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

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Abstract. Among reactions with strong impact on classical novae model predictions, ^{30}P$(p, \gamma)^{31}$S is one of the few remained that are worthy to be measured accurately, because of their rate uncertainty, as like as ^{18}F$(p, \alpha)^{15}$O and ^{25}Al$(p, \gamma)^{26}$Si. To reduce the nuclear uncertainties associated to this reaction, we performed an experiment at ALTO facility of Orsay using the ^{31}P$(^{3}$He$, t)^{31}$S reaction to populate ^{31}S excited states of astrophysical interest and detect in coincidence the protons coming from the decay of the populated states in order to extract the proton branching ratios. After a presentation of the astrophysical context of this work, the current situation of the ^{30}P$(p, \gamma)^{31}$S reaction rate will be discussed. Then the experiment set-up of this work and the analysis of the single events will be presented.

1 Introduction

Classical novae are stellar explosions occurring in binary systems consisting of a white dwarf accreting hydrogen-rich material from a companion main sequence star. This accreted matter is mixed

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with the outer layers of the underlying white dwarf. This mixture is heated and compressed until a thermonuclear runaway takes place, leading to new elements ejected into the circumstellar medium. The overall characteristics of classical novae are well described by theoretical models but several key issues remain unexplained: the mixing mechanism and the degree of mixing between the outer white dwarf layers and the accreted material and the observed ejecta masses which are underpredict by an order of magnitude or more.

The study of nuclear reactions during the explosion allow to constrain the physical properties of classical novae. Hydrodynamic models [1] and post-processing calculations [2] have shown that the $^{30}P(p, \gamma)^{31}S$ reaction is a bottleneck for nucleosynthesis of nuclei up to Ca. Its rate therefore affects strongly the abundance predictions for these nuclei. It is also particularly important for understanding the large $^{30}Si/^{28}Si$ isotopic ratios found in presolar meteoritic grains, that are used to be classified as originating from a nova event [3]. Moreover, it was found that the $^{30}P(p, \gamma)^{31}S$ reaction rate uncertainty has the largest impact on the predicted ratios of Si/H, O/S, S/Al, O/P and P/Al, which can be used to constrain the degree of mixing [4] and the peak temperature [5] during the explosion.

2 Current situation and goal

The direct measurement of the $^{30}P(p, \gamma)^{31}S$ reaction rate is currently not feasible due to the difficulty to produce high intensity radioactive ^{30}P beam. So far, indirect methods were used to populate the states of the compound nucleus ^{31}S in the Gamow window, which corresponds, for temperature achieved in novae between 0.1 and 0.4 GK, to excitation energies up to 600 keV above the proton threshold ($S_p = 6.131$ MeV). More recent experimental works are focused on determining the energies, spins and parities of the states of astrophysical interest [6] [7] [8] [9] [10], leading to a more consistent picture of the level scheme of ^{31}S.

In order to calculate the reaction rate, the resonance strengths ($\omega\gamma$) are needed:

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

where J_R, J_p and J_{30P} are the spins of the resonance in ^{31}S, the proton and ^{30}P (ground state), respectively, and the total width of the resonance Γ is the sum of the proton and the γ-ray partial widths (Γ_p and Γ_γ respectively). Experimental constraints on strengths of key low energy resonances have recently been reported [10], and only one experiment so far has measured proton branching ratios for states above 6.7 MeV [11]. We performed a new measurement of proton branching ratios to extend the existing data to states at lower excitation energy and to reduce the current uncertainties using the $^{31}P(^3He, t)^{31}S^*(p)^{30}P$ reaction.

3 Experiment

We measured the $^{31}P(^3He, t)^{31}S^*(p)^{30}P$ reaction at ALTO facility of Orsay. A 25 MeV ^3He beam impinged onto a 60 μg/cm^2-thick ^{31}P target with a 100 μg/cm^2-thick carbon backing (see Fig. 1). The tritons were momentum analyzed with an Enge split-pole magnetic spectrometer [12] at 10° in the laboratory. They were detected and identified at its focal-plane by a position-sensitive gas chamber, a ΔE proportional gas-counter and a plastic scintillator. The decaying protons emitted in coincidence with the tritons were detected in 6 Double Sided Silicon Strip Detectors (DSSSDs) having 16 strips on each side and covering about 15 % of the solid angle. In this experiment we lowered the discriminator threshold in order to detect low energy protons associated to resonances of interest. Furthermore, given that the split-pole angle is 10° in the laboratory, this corresponds to $\theta_{c.m.} \simeq 28°$ for the recoiling

^{31}S nuclei, leading to c.m. angular coverage of the DSSSD array between [75.1°; 177.5°], thereby extending the angular range of Wrede *et al.* set-up [11].

