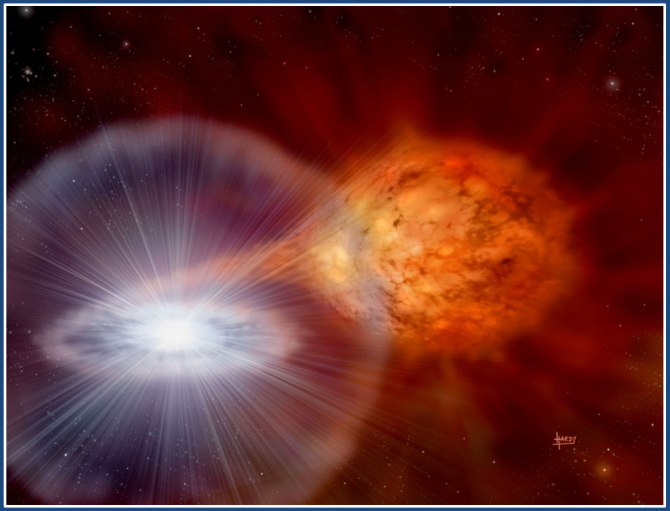
Study of key resonances in the $^{30}P(p,\gamma)^{31}S$ reaction in classical novae

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

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

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



Anne Meyer
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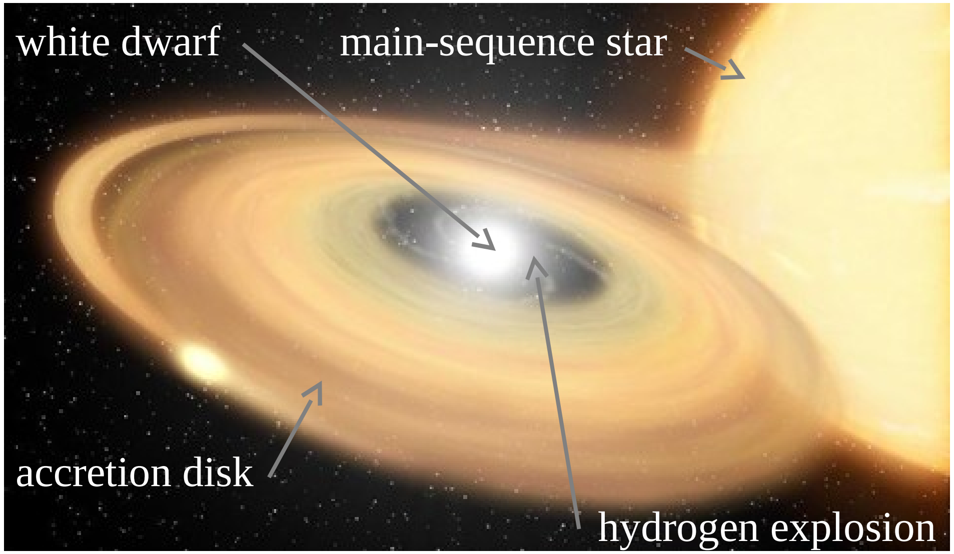
Classical novae

✔ **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.**



Artist's portrayal

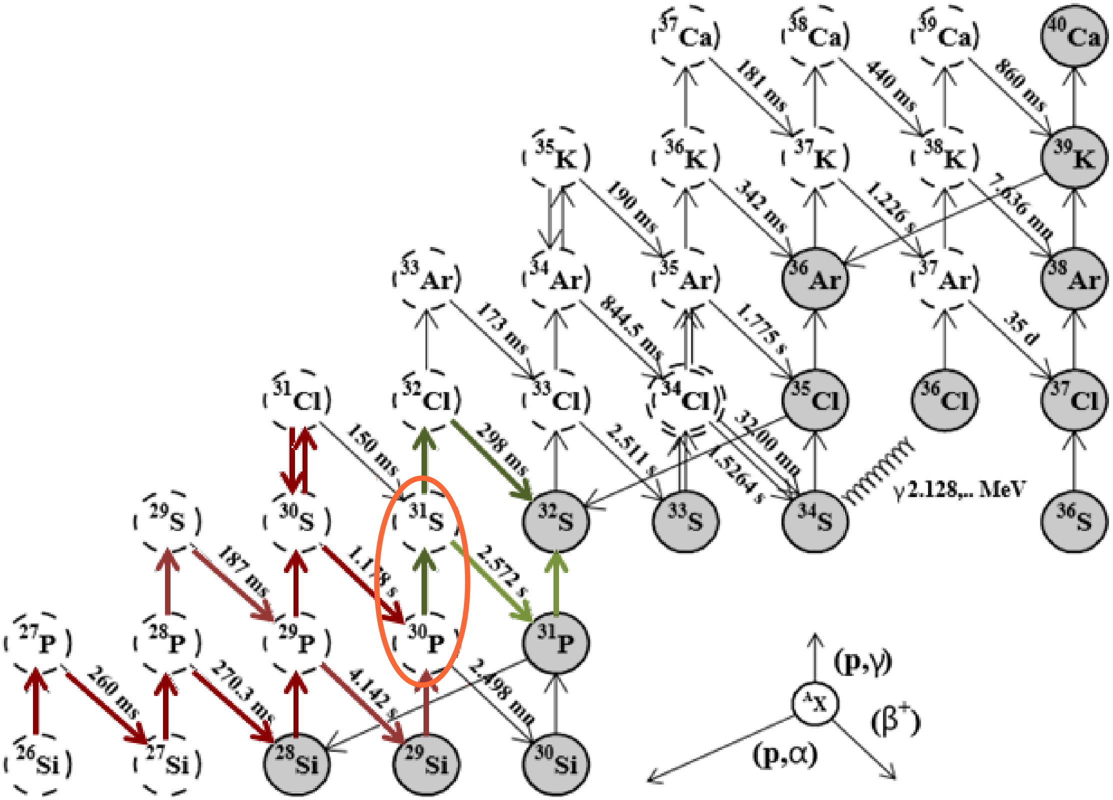
✔ **Two types, corresponding to different constitution of the underlying white dwarf, CO or ONe.**

