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γ-ray spectroscopy study of states in ^{27}Si relevant for the ^{26}Al$^m(p,\gamma)^{27}$Si reaction in novae and supernovae

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The heavy-ion, fusion-evaporation reaction ^{12}C(^{16}O, n) was used to identify γ-decay transitions from excited states in ^{27}Si above the proton threshold. The precise level energy measurements, J^π assignments, and lifetime measurements of astrophysically important ^{26}Al$^m + p$ resonances have allowed an evaluation of the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate. An $l_p = 0$ resonance has been newly identified at a center-of-mass energy in the ^{26}Al$^m + p$ system of 146.3(3) keV and is expected to dominate the rate for low stellar temperatures. In addition, an $l_p = 1$ resonance has been identified at 378.3(30) keV and is likely to dominate the rate at high astrophysical temperatures, such as those found in oxygen-neon novae and core-collapse supernovae.

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I. INTRODUCTION

The cosmic γ-ray-emitting isotope ^{26}Al has been the subject of considerable interest during the past 27 years. Its existence in the modern-day galaxy and in the early solar system has been inferred from the observation of characteristic 1.809-MeV γ rays throughout the interstellar medium [1–3] and from isotopic excesses of ^{26}Mg found in meteoritic inclusions [4–7]. In recent years, it has been suggested that stellar production of ^{26}Al is dominated by Wolf-Rayet stars [3]. However, additional contributions to the overall galactic abundance of ^{26}Al from asymptotic giant branch (AGB) stars, classical novae and core-collapse supernovae (CCSN), are also expected. In particular, several presolar grains of possible novae and supernovae origins have been found with large ^{26}Al:^{27}Al ratios.

Stellar nucleosynthesis of ^{26}Al is complicated by the presence of an isomer, ^{26}Al^m($J^\pi = 0^+$, $t_{1/2} = 6.3$ s), located 228.31(3) keV above the ground state, ^{26}Al^g ($J^\pi = 5^+$, $t_{1/2} = 7.2 \times 10^5$ yr); the isomeric state undergoes a superallowed β^+-decay transition directly to the ^{26}Mg ground state, bypassing emission of the 1.809-MeV γ ray. Communication between the isomeric state and the ground state of ^{26}Al is severely hindered by the large spin difference ($\Delta J = 5$), and it has been suggested that the two levels should be entered into nuclear reaction networks separately [8]. However, thermal equilibrium between these two states may be achieved via transitions involving higher lying levels in ^{26}Al [8], and an effective decay rate between the two levels, which can reduce the effective lifetime of ^{26}Al, must be incorporated to determine the amount of ^{26}Al synthesized in any particular astrophysical environment. It was noted that this effect will only become significant in high-temperature astrophysical environments [8]. Therefore, to determine the amount of ^{26}Al synthesized in such environments, it is necessary to investigate the nuclear reactions involved in the production and destruction of both ^{26}Al^g and ^{26}Al^m. These reactions are also important for comparing accurately the abundances of ^{26}Mg found in presolar grains with the yields of the precursor isotope ^{26}Al. These grains are expected to be formed around AGB stars, classical novae and supernovae [9].

In general, the abundance of ^{26}Al^m in stellar scenarios will remain considerably less than that of ^{26}Al^g until the rate of the ^{25}Al$(p,\gamma)^{26}$Si reaction, which leads to the exclusive population of ^{26}Al^m through the β^+ decay of ^{26}Si, becomes appreciable. The most recent study of the ^{25}Al$(p,\gamma)^{26}$Si reaction, by Peplowski *et al.* [10], has identified the lowest lying $l_p = 0$ resonance in ^{26}Si, constraining uncertainties in the rate. In Ref. [10], it was found that for $T \geqslant 0.3$ GK, the ^{25}Al$(p,\gamma)^{26}$Si reaction competes significantly with the β^+ decay of ^{25}Al, and a large fraction of explosive hydrogen burning events bypass the direct population of the ^{26}Al ground state. Consequently, in stellar environments in which temperatures in excess of 0.3 GK are achieved, such as oxygen-neon (ONe) novae and CCSN, the abundance of ^{26}Al^m will be larger than that of ^{26}Al^g and nuclear reactions on the isomer will have significant consequences for the final isotopic abundances synthesized in these environments.

