Spectroscopy of ^{30}P and the abundance of ^{29}Si in presolar grains

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The astrophysical ^{29}Si(p, γ) reaction is expected to play a key role in determining the final ^{29}Si yields ejected in nova explosions. Such yields are used to accurately identify the stellar origins of meteoritic stardust and recently, distinctive silicon isotopic ratios have been extracted from a number of presolar grains. Here, the light-ion ^{28}Si(^{3}He, p) fusion-evaporation reaction was used to populate low-spin proton-unbound excited states in the nucleus ^{30}P that govern the rate of the astrophysical ^{29}Si(p, γ) reaction. In particular, γ decays were observed from resonances up to $E_r = 500$ keV, and key resonances at 217 and 315 keV have now been identified as 2^+ and 2^- levels, respectively. The present paper provides the first estimate of the 217-keV resonance strength and indicates that the strength of the 315-keV resonance, which dominates the rate of the ^{29}Si(p, γ) reaction over the entire peak temperature range of oxygen-neon novae, is higher than previously expected. As such, the abundance of ^{29}Si ejected during nova explosions is likely to be less than that predicted by the most recent theoretical models.

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Nova explosions are understood to result from the thermonuclear runaway of accreted hydrogen- and helium-rich shells on the surfaces of white dwarf stars in close binary systems. During such events, peak temperatures ≈0.1–0.4 GK are readily achieved and $\approx 10^{-7}$–10^{-3} $M_\odot$ of nuclear processed material, containing nonsolar isotopic abundance ratios, is ejected into the interstellar medium at velocities of several thousand km s^{-1} [1–4]. This makes classical novas among the most violent stellar explosions to occur in our Galaxy. Spectroscopically speaking, there are two classes of novae: (i) oxygen-neon (ONe) that are characterized by the presence of intense neon lines in their ejecta and (ii) carbon-oxygen (CO) that exhibit an absence of such lines. In ONe novae, which involve more massive white dwarf companions than CO novae, it is expected that higher temperatures and pressures allow for the synthesis of elements up to the Si-Ca mass region [5,6]. That being said, a number of key questions remain about the exact contribution of ONe novae to the chemical evolution of the Milky Way.

Recently, the discovery of presolar grains in primitive meteorites has offered fresh insight into stellar nucleosynthesis throughout the cosmos [7–11]. These microscopic pieces of matter are characterized by large isotopic anomalies that can only be explained by nuclear processes that took place in the parent star, around which they were formed. Consequently, if uniquely identified, presolar grains offer a versatile tool for studying nucleosynthesis within specific stellar sites.

For presolar grains that have condensed in the ejecta of ONe novae, it is expected that high ^{30}Si / ^{28}Si ratios and close-to-solar ^{29}Si / ^{28}Si yields may provide a distinctive signature [12–14]. However, uncertainties in the underlying nuclear physics processes responsible for the production and destruction of silicon isotopes in nova events has made the accurate classification of presolar grains from these ratios challenging. In this regard, whereas the expected ^{29}Si / ^{28}Si ratio may be similar to the solar value, it is still important to constrain for novae nucleosynthesis calculations. Furthermore, in contrast to other isotopic species ejected in nova explosions, the abundance of ^{29}Si is largely determined by a single reaction—the ^{29}Si(p, γ)^{30}P reaction. Specifically, a landmark sensitivity study of nova's nucleosynthesis by Iliadis *et al.* [15], highlighted that variations of the astrophysical ^{29}Si(p, γ)^{30}P reaction rate, within its then known experimental uncertainties [16–18], could result in changes in the ejected abundance of ^{29}Si by up to a factor ≈4.

Previous studies of the astrophysical ^{29}Si(p, γ)^{30}P reaction [19] indicate that, under explosive astrophysical conditions, the rate is dominated by resonant capture on the ground

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TABLE I. Properties of excited states in ^{30}P. Level energies are corrected for the recoil of the compound nucleus. Spin-parity assignments are based on present angular distribution coefficients, shell model calculations, and previous studies [21–23].