✔ **Overall characteristics well described by theoretical models, but still key issues:**
- degree of mixing
- mixing mechanism
- observed ejecta masses

Nucleosynthesis in classical novae

✔ Study of nuclear reactions during the explosion can be used to constrain the physical properties of classical novae.

✔ Bottleneck $^{30}P(p,\gamma)^{31}S$ 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:

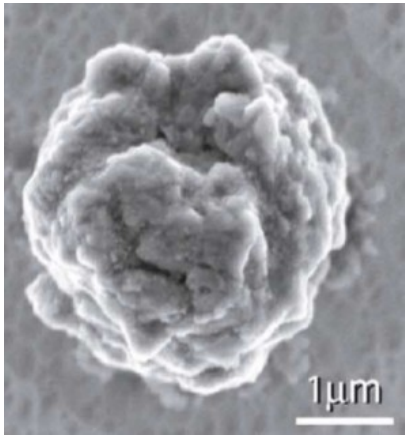


Main nuclear paths in the Si-Ca mass region
© José et al., ApJ 560 (2001)

Impact of the $^{30}P(p,\gamma)^{31}S$ reaction

✔ **Important for understanding the high $^{30}Si/^{28}Si$ isotopic ratio found in presolar meteoritic grains from novae:**

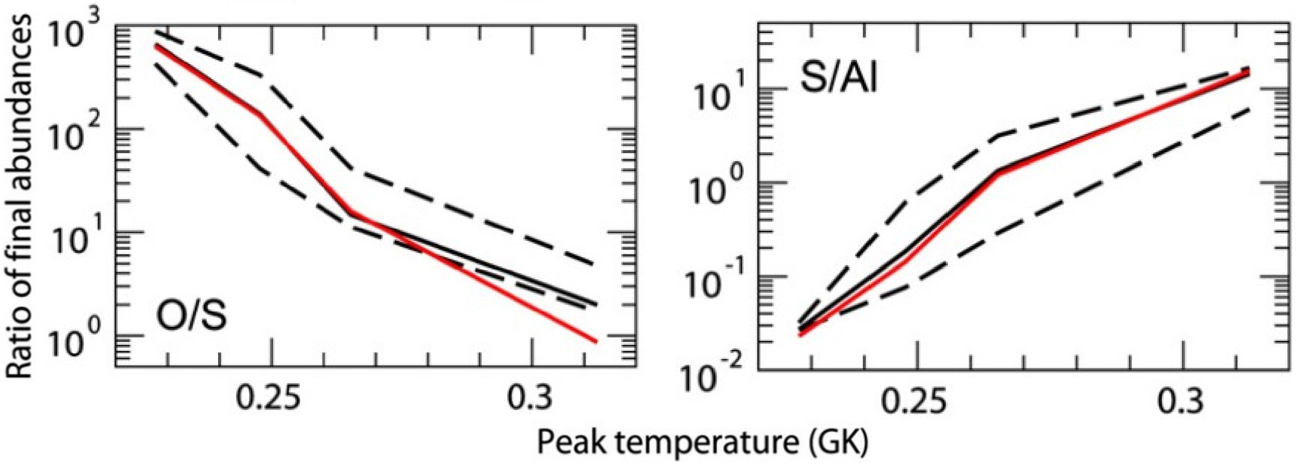
- $^{30}Si/^{28}Si$ ratio depends on $^{30}P(p,\gamma)^{31}S$ reaction which is in competition with $^{30}P(\beta+)$ decay to ^{30}Si.



Presolar SiC grain

✔ **Elemental abundance ratios can be used to constrain the degree of mixing ("mixing meters") and the peak temperature during the explosion ("nova thermometers"):**

- $^{30}P(p,\gamma)^{31}S$ reaction rate uncertainty has the largest impact on the predicted ratios of Si/H, O/S, S/Al, O/P, P/Al.



