ Reaction Rate

- Monte Carlo calculations using **RatesMC.**
- 68% uncertainty bands (log-normal distribution)



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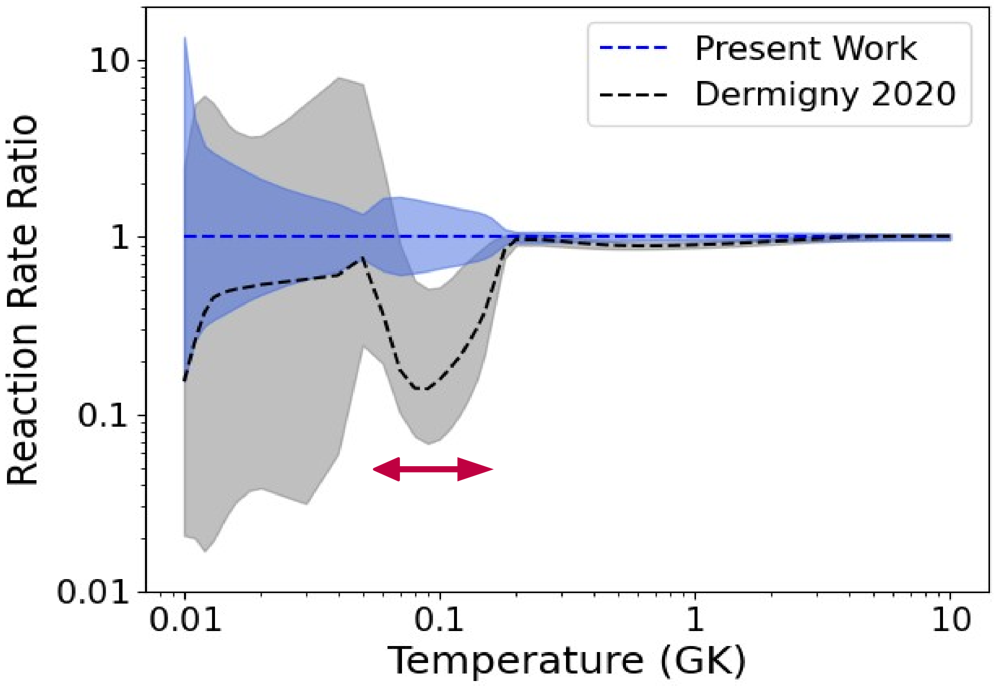

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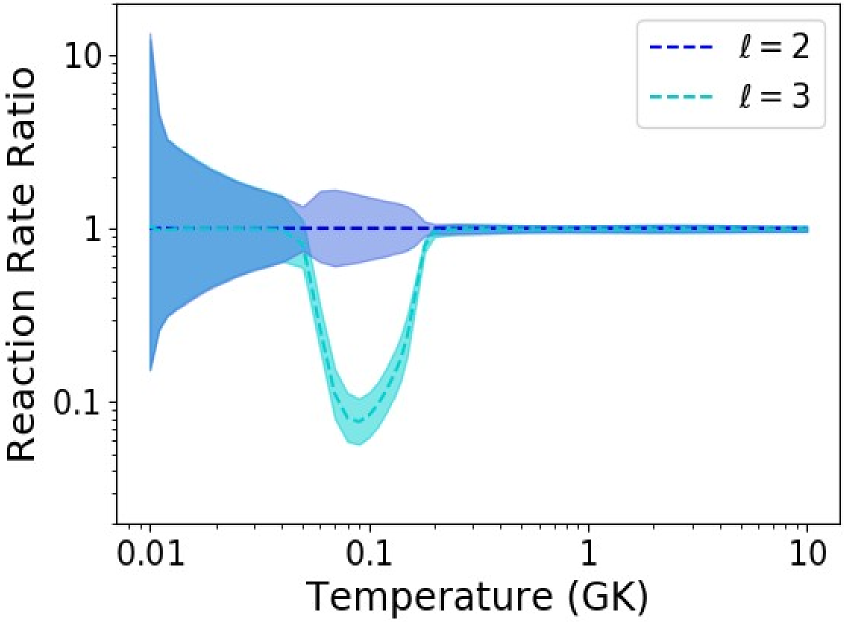