E_x (keV) Present	E_x (keV) Basunia [21]	E_r (keV)	E_γ (keV)	a_2/a_4	R_{dco}	Assignment
5506.7(5)	5506.3(2)		4829.1(5)	−0.21(3)/0.00(3)	0.85(2)	$1^+ \to 0^+$
5509.2(4)	5508.55(8)		3535.0(3)			$3^+ \to 3^+$
			4054.3(3)	−0.24(4)/0.09(5)	0.73(5)	$3^+ \to 2^+$
5577.3(8)	5576.3(1)		4122.5(21)			$2^+ \to 2^+$
			4867.9(5)	−0.16(41)/0.01(35)	0.81(12)	$2^+ \to 1^+$
5596.3(3)	5597(5)	1.8(5)	3056.9(3)	0.20(5)/ − 0.04(6)	1.16(11)	$5^+ \to 3^+$
5599.8(3)	5597(5)	5.3(5)	2661.6(2)	0.04(2)/ − 0.02(3)	0.99(6)	$4^+ \to 3^+$
5701.1(3)	5701.3(2)	106.6(5)	1518.3(2)	−0.23(8)/0.02(10)	0.70(19)	$1^+ \to 2^+$
			2763.0(2)	−0.14(3)/0.08(6)	0.68(4)	$1^+ \to 2^+$
			3161.6(19)	0.29(7)/0.06(10)	1.17(8)	$1^+ \to 3^+$
5717.0(18)	5715(4)	122.5(18)	5039.4(18)	−0.24(9)/0.02(12)	0.92(10)	$1^- \to 0^+$
5775.9(6)	5788(5)	181.4(7)	3801.9(6)	0.59(9)/0.03(12)	1.17(8)	$5^+ \to 3^+$
5811.2(4)	5808(5)	216.7(6)	3271.3(4)	−0.11(3)/0.01(4)	0.86(3)	$2^+ \to 3^+$
			3837.3(3)	−0.17(7)/0.08(9)	0.82(6)	$2^+ \to 3^+$
5898.9(3)	5896(5)	304.4(4)	1716.3(2)	−0.13(4)/0.08(5)	0.78(3)	$3^+ \to 2^+$
			2960.6(2)	0.02(3)/ − 0.07(4)	0.93(5)	$3^+ \to 2^+$
5909.1(6)	5907.8(8)	314.6(7)	5199.8(6)	−0.20(9)/ − 0.12(10)	0.79(7)	$2^- \to 1^+$
5934.8(8)	5934.0(1)	340.3(9)	1590.1(2)	0.03(2)/0.03(3)	0.85(12)	$4^+ \to 5^+$
			2996.6(6)	0.56(11)/0.14(11)	1.06(12)	$4^+ \to 2^+$
			3095.0(40)		0.60(18)	$4^+ \to 3^+$
			3961.1(4)	−0.41(8)/ − 0.04(11)	0.98(10)	$4^+ \to 3^+$
5996.8(5)	5997.2(8)	402.3(6)	5287.6(2)		1.10(12)	$1^- \to 1^+$
			5319.1(6)		0.94(6)	$1^- \to 0^+$
6006.2(8)	6006.0(1)	411.7(9)	3466.4(7)	0.00(4)/ − 0.09(5)*f*	1.12(11)	$3^+ \to 3^+$
			4032.2(8)		1.30(37)	$3^+ \to 3^+$
Unobserved	6051(5)	456.5(50)				0^+
6094.7(3)	6093.5(1)	500.2(4)	1467.7(1)	0.33(2)/ − 0.02(2)	1.37(5)	$3^- \to 3^-$
			1861.8(1)			$3^- \to 4^-$

