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Level structure of ^{30}S: Implications for the astrophysical ^{29}P$(p,\gamma)^{30}$S reaction rate in ONe novae and x-ray bursts

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A γ-ray spectroscopy study of ^{30}S is presented. Excitation energies have been determined with improved precision over previous studies and firm spin-parity assignments have been made for key ^{29}P + p resonant states. An evaluation of the ^{29}P$(p,\gamma)^{30}$S reaction for $T = 0.08$–2.5 GK shows that the 3^+ and 2^+ resonant states located at $E_r = 289(3)$ and 410(3) keV, respectively, dominate the ^{29}P$(p,\gamma)^{30}$S reaction rate in ONe novae, while the 410-keV resonance is expected to govern the rate in x-ray burster environments. These new, precise resonance energy measurements and firm spin-parity assignments have significantly reduced uncertainties in the ^{29}P$(p,\gamma)^{30}$S reaction in ONe novae and x-ray bursts. In particular, the reaction rate is now specified precisely enough for calculations of isotopic abundances in ONe novae ejecta.

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Classical novae are among the most frequent and violent stellar explosions to occur in our Galaxy [1]. These cataclysmic astronomical events are driven by thermonuclear runaways that occur on white dwarf stars in close binary systems, with the exact path of nucleosynthesis depending on the size and underlying composition of the compact companion involved. More massive oxygen-neon (ONe) novae achieve significantly higher peak temperatures ($T \sim 0.4$ GK) than those found in carbon-oxygen (CO) novae ($T \sim 0.2$ GK) and, as such, are expected to be responsible for the synthesis of intermediate-mass nuclei up to the Si-Ca region [2]. In particular, hydrodynamic models indicate that ONe novae may yield large silicon and sulfur isotopic abundances relative to the solar one [2].

Recently, several presolar grains recovered from primitive meteorites, which are characterized by large isotopic anomalies that can only be explained by nucleosynthetic processes that took place at the stellar formation site, have been attributed to being of potential nova origins [3,4]. Detailed ion microprobe analysis of these grains has revealed high ^{30}Si/^{28}Si and close-to-solar ^{29}Si/^{28}Si ratios [3,4]. Such measurements are of particular astrophysical significance since ^{30}Si and ^{29}Si abundances are good indicators of the peak temperatures achieved and of the main nucleosynthetic path followed during the thermonuclear runaway. A detailed sensitivity study of novae nucleosynthesis by Iliadis *et al.* [5] highlighted that an increase in the ^{29}P$(p,\gamma)^{30}$S reaction rate compared to the β^+ decay of ^{29}P will drive the flow of material away from ^{29}Si and toward ^{30}Si via the ^{29}P$(p,\gamma)^{30}$S$(\beta^+)^{30}$P$(\beta^+)^{30}$Si reaction sequence. Specifically, it was noted that variations in the ^{29}P$(p,\gamma)^{30}$S reaction rate within its then prescribed uncertainty limits affected predicted ^{29}Si and ^{30}Si isotopic abundances in ONe novae ejecta by a factor of $\sim$3 [5]. Consequently, in order to provide a more reliable classification of novae presolar grains, detailed knowledge of the ^{29}P$(p,\gamma)^{30}$S reaction rate is required.

The ^{29}P$(p,\gamma)^{30}$S reaction is also expected to play a crucial role in x-ray burster environments, which are interpreted as thermonuclear explosions in the atmosphere of an accreting neutron star in a close binary system. During the burst, significantly higher peak temperatures than those found in novae are achieved ($T \sim 0.5$–1.5 GK) and it is possible to break out from the β-limited hot CNO cycles into the rp process, associated with a series of rapid proton capture reactions synthesizing nuclei up to the Sb-Te mass region [6]. However, due to its long half-life ($t_{1/2} \sim 1.2$ s) and the very low Q value of the ^{30}S$(p,\gamma)^{31}$Cl reaction [$Q_{p\gamma} = 287(4)$ keV], the proton-rich nucleus ^{30}S has been identified as a key waiting point in the rp process [7,8]. This causes a significant bottleneck in the reaction flow to ensue at $A = 30$, influencing the time scale of the explosion, the energy generation of the burst, and the structure of the resulting light curve [7,8]. As such, the astrophysical ^{29}P$(p,\gamma)^{30}$S reaction that governs the production of ^{30}S in x-ray bursts is expected to be critical to the theoretical modeling of such environments [9].