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→ **spin/parity have to be better constrained!**

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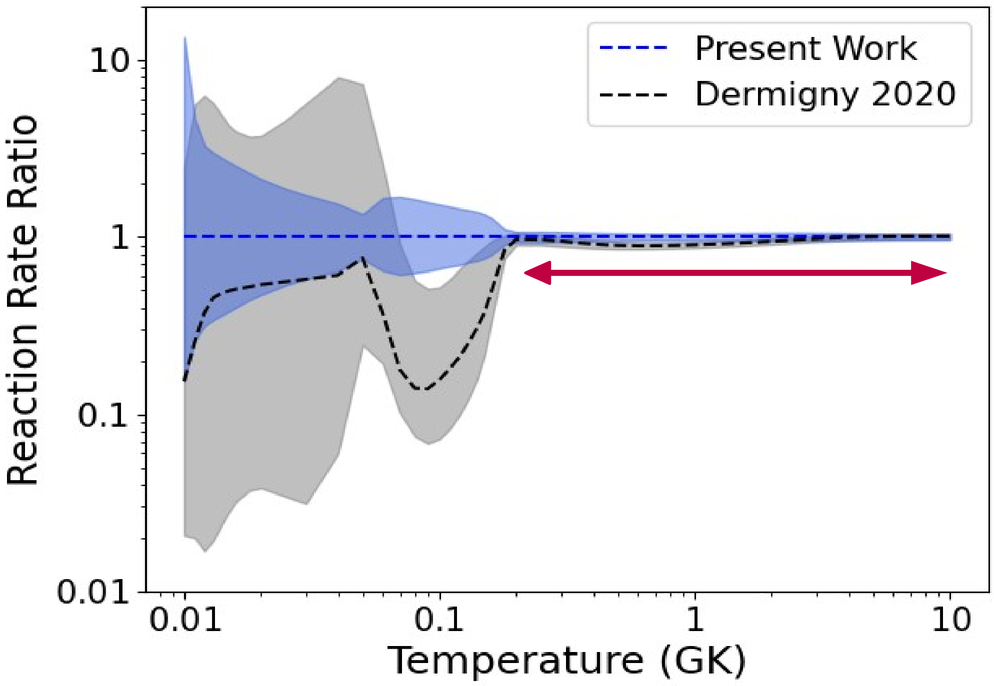

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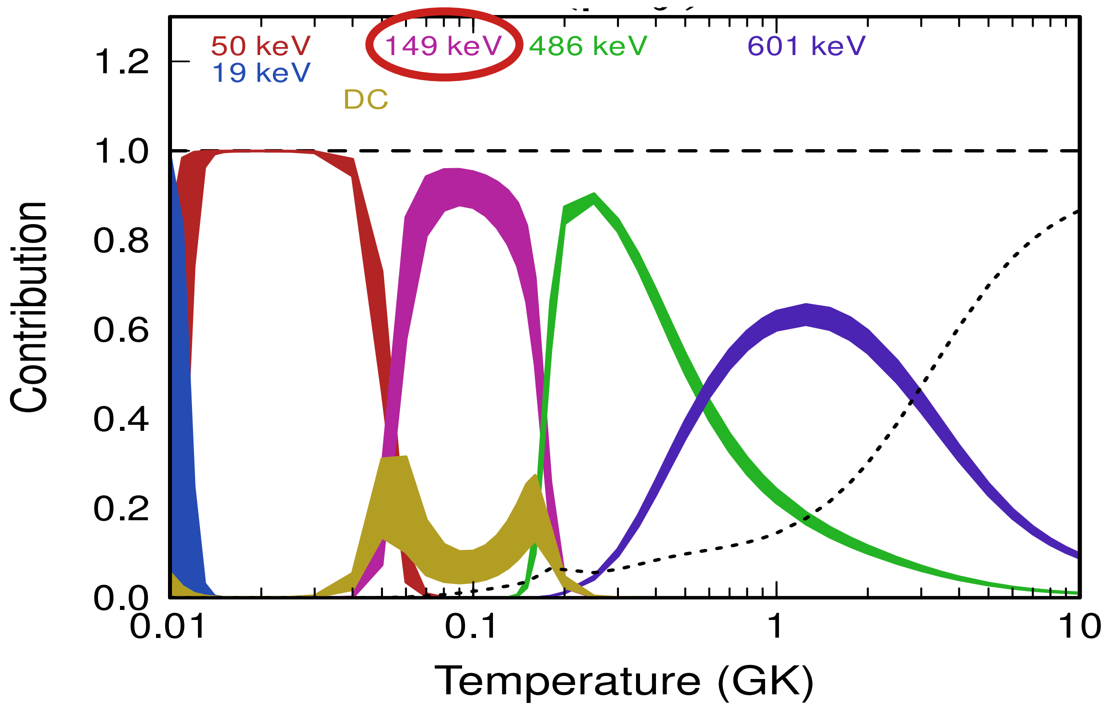
- Observation of the E_r = 149 keV → **key resonance** in T = 100-200 MK
- → ℓ = 2 or ℓ = 3, induces a factor of 10 difference in the reaction rate
  → **spin/parity have to be better constrained!**
- E_r = 418 - 440 keV doublet resolved → E_r = 418 keV has ℓ=3, negligible contribution to the reaction rate, in agreement with direct measurements *(Dermigny et al. 2020)*
- E_r = 486 keV: good agreement for strength values (within 30%) with direct measurements.