In AGB stars, classical novae and CCSN, the destruction of ^{26}Al is governed by proton radiative captures on ^{26}Al^g and ^{26}Al^m, respectively. The ^{26}Al$^g(p,\gamma)^{27}$Si reaction has been extensively studied during the past two decades [11–17], including a recent publication by our collaboration [18]. In contrast, almost no experimental information is available on the rate of the ^{26}Al$^m(p,\gamma)^{27}$Si reaction and previous estimates have been largely based on ^{26}Al$^g + p$ resonances and Hauser-Feshbach calculations [19]. A postprocessing study by Iliadis *et al.* [20] investigated the effects of reaction rate uncertainties on novae nucleosynthesis, and from the 175 different reactions varied through their associated uncertainties, the ^{26}Al$^m(p,\gamma)^{27}$Si reaction was one of only a handful highlighted as being of significance. In that study [20], it was found that uncertainties in the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate may affect the isotopic abundances of ^{26}Mg synthesized in novae environments by up to a factor of 14. Furthermore, in the recent study of the ^{25}Al$(p,\gamma)^{26}$Si reaction [10], Peplowski *et al.* concluded that the main experimental uncertainty in the nucleosynthesis of ^{26}Al in high-temperature astrophysical environments, such as CCSN, has now shifted from the investigation of the ^{25}Al(p,γ)^{26}Si reaction to the destruction processes of ^{26}Al^m through the (p,γ) reaction.

The unpublished thesis work of C. M. Deibel [21] represents the most detailed previous study of the astrophysical ^{26}Al^m(p,γ)^{27}Si reaction, the results of which were recently published in *Physical Review C* [22]. In AGB stars, classical novae and CCSN, the ^{26}Al^m(p,γ)^{27}Si reaction rate is expected to be dominated by resonant capture to excited states above the proton threshold in ^{27}Si. In Ref. [21], ^{27}Al(^{3}He,t)^{27}Si*(p)^{26}Al and ^{28}Si(^{3}He,α)^{27}Si*(p)^{26}Al reactions were used to observe proton decays from excited states above the ^{26}Al^m + p threshold energy of 7691.3(2) keV in ^{27}Si [23] to both the ground and metastable levels of ^{26}Al, respectively. Both angular correlations and proton branching ratios were measured. In the study of Deibel [21], the lowest energy excited state above the ^{26}Al^m + p threshold was observed at an excitation energy E_x of 8136(4) keV, corresponding to a resonance energy in relation to the ^{26}Al isomeric state E_r^m of 445(4) keV. This resonant state was found to dominate the ^{26}Al^m(p,γ)^{27}Si reaction rate. However, 445 keV also represented the resonance energy threshold cutoff in that study and ^{26}Al^m + p resonances with $E_r^m < 445$ keV could not be observed. Furthermore, only the minimum angular momentum transfer of the protons l_{min} to the ground and metastable states of ^{26}Al could be determined from angular distribution measurements, leaving many of the spin assignments of ^{26}Al^m + p resonant states ambiguous. Consequently, significant uncertainties remained in the ^{26}Al^m(p,γ)^{27}Si reaction rate, and, in fact, Deibel [21] noted that the rate could well be dominated by unobserved ^{26}Al^m + p resonances, with $E_r < 445$ keV.

This article describes new γ-ray spectroscopy measurements leading to identification of states in ^{27}Si affecting the ^{26}Al^m(p,γ)^{27}Si resonant reaction rate. The data were taken at the same time, and under the same experimental conditions, as work our collaboration has already published on the identification of states relevant for the ^{26}Al^g(p,γ)^{27}Si reaction [18]. Hence, this study should be considered a companion paper to that study.