Nova thermometers
© Downen et al., ApJ 762 (2009)

$^{30}P(p,\gamma)^{31}S$ state of the art

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

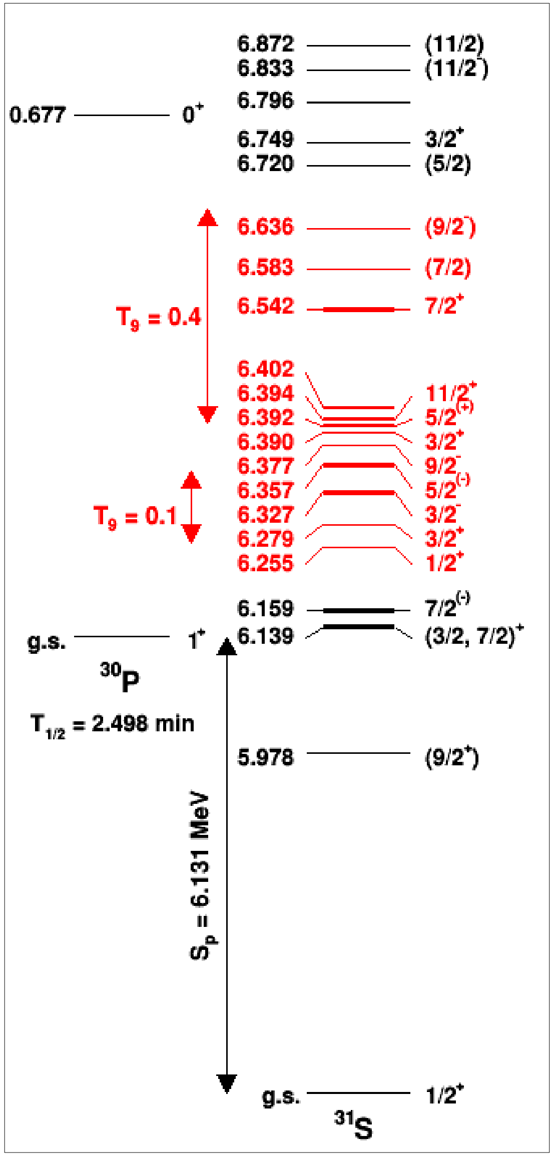
✓ **Indirect methods used to populate the states of the ^{31}S compound nucleus in the Gamow window:**

- 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:**

$$N_A\langle\sigma v\rangle \propto (\omega\gamma)_r\, e^{-E_r/kT} \qquad (\omega\gamma)_r = \frac{(2J_r+1)}{(2J_p+1)(2J_{30_P}+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma}$$

✓ **Level scheme:**



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✓ **Energies, spins and parities:**

- Er relatively well known, some J^π 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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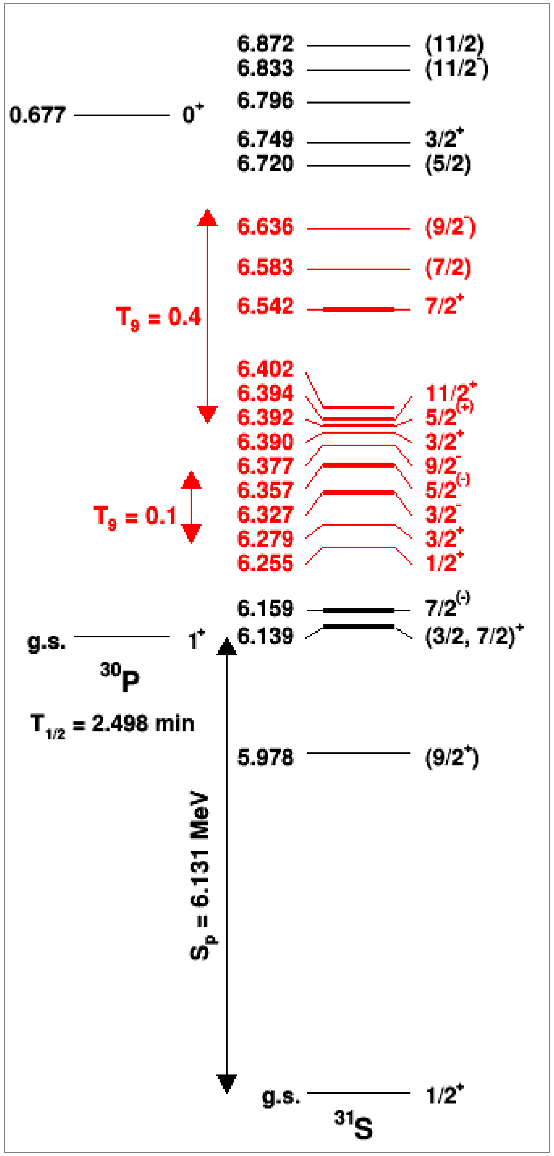