Previous studies of the ^{29}P$(p,\gamma)^{30}$S reaction [10–12] indicate that, under explosive astrophysical conditions, the rate is dominated by resonant capture to low-spin excited states above the proton-emission threshold of 4399(3) keV in ^{30}S [13]. In particular, levels located in the excitation energy range $E_x \sim 4.5$–5.6 MeV, which lie within the Gamow window ($E_{cm} \sim 100$–1100 keV) for $T = 0.1$–1.5 GK, are expected to govern the rate in classical novae and x-ray bursts [11]. Two recent ^{32}S$(p,t)^{30}$S transfer reaction studies performed by Bardayan *et al.* [10] and Setoodehnia *et al.* [11] have identified seven excited states in this energy region in ^{30}S. However, with the exception of a single $l_p = 3$ resonance in the ^{29}P + p system located at 5314(7) keV [11], which is not expected to influence the ^{29}P$(p,\gamma)^{30}$S reaction, no firm spin-parity assignments were proposed for any resonant state in ^{30}S [10,11]. Setoodehnia *et al.* attempted to establish spin-parity assignments to ^{29}P + p resonances through a

TABLE I. γ-ray energies, angular distribution coefficients, R_{dco} ratios, γ-ray intensities, normalized to the 2210-keV ground-state transition, and level energies of excited states in ^{30}S. Level energies were corrected for the recoil of the compound nucleus. Resonance energies were calculated from the Q value of 4399(3) keV [13].

E_x (keV) Previous	E_x (keV) Present	E_r(keV)	E_γ (keV)	I_γ	a_2/a_4	R_{dco}	Assignment
2210.6(5)[a]	2210.1(1)		2210.0(1)	100.0(7)	0.14(1)/−0.08(2)	1.21(3)	$2_1^+ \to 0_1^+$
3402.6(5)[a]	3404.1(1)		1194.1(1)	44.9(2)	0.06(1)/0.00(2)	1.12(4)	$2_2^+ \to 2_1^+$
3667.5(10)[a]	3668.0(4)		1457.9(4)	3.2(1)	−0.01(11)/−0.13(13)	0.90(10)	$0_2^+ \to 2_1^+$
3676(3)[a]	3677.1(4)		1467.0(4)	2.3(1)	−0.09(13)/−0.12(14)	0.41(34)	$1_1^+ \to 2_1^+$
4688.0(4)[b]	4687.6(2)	289(3)	1283.4(3)	2.6(1)	−0.10(9)/−0.11(11)	0.44(16)	$3_1^+ \to 2_2^+$
			2477.4(1)	14.8(2)	−0.47(3)/−0.04(4)	0.51(2)	$3_1^+ \to 2_1^+$
4810.4(6)[b]	4808.7(3)	410(3)	1404.5(1)	3.1(1)	0.12(12)/−0.05(15)	1.13(13)	$2_3^+ \to 2_2^+$
			2598.6(4)	3.1(1)			$2_3^+ \to 2_1^+$
5132.7(4)[b]	5132.1(1)	733(3)	2921.8(1)	26.7(2)	0.37(2)/−0.12(3)	1.28(3)	$4_1^+ \to 2_1^+$
5168(6)[a]		769(7)					0_3^+
5217.8(14)[c]	5218.8(3)	820(3)	1814.4(3)	1.4(8)	−0.32(11)/0.02(12)	0.56(34)	$3_2^+ \to 2_2^+$
			3008.5(2)	5.5(1)	−0.28(9)/0.03(11)	0.59(10)	$3_2^+ \to 2_1^+$
5314(7)[c]		915(8)					3_1^-
5391(3)[c]		992(4)					2_4^+
5843(5)[a]	5848.0(4)	1449(3)	3637.7(4)	4.5(1)	0.30(4)/−0.05(6)	1.30(8)	$4_2^+ \to 2_1^+$

[a]Endt [16].
[b]Setoodehnia et al. [14].
[c]Setoodehnia et al. [11].

