Identification of Key Astrophysical Resonances Relevant for the ^{26g}Al$(p,\gamma)^{27}$Si Reaction in Wolf-Rayet Stars, AGB stars, and Classical Novae

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A γ-ray spectroscopy study of ^{26g}Al + p resonant states in ^{27}Si is presented. Excitation energies were measured with improved precision and first spin-parity assignments made for excited states in ^{27}Si above the proton threshold. The results indicate the presence of low-lying resonances with $l_p = 0$ and $l_p = 2$ captures that could strongly influence the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate at low stellar temperatures, found in low-mass asymptotic giant branch (AGB), intermediate-mass AGB, super AGB, and Wolf-Rayet stars.

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The nucleus ^{26}Al was the first radioisotope detected in the interstellar medium (ISM) through its characteristic γ-ray line [1]. Given the relatively short ^{26}Al lifetime ($t_{1/2} = 7.2 \times 10^5$ yr), the observation of γ rays associated with its decay provides clear evidence of continuing nucleosynthesis in the Milky Way [2]. Since the initial detection of the 1.809 MeV line by the HEAO-3 satellite in 1982, state-of-the-art, space-based, γ-ray observatories have been used to ascertain the Galactic origin of ^{26}Al. The COMPTEL all-sky map of this γ ray reported irregular emission along the Galactic plane, suggesting a Galaxy-wide origin dominated by high-mass progenitors, such as core collapse supernovae (CCSN) and Wolf-Rayet (WR) stars [3]. Recent observations by the RHESSI and INTEGRAL satellites indicate CCSN may make a much smaller contribution than initially expected [4] and WR stars are the likely dominant astrophysical source of ^{26}Al [5]. WR stars are very massive, $\gtrsim 30M_\odot$, and pollute the ISM with the products of hydrogen burning, via a strong stellar wind. Peak temperatures of $\sim$0.05 GK are reached in such environments and, at temperatures $\gtrsim$0.03 GK, the ^{26g}Al$(p,\gamma)^{27}$Si reaction is expected to govern the destruction of ^{26}Al. Over the temperature range $T =$ 0.03–0.05 GK, the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate carries a factor 10^5 uncertainty [6]. It is essential to reduce this uncertainty to determine the contribution of WR stars to the overall Galactic abundance of ^{26}Al of $2.8(8)M_\odot$ [5].

Intermediate-mass (IM) asymptotic giant branch (AGB) stars, super (S) AGB stars, and classical novae are all potential astrophysical sources of ^{26}Al that may contribute up to $0.2M_\odot$, $0.3M_\odot$, and $0.4M_\odot$ to the observed Galactic abundance [7–9]. The temperatures of IM AGB stars, S AGB stars, and classical novae range from 0.06 to 0.42 GK and, as such, the ^{26g}Al$(p,\gamma)^{27}$Si reaction is also expected to govern the destruction of ^{26}Al. In the temperature region $T = 0.06$–0.10 GK, achieved in all three scenarios, uncertainties in the rate range up to 4 orders of magnitude [6]. The presence of ^{26}Al can also be traced through excesses of its daughter nucleus ^{26}Mg in meteoritic material. The excess of ^{26}Mg was found in calcium and aluminum inclusions (CAIs) of the Allende meteorite, which inferred an ^{26}Al/^{27}Al ratio of 5×10^{-5} present in the Solar System at the time of its formation 4.57×10^9 years ago [10]. A much debated question relates to the origin of ^{26}Al and other short-lived radioactive nuclei in the early Solar System [11] and both WR and AGB stars have been suggested as possible sources [11–13].

Previous studies of the ^{26g}Al$(p,\gamma)^{27}$Si reaction [14–20] indicate that, above 0.02 GK, the rate is dominated by resonant capture to excited states in ^{27}Si above the proton threshold energy of 7463.0(2) keV [21]. Three direct (p,γ) studies of the ^{26g}Al$(p,\gamma)^{27}$Si reaction have been performed to date and are expected to have identified all strong resonant states in ^{27}Si with excitation energy $E_x >$ 7633 keV (resonance energy $E_r > 170$ keV), constraining the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate for $T \geq 0.2$ GK [15,16,18]. However, ^{27}Al$(^3$He$,t)^{27}$Si and ^{28}Si$(^3$He$,\alpha)^{27}$Si reaction studies, performed by Schmalbrock *et al.* [19] and Wang *et al.* [20], respectively, reported lower energy proton-unbound states in ^{27}Si that could dominate the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate for $T < 0.2$ GK. No firm spin-parity assignments were reported in any of these previous studies of proton-unbound states in ^{27}Si. In this Letter we employ a heavy-ion fusion-evaporation reaction to populate these states, and study their γ decays to make the first firm spin-parity assignments of these resonances. In combination with the new precise level energies, this reduces the previous uncertainty in the reaction rate by orders of magnitude.