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✓ **Resonance strength:**

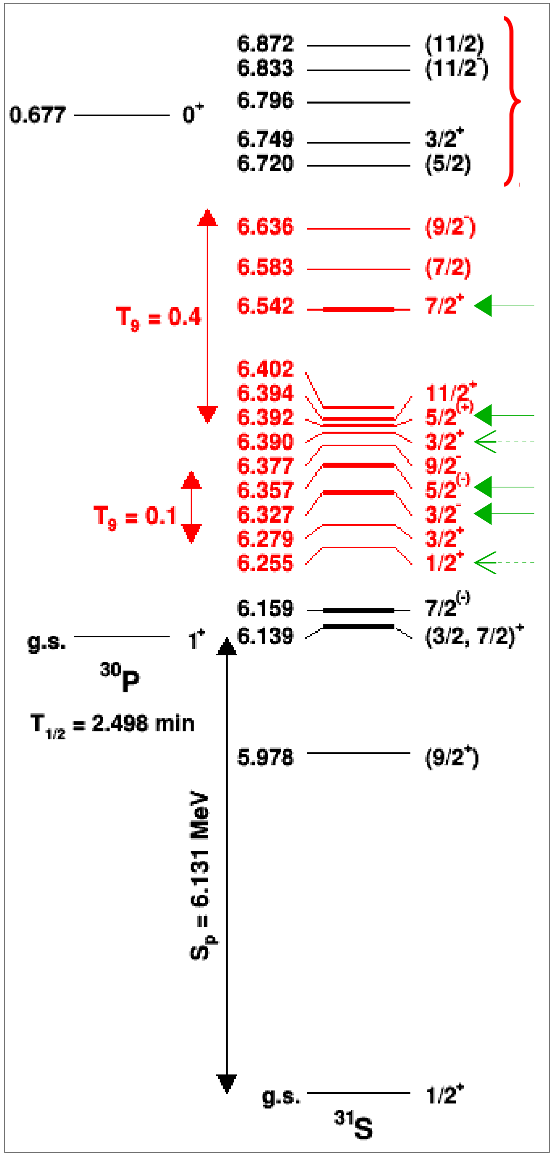
- Proton branching ratios Γ_p/Γ measured for states above 6.7 MeV.

Wrede et al. (2009)

- Resonance strength $(\omega\gamma)_r$ constrained for key low energy resonances close to S_p.

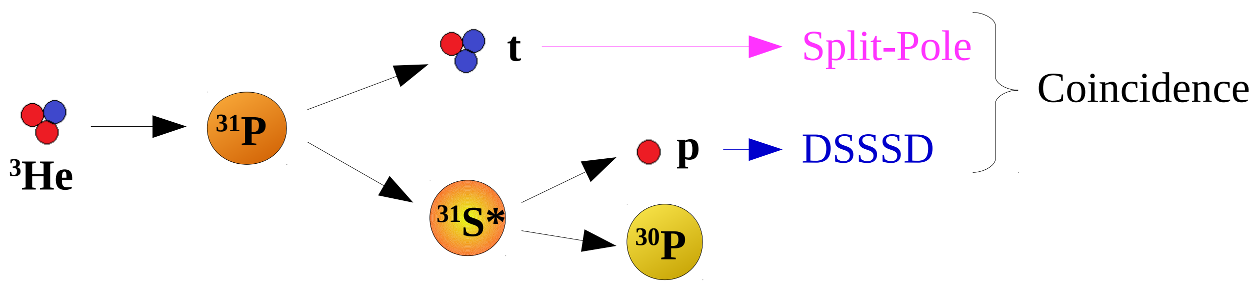
Kankainen et al. (2017)

✓ **Level scheme:**



$^{31}P(^{3}He,t)^{31}S^{*}(p)^{30}P$ 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:**

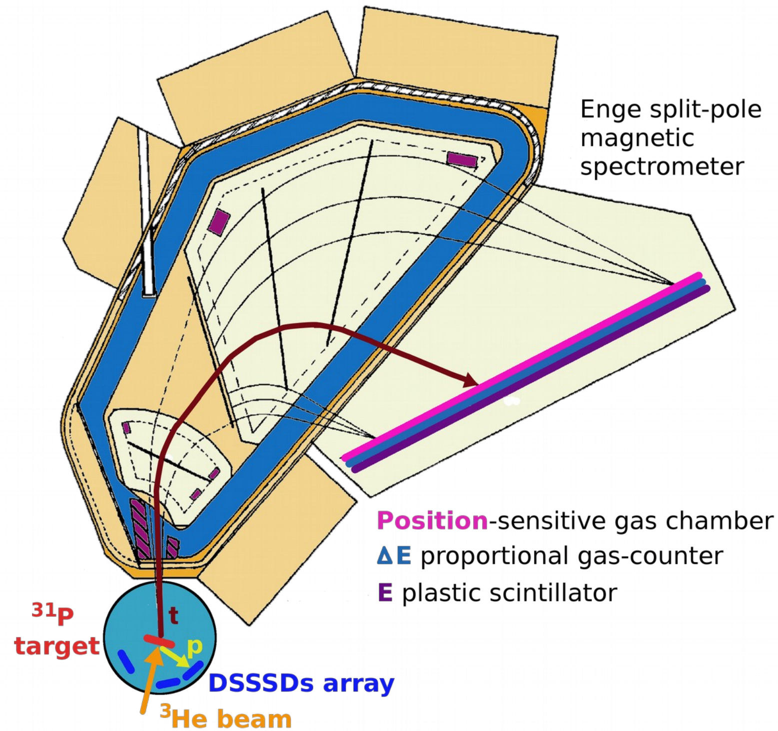


✓ **Set-up: Split-Pole (SP) magnetic spectrometer + Double Sided Silicon Strip Detector (DSSSD) array:**

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

Target:
$^{31}P \approx 60\ \mu g.cm^{-2}$
$^{nat}C_{backing} \approx 100\ \mu g.cm^{-2}$