state of ^{29}Si ($J^\pi = 1/2^+$) to low-spin excited states above the proton-emission threshold of 5594.75(7) keV [20] in ^{30}P. In particular, three excited states at 5811, 5909, and 5997 keV in ^{30}P [21], corresponding to resonances at 217, 315, and 402 keV in the ^{29}Si$+p$ system, have been reported to have large proton spectroscopic factors [22]. Hence, their respective resonance strengths $\omega\gamma$ are expected to have the most significant impact on the ^{29}Si$(p,\gamma)^{30}$P reaction. The 402-keV resonance has been studied precisely using direct techniques [16]. However, very little information exists on the 217-keV resonance and previous measurements of the 315-keV state have yielded conflicting results [$\omega\gamma = 0.015(5)$ eV [17] and $\omega\gamma = 0.028(4)$ eV [18]). In this regard, a determination of the unknown spin-parity assignments of the 217- and 315-keV resonances may offer an explicit solution. For instance, a spin assignment of $J = 2$ for the 315-keV resonance would support the strength reported by Harris *et al.* [18] and not that of the most recent study [17]. In this paper, we employ a ^{28}Si(^{3}He, p) fusion-evaporation reaction to perform an in-beam γ-ray spectroscopy study of the astrophysically important nucleus ^{30}P. The choice of a light-ion transfer reaction allows for a selective population of key low-spin proton-unbound resonant states, and for constraints to be made on the spin-parity assignments.

Here, a 13-MeV 5-pnA beam of ^{3}He ions, delivered by the Argonne ATLAS accelerator, was used to bombard a $\approx$ 120 μg/cm^2-thick ^{28}Si target for 49 h in order to produce ^{30}P nuclei via the one-proton evaporation channel. Gamma decays were detected with the Gammasphere detector array [24], which, in this instance, consisted of 97 Compton-suppressed HPGe detectors. 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}P γ-decay scheme. Angular distributions were extracted by fitting γ-ray intensities as a function of detection angle with respect to the beam axis, and angular correlation measurements were performed, defining R_{dco} as the ratio of the γ-ray intensity at forward and backward angles to the intensity at 90° [$R_{dco} = I(\approx 0^\circ) + I(\approx 180^\circ)/I(\approx 90^\circ)$]. R_{dco} values for $\Delta J = 1$ [0.85(3)] and $\Delta J = 2$ [1.21(1)] transitions were determined by fitting known transitions in ^{30}P [21] observed in this paper. In total, over 50 excited states in ^{30}P were identified by their γ decays. However, for the purposes of the present paper, we restrict our discussion to the properties of proton-unbound resonant states that affect the astrophysical ^{29}Si$(p,\gamma)^{30}$P reaction.

Table I presents the properties of excited states in ^{30}P close to, and above, the proton-emission threshold energy.