^{28}Si(^{3}He, n) γ-ray spectroscopy study of ^{30}S [14]. They reported γ decays from the two lowest-lying proton-unbound levels in ^{30}S, which are expected to most strongly influence the ^{29}P(p,γ)^{30}S reaction rate. However, they were unable to obtain angular distribution information, leaving spin-parity assignments ambiguous with considerable uncertainty in the rate as a result.

Here, a 13-MeV, 5-pnA beam of ^{3}He ions delivered by the Argonne ATLAS accelerator was used to bombard a $\sim$120 μg/cm^2 thick ^{28}Si target for 49 h in order to produce ^{30}S nuclei via the one-neutron evaporation channel. The resulting γ decays were detected with the highly efficient, high-resolution Gammasphere detector array [15], which in this instance consisted of 97 Compton-suppressed HPGe detectors. The main fusion reaction channels correspond to one-proton and two-proton evaporation from the compound nucleus ^{31}S, leading to ^{30}P and ^{29}Si, respectively. Energy and efficiency calibrations were obtained using standard ^{152}Eu and ^{56}Co sources. A γ-γ coincidence matrix and a γ-γ-γ cube were produced and analyzed to obtain information on the ^{30}S γ-decay scheme. An angular distribution analysis was performed by fitting γ-ray intensities as a function of detection angle with respect to the beam axis. Due to the relatively low statistics observed for several γ-ray lines, an additional angular correlation analysis was performed. Here, the ratio R_{dco} was defined as the ratio of the γ-ray intensity at forward and backward angles to the intensity at 90° [$R_{dco} = I(\sim 0°) + I(\sim 180°)/I(\sim 90°)$]. R_{dco} values for $\Delta J = 0$ [1.15(3)], $\Delta J = 1$ [0.57(4)], and $\Delta J = 2$ [1.30(5)] transitions were determined by fitting known transitions observed in this study.

Table I presents a summary of the properties of excited states in ^{30}S. The presently observed γ-decay level scheme for ^{30}S is displayed in Fig. 1. Figure 2 provides a coincidence spectrum with a gate placed on the 2210-keV transition in ^{30}S, while a spectrum from the $\gamma\gamma\gamma$ cube with gates placed on the 2210- and 1194-keV transitions in ^{30}S is displayed in Fig. 3.

In the current work, four γ-decay transitions at 2210.0(1), 1194.1(1), 1457.9(4), and 1467.0(4) keV were observed from bound levels in ^{30}S at 2210.1(1), 3404.1(1), 3668.0(4), and 3677.1(4) keV, respectively. This is in good agreement with the previously reported γ-decay transitions from bound states in ^{30}S [16]. An angular distribution analysis of the observed, coincident 2210- and 1194-keV γ rays revealed a_2 and a_4 coefficients consistent with $\Delta J = 2$ and 0 transitions, respectively, indicating $J = 2$ spin assignments for the 2210- and 3404-keV excited levels in ^{30}S. Previous studies have firmly established 2^+ spin-parity assignments for these two lowest-lying excited states in ^{30}S [16]. Consequently, we also adopt 2_1^+ and 2_2^+ spin-parity assignments for the 2210- and 3404-keV excited levels. Considering bound states in ^{30}S further, one finds that the 3677-keV level has been previously tentatively assigned 1^+ [16]. The presently observed 1467-keV γ-decay transition to the 2_1^+ level from the 3677-keV state was measured to have an R_{dco} ratio consistent with a $\Delta J = \pm 1$ transition, indicating a $J = 1$ or 3 spin assignment. Examining the mirror nucleus, ^{30}Si, in the energy range 3.0–4.5 MeV, we see that there are no $J = 3$ states and only a single 1^+ level is known to exhibit a strong γ-decay branch to the 2_1^+ level [16,17]. As such, we assign a 1467-keV γ ray from a 1_1^+, 3677-keV excited state in ^{30}S. Finally, to conclude the discussion of bound states in ^{30}S, the remaining transition at 1458 keV was measured to have an isotropic angular distribution, pointing toward a $J = 0$ spin assignment for the 3668-keV excited state in ^{30}S. In comparison with the mirror nucleus, the 0_2^+, 3788-keV level is the only $J = 0$ state in the energy range 3.0–4.5 MeV [16]. Consequently, we