$\theta_{SP} = 10°$



Triton separation in **Magnetic rigidity:**
$B\rho = p/q$
ρ: bending radius

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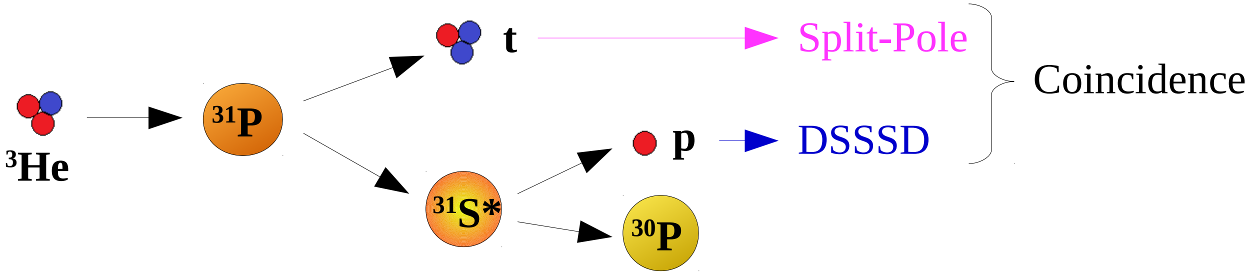

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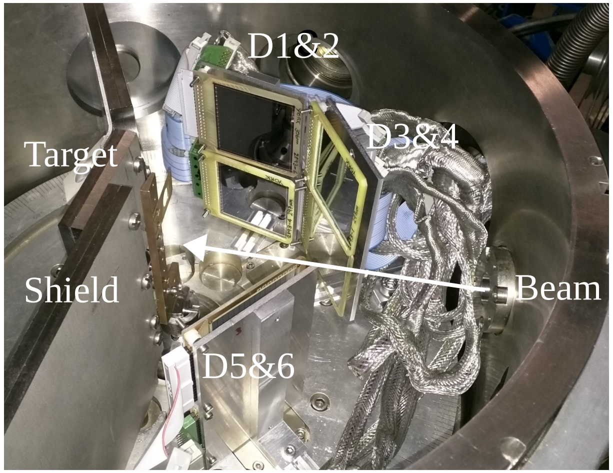
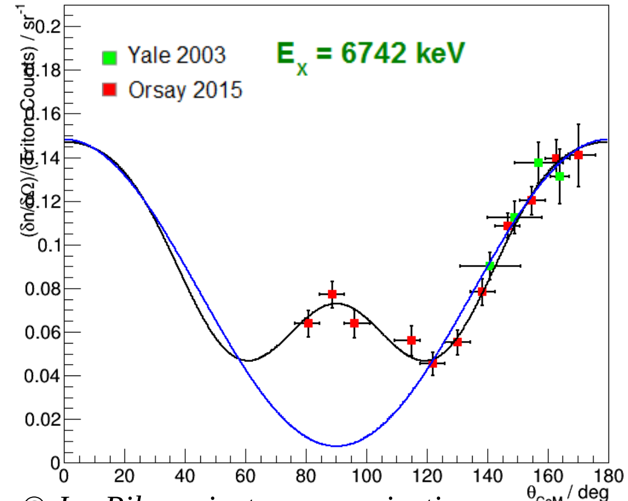


- 6 DSSSDs (16+16 strips) at backward angles
- ε ≈ 15%, ΔE ≈ 20 keV FWHM
- Thick shield between 0° FC and DSSSDs
- Lower discriminator threshold to detect low energy protons associated to resonances of interest

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



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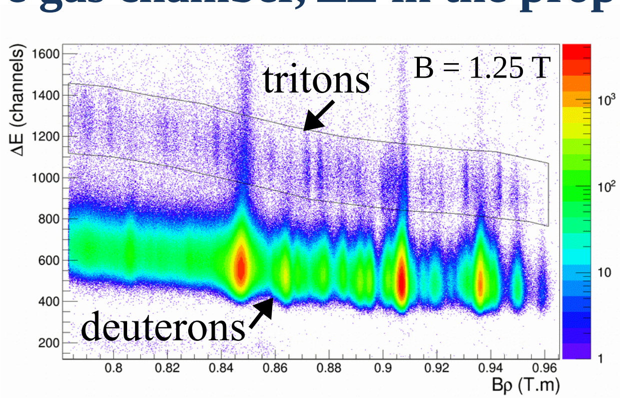
Red: same experimental set-up as this work
Green: experimental set-up used by Wrede et al.

- Better c.m. angular coverage toward 90°

$^{31}P(^{3}He,t)^{31}S$: 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):**