A 6 pnA, 26 MeV beam of ^{16}O ions, produced by the Argonne ATLAS accelerator, was used to bombard a $\sim$150 $\mu g/\mathrm{cm}^2$ thick ^{12}C target for 63 h to produce ^{27}Si nuclei. The resulting γ decays were detected with the Gammasphere array [22]. At this low energy, the single particle evaporation channels ^{27}Al, ^{27}Si, and ^{24}Mg are produced most abundantly. Energy and efficiency calibrations were obtained using ^{152}Eu and ^{56}Co sources and a high-energy 6.129 MeV γ ray observed in ^{16}O. A γ-γ coincidence matrix and a γ-γ-γ cube were produced and analyzed to obtain information on the ^{27}Si γ-decay scheme. Table I presents a summary of the properties of excited states in ^{27}Si of relevance for the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate, together with a comparison to previous work. Examples of the γ-γ and γ-γ-γ gated spectra used in the analysis of excited states above the proton threshold in ^{27}Si are shown in Figs. 1(a)–1(c). Centroids were determined from Gaussian peak fits on a flat background. In the following discussion we will focus on the key results affecting the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate.

Transitions at 6511.1(6) and 6573.5(9) keV to the $3/2_1^+$ 957 keV level in ^{27}Si were observed, as shown in Fig. 1(a), indicating proton-unbound states at 7469.0(6) and 7531.3 (7) keV, in good agreement with previously reported values for the two lowest-lying proton-unbound excited states in ^{27}Si [20]. Consequently, it is expected that the presently observed 7469.0(6) and 7531.3(7) keV states represent the two lowest-lying resonant states in the ^{26g}Al + p system at 6.0(6) and 68.3(7) keV. The 6 keV resonance is too low in energy to contribute significantly to the reaction rate and will not be considered further. The 68 keV resonance, however, can considerably affect the rate at low stellar temperatures. Angular distribution measurements of the 6574 keV γ ray are consistent with a $\Delta I = \pm 1$ transition, shown in Fig. 1(a), indicating a $1/2$ or $5/2$ spin assignment for the 7531.3(7) keV level in ^{27}Si. In comparison with the mirror nucleus, ^{27}Al, in an energy range 7.3–8.0 MeV (Champagne *et al.* suggest a typical global energy shift between ^{27}Al and ^{27}Si mirror states of ~200 keV [14]), there are no known $1/2$ states and the two $5/2^+$ levels in this region are the only states known to γ-decay to the $3/2_1^+$ level [23]. Consequently, a $5/2^+$ 7531.3(7) keV excited state in ^{27}Si was assigned. The spin-parity assignment for the 68.3(7) keV resonance indicates an $l_p = 2$ capture component to the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate.

A high-intensity coincidence relationship with the $7/2_1^+$ 2163 keV level in ^{27}Si was observed at 5425.9(1) keV, as shown in Fig. 1(b), indicating an excited state at 7589.7 (8) keV. This energy is again in excellent agreement with a previously observed 7589(3) keV excited level in ^{27}Si [20], and corresponds to a resonance at 126.7(8) keV. The 5426 keV γ ray to the $7/2_1^+$ state is measured to have angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition, indicating a $5/2$ or $9/2$ assignment. Further γ-decay branches from the 7590 keV state to the $11/2_1^+$, shown in Fig. 1(c), and $7/2_2^+$ levels were also observed, and as such, a $5/2$ assignment can be ruled out. In comparison with the mirror nucleus, the 7806 keV state in ^{27}Al is the only one, in the energy range 7.7–8.5 MeV, that has γ-decay branches to the $7/2_2^+$, $11/2_1^+$, and $7/2_1^+$ levels [23]. This 7806 keV level is a known $9/2^+$ state [23], which is consistent with the present spin assignment restrictions for the mirror analog and, consequently, a $9/2^+$ 7589.7(8) keV excited state was assigned in ^{27}Si. The newly determined spin-parity assignment in-

TABLE I. γ-ray energies, angular distribution coefficients, and level energies of excited states above the proton threshold in ^{27}Si. Level energies were corrected for the recoil of the compound nucleus. Resonance energies were calculated from the Q value of 7463.0 (2) keV [21] and determined from the presently measured excitation energies.

