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

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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 $T \sim 75$ 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? $(T, \rho)$?
**NGC2419 Abundances**

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

**Sensitivity Studies**
- Simulate nucleosynthesis reaction network in **H-burning conditions** (with Monte Carlo calculation) for uniform $T$ and $\rho$ distributions, and varying reaction rates within uncertainties.
- Uncertainty on reaction rates $\rightarrow T$ spread increased by 70%.
State of the art for $^{30}\text{Si}(p,\gamma)^{31}\text{P}$ reaction

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

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

  \item $E_r = 422$, 486 keV sole direct measurements using $\gamma\gamma$ coincidences \textit{(Dermigny et al. 2020)}
  \item $E_r = 603$ keV: several direct measurements, reference resonance
\end{itemize}
Experimental Strategy

Thermonuclear reaction rate for single and isolated narrow resonance:

\[
\langle \sigma v \rangle \propto (\omega \gamma) e^{-E_{R}/kT}
\]

\[
\omega \gamma = \frac{2J_{R} + 1}{(2J_{p} + 1)(2J_{30}S_{i} + 1)} \frac{\Gamma_{p}\Gamma_{\gamma}}{\Gamma}
\]

High energy

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

Low energy

\[
\begin{aligned}
\Gamma &= \Gamma_{p} + \Gamma_{\gamma} \\
\Gamma_{p} &\ll \Gamma_{\gamma}
\end{aligned}
\]

\[
\omega \gamma \approx \omega \Gamma_{p}
\]

\(^{30}\text{Si}(^{3}\text{He},d)^{31}\text{P}\) 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

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

\[
\Gamma_p = C^2 S \; \Gamma_{p}^{s.p}(E_r, \ell)
\]

Shape of the distribution
→ transferred angular orbital momentum \(\ell\)
$^{30}\text{Si}(^3\text{He},d)^{31}\text{P}$ reaction 
@Q3D

- **Beam $^3\text{He}$**: $E = 25$ MeV, $I = 200\text{nAe}$
- **Targets**: $^{30}\text{SiO}_2$ (40 $\mu$g/cm$^2$) enriched at 95% on natC
  $^{\text{nat}}\text{SiO}_2$ (20 $\mu$g/cm$^2$) on natC
- **Solid Angle**: 4 to 12 msr
- **Energy resolution**: $\frac{\Delta E}{E} \sim 2 \times 10^{-4}$

Focal plane detectors:

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

$\theta_{Q3D} = 20^\circ$
Doublet at $E_x = 7719 - 7737$ keV separated.

Levels at $E_x = 7446$ and 7470 keV observed for $\theta_{Q3D} \geq 20^\circ$. 
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
- $<^{3}\text{He}|d+p>$ overlap: GFMC Brida (2011)

→ $C^2S$ extrapolated to correct unbound energy

\[ \Gamma_p \propto C^2S \mid R(r) \mid^2 \quad r = 7\text{ fm} \]

Radial wave-function calculation
→ performed with DWUCK4 code

Vincent & Fortune (1970) procedure

- $\Gamma_p$ uncertainties ~ 30% (from optical pot.)

\[ \theta_{c.m.} \]
\^30\text{Si}(p,\gamma)^{31}\text{P Reaction Rate}

- Monte Carlo calculations using \textit{RatesMC}.
- 68% uncertainty bands (log-normal distribution)

- Determination of C\(^2\)S for \(E_r = 19\) keV, \(E_r = 51\) keV and \(E_r = 170\) keV (previously upper limits)
- Monte Carlo calculations using RatesMC.
- 68% uncertainty bands (log-normal distribution)

- Determination of $C^2S$ for $E_r = 19$ keV, $E_r = 51$ keV and $E_r = 170$ keV (previously upper limits)
- Observation of the $E_r = 149$ keV $\rightarrow$ key resonance in $T = 100$-200 MK
\( ^{30}\text{Si}(p,\gamma)^{31}\text{P} \) Reaction Rate

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- Determination of \( C^2S \) for \( E_r = 19 \text{ keV}, E_r = 51 \text{ keV} \) and \( E_r = 170 \text{ keV} \) (previously upper limits)
- Observation of the \( E_r = 149 \text{ keV} \) → \textit{key resonance} in \( T = 100-200 \text{ MK} \)
  → \( \ell = 2 \) or \( \ell = 3 \), induces a factor of 10 difference in the reaction rate
  → \textit{spin/parity} have to be better constrained!
Monte Carlo calculations using RatesMC.

68% uncertainty bands (log-normal distribution)

Determination of $C^2S$ for $E_r = 19$ keV, $E_r = 51$ keV and $E_r = 170$ keV (previously upper limits)

Observation of the $E_r = 149$ keV → key resonance in $T = 100$-200 MK

$\rightarrow \ell = 2$ or $\ell = 3$, induces a factor of 10 difference in the reaction rate

$\rightarrow$ spin/parity have to be better constrained!

$E_r = 418 - 440$ keV doublet resolved → $E_r = 418$ keV has $\ell = 3$, negligible contribution to the reaction rate, in agreement with direct measurements (Derigny 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)
Conclusion

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Perspectives

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

![Graph showing data](image)

$E_{c.m.} = 602$ keV

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Preliminary Work
Conclusion

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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

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