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First measurement of the ^{31}P(^{3}He,t)^{31}S reaction: a study of the thermonuclear ^{30}P(p,γ)^{31}S reaction rate

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The non-selective ^{31}P(^{3}He,t)^{31}S reaction has been studied for the first time using 20- and 25-MeV ^{3}He beams from the tandem Van de Graaff accelerator at Yale University's Wright Nuclear Structure Laboratory. The Yale Enge magnetic spectrograph has been used to momentum-analyze reaction products; a position-sensitive ionization drift chamber backed by a scintillator at the focal plane has been used to identify tritons and measure the excitation energies of corresponding states in ^{31}S. Proton branching ratios and spins of ^{30}P$+p$ resonances have also been constrained by measuring the angular correlations of decay protons in coincidence with the tritons using the Yale Lamp Shade Array of silicon strip detectors. The ^{31}S energy-level scheme has been considerably extended and refined above the proton threshold of 6133 keV, and the new information has been used to calculate the thermonuclear ^{30}P(p,γ)^{31}S reaction rate up to $T = 10$ GK. Most importantly, the existence of new resonances at $E_{c.m.} = 194.0(25)$ and $266.4(27)$ keV has been deduced which should have a significant impact on ONe nova nucleosynthesis and the classification of presolar ONe nova grains. It is recommended that these resonances be targeted in future direct measurements of the ^{30}P$(p,\gamma)^{31}$S reaction using radioactive ^{30}P ion beams.

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1. Introduction

The uncertain ^{30}P(p,γ)^{31}S reaction rate in oxygen-neon (ONe) novae influences predicted ejecta abundances [1, 2] in the Si-Ca mass region that are observed [3, 4, 5] using optical astronomy and measured [6, 7] in presolar grains [9]. Several presolar SiC and graphite grains that may be of nova origin [6, 7, 8] have ^{30}Si/^{28}Si ratios in excess of the solar abundance by factors of $1.04-2.11$. The predicted value of this ratio [1] is sensitive to the rate of the ^{30}P(p,γ)^{31}S reaction [$Q_{p\gamma} = 6133.0(15)$ keV] since ^{30}P can either capture a proton to form ^{31}S (initiating a path of nucleosynthesis that is unlikely to form ^{30}Si) or β decay ($t_{1/2} = 2.5$ min) to ^{30}Si.

Until 2006, the only available rates for the ^{30}P(p,γ)^{31}S reaction in ONe novae were based on Hauser-Feshbach (HF) statistical model calculations (eg. [10, 11]). Using a HF rate [10], hydrodynamic models of ONe novae [7] on massive $(1.25-1.35\ M_{\odot})$ white dwarfs yield ^{30}Si/^{28}Si ejecta ratios $2.4-9.2$ times the solar value, qualitatively consistent with presolar grain measurements. The predicted ^{30}Si/^{28}Si ejecta ratio can be tuned to agree quantitatively with measurements by invoking mixing with solar composition material [7], or by increasing the ^{30}P$(p,\gamma)^{31}$S reaction rate. The rate may deviate significantly from HF estimates which may not be reliable for a nucleus as light as ^{31}S at the relatively low explosive temperatures of ONe novae where a few resonances could dominate [2]. Therefore, an experimental determination is required to constrain nucleosynthesis in ONe nova models.

Recently, ^{30}P(p,γ)^{31}S rates based on new measurements and compilations of experimental data have been published [12, 13]. However, the measured ^{31}S level density remains relatively low with respect to the level density in its mirror nucleus, ^{31}P, indicating that there are likely undiscovered ^{31}S levels. This results in a reaction rate much lower than the HF estimates, and compounds the quantitative discrepancy between nova-model predictions and presolar-grain measurements.

2. Experiment

We have measured the energies of known ^{30}P(p,γ)^{31}S resonances and searched for new resonances using the non-selective ^{31}P(^{3}He,t)^{31}S reaction [14, 15] at Yale University's Wright Nuclear Structure Laboratory. A tandem Van de Graaff accelerated ^{3}He ions to 20 MeV with intensity up to 50 pnA. An Enge magnetic spectrograph accepted light reaction products through a rectangular aperture of variable solid angle, and momentum analyzed them. Tritons were focused on a detection plane spanned by a position-sensitive ionization drift chamber over radii $70 < \rho < 87$ cm. It measured the position and the energy loss, ΔE, of the particles. The residual energy, E, of particles was deposited into a backing scintillator.