E_x (keV) (Endt [23])	E_x (keV) (Present)	E_r (keV)	E_γ (keV)	a_2/a_4	Assignment	$\omega\gamma$ (meV)
7468(3)	7469.0(6)	6.0(6)	6511.1(6)	−0.64(25)/0.39(34)	$5/2^+ \to 3/2_1^+$	
7532(3)	7531.3(7)	68.3(7)	4883.5(5)		$5/2^+ \to 5/2_2^+$	
			6573.5(9)	−0.85(9)/0.20(13)	$5/2^+ \to 3/2_1^+$	
7557(3)		94(3)				
7592(3)	7589.7(8)	126.7(8)	3115.6(14)		$9/2^+ \to 7/2_2^+$	
			3142.6(27)		$9/2^+ \to 11/2_1^+$	
			5425.9(1)	−0.52(2)/0.01(3)	$9/2^+ \to 7/2_1^+$	
7652(3)	7651.6(3)	188.6(4)	2371.0(40)		$11/2^+ \to 11/2_2^+$	0.055(9) [16], 0.035(7) [18]
			3204.1(1)	0.40(3)/−0.01(4)	$11/2^+ \to 11/2_1^+$	
7690(3)	7693.8(9)	230.8(9)	5530.1(9)	0.50(7)/0.24(9)	$5/2^+ \to 7/2_2^+$	≤ 0.010 [16]
7702(2)	7704.3(2)	241.3(3)	5056.7(1)	−0.21(7)/0.09(9)	$7/2^+ \to 5/2_2^+$	0.010(5) [16]
7740.8(9)	7739.3(4)	276.3(4)	2421.6(4)		$9/2^+ \to 9/2_2^+$	3.8(10) [15], 2.9(3) [16]
			2455.9(4)		$9/2^+ \to 11/2_2^+$	
			3291.3(1)		$9/2^+ \to 11/2_1^+$	
			4828.7(5)	0.25(12)/−0.25(17)	$9/2^+ \to 9/2_1^+$	
			5575.7(2)	−0.10(4)/0.11(5)	$9/2^+ \to 7/2_1^+$	
7792(3)	7794.8(19)	331.8(19)	5631.0(19)		$7/2^+ \to 7/2_1^+$	
7831(3)	7831.5(4)	368.5(4)	2329.8(8)		$9/2^- \to 5/2_1^-$	65(18) [15], 69(7) [16]
			3383.8(2)		$9/2^- \to 11/2_1^+$	
			4921.0(4)	0.18(7)/0.05(9)	$9/2^- \to 9/2_1^+$	
			5668.0(3)		$9/2^- \to 7/2_1^+$	

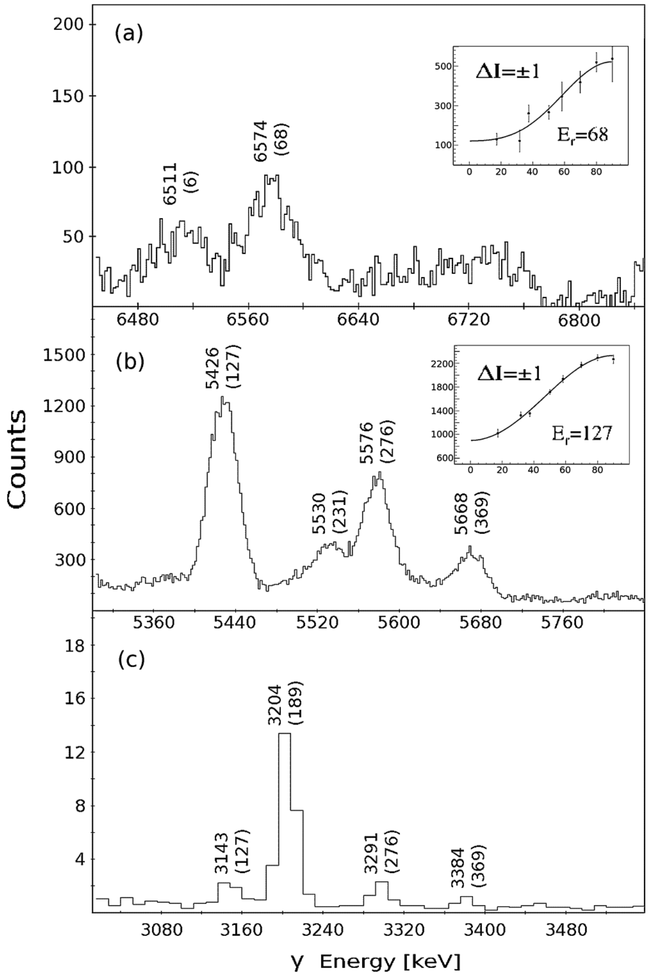

FIG. 1. (a) γ-γ coincidence spectrum gated on the 957 keV transition; numbers in parentheses represent resonance energies. Inset: Angular distribution of the 6574 keV γ ray, showing relative intensity as a function of angle. A Legendre polynomial fit for a $\Delta I = \pm 1$ transition is shown. (b) γ-γ coincidence spectrum gated on the 2163 keV transition. Inset: Angular distribution of the 5426 keV γ ray. (c) γ-γ-γ coincidence spectrum gated on the 2163 and 2284 keV transitions.