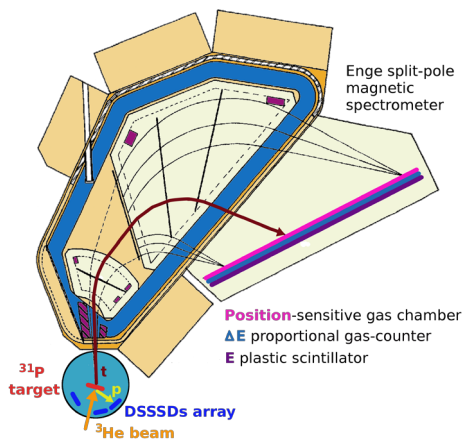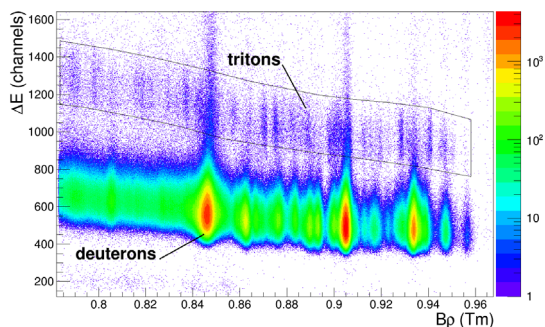**Figure 1.** Schematic of the experimental set-up

Figure 2. Bρ-ΔE identification of the light particles using the split-pole focal-plane detectors. One can see the deuteron loci extending into the triton region.

4 ^{31}P(^{3}He, t)^{31}S triton-singles spectrum

The calibration in magnetic rigidity (Bρ) of the focal-plane position detector was obtained using the triton spectrum at low excitation energies, taking into account the target and backing thickness. During the experiment the spectrometer magnetic field has been recorded, and showed unexpected variations in time, leading to Bρ variations. The maximum field variation observed was about 6×10^{-3} T, which corresponds to about 160 keV variation in excitation energy, while the energy resolution is 50 keV. In order to improve the spectrum quality the magnetic field and the position signals had to be precisely aligned in time.

Then the triton-singles spectrum at energies of interest was obtained after particle identification. However, as one can see in Fig. 2, the deuteron loci extend into the triton region. To remove this deuteron contamination, it was necessary to do several cuts using the signals recorded in the various focal-plane detectors, ie the position-sensitive gas chamber (Bρ), the proportional gas-counter (ΔE), the plastic scintillator (E$_{PlasG}$ and E$_{PlasP}$) and the wire of the position-sensitive gas chamber (ΔE$_{Fil}$). The effect of the different cuts on the triton spectrum are shown in Fig. 3, considering only 7% of all statistic which has been analyzed so far. The comparison of the final spectrum, in red, with the level scheme observed by Wrede *et al.* [11], in blue, shows a satisfying agreement.

5 Perspectives

Analysis will proceed obtaining the coincidence spectrum and then extracting the proton branching ratios. This will be accomplished comparing the number of tritons detected in coincidence with
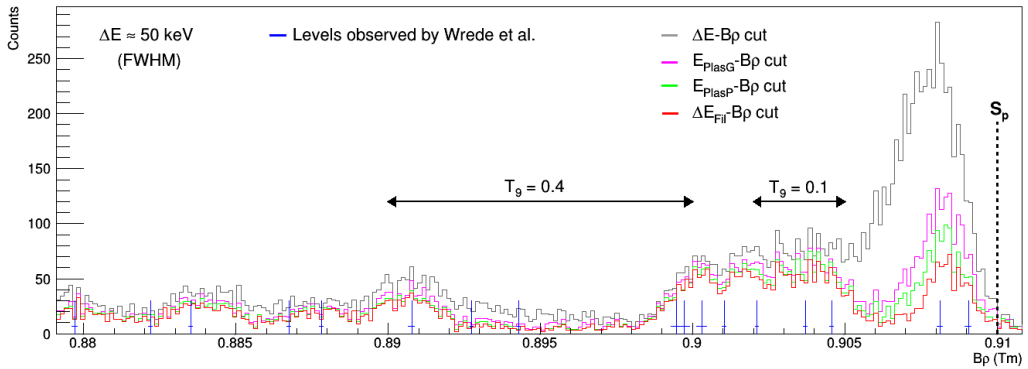
Figure 3. Focal-plane triton spectra from the ^{31}P(^{3}He, t)^{31}S reaction at 25 MeV and $\theta_{\text{lab}} = 10°$, for 7% of all statistic. The effect of the different cuts using combination of focal-plane detectors signals are shown and the final spectrum (in red) can be compared to the levels observed by Wrede *et al.* (in blue).

decaying protons with the number of tritons detected without coincidence. Finally, the obtained proton branching ratios will be used in the ^{30}P(p, γ)^{31}S reaction rate calculation.

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