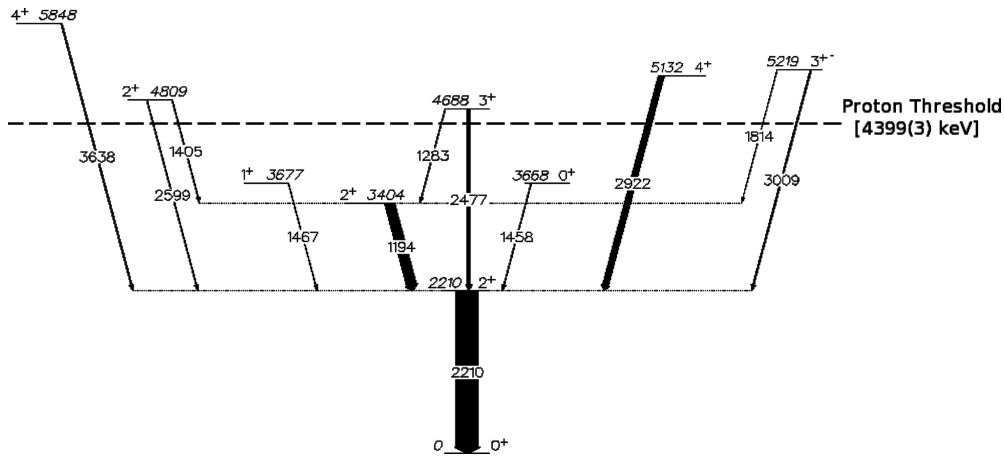

FIG. 1. Observed γ-decay scheme for ^{30}S from the present work.

assign the presently observed 3668-keV excited state in ^{30}S as 0_2^+.

The lowest-lying excited state to be observed above the proton threshold in ^{30}S appears at 4687.6(2) keV, in good agreement with Setoodehnia *et al.* [14]. This level, corresponding to a resonance in the ^{29}P + p system at 289(3) keV, was observed to exhibit 1283.4(3)- and 2477.4(1)-keV γ-decay branches to the 2_2^+ and 2_1^+ excited states in ^{30}S, respectively, as demonstrated in Figs. 2 and 3. These transitions were also reported in Ref. [14]. An angular distribution analysis of the 1283- and 2477-keV γ rays from the 4688-keV state reveals $\Delta J = \pm 1$ character, indicating a $J = 1$ or 3 spin assignment. In comparison with the mirror nucleus ^{30}Si in the energy range 4.2–5.0 MeV, there are no known $J = 1$ states and the 3_1^+, 4828-keV excited is the only $J = 3$ excited level [16,17]. Consequently, we assign 1283- and 2477-keV γ-ray transitions from the 3_1^+, 4688-keV state in ^{30}S.

A low-intensity γ-ray coincidence with the 2_1^+ level in ^{30}S was observed at 2598.6(4) keV, as seen in Fig. 2, indicating a proton-unbound state at 4808.7(3) keV. The precise excitation energy reported here is in slight disagreement with that of Ref. [14], although the γ-ray energy matches well. The 4809-keV level was also observed to exhibit an additional 1404.5(1)-keV γ-decay branch to the 2_2^+ level in ^{30}S (see Fig. 3). This γ ray was measured to have an R_{dco} ratio consistent with a $\Delta J = 0$ transition, indicating a $J = 2$ assignment for the 4809-keV excited state. In the mirror nucleus, ^{30}Si, in the energy range 4.2–5.1 MeV, the 2_3^+, 4810-keV state is the only known $J = 2$ level [16,17]. As such, we assign 1405- and 2599-keV γ rays from the 2_3^+, 4809-keV excited level in ^{30}S.