II. EXPERIMENT AND ANALYSIS PROCEDURE

The experimental technique used in the current study was discussed in Ref. [18], in which a 6-pnA beam of ^{16}O ions was used to bombard a ∼150 μg/cm^2 thick ^{12}C target to produce ^{27}Si nuclei, and the resulting γ decays were detected with the Gammasphere array [24]. Gamma-ray energy and efficiency calibrations were made using ^{152}Eu and ^{56}Co sources and a high-energy 6.129-MeV γ ray observed in ^{16}O. In this study, because of the large number of transitions present in the γ-ray singles spectra, decay transitions from excited states in ^{27}Si directly to the ground state could not be resolved. Consequently, a γ-γ coincidence matrix and a γ-γ-γ cube were produced and analyzed to obtain information on the ^{27}Si-decay scheme. Lifetimes for some excited states observed were extracted using the fractional Doppler shift method [25]. These values are, in fact, effective lifetimes, corresponding to the combined lifetimes of the states of interest and the states feeding them, although it is reasonable to assume that for high-lying, unbound excited states, the feeding is most likely direct. Experimental Doppler shifts were obtained by fitting the peak centroids of γ-ray transitions from excited states above the threshold in spectra without Doppler correction at 14 different angles: 32°, 37°, 50°, 58°, 70°, 80°, 90°, 100°, 110°, 122°, 130°, 143°, 148°, and 163°. The initial velocity of the recoiling nucleus, β_0, was calculated to be 0.03322 for our experimental conditions, assuming that these nuclei were formed at the center of the target. The program SRIM [26] was then used to model the slowing of the recoils through the target material and to relate experimental Doppler shifts to the lifetime of the excited state of interest above the proton threshold. As a test of our methodology, Doppler shifts of excited levels in ^{27}Si, with known lifetimes [27], at 2648, 3804, 4138, 4289, 4704, and 5283 keV were extracted. The lifetimes obtained for these states showed excellent agreement with previously reported values [27]. Examples of the Doppler shifts observed for the 5425.9(1)-keV transition from the 7589.7(8)-keV excited state can be found in Figs. 1 and 2.

The stable mirror nucleus ^{27}Al is strongly produced through the 1p evaporation channel in this study. This is a nice by-product of the experimental method, because information on analog states in the more stable nucleus is useful for unknown states in the unstable mirror system (see Refs. [28–30]). In this case, Champagne *et al.* [15] predicted a global ∼200-keV energy shift between even-parity analog states in ^{27}Al and ^{27}Si in the excitation energy region of interest, above the proton threshold. Although the stable nucleus ^{27}Al has been well studied [27], it was possible to obtain new information on

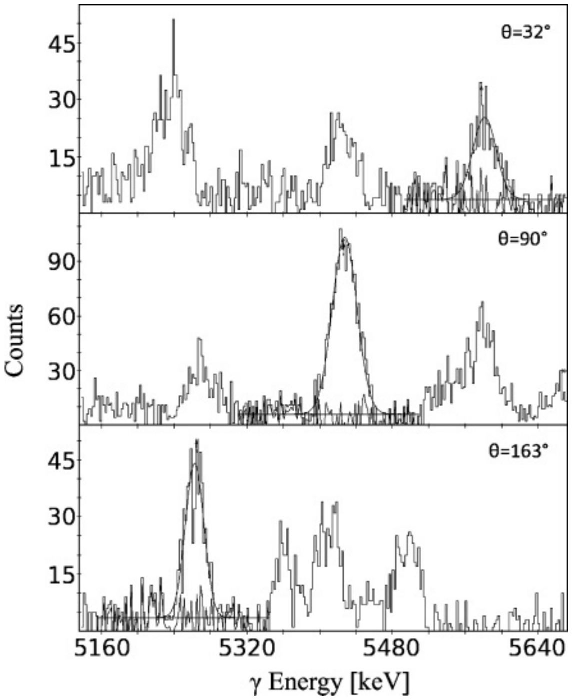

FIG. 1. Centroid peak fits for the 5426-keV γ ray at 32°, 90°, and 163°.

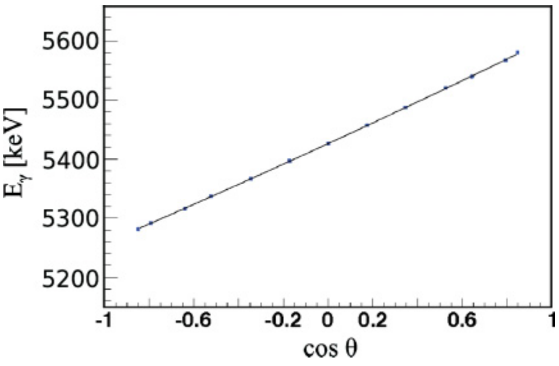

FIG. 2. Observed variations in energy over all 14 angles for the 5426-keV γ ray. The velocity of the recoil, β, is obtained from the straight-line fitted function $E_\gamma = E_{\gamma 0}[(1-\beta^2)^{1/2}/(1-\beta\cos\theta)]$, where $E_{\gamma 0}$ is the unshifted γ-ray energy.

certain levels in ^{27}Al, including the observation of new γ-decay branches, of relevance for the identification of analog states in ^{27}Si.