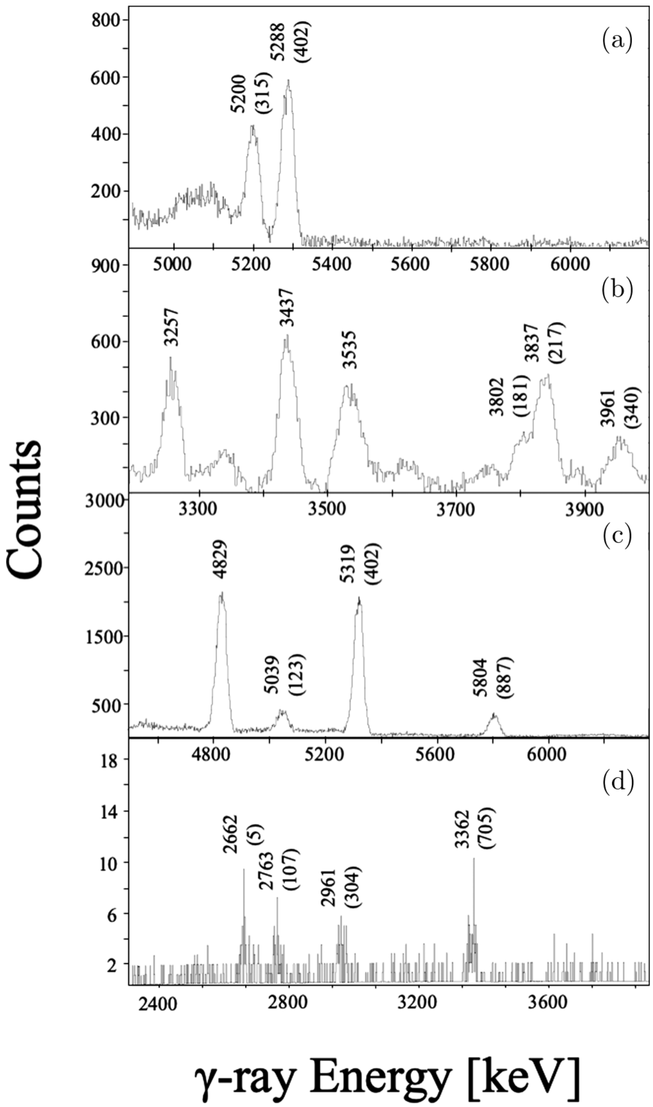

FIG. 1. (a) γ-γ coincidence spectrum with a gate placed on the 709-keV $1_2^+ \rightarrow 1_1^+$ transition in ^{30}P. Numbers in parentheses represent resonance energies. (b) γ-γ coincidence spectrum with a gate placed on the 1973-keV $3_1^+ \rightarrow 1_1^+$ transition. (c) γ-γ coincidence spectrum with a gate placed on the 677-keV $0_1^+ \rightarrow 1_1^+$ transition and (d) γ-γ-γ coincidence spectrum with gates placed on the 677-keV $0_1^+ \rightarrow 1_1^+$ and 2260-keV $2_3^+ \rightarrow 0_1^+$ transitions.

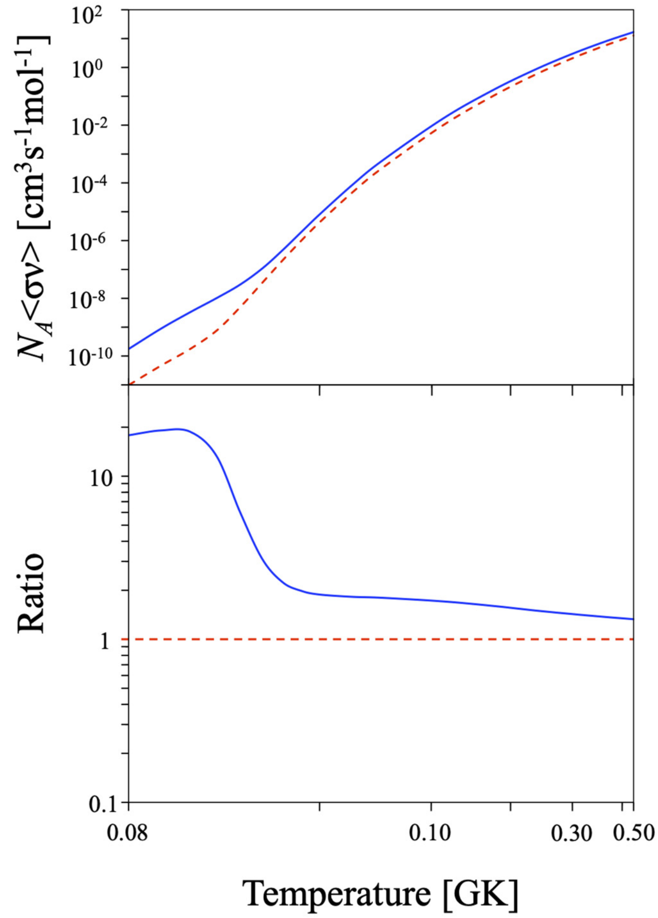

FIG. 2. (Top) The ^{29}Si$(p, \gamma)^{30}$P stellar reaction rate as a function of temperature. The solid blue line represents the present rate as per the resonant parameters presented in Table II (the direct capture component is negligible for temperatures $T \geqslant 0.03$ GK [25]), whereas the dashed red line represents the rate reported in Refs. [19,26]. (Bottom) The solid blue line shows the ratio of the present rate to the rate of Refs. [19,26]. A dashed red line has been included to highlight what would be expected for a ratio of 1:1.

