Study of key resonances in the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction in classical novae

I. Classical novae and the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction.

II. $^{30}\text{P}(p,\gamma)^{31}\text{S}$ current status.

III. Experimental study of the $^{31}\text{P}(^{3}\text{He},t)^{31}\text{S}*(p)^{30}\text{P}$ reaction.
Classical novae

- Stellar explosions in binary systems consisting of a white dwarf accreting hydrogen-rich material from a companion main-sequence star.

- Powered by thermonuclear runaway on the surface of the white dwarf.

- Explosive nucleosynthesis leading to new elements ejected into the circumstellar medium.

- Two types, corresponding to different constitution of the underlying white dwarf, CO or ONe.

- Overall characteristics well described by theoretical models, but still key issues:
  - degree of mixing
  - mixing mechanism
  - observed ejecta masses
Study of nuclear reactions during the explosion can be used to constrain the physical properties of classical novae.

Bottleneck $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction plays an important role in determining the synthesis of elements in the Si-Ca region, the heaviest species that can be produced in ONe novae:

Main nuclear paths in the Si-Ca mass region
Impact of the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction

✔ Important for understanding the high $^{30}\text{Si}/^{28}\text{Si}$ isotopic ratio found in presolar meteoritic grains from novae:
- $^{30}\text{Si}/^{28}\text{Si}$ ratio depends on $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction which is in competition with $^{30}\text{P}(\beta^+)$ decay to $^{30}\text{Si}$.

✔ Elemental abundance ratios can be used to constrain the degree of mixing ("mixing meters") and the peak temperature during the explosion ("nova thermometers"):
- $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rate uncertainty has the largest impact on the predicted ratios of Si/H, O/S, S/Al, O/P, P/Al.

Presolar SiC grain

Nova thermometers
Direct measurement of the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ cross section not feasible due to the low intensities of $^{30}\text{P}$ radioactive ion beams.

Indirect methods used to populate the states of the $^{31}\text{S}$ compound nucleus in the Gamow window:
- For temperature achieved in novae ($T_9 = 0.1$-$0.4$): excitation energies up to 600 keV above $S_p$ (6.131 MeV).

Reaction rate for a single narrow, isolated resonance:

$$N_A \langle \sigma v \rangle \propto (\omega \gamma)_r e^{-E_r/kT} \quad (\omega \gamma)_r = \frac{(2J_r + 1)}{(2J_p + 1)(2J_{^{30}\text{P}} + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$
**30P(p,γ)31S state of the art**

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- Energies, spins and parities:
  - $E_r$ relatively well known, some $J^\pi$ still uncertain.
  - Parikh et al. (2011), Irvine et al. (2013), Doherty et al. (2014), Brown et al. (2014), Kankainen et al. (2017), Bennett et al. (2016, 2018)
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- Resonance strength:
  - Proton branching ratios $\Gamma_p/\Gamma$ measured for states above 6.7 MeV.
  - Wrede et al. (2009)
  - Resonance strength $(\omega \gamma)_r$ constrained for key low energy resonances close to $S_p$.
  - Kankainen et al. (2017)
\[ ^{31}P(^{3}He,t)^{31}S*(p)^{30}P \] coincidence measurement in Orsay

✓ Coincidence measurement using the \(^{31}P(^{3}He,t)^{31}S\) reaction to populate indirectly \(^{31}S\) which proton decay to \(^{30}P\):

\[ ^{3}He \rightarrow ^{31}P \rightarrow ^{31}S* \rightarrow ^{30}P \]

Set-up: Split-Pole (SP) magnetic spectrometer + Double Sided Silicon Strip Detector (DSSSD) array:

Beam:
\[ E(^{3}He) = 25 \text{ MeV} \]
\[ I(^{3}He) \approx 100 \text{ enA} \]

Target:
\[ ^{31}P \approx 60 \mu g.cm^{-2} \]
\[ ^{nat}C_{\text{backing}} \approx 100 \mu g.cm^{-2} \]
\[ \theta_{SP} = 10^\circ \]

Magnetic rigidity:
\[ B\rho = p/q \]
\[ \rho: \text{bending radius} \]

Triton separation in Position-sensitive gas chamber
\[ \Delta E \text{ proportional gas-counter} \]
\[ E \text{ plastic scintillator} \]
Coincidence measurement using the $^{31}\text{P}(^{3}\text{He},t)^{31}\text{S}$ reaction to populate indirectly $^{31}\text{S}$ which proton decay to $^{30}\text{P}$:

Set-up: Split-Pole (SP) magnetic spectrometer + Double Sided Silicon Strip Detector (DSSSD) array:

- 6 DSSSDs (16+16 strips) at backward angles
- $\varepsilon \approx 15\%$, $\Delta E \approx 20$ keV FWHM
- Thick shield between 0° FC and DSSSDs
- Lower discriminator threshold to detect low energy protons associated to resonances of interest

$t$-$\alpha$ angular correlation of $^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}*(\alpha)^{15}\text{O}$

Red: same experimental set-up as this work
Green: experimental set-up used by Wrede et al.

- Better c.m. angular coverage toward 90°
**31P(3He,t)31S: Triton-singles events spectrum**

- **Bρ calibration of the SP focal-plane position detector, using the triton spectrum at low excitation energies.**

- **Triton identification by combining focal-plane detectors signals (Bρ in the position-sensitive gas chamber, ΔE in the proportional gas counter, E in the plastic scintillator):**

- **Triton-singles events spectrum:**
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**$^{31}\text{P}(^{3}\text{He},t)^{31}\text{S}$**: Triton-singles events spectrum

- **$B\rho$** calibration of the SP focal-plane position detector, using the triton spectrum at low excitation energies.

- Triton identification by combining focal-plane detectors signals ($B\rho$ in the position-sensitive gas chamber, $\Delta E$ in the proportional gas counter, $E$ in the plastic scintillator):

  - Triton-singles events spectrum:

    - $\Delta E \approx 50$ keV (FWHM)
    - $\Delta E - B\rho$ cut
    - $E_{\text{PlasG}} - B\rho$ cut
    - $E_{\text{PlasP}} - B\rho$ cut
    - $\Delta E_{\text{Fil}} - B\rho$ cut
    - Levels observed by Wrede et al.

    - $T_g = 0.4$  
    - $T_g = 0.1$
DSSSDs energy calibration using a pulse generator to obtain the electronic offset and a triple alpha-particle source ($^{239}$Pu, $^{241}$Am and $^{244}$Cm) to measure the gain factor.

Triton-proton timing spectrum:

- Delta T $\approx$ 25 ns FWHM
- Cut on the timing peak
- Random coincidence background

SP focal plane spectrum gated on tritons (preliminary):

- Blue: triton-singles events
- Red: candidate t-p coincidence events

DSSSD energy vs SP Bp spectrum:

- Proton decays of resonances in $^{31}$S to the ground state of $^{30}$P

$31P(3He,t)31S*(p)30P$: t-p coincidence events
The $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction is important for classical novae nucleosynthesis.

We performed a coincidence measurement using the $^{31}\text{P}(^{3}\text{He},t)^{31}\text{S}^*(p)^{30}\text{P}$ reaction to extract the proton branching ratios.

The triton-singles events spectrum and the preliminary coincidence spectrum have been presented.

Next: extract the angular correlations and then the proton branching ratios, which will be used in the calculation of the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rate.
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