The ^{31}P(^{3}He,t)^{31}S and ^{27}Al(^{3}He,t)^{27}Si reactions were measured over a five-day period with $B = 9$ kG, at spectrograph angles $\theta_{lab} = 1^{\circ}$, 10°, and 20°. Two additional high statistics measurements (five days each) at 8.5 kG were made with $\theta_{lab} = 1.0^{\circ}$ and 1.5°.

3. Analysis

Particle groups (p,d,t,α) were identified by combining ρ, ΔE and E in 2D histograms. Tritons were selected by sorting the data offline through software gates in these histograms, and spectra of focal-plane position were plotted for the ^{31}P(^{3}He,t)^{31}S (Fig. 1) and ^{27}Al(^{3}He,t)^{27}Si reactions.

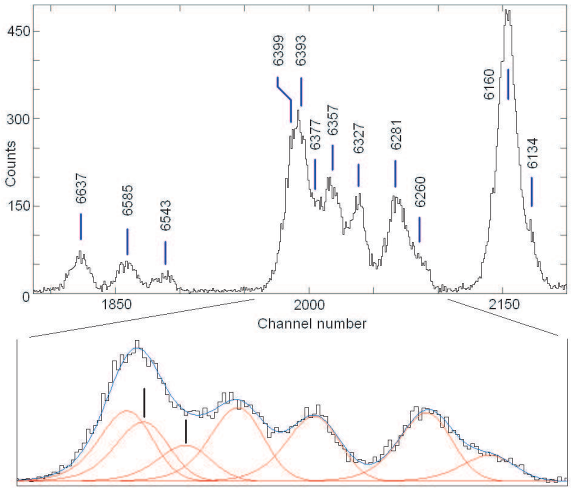

Figure 1: Focal-plane triton spectrum from the ^{31}P(^{3}He,t)^{31}S reaction, corresponding to adopted $E_x(^{31}\mathrm{S}) \approx 6100-6700$ keV (labeled). The spectrum was acquired with $\theta_{lab} = 1.5°$. Magnified: the overall best fit (blue) and seven constituent exponentially modified gaussian peaks (red). The positions of the 6376.9 and 6393.3 keV peaks (markers) and the widths of all peaks were held fixed.

Peaks were fit with exponentially-modified gaussian functions ($\approx$ 25 keV FWHM), and those corresponding to isolated excited states of ^{27}Si in the range $5 < E_x < 9$ MeV [from the ^{27}Al(^{3}He,t)^{27}Si reaction] with uncertainties as low as 0.4 keV (but typically 3 keV) were used for initial focal-plane calibrations. Second-order polynomial least-squares fits of ρ to focal plane position were derived from known ^{27}Si excitation energies [16] and measured peak centroids. These fits were used to identify and determine ^{31}S excitation energies to an uncertainty of 3 keV. Precisely known ^{31}S levels at 5978.2(7) keV, 6160.2(7) keV, 6636.3(15) keV, and 7302.8(8) keV [12] were then used for an internal calibration of the ^{31}S spectra. This eliminated systematic uncertainties associated with using a different target for the calibration and yielded a 2 keV excitation energy uncertainty for most levels. This uncertainty was dominated by reproducibility, not statistics.

4. Results

All known ^{31}S states from the proton threshold to 6.7 MeV were populated, 3 previously unresolved levels were excited at $E_x = 6134(2)$ keV, 6327(2) keV, and 6401(3) keV, and the existence of a level observed to date only tentatively was confirmed at $E_x = 6585(2)$ keV [17].

The ^{30}P(p,γ)^{31}S reaction rate was recalculated using our measurements of $E_r = E_x - Q_{p\gamma}$ together with all other available experimental information. To constrain the J^{π} values of the new ^{31}S levels and aid in the estimation of other resonance parameters, we appealed to its mirror ^{31}P.