Conclusion

- Extraction of spectroscopic information for the ^{31}P nucleus between E_x = 6800 – 8100 keV from the $^{30}Si(^{3}He,d)^{31}P$ reaction.
- Calculation of strengths for resonances up to E_r = 600 keV.
- Improved determination of the $^{30}Si(p,\gamma)^{31}P$ reaction rate.
- Evincing the importance of key resonance at E_r = 149 keV → **need to determine its spin/parity**

Harrouz *et al.* (submitted to PRC 2021)



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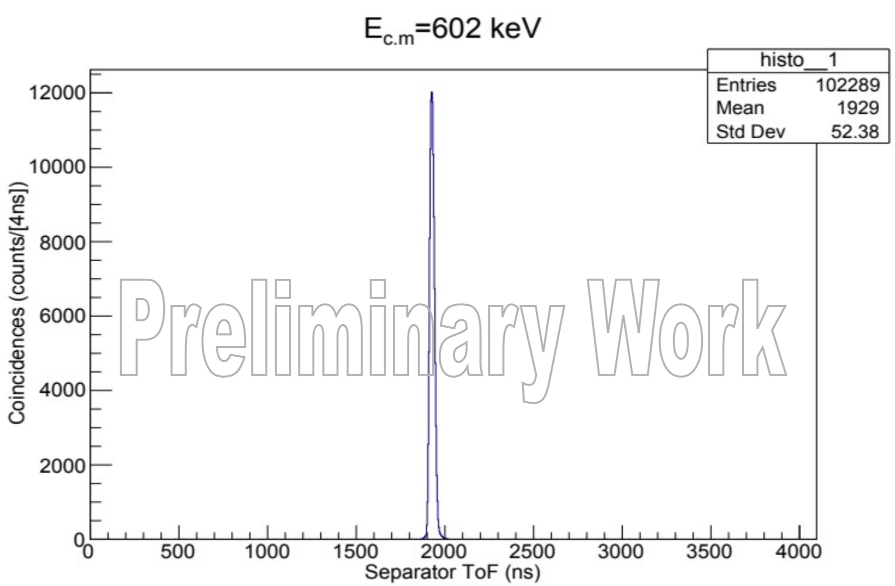
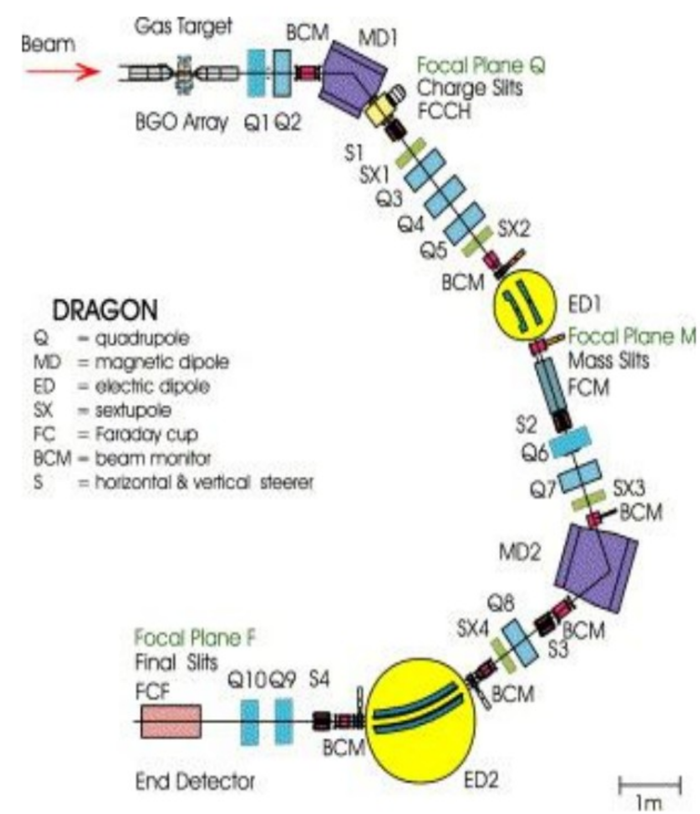
Perspectives