The next section describes the results of measurements on states above the energy threshold for proton emission from ^{27}Si to the isomeric state in ^{26}Al ($E_x = 7691.3(2)$ [23]) of relevance to the ^{26}Al$^m(p,\gamma)^{27}$Si reaction.

III. RESULTS

Table I presents the level energies, spin-parity assignments, γ-ray energies, angular distribution coefficients, and lifetime information of observed excited states in ^{27}Si above the proton-emission threshold, together with a comparison with previous studies. The influence of levels in ^{27}Si up to $E_x =$ 7832 keV on the ^{26}Al$^g(p,\gamma)^{27}$Si reaction rate has already been discussed in Ref. [18]. Here, lifetimes for these levels are reported for the first time. Two key, low-energy resonances for the ^{26}Al$^g(p,\gamma)^{27}$Si reaction at $E_x = 7589.7(8)$ keV [$E_r =$ 126.7(8) keV] and $E_x = 7651.6(3)$ [$E_r = 188.6(4)$ keV] have been measured to have lifetimes of 20(3) and 12(3) fs, respectively. For the 126.7(8)-keV resonant state, the obtained lifetime value of 20(3) fs is comparable with that of the assigned $9/2^+$ 7806-keV mirror state in ^{27}Al [18], which is known to have a lifetime of 26(6) fs [27]. This finding provides further support for the mirror assignment made for the 127-keV state in Ref. [18]. In the case of the 188.6(4)-keV resonance, an $11/2^+$ assignment was made [18]. We note here that taking this spin value gives a proton spectroscopic factor $C^2S \sim 0.18$, assuming $l_p = 0$ for the (^{3}He,d) transfer reaction study of Vogelaar *et al.* [16]. Taking the new precise energy of this state [18], a resonance strength value of 45 μeV [18] (combined from the measurements of Refs. [14] and [17]), and by using the prescription of Iliadis [20] for calculating proton single-particle reduced widths for unbound states [31], we obtain $C^2S \sim 0.13$. This value is consistent with the transfer reaction study of Ref. [16]. In contrast, by taking $l_p = 2$, an unfeasibly large C^2S value would be required to account for the measured resonance strength; therefore, we conclude that $l_p = 0$ is the dominant capture component for this resonance.

The excited states already presented in Ref. [18] up to $E_x =$ 7832 keV are not expected to have any significant impact on the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate and, consequently, will not be discussed in this article. It should be noted that the following excited levels at 7693.8(9), 7704.3(2), 7739.3(4), 7794.8(19), and 7831.5(4) keV previously reported in Ref. [18] are all located above the ^{26}Al$^m + p$ threshold energy. However, the 7694-, 7704-, and 7739-keV states are too low in energy to make a considerable contribution to the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate. Furthermore, the 7795- and 7832-keV levels are of high spin in nature and, as such, will not be of importance for the ^{26}Al$^m(p,\gamma)^{27}$Si reaction.

It is expected that γ-decay transitions from low-spin excited states above the ^{26}Al$^m + p$ threshold predominantly feed through the lowest lying $1/2^+_1$ 781-keV and $3/2^+_1$ 957-keV excited states in ^{27}Si. Figures 3(a) and 3(b) display γ-γ coincidence relationships with the $1/2^+_1$ and $3/2^+_1$ levels, respectively. In the following subsections, we will discuss the identification of excited states in ^{27}Si of potential importance for the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate, in order of increasing excitation energy. The number given in the parentheses of the title of each subsection represents the resonance energy E_r^m of the state with respect to the ^{26}Al$^m + p$ threshold.