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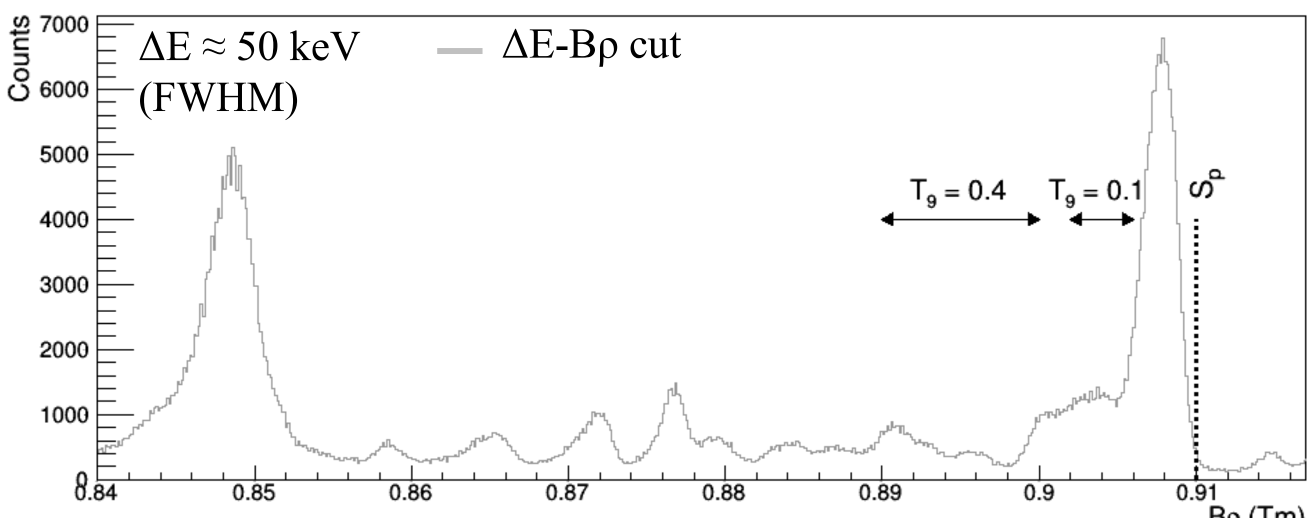

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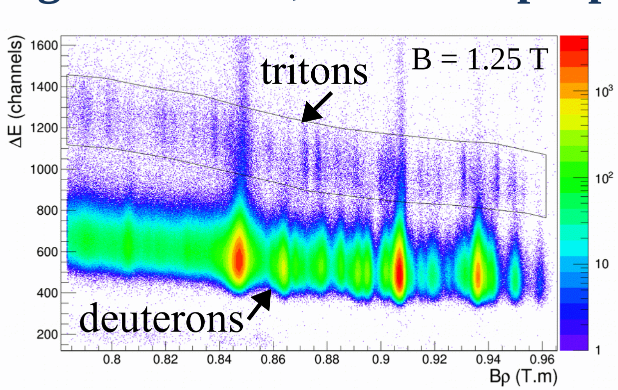

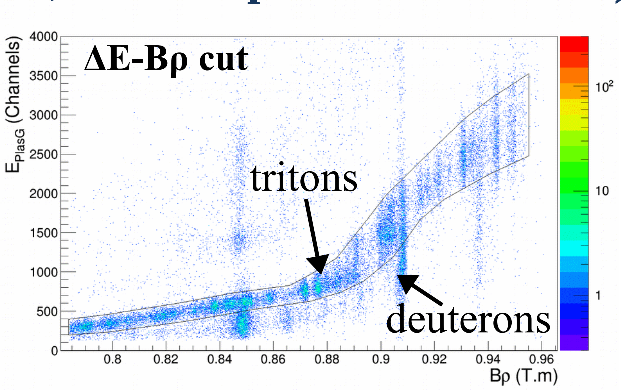

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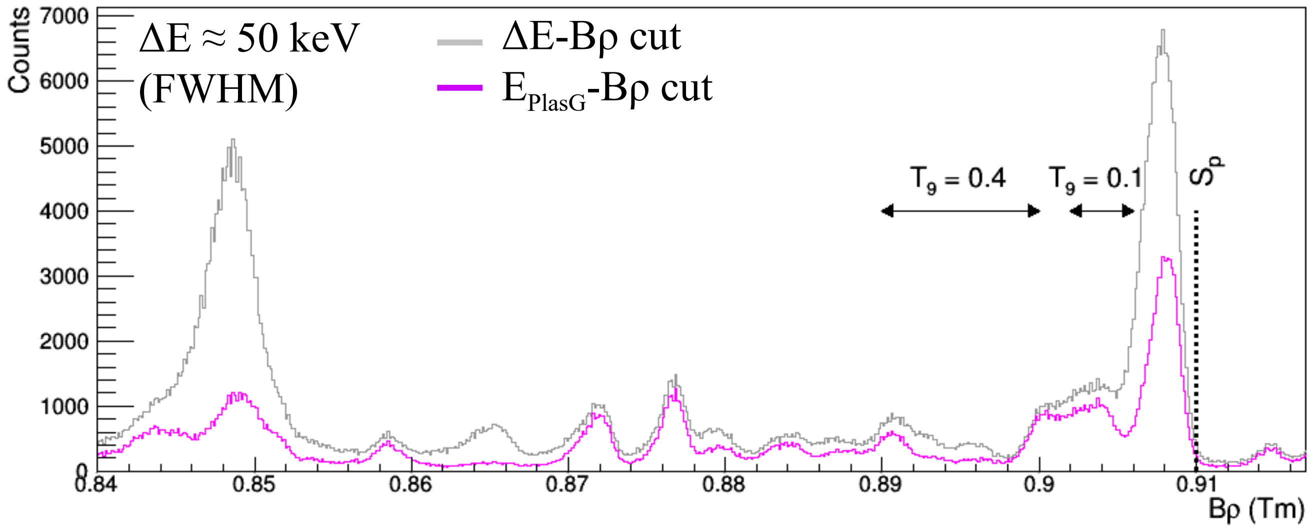

