Spectroscopy of ^{30}P and the abundance of ^{29}Si in Presolar Grains

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The astrophysical $^{29}\text{Si}(p, \gamma)$ 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 $^{28}\text{Si}(^3\text{He}, p)$ 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 $^{29}\text{Si}(p, \gamma)$ 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. Present calculations indicate that the strength of the 315 keV resonance, which dominates the rate of the $^{29}\text{Si}(p, \gamma)$ reaction over the entire temperature range of Oxygen-Neon (ONe) novae, is considerably higher than previously expected and as such, significantly affects the abundance of ^{29}Si ejected during nova explosions. In contrast, the 217 keV resonance is expected to make a negligible contribution to the $^{29}\text{Si}(p, \gamma)$ reaction rate, even at relatively low temperatures ($T \sim 0.1$ GK).

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Nova explosions are understood to result from the thermonuclear runaway of accreted hydrogen shells on the surfaces of white dwarf stars in close binary systems. During such events, peak temperatures $\sim 0.1 - 0.4$ GK are readily achieved and $\sim 10^{-7} - 10^{-3} M_\odot$ of nuclear processed material, containing non-solar isotopic abundance ratios, is ejected into the interstellar medium at velocities of several thousand kms^{-1} [1–3]. This makes classical novae 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 the more massive, ONe novae, it is expected that higher temperatures and pressures, compared to CO novae, allow for the synthesis of elements up to the Si-Ca mass region [4, 5]. 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 [6–10]. These microscopic pieces of matter are characterized by large isotopic anomalies that can only be explained by nuclear pro-

cesses 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 excesses and close-to-solar ^{29}Si yields may provide a distinctive signature [6, 7]. However, large uncertainties in the underlying nuclear physics processes responsible for the production and destruction of silicon isotopes in nova events make the accurate classification of presolar grains from $^{29,30}\text{Si}$ abundances challenging. In this regard, a landmark sensitivity study of novae nucleosynthesis by Iliadis *et al.* [11], highlighted that variations of the astrophysical $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction rate, within its associated uncertainty, could result in changes in the ejected abundance of ^{29}Si by up to a factor ~ 75 .

Previous studies of the astrophysical $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction [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 5594.75(7) keV [13] in ^{30}P . In particular, three excited states at 5811, 5909 and 5997 keV in ^{30}P [14], corresponding to resonances at 217, 315 and 402 keV in the $^{29}\text{Si} + p$ system, have been reported to have large proton spectroscopic factors [15]. Hence, their respective strengths are expected to have the most significant impact on the $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ stellar reaction rate. The 402-keV resonance has been studied precisely using direct techniques [16]. However, very little information ex-

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TABLE I: Properties of excited states in ^{30}P . Level energies are corrected for the recoil of the compound nucleus.