- Analysis of the $^{30}Si(p,\gamma)^{31}P$ reaction rate with the Recoil spectrometer **DRAGON**





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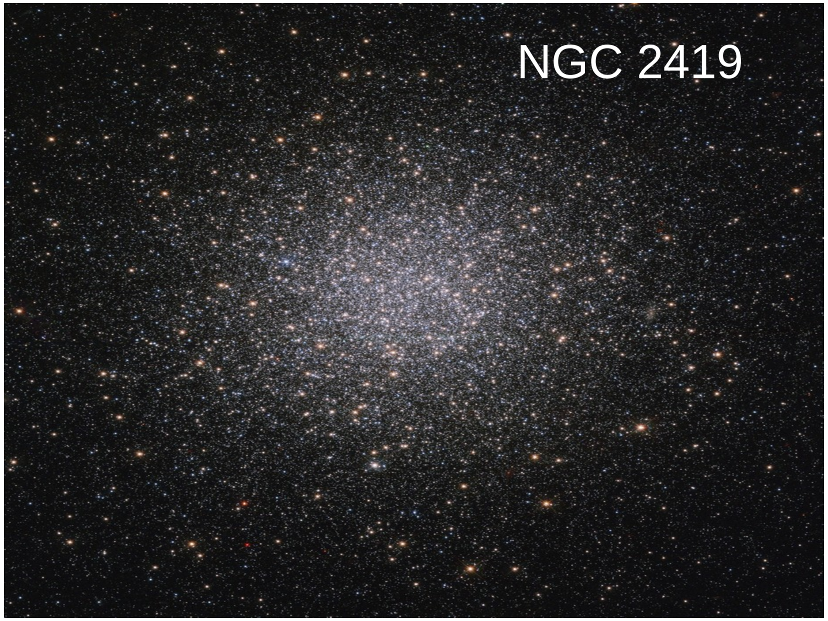
Perspectives

- Analysis of the $^{30}Si(p,\gamma)^{31}P$ reaction rate with the Recoil spectrometer **DRAGON**
- Investigate the impact of the new measurements on the temperature locus for constraining "the polluter" candidates in **Globular Clusters.**



Thank you for your attention

Collaborators :

Philip Adsley (iThemba)
Beyhan Bastin (GANIL)
Thomas Fastermann (TUM)
Faïrouz Hammache (IJCLab)
Ralf Hertenberger (TUM)
Marco La Cognata (LNS)
Livio Lamia (LNS)
Richard Longlond (aNCSU / TUNL)
Anne Meyer (IJCLab)
Sara Palmerini (LNS)
Gianluca Pizzone (LNS)
Stefano Romano (LNS)
Nicolas de Séréville (IJCLab)
Aurora Tumino (LNS)
Hans-Friedrich Wirth (TUM)