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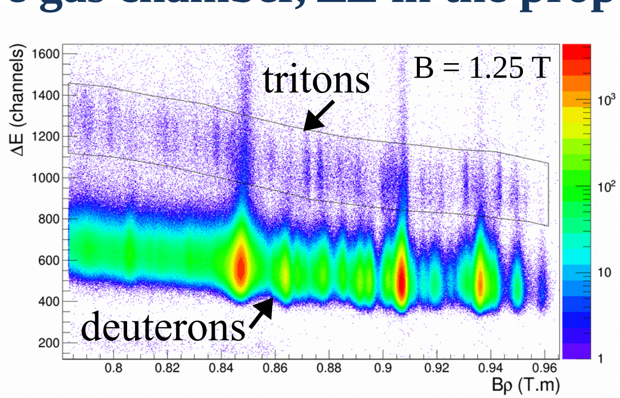

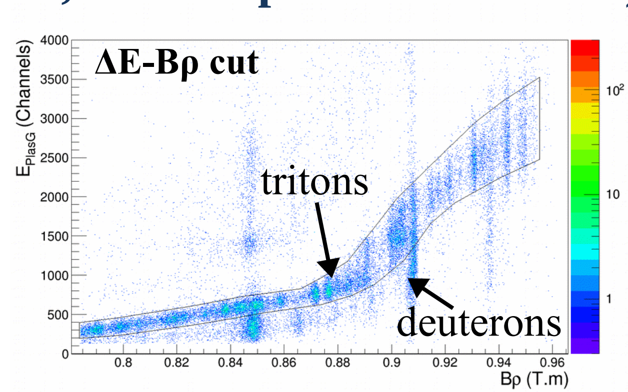

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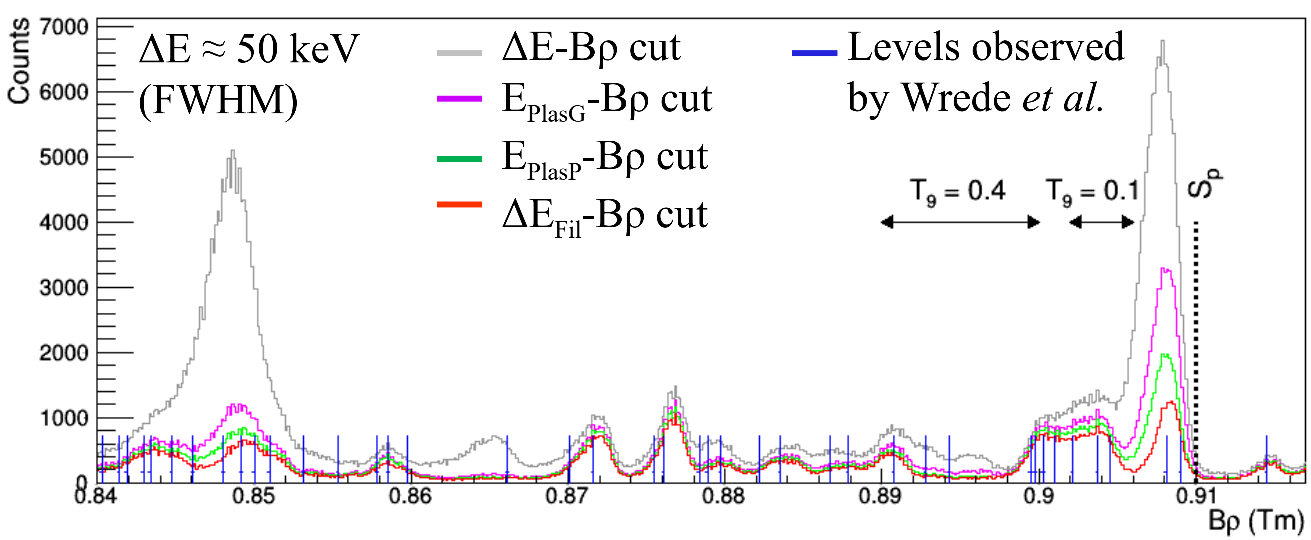
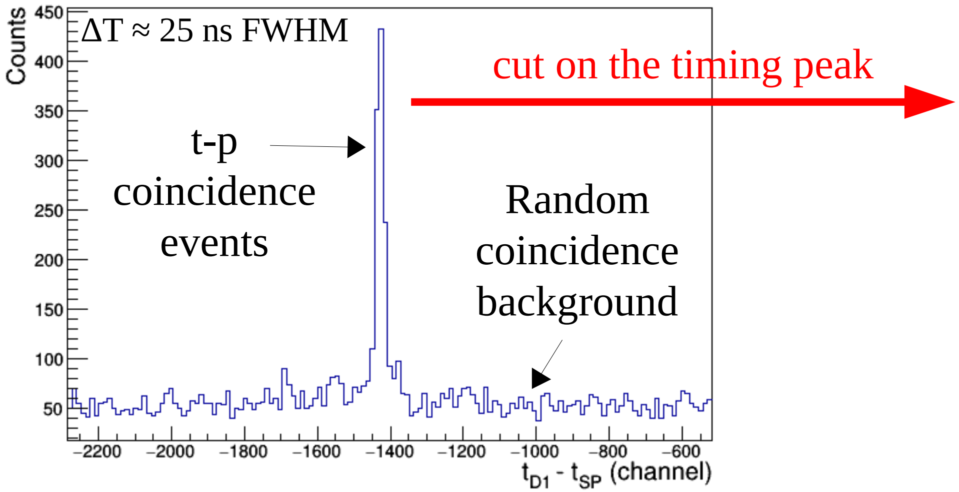