We find that the ^{30}P(p,γ)^{31}S reaction rate (Fig. 2) has increased in comparison to the former evaluations [12, 13] by over a factor 2 for $0.09 < T < 0.32$ GK and by over a factor 8 for $0.12 < T < 0.18$ GK. The previously unidentified resonances at $E_r = 194.0(25)$ and $266.4(27)$ keV dominate the rate for $0.08 < T < 0.25$ GK under the present assumptions, spanning over half the range [1] of temperatures ($0.10 \leq T \leq 0.35$ GK) relevant to ONe novae. The $\ell = 0$ resonance at 126.9(23) keV remains dominant for $0.02 < T < 0.08$ GK and the 410.1(25) and 452.1(25) keV resonances still

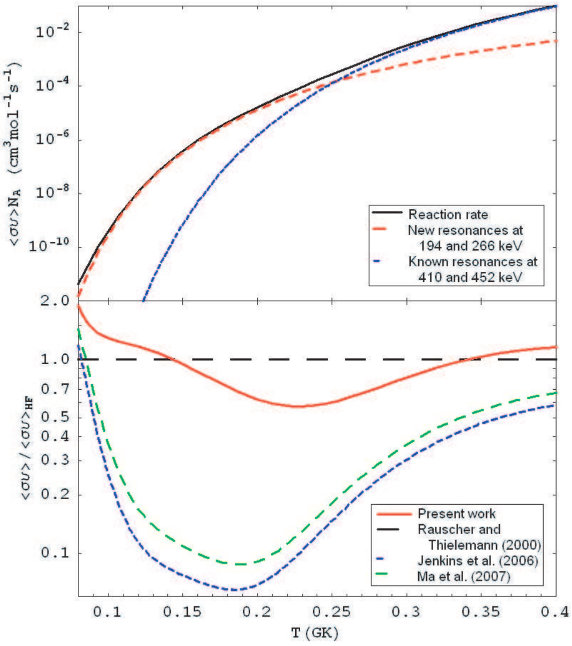

Figure 2: Top: astrophysical ^{30}P$(p,\gamma)^{31}$S reaction rate, showing the dominant contribution of the new resonances from this work for $T < 0.25$ GK. Bottom: ratio of experimental rates derived from this work, Jenkins *et al.* [12], and Ma *et al.* [13] to the Hauser-Feshbach calculations of Rauscher and Thielemann [11].

dominate for $0.25 < T < 0.4$ GK. The 223.8(25) keV ($\ell = 2$) resonance now makes only a minor $2-11\%$ contribution to the rate for $0.10 < T < 0.30$ GK.

The ^{30}P(p,γ)^{31}S rate from the present work is in accord with the rate derived from HF models [10, 11] within a factor two for $T > 0.08$ GK. Therefore any general conclusions drawn using these HF rates in hydrodynamic ONe nova models [7] are supported. In particular, despite the increase in the experimentally determined rate there remains a discrepancy between the ^{30}Si/^{28}Si ratios measured in presolar grains and those predicted for the ejecta of hydrodynamic models. At present this problem seems to require mixing of the ejecta with solar composition material prior to grain condensation, but this picture could change if any resonances are stronger than assumed.

5. Coincidence measurements

We have also measured the ^{31}P(^{3}He$,t)^{31}$S$^*(p)^{30}$P reaction/decay using the Yale Lamp Shade Array of silicon strip detectors to detect decay protons in coincidence with the tritons at the focal plane of the spectrograph. These measurements have been used to constrain the spins, isospins and proton branching ratios (in addition to excitation energies) of higher-lying ^{31}S levels.

The new information has been used to extend the ^{31}S level scheme up to $E_x \approx 8.4$ MeV and evaluate the ^{30}P(p,γ)^{31}S rate up to $T = 10$ GK. This temperature range extends sufficiently high to be used in models of hydrogen burning in type I X-ray bursts ($T < 2$ GK), and oxygen burning in massive stars [where the ^{31}S$(\gamma,p)^{30}$P photodisintegration plays a role].

The measured energies of the first two $T = 3/2$ levels in ^{31}S have been used together with the isobaric multiplet mass equation to constrain the ^{30}S(p,γ)^{31}Cl reaction rate and Q value, which play important roles in the proposed ^{30}S waiting point in type I X-ray bursts and may cause an observed class of double-peaked bursts [18].

6. Future

Although a more complete set of ^{30}P(p,γ)^{31}S resonances has been deduced in this work and the reduction in resonance energy uncertainties has exponentially reduced the related uncertainty in the reaction rate, the resonance strengths used were influenced by partial widths that were necessarily approximated resulting in a large uncertainty in the reaction rate calculation that is still difficult to quantify. Challenging experiments that measure resonance strengths directly using intense radioactive ^{30}P beams will ultimately determine the astrophysical ^{30}P(p,γ)^{31}S reaction rate (eg. [19, 20]), but progress in the near future must be driven by further indirect measurements of resonance parameters because of the difficulty producing ^{30}P beams by the ISOL technique.

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