dicates an $l_p = 0$ contribution to the reaction rate from the 126.7(8) keV resonant state.

Vogelaar *et al.* [16,17] reported γ decays from a resonant state at $\sim$195 keV in the ^{26g}Al + p system and observed a 90% decay branch to the known $11/2_1^+$ excited state. In that work it was indicated that this resonance corresponds to a ^{27}Si excited state at 7652(3) keV, which was also previously observed in Refs. [19,20]. Here, we identify an excited state in ^{27}Si at 7651.6(3) keV, in good agreement with Refs. [16,17,19,20], and observe a strong 3204.1(1) keV γ-ray transition to the known $11/2_1^+$ state in ^{27}Si, shown in Fig. 1(c), together with an additional weaker 2371.0(40) keV γ-decay branch to the $11/2_2^+$ level. An angular distribution analysis of the 3204 keV γ ray revealed coefficients consistent with a $\Delta I = 0$ transition, indicating an 11/2 assignment for the 7651.6(3) keV state. In considering the mirror nucleus in an energy region 7.7–8.3 MeV, the $11/2^+$ 7948 keV state is the only 11/2 state known to exhibit γ-decay transitions to both the $11/2_1^+$ and $11/2_2^+$ levels [23]. Thus, 2371 and 3204 keV γ-ray transitions from an $11/2^+$ 188.6(4) keV resonant state in the ^{26g}Al + p system are assigned. It should be noted that two separate resonance strength measurements have been performed for this 188.6(4) keV resonance [16,18] and, consequently, although an $11/2^+$ spin-parity assignment has been determined for this state, such an assignment is not critical for a determination of the astrophysical ^{26g}Al$(p,\gamma)^{27}$Si reaction rate. However, the presently obtained more precise 188.6(4) keV resonance energy is important and is in disagreement with the recent measurement of 184(1) keV by Ruiz *et al.* [18]. For temperatures $\sim$0.1 GK, the influence of such a shift in resonance energy is larger than the change in reaction rate due to a resonance strength variation of 45^{+19}_{-17} μeV [16,18]. Furthermore, although previous work has assumed an $l_p = 1$ capture component for this resonant state [18], the current $11/2^+$ assignment indicates that this is not the case. Consequently, by considering the angular distribution measurements of Ref. [17], an admixture of $l_p = 0$ and $l_p = 2$ resonant capture components is favored for this 188.6 (4) keV resonance.

Two further, previously identified, strong resonant states at 277.8(9) and 368.0(30) keV in the ^{26g}Al + p system [15,16] were also observed in the current study at 276.3 (4) and 368.5(4) keV, as shown in Figs. 1(b) and 1(c). As with the 188.6(4) keV state, the resonance strengths of these states have been previously measured [15,16]. Consequently, a detailed discussion of the present spin-parity assignments of these levels is not presented here. The 276.3(4) and 368.5(4) keV resonant states are expected to dominate the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate over the temperature range $T = 0.20$–0.42 GK, corresponding to the peak temperatures reached in classical novae environments. As a result, the more precise level energies have reduced uncertainties in the contributions of the 276.3(4) and 368.5(4) keV resonant states to the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate, at novae temperatures, by factors of 2 and 8, respectively.

In the current study, only the 7557(3) keV state, tentatively reported by Wang *et al.* [20], was not observed. This state was only weakly populated in Ref. [20] and has not been observed in any other study. If the 7557 keV state does exist, its nonobservation would tend to indicate either a low-spin and/or a $T = 3/2$ assignment, both of which would not be strongly produced here (the possible mirror $T = 3/2$, $3/2^+$ 7858 keV state in the more strongly populated ^{27}Al was the only level in the energy range 7.6–8.0 MeV not observed here). This would indicate the 7557 keV level does not make a significant contribution to the ^{26g}Al$(p,\gamma)^{27}$Si reaction, and for present purposes we do not consider its influence on the rate.