Examples of γ-γ coincidence spectra produced in this paper are shown in Figs. 1(a)–1(c), whereas an example γ-γ-γ cube spectrum is displayed in Fig. 1(d).

In Fig. 1(a), high-intensity γ-ray transitions to the 1_2^+ level at 709 keV in ^{30}P [21] are observed at 5199.8(6) and 5287.6(2) keV, indicating excited states at 5909.1(6) and 5996.8(5) keV that correspond to ^{29}Si$\,+p$ resonances at 314.6(7) and 402.3(6) keV, respectively. The 402-keV resonance is also observed to γ decay via a 5319.1(6)-keV transition to the 0_1^+ level in ^{30}P as illustrated in Fig. 1(c). These transitions have been observed previously, and the presently reported γ-ray energies are in good agreement with earlier work [21]. In the ^{29}Si$(^3$He$, d)$ study of Dykoski and Dehnhard [22], population of the 315- and 402-keV resonances were described by $\ell = 1$ transfers on the $1/2^+$ ground state of ^{29}Si, pointing to $(0, 1, 2)^-$ spin-parity assignments for these states. Here, an angular distribution analysis of the 5200-keV γ ray revealed a_2 and a_4 coefficients as well as an R_{dco} ratio, consistent with a momentum change of $\Delta J = \pm 1$. Consequently, a 2^- assignment is firmly assigned for the 315-keV resonance (γ decay from a spin zero state would result in an isotropic distribution). In contrast, the observed 5319-keV decay to the 0^+, 677-keV level, from the excited state at 5997 keV, rules out a 0^- or 2^- assignment. As such, we adopt a spin-parity assignment of 1^- for the 402-keV resonant state in ^{30}P.

Considering Fig. 1(b), 3801.9(6)-, 3837.3(3)-, and 3961.1(4)-keV γ-decay transitions to the 3_1^+ excited state in ^{30}P are observed, indicating proton-unbound levels at 5775.9(6), 5811.2(4), and 5934.8(8) keV, respectively. Of these states, only the 5811-keV level, which corresponds to

TABLE II. Summary of resonance parameters for the evaluation of the astrophysical ^{29}Si(p,γ) stellar reaction rate. Lifetimes for the determination of γ-ray partial widths have been adopted from Ref. [21] unless otherwise noted.

E_r (keV)	J^π	C^2S	Γ_p (eV)	Γ_γ (eV)	$\omega\gamma$
2	5^+	0.016(2)			
5	4^+	0.020(3)			
107	1^+	$\leqslant 0.01$	$\leqslant 1.4 \times 10^{-10}$	6.0×10^{-2}	$\leqslant 1.1 \times 10^{-10}$
123	1^-	$\leqslant 0.01$	$\leqslant 6.7 \times 10^{-10}$	1.3×10^{-1}[a]	$\leqslant 5.0 \times 10^{-10}$
181	5^+	$\leqslant 0.01$	$\leqslant 2.1 \times 10^{-12}$	1.3×10^{-1}[a]	$\leqslant 5.7 \times 10^{-12}$
217	2^+	0.012(2)	$3.7(7) \times 10^{-7}$	1.3×10^{-1}[a]	$4.7(7) \times 10^{-7}$
304	3^+	$\leqslant 0.01$	$\leqslant 2.9 \times 10^{-5}$	1.3×10^{-1}[a]	$\leqslant 4.7 \times 10^{-5}$
315	2^-	0.17	$2.5(5) \times 10^{-2}$	1.1×10^{-1}[a]	$2.5(4) \times 10^{-2}$
340	4^+	$\leqslant 0.01$	$\leqslant 2.2 \times 10^{-8}$	1.3×10^{-1}[a]	$\leqslant 4.9 \times 10^{-8}$
402	1^-	0.21(3)	$5.0(8) \times 10^{-1}$	1.1[b]	$2.60(25) \times 10^{-1}$[c]
412	3^+	$\leqslant 0.01$	$\leqslant 9.9 \times 10^{-4}$	1.3×10^{-1}[a]	$\leqslant 1.7 \times 10^{-3}$
457	0^+	$\leqslant 0.01$	$\leqslant 2.9 \times 10^{-1}$	3.7×10^{-1}[d]	$\leqslant 4.1 \times 10^{-2}$
500	3^-	0.17(3)	$3.1(6) \times 10^{-3}$	1.1×10^{-3}	$5.3(9) \times 10^{-3}$