Considering Fig. 2 further, one sees that γ-ray transitions to the 2_1^+ level are observed at 2921.8(1) and 3637.7(4) keV, indicating excited states in ^{30}S at 5132.1(1) and 5848.0(4) keV. The excitation energies reported here are in reasonable agreement with previous values [14,16] and correspond to resonance energies in the ^{29}P + p system of 733(3) and 1449(3) keV, respectively. Both the 2922- and 3638-keV γ rays were measured to have a_2/a_4 coefficients consistent with $\Delta J = \pm 2$ transitions. Since the observed distributions are anisotropic, 0^+ assignments are ruled out, leading to 4_1^+ and 4_2^+ assignments for the 5132- and 5848-keV excited levels in ^{30}S, respectively.

A previous β-delayed $2p$ decay study of ^{31}Ar [18] and a ^{32}S$(p,t)^{30}$S transfer reaction study [11] have identified an excited state in ^{30}S at 5217.8(14)/keV. In the present work, we observe 1814.4(3)- and 3008.5(2)-keV γ-decay branches to the 2_2^+ and 2_1^+ levels in ^{30}S, as shown in Figs. 2 and 3, respectively. This establishes an excited state at 5218.8(3) keV, in good agreement with the previously reported level energy [11]. Both the 1814- and 3009-keV γ rays were found to have a_2, a_4, and R_{dco} values consistent with $\Delta J = \pm 1$ transitions, indicating a $J = 1$ or 3 spin assignment for the presently

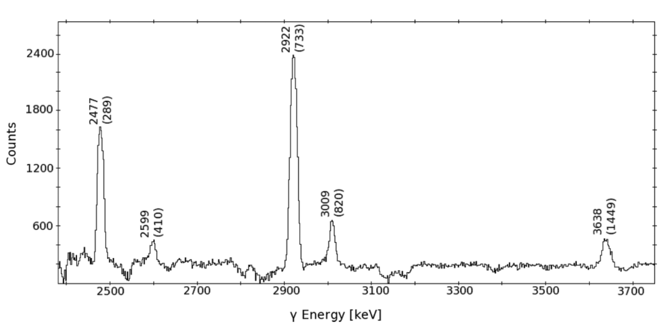

FIG. 2. Coincidence spectrum gated on the 2210-keV transition in ^{30}S. Numbers in parentheses represent resonance energies.

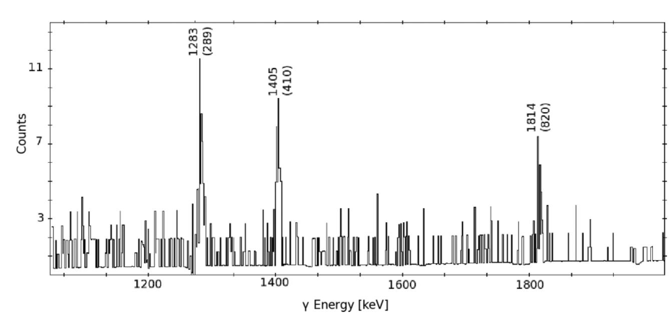

FIG. 3. Spectrum from the coincidence cube gated on the 2210- and 1194-keV transitions in ^{30}S. Numbers in parentheses represent resonance energies.

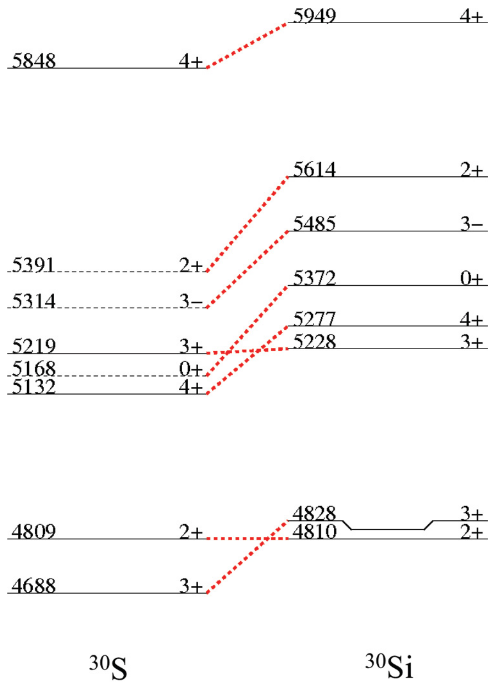

FIG. 4. (Color online) Mirror assignments of excited states in ^{30}S over the energy range 4.6–5.9 MeV. Dashed horizontal lines indicate excited states not observed in the present work. These levels are expected to decay predominantly by proton emission.