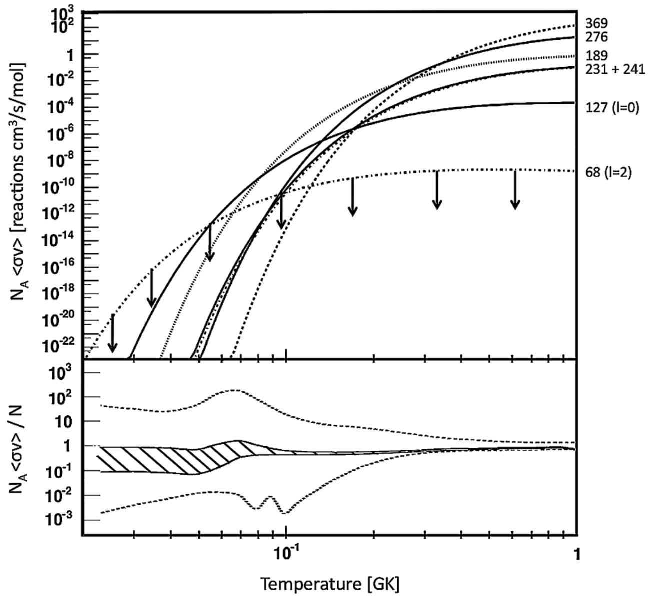

FIG. 2. Top: Reaction rate showing identified resonant contributions to the ^{26g}Al$(p, \gamma)^{27}$Si stellar reaction. Arrows on the 68 keV resonance represent an approximate upper limit. Bottom: Comparison of the total reaction rate normalized to the analytical rate presented in Angulo *et al.* [24]. The shaded region bounds the uncertainties in the present work and the dashed lines represent the uncertainties in [24].

Figure 2 displays contributions of individual resonances to the ^{26g}Al$(p, \gamma)^{27}$Si reaction rate, incorporating the present results. The upper limit for the strength of the 68.3(7) keV resonance assumes a pure $l_p = 2$ capture and $C^2S \sim 0.3$, similar to that suggested by Vogelaar *et al.* for the strong single-particle 189 keV resonant state [17], although the value could be considerably lower (a lower limit of $C^2S = 0.01$ is taken in estimating the uncertainty in the reaction rate in Fig. 2, as was also used for the lower limit in [14,24]). As can be seen in Fig. 2, for $l_p = 2$ capture, the value of the 68.3(7) keV resonance strength significantly influences the ^{26g}Al$(p, \gamma)^{27}$Si reaction rate for $T = 0.03$–0.05 GK. This corresponds to the temperature range of WR stars, the expected dominant astrophysical source of ^{26}Al. The reaction rate estimate for the 126.7(8) keV resonance strength assumes a pure $l_p = 0$ capture and a spectroscopic factor of 0.02, corresponding to the upper limit suggested by Vogelaar *et al.* [17] in a $(^3\text{He}, d)$ transfer reaction study (we assume a lower limit of $C^2S = 0.001$ in estimating the uncertainty in the reaction rate). It can be seen that this 126.7(8) keV resonance makes a significant contribution to the ^{26g}Al$(p, \gamma)^{27}$Si stellar reaction rate for $T = 0.05$–0.07 GK. However, given the newly determined spin-parity assignment of $9/2^+$ for this level, indicating an $l_p = 0$ contribution to the rate, a larger spectroscopic factor than presently used could dramatically affect the reaction rate over the much larger temperature range $T = 0.03$–0.20 GK. It is, therefore, the unknown resonance strengths of the $5/2^+$ state at 68.3(7) keV and the $9/2^+$ level at 126.7(8) keV that now represent the dominant remaining uncertainties in the ^{26g}Al$(p, \gamma)^{27}$Si reaction rate. These strengths are likely to remain too low [certainly for the 68.3(7) keV state] for direct measurements. Hence, the key next step in reducing the uncertainty in the rate will be to measure the proton spectroscopic factors of the 68.3(7) and 126.7(8) keV resonances.

In summary, the consequences of this work for the determination of the ^{26g}Al$(p, \gamma)^{27}$Si stellar reaction rate are that $l_p = 0$ and $l_p = 2$ resonances have been identified at 126.7(8) and 68.3(7) keV, respectively, and uncertainties in the rate for $T = 0.03$–0.42 GK have been greatly reduced, influencing the predicted ^{26}Al yields from low-mass AGB stars, IM AGB stars, *S* AGB stars, WR stars, and classical novae. Further constraints on the stellar reaction rate require a determination of proton spectroscopic factors of the 68.3(7) and 126.7(8) keV resonances.

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