E_x (keV) Present	E_x (keV) Basunia [14]	E_x (keV) Shell Model	E_r (keV)	E_γ (keV)	a_2/a_4	R_{dco}	$J^\pi ; T$
5506.7(5)	5506.3(2)	5896		4829.1(5)	-0.21(3)/0.00(3)	0.85(2)	$1^+ ; 0$
5509.2(4)	5508.55(8)	5654		3535.0(3)			$3^+ ; 1$
				4054.3(3)	-0.24(4)/0.09(5)	0.73(5)	
5577.3(8)	5576.3(1)	5741		4122.5(21)			$2^+ ; 1$
				4867.9(5)	-0.16(41)/0.01(35)	0.81(12)	
5596.3(3)	5597(5)	5105	1.8(5)	3056.9(3)	0.20(5)/-0.04(6)	1.16(11)	$5^+ ; 0$
5599.8(3)	5597(5)	5455	5.3(5)	2661.6(2)	0.04(2)/-0.02(3)	0.99(6)	$4^+ ; 0$
5701.1(3)	5701.3(2)	6085	106.6(5)	1518.3(2)	-0.23(8)/0.02(10)	0.70(19)	$1^+ ; 0$
				2763.0(2)	-0.14(3)/0.08(6)	0.68(4)	
				3161.6(19)	0.29(7)/0.06(10)	1.17(8)	
5717.0(18)	5715(4)		122.5(18)	5039.4(18)	-0.24(9)/0.02(12)	0.92(10)	$1^- ; 0$
5775.9(6)	5788(5)	5571	181.4(7)	3801.9(6)	0.59(9)/0.03(12)	1.17(8)	$5^+ ; 0$
5811.2(4)	5808(5)	5471	216.7(6)	3271.3(4)	-0.11(3)/0.01(4)	0.86(3)	$2^+ ; 0$
				3837.3(3)	-0.17(7)/0.08(9)	0.82(6)	
5898.9(3)	5896(5)	5888	304.4(4)	1716.3(2)	-0.13(4)/0.08(5)	0.78(3)	$3^+ ; 1$
				2960.6(2)	0.02(3)/-0.07(4)	0.93(5)	
5909.1(6)	5907.8(8)		314.6(7)	5199.8(6)	-0.20(9)/-0.12(10)	0.79(7)	$2^- ; 0$
5934.8(8)	5934.0(1)	6221	340.3(9)	1590.1(2)	0.03(2)/0.03(3)	0.85(12)	$4^+ ; 0$
				2996.6(6)	0.56(11)/0.14(11)	1.06(12)	
				3095.0(40)		0.60(18)	
				3961.1(4)	-0.41(8)/-0.04(11)	0.98(10)	
5996.8(5)	5997.2(8)		402.3(6)	5287.6(2)	-0.02(7)/0.03(7)	0.96(11)	$1^- ; 0$
				5319.1(6)	0.01(2)/-0.01(3)	1.04(3)	
6006.2(8)	6006.0(1)	6166	411.7(9)	3466.4(7)	0.00(4)/-0.09(5)	1.12(11)	$3^+ ; 0$
				4032.2(8)		1.30(37)	
<i>unobserved</i>	6051(5)	6218	456.5(50)				$0^+ ; 1$
6094.7(3)	6093.5(1)		500.2(4)	1467.7(1)	0.33(2)/-0.02(2)	1.37(5)	$3^- ; 1$
				1861.8(1)			

ists on the 217-keV resonance and current direct measurements of the strength of the 315-keV state, in normal kinematics, differ by a factor ~ 2 [17, 18]. In this regard, a key uncertainty relates to the unknown spin-parity assignments of the 217- and 315-keV resonances. 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 $^{28}\text{Si}(^3\text{He}, p)$ 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 unambiguous determinations of spin-parity assignments.

Here, a 13 MeV, 5-pnA beam of ^3He ions, delivered by the Argonne ATLAS accelerator, was used to bombard a $\sim 120 \mu\text{g}/\text{cm}^2$ -thick ^{28}Si target for 49 hours in order to produce ^{30}P nuclei via the one-proton evaporation channel. Gamma decays were detected with the Gammasphere detector array [19], 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 distri-

butions 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 degrees [$R_{dco} = I(\sim 0^\circ) + I(\sim 180^\circ) / I(\sim 90^\circ)$]. 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 [14] observed in this study. 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 $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction.

Table I presents the properties of excited states in ^{30}P close to, and above, the proton-emission threshold energy. Examples of γ - γ coincidence spectra produced in this study are shown in Figs. 1(a)–(c), while 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 [14] 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 $^{29}\text{Si} + p$ 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 pre-

viously and the presently reported γ -ray energies are in good agreement with earlier work [14]. In the $^{29}\text{Si}(^3\text{He},d)$ study of Dykoski *et al.* [15], 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. In contrast, the a_2 and a_4 coefficients extracted for the 5288- and 5319-keV γ rays indicate that the 402-keV resonance could have a spin-parity assignment of either 0^- or 1^- . However, an earlier $^{29}\text{Si}(p,\gamma)$ investigation by Reinecke *et al.* [17] concluded that $J = 1$ for the 402-keV resonance. As such, we adopt a spin-parity assignment of 1^- for this 402-keV resonant state in ^{30}P in the present work.