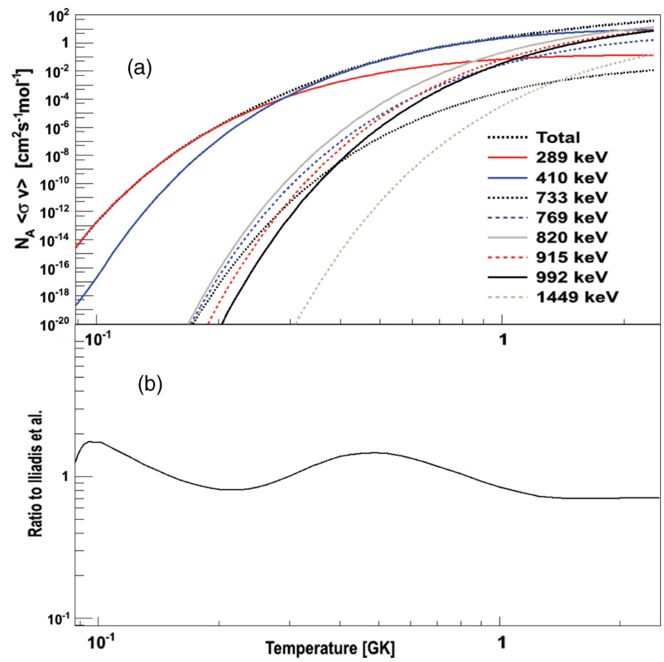

FIG. 5. (Color online) (a) Contributions of individual resonances to the ^{29}P$(p,\gamma)^{30}$S reaction rate. (b) Ratio of the presently estimated ^{29}P$(p,\gamma)^{30}$S reaction rate to the most recent theoretical estimate of Iliadis *et al.* [21].

observed 5219-keV state. In comparison with the mirror nucleus ^{30}Si, in the energy range 5.0–6.0 MeV, there are no $J = 1$ states and only the 3_2^+, 5228-keV and 3_1^-, 5485-keV levels are known to exhibit γ-decay branches to the 2_2^+ and 2_1^+ excited states [16,17] (see Fig. 4 for the matching of ^{30}S resonant levels with their mirror partners). The 3_1^-, 5485-keV level has already been paired with the firmly established 3_1^-, 5314-keV state in ^{30}S [11,19], which was not observed in this study. As such, we assign the 5219-keV excited state in ^{30}S, corresponding to a resonance in the ^{29}P + p system at 820(3) keV, as 3_2^+.

Proton-unbound excited states previously reported at 5168(6) and 5391(3) keV in ^{30}S in the ^{32}S(p,t) studies of Bardayan *et al.* [10] and Setoodehnia *et al.* [11], respectively, corresponding to ^{29}P + p resonances at 769(7) and 992(4) keV, were not observed in the present work. An examination of ^{30}Si in the excitation energy region 0.0–6.0 MeV [16,17] reveals that only the 0_3^+, 5372-keV and 2_4^+, 5614-keV levels remain unmatched to mirror analogs in ^{30}S. In Ref. [10], the 5168-keV state in ^{30}S was highlighted as a likely doublet and angular distributions indicated a $4^+ + 0^+$ assignment for this level. In the present work, we have firmly assigned the 5132-keV excited state in ^{30}S, which lies in close proximity to the 5168-keV level reported in Ref. [10], as 4_1^+. Consequently, we conclude that the 5168-keV state represents the 0_3^+ excited level in ^{30}S and assign the unobserved state at 5391 keV as 2_4^+, which is also consistent with the angular distribution measurements reported in Ref. [10]. Barrier penetrability calculations indicate that the proton widths of $l_p = 0$ and $l_p = 2$ captures to excited states in ^{30}S at 5168 and 5391 keV, respectively, are several orders of magnitude larger than the corresponding γ widths and, as such, would not be expected to be observed here.