A. E_x = 7838 keV (E_r^m = 146 keV)

In the current study, a γ-ray transition is observed at 6879.6(2) keV, as indicated in Fig. 3(b), pointing to a newly observed excited state in ^{27}Si at 7837.6(2) keV. No other decay transitions were observed from this level. The 6880-keV γ ray was measured to have angular distribution coefficients

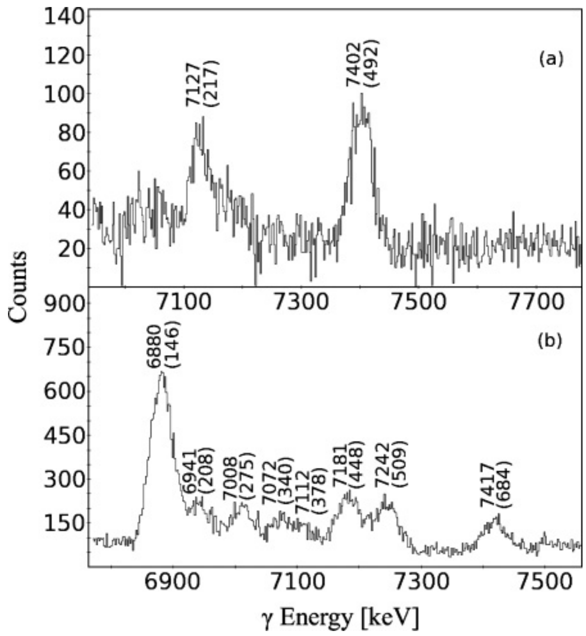

FIG. 3. (a) γ-γ coincidence spectrum with a gate placed on the 781-keV transition in ^{27}Si. Numbers in parentheses represent resonance energies. (b) γ-γ coincidence spectrum with a gate placed on the 957-keV transition in ^{27}Si.

TABLE I. Properties of excited states above the proton-emission threshold of 7463.0(2) keV [23] in ^{27}Si. Level energies were corrected for the recoil of the compound nucleus.