[a]A lifetime of 5 fs has been assumed.
[b]Determined from measured resonance strength [17].
[c]Adopted from Ref. [17].
[d]A lifetime of 1 fs has been assumed.

a ^{29}Si$+p$ resonance at 216.7(6) keV, has been reported to have a measurable proton spectroscopic factor ($C^2S = 0.01$) [22]. In Ref. [22], the 217-keV resonance was fit with a $\ell = 2$ distribution, indicating possible spin-parity assignments of $(1, 2, 3)^+$. No γ decays have ever been reported for this resonance, and an angular distribution of the 3837-keV γ ray to the 3_1^+ level in ^{30}P provided a_2/a_4 coefficients as well as an R_{dco} ratio, consistent with a $\Delta J = \pm 1$ transition. Furthermore, an additional 3271.3(4)-keV γ ray from the 217-keV resonance to the 3_2^+ state in ^{30}P also exhibited a $\Delta J = \pm 1$ nature. Consequently, we assign the 5811-keV excited state in ^{30}P, corresponding to a 217-keV resonance in the ^{29}Si$+p$ system as a 2^+ level.

For an evaluation of the astrophysical ^{29}Si$(p,\gamma)^{30}$P reaction rate, we consider all resonances from $E_r = 0$–500 keV and use the new precise resonance energies together with our unambiguous spin-parity assignments. Proton spectroscopic factors C^2S of 0.012 and 0.17, obtained in an earlier (^{3}He, d) study by Dykoski and Dehnhard [22], have been adopted for the determination of the 217- and 500-keV resonance strengths, respectively. However, in the case of the 315-keV resonance, values of 0.14 [22] and 0.21 [23] have previously been reported. Here, we adopt an average value of $C^2S = 0.17$ for the 315-keV resonance and estimate a strength of $\omega\gamma = 0.025 \pm 0.004$ eV (In Ref. [22], an overall uncertainty of 15% was ascribed to the extraction of absolute cross sections). All other resonances are assumed to have nominal spectroscopic factors of $C^2S = 0.01$ except the 402-keV resonance for which we adopt the direct resonance strength measurement reported in Ref. [16]. A summary of resonance parameters used to evaluate the astrophysical ^{29}Si$(p,\gamma)^{30}$P reaction is provided in Table II, and Fig. 2 shows a comparison of the newly determined rate with the most recent previous study [19]. In particular, we find that our newly calculated strength for the 2^- 315-keV resonance is approximately twice as large as the most recent direct measurement [17] but agrees well with the value reported in Ref. [18]. As such, the 315-keV state is now expected to dominate the ^{29}Si$(p,\gamma)^{30}$P reaction over the entire peak temperature range of ONe novas ($T =$ 0.1–0.4 GK), and the overall rate is higher than previously reported [19]. Moreover, whereas the 217-keV resonance is unlikely to make a significant contribution to the rate at the peak temperatures of ONe novas, the first estimate of its strength [$\omega\gamma = 0.47(7)$ μeV] indicates that it is likely to govern the ^{29}Si(p,γ) reaction for temperatures $T < 0.1$ GK.