For the estimate of the ^{29}P$(p,\gamma)^{30}$S reaction rate, shown in Fig. 5(a), we use our precise energy measurements, together with the new unambiguous spin-parity assignments. Proton partial widths of ^{29}P + p resonant states were calculated by using spectroscopic factors, C^2S, of mirror states in ^{30}Si measured with the ^{29}Si(d,p) reaction [20] (and where states were too weak to be observed in that study a value of $C^2S = 0.01$ has been assumed). Analog states of the low-lying resonances in ^{30}S at 289 and 410 keV, in particular, were measured to have spectroscopic factors, C^2S, of 0.04 and 0.11, respectively [20], with no errors quoted. Gamma-ray partial widths of ^{29}P + p resonant states have been estimated using the measured lifetimes of proposed mirror states in ^{30}Si based on the present work. In the case of the 992-keV resonance, for which no measured lifetime is available for its mirror analog, we adopt the γ-ray partial width reported for this state in the most recent theoretical study of the ^{29}P$(p,\gamma)^{30}$S reaction by Iliadis *et al.* [21]. For temperatures $T = 0.1$–0.4 GK, covering the entire range of ONe novae, the rate is found to be dominated by $l_p = 2$ capture resonances at 289 and 410 keV, with spin-parity assignments of 3^+ and 2^+, respectively. At higher astrophysical temperatures, $T \geqslant 0.5$ GK, corresponding to those found in x-ray bursts, the 410-keV resonance is expected to govern the ^{29}P$(p,\gamma)^{30}$S reaction rate, with an additional contribution from the 3^+, 820-keV resonance at ∼2 GK.

Figure 5(b) displays the presently estimated ^{29}P$(p,\gamma)^{30}$S reaction rate as a ratio to the most recent estimate of the rate by Iliadis *et al.* [21]. It can be seen that good agreement is found between the rates in the burning regions of ONe novae and x-ray burster environments. These rates are approximately a factor of 2 higher than the ^{29}P$(p,\gamma)^{30}$S reaction rate reported in the novae nucleosynthesis sensitivity study of Iliadis *et al.* [5]. Assuming, conservatively, uncertainties in the proton and γ-ray partial widths of the key 3^+, 289-keV and 2^+, 410-keV low-lying resonant states in ^{30}S of a factor of 2 gives a range of values ∼90%–100% of the nominally predicted abundances for ^{29}Si and ^{30}Si isotopes in novae ejecta [5].

In summary, a ^{28}Si(^{3}He, n) fusion-evaporation reaction was used to populate excited states in the proton-rich nucleus ^{30}S. An analysis of the resulting γ decays has allowed for excitation energies to be measured with improved precision over previous studies and for firm spin-parity assignments to key resonant states above the proton threshold in ^{30}S to be made. In estimating the ^{29}P$(p,\gamma)^{30}$S reaction rate in ONe novae and x-ray burster environments, good agreement has been found between the present results and the theoretical predictions of Iliadis *et al.* [21]. This highlights the quality of the work carried out in Ref. [21] and the importance of theoretical estimates of astrophysical reaction rates in the absence of experimental data. However, the current work now represents the most recent, precise experimental determination of the rate and has both affirmed the results of Ref. [21] and significantly reduced uncertainties in the ^{29}P$(p,\gamma)^{30}$S reaction in ONe novae and x-ray bursts. In particular, the present energy measurement of the key 410(3)-keV resonance has reduced uncertainties in its energy by a factor ∼13 compared to the theoretical estimate of Iliadis *et al.* [21]. Furthermore, the new firm 4^+ spin-parity assignment of the 733-keV resonance has reduced its resonance strength by ∼4 orders of magnitude compared to that reported in Ref. [21]. It is expected that the reaction rate is now determined well enough for the purposes of precise calculations of abundances in ONe novae ejecta [5].

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