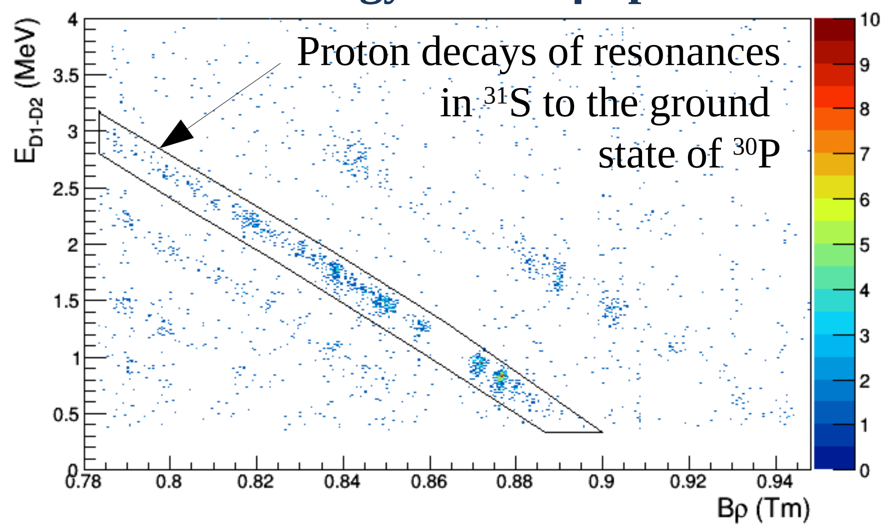
$^{31}P(^{3}He,t)^{31}S^{*}(p)^{30}P$: t-p coincidence events

✓ **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.**

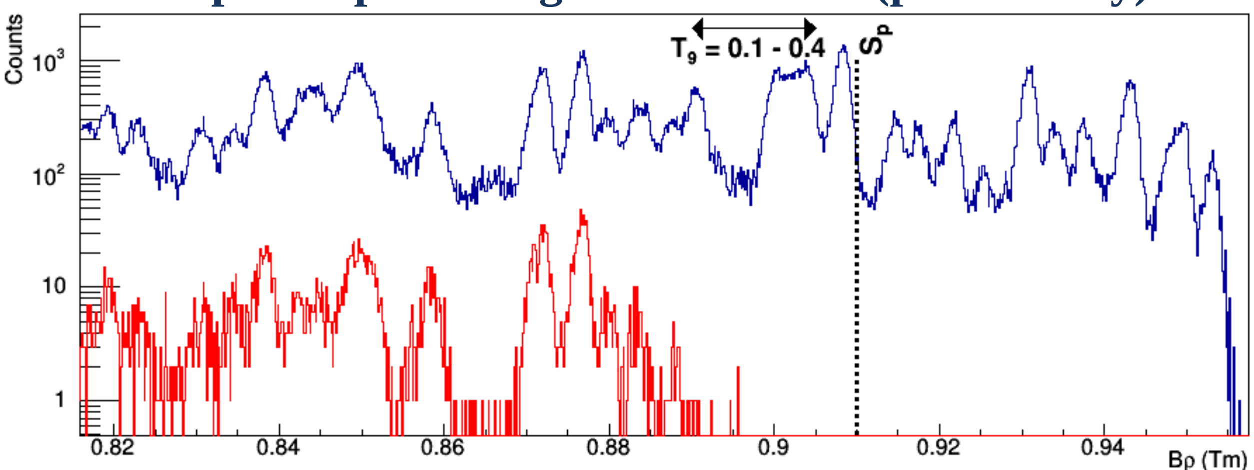
✓ **Triton-proton timing spectrum:**



✓ **DSSSD energy vs SP Bρ spectrum:**



✓ **SP focal plane spectrum gated on tritons (preliminary):**



Blue: triton-singles events

Red: candidate t-p coincidence events

SUMMARY

- The $^{30}P(p,\gamma)^{31}S$ reaction is important for classical novae nucleosynthesis.

- We performed a coincidence measurement using the $^{31}P(^{3}He,t)^{31}S^{*}(p)^{30}P$ 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 $^{30}P(p,\gamma)^{31}S$ reaction rate.

Participants

- A. Meyer, N. De Séréville, F. Hammache, P. Adsley, M. Assié, D. Beaumel, C. Delafosse, F. Flavigny, A. Georgiadou, A. Gottardo, L. Grassi, J. Guillot, T. Id Barkach, M. MacCormick, I. Matea, L. Olivier, L. Perrot, C. Portail, I. Stefan (**Institut de Physique Nucléaire d'Orsay, France**)

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- F. De Oliveira, B. Bastin (**GANIL, France**)

- K. Béroff (**ISMO-Orsay, France**)

- Á. M. Sánchez Benítez (**Faculdade de Ciéncias da Universidade de Lisboa, Portugal**)

- A. Alellara, M. Assunção, V. Guimaraes (**Universidade de São Paulo, Brazil**)

- N. Oulebsir (**Université de Bejaia, Algérie**)

- G. D'Agata (**Università degli Studi di Catania, Italy**)