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 a $^{29}\text{Si} + p$ resonance at 216.7(6) keV, has been reported to have a measurable proton spectroscopic factor ($C^2S = 0.01$) [15]. In Ref. [15], the 217-keV resonance was fit with an $\ell = 2$ 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 $^{29}\text{Si} + p$ system, as a 2^+ level.

For an evaluation of the astrophysical $^{29}\text{Si}(p,\gamma)^{30}\text{P}$ 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 , for the determination of resonance strengths have been taken, where available, from earlier $(^3\text{He},d)$ reaction studies [15, 20]. In particular values of 0.01 and 0.17 [15], have been adopted for the 217 and 500 keV resonances, respectively, while an average value of $C^2S = 0.17$ [15, 20] has been used for the 315-keV resonance. 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]. We find that our newly calculated strength for the 2^- , 315-keV resonance ($\omega\gamma \sim 25$ meV) 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 $^{29}\text{Si}(p,\gamma)^{30}\text{P}$ reaction over the entire peak temperature range of ONe novae ($T = 0.1 - 0.4$ GK), and the overall

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.

rate is higher than previously reported [11], as shown in Fig. 2. In contrast, we find that the 2^+ , 217-keV resonance ($\omega\gamma \sim 0.39 \mu\text{eV}$) makes a negligible contribution to the stellar reaction rate, even at $T \sim 0.1$ GK.

In order to fully assess the astrophysical implications of the present work, we have performed a series of nova outburst simulations using the hydrodynamic, Lagrangian, time-implicit code SHIVA [21, 22]. 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.

FIG. 2: (Color online) (Top) The $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ stellar reaction rate as a function of temperature. The solid blue line represents the present, recommended rate as per Table II. The dashed red line represents the rate reported in Ref. [11]. (Bottom) The solid blue line shows the ratio of the present rate to the rate of Ref. [11]. A dashed red line has been included to highlight what would be expected for a ratio of 1:1.

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 ^1H to ^{48}Ti), linked through 630 nuclear processes, with updated reaction rates from the STARLIB database [23]. 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 ($2 \times 10^{-10} M_{\odot}$ 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 work resulted in the ejection of $\sim 5 \times 10^{-6} M_{\odot}$ of nuclear-processed material, after achieving a peak

temperature of $\sim 3.1 \times 10^8$ K. Nucleosynthesis results using the present $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ rate, a statistical model rate [23], as well as a high rate, based on the upper limit for the strength of the 315-keV resonance of Ref. [18], are displayed in Table II.

In general, results for the new $^{29}\text{Si} + p$ rate are very similar to those obtained with STARLIB. 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 $^{29}\text{Si}/^{28}\text{Si}$ and $^{30}\text{Si}/^{28}\text{Si}$ ratios. At present, grains condensed in the ejecta of ONe novae are identified, among other features, by high ^{30}Si excesses and solar ^{29}Si yields. The strength of the 315 keV resonance plays a pivotal role in this regard and our present estimate brings the expected final $^{29}\text{Si}/^{28}\text{Si}$ yields from nova explosions closer to solar abundances than that indicated by the most recent direct measurement [17].

TABLE II: 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	Statistical model	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}

In summary, 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 $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction over novae peak 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 $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction. This resonance governs the rate of the $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction over the entire peak temperature range of ONe novae, and present model calculations indicate that its strength strongly influences the final ^{29}Si yields expected from such explosions. Given that ^{29}Si yields are likely to provide a key identifier for nova presolar grains, a new, direct measurement of the $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction at $E_r = 315$ keV is suggested.

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