In order to fully assess the astrophysical implications of the present paper we have performed a series of nova outburst simulations using the hydrodynamic Lagrangian time-implicit code SHIVA [4,27]. This code, which relies on a standard set of differential equations of stellar evolution in finite-difference form, has been extensively used for simulations of nova outbursts, Type-I x-ray bursts and sub-Chandrasekhar supernova explosions. The equation of state used in SHIVA includes contributions from the degenerate electron gas, the ion plasma, and radiation. Coulomb corrections to the electron pressure are taken into account and radiative and conductive opacities are considered in the energy transport. Energy generation by nuclear reactions is obtained using a network that contains 120 nuclear species (from ^{1}H to ^{48}Ti), linked through 630 nuclear processes with updated reaction rates from the STARLIB database [26]. As nucleosynthesis in the Si-Ca mass region only occurs for very massive white dwarfs, we have considered an accreting 1.35 $M_\odot$ white dwarf with characteristic values for its initial luminosity (10^{-2} $L_\odot$) and mass-accretion rate (2×10^{-10} $M_\odot$ per year). The accreted matter is assumed to mix with material from the outer layers of the white dwarf to a level of 50%. All the hydrodynamic simulations performed in this paper resulted in the ejection of $\approx 5 \times 10^{-6}$ $M_\odot$ of nuclear-processed material after achieving a peak temperature of $\approx 3.1 \times 10^8$ K. Nucleosynthesis results using the present ^{29}Si$(p,\gamma)^{30}$P rate, a statistical model rate [26], as well as a high rate, based on the upper limit for the

TABLE III. Mean composition of nova ejecta (in mass fractions of the total ejected mass for Si-S isotopes) from models of nova explosions on 1.35 $M_\odot$ ONe white dwarfs. A high rate using the upper limit of the 315-keV resonance strength reported in Ref. [18] is included to highlight its impact on ^{29}Si nucleosynthesis.

Nuclide	STARLIB rate [26]	Present rate	High rate
^{28}Si	3.08×10^{-2}	3.09×10^{-2}	3.09×10^{-2}
^{29}Si	2.39×10^{-3}	1.92×10^{-3}	1.83×10^{-3}
^{30}Si	1.54×10^{-2}	1.56×10^{-2}	1.57×10^{-2}
^{31}P	8.73×10^{-3}	8.75×10^{-3}	8.76×10^{-3}
^{32}S	5.26×10^{-2}	5.28×10^{-2}	5.28×10^{-2}
^{33}S	7.99×10^{-4}	8.03×10^{-4}	8.02×10^{-4}
^{34}S	3.62×10^{-4}	3.63×10^{-4}	3.64×10^{-4}

strength of the 315-keV resonance of Ref. [18], are displayed in Table III.

In general, the expected ejected abundances as a result of the new ^{29}Si$+p$ rate are similar to those obtained with the previously reported rate [19,26]. However, differences are observed for final ^{29}Si yields. Such yields are of significant interest for the identification of presolar meteoritic grains of putative nova origins as accurate classifications require robust estimates of ^{29}Si / ^{28}Si and ^{30}Si / ^{28}Si ratios. At present, grains condensed in the ejecta of ONe novas are identified, among other features, by high ^{30}Si / ^{28}Si ratios and solar ^{29}Si / ^{28}Si yields. The strength of the 315-keV resonance plays a pivotal role in this regard, and our present estimate brings the expected final ^{29}Si / ^{28}Si yields from nova explosions closer to the solar abundance value of 0.05063 than that indicated by the most recent direct measurement [17].

To summarize, we have performed a detailed γ-ray spectroscopy study of the nucleus ^{30}P. The choice of a light-ion fusion-evaporation reaction allowed for the strong population of low-spin excited states and γ decays were observed from proton-unbound resonant states up to energies of $E_r =$ 500 keV. In particular, the spin-parity assignments of resonances at 217 and 315 keV, which are expected to play a significant role in the astrophysical ^{29}Si$(p,\gamma)^{30}$P reaction over nova temperatures, were determined as 2^+ and 2^-, respectively. Based on its new spin-parity assignment, the strength of the 315-keV resonance is now expected to be considerably higher than that reported in the most recent direct measurement of the ^{29}Si$(p,\gamma)^{30}$P reaction. This resonance governs the rate of the ^{29}Si$(p,\gamma)^{30}$P reaction over the entire peak temperature range of ONe novas, and present hydrodynamic calculations indicate that its strength strongly influences the final ^{29}Si yields expected from such explosions. Given that ^{29}Si yields are expected to provide useful information for the identification of nova presolar grains, a new direct measurement of the ^{29}Si$(p,\gamma)^{30}$P reaction at $E_r = 315$ keV is suggested.

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