E_x (keV) Present	E_x (keV) Endt [27]	E_x (keV) Deibel [22]	E_r (keV)	E_r^m (keV)	E_γ (keV)	J^π_{final}	a_2/a_4	Assignment	τ (fs)
7469.0(6)	7468(3)		6.0(6)		6511.1(6)	$3/2_1^+$	−0.64(25)/0.39(34)	$5/2^+$	
7531.3(7)	7532(3)		68.3(7)		4883.5(5)	$5/2_2^+$		$5/2^+$	<6
					6573.5(9)	$3/2_1^+$	−0.85(9)/0.20(13)		
–	7557(3)		94.0(30)					$(3/2^+)$	
7589.7(8)	7592(3)		126.7(8)		3115.6(14)	$7/2_2^+$		$9/2^+$	20(3)
					3142.6(27)	$11/2_1^+$			
					5425.9(1)	$7/2_1^+$	−0.52(2)/0.01(3)		
7651.6(3)	7652(3)		188.6(4)		2371.0(40)	$11/2_2^+$		$11/2^+$	12(3)
					3204.1(1)	$11/2_1^+$	0.40(3)/−0.01(4)		
7693.8(9)	7690(3)		230.8(9)	2.5(9)	5530.1(9)	$7/2_1^+$	0.50(7)/0.24(9)	$5/2^+$	<5
7704.3(2)	7702(2)		241.3(3)	11.2(3)	5056.7(1)	$5/2_2^+$	−0.21(7)/0.09(9)	$7/2^-$	<1
7739.3(4)	7740.8(9)		276.3(4)	48.0(4)	2421.6(4)	$9/2_2^+$		$9/2^+$	22(4)
					2455.9(4)	$11/2_2^+$			
					3291.3(1)	$11/2_1^+$			
					4828.7(5)	$9/2_1^+$	0.25(12)/−0.25(17)		
					5575.7(2)	$7/2_1^+$	−0.10(4)/0.11(5)		
7794.8(19)	7792(3)		331.8(19)	103.5(19)	5631.0(19)	$7/2_1^+$	0.86(26)/−0.26(28)	$7/2^+$	
7831.5(4)	7831(3)		368.5(4)	140.2(4)	2329.8(8)	$5/2_1^-$		$9/2^-$	8(5)
					3383.8(2)	$11/2_1^+$			
					4921.0(4)	$9/2_1^+$	0.18(7)/0.05(9)		
					5668.0(3)	$7/2_1^+$			
7837.6(2)			374.6(3)	146.3(3)	6879.6(2)	$3/2_1^+$	−0.29(3)/0.03(1)	$1/2^+$	<1
7899.0(8)	7893(4)		436.0(8)	207.7(8)	3424.9(8)	$7/2_2^+$		$5/2^+$	14(10)
					6941.1(8)	$3/2_1^+$	−0.14(9)/−0.02(12)		
7909.1(7)	7911(3)		446.1(7)	217.8(7)	7127.1(7)	$1/2_1^+$	−0.14(16)/0.46(19)	$3/2^+$	
7966.3(8)	7972(3)		503.3(8)	275.0(8)	7008.2(8)	$3/2_1^+$	−0.08(10)/−0.03(13)	$5/2^+$	11(8)
8031.5(11)	8036(3)		568.5(11)	340.2(11)	5384.2(9)	$5/2_2^+$		$5/2^+$	
					7071.6(19)	$3/2_1^+$	−0.18(17)/0.12(21)		
8069.6(30)	8074(3)		606.6(30)	378.3(30)	7111.5(30)	$3/2_1^+$	0.51(49)/0.28(54)	$3/2^-$	
8139.0(6)	8140(4)	8136(4)	676.0(6)	447.7(6)	7180.9(6)	$3/2_1^+$	−0.05(7)/0.20(9)	1/2	<1
–	8157(2)	8156(5)	693.5(35)	465.2(25)				(7/2–13/2)	
8168.2(20)	8165(2)	8162(2)	705.2(20)	476.9(20)	3719.4(12)	$11/2_1^+$	0.21(7)/0.04(9)	$11/2^+$	
					5261.0(40)	$9/2_1^+$			
8183.5(4)	8184(4)		720.5(4)	492.2(4)	7401.7(4)	$1/2_1^+$	−0.04(9)/0.00(12)	$3/2^-$	4(3)
8199.8(7)			736.8(7)	508.5(7)	7241.7(7)	$3/2_1^+$	−0.27(9)/−0.09(11)	(1/2, 5/2)	13(7)
8209.0(22)	8207(3)	8210(4)	746.0(22)	517.7(22)	5298.3(22)	$9/2_1^+$		$(7/2^-)$	
–	8226(3)		763.0(30)	534.7(30)				$7/2^+$	
–	8289(3)	8299(5)	831.0(40)	602.7(40)				$(7/2\text{–}13/2)^+$	
–	8328(2)	8318(3)	860.0(25)	631.7(25)				$(1/2, 3/2)^+$	
8344.5(10)			881.5(10)	653.2(10)	5434.0(19)	$9/2_1^+$		(7/2)	
					6180.6(7)	$7/2_1^+$	0.33(9)/−0.11(13)		
–	8358(2)	8354(3)	893.0(25)	664.7(25)				$(3/2\text{–}9/2)^+$	
8375.5(9)		8375(3)	912.5(9)	684.2(9)	7417.3(9)	$3/2_1^+$	0.52(16)/0.22(17)	$5/2^+$	3(2)

consistent with a $\Delta I = \pm 1$ transition. Therefore, the 7838-keV level has a 1/2 or 5/2 spin assignment. The effective lifetime of this state was measured to be <1 fs. In comparison with the mirror nucleus ^{27}Al in the $E_x = 7.8$–8.2 MeV range, only the $1/2^+$ 8130-keV excited state is known to exhibit a γ-decay branch to the $3/2_1^+$ level with no additional branches to other excited states. The $3/2_1^+$ branch from the 8130-keV state in ^{27}Al was observed in this study at 7111 keV. An analysis of this γ ray revealed an effective lifetime for the 8130-keV state of <1 fs, which is similar to the lifetime obtained for the newly observed 7838-keV level in ^{27}Si. Consequently, a $1/2^+$ 7838-keV excited was assigned in ^{27}Si.

B. $E_x = 7899$ keV ($E_r^m = 208$ keV)

Wang *et al.* [13] reported an excited state in ^{27}Si at 7893(4) keV. This was observed in this study at 7899.0(8) keV, with 3424.9(8)- and 6941.1(8)-keV γ-decay branches to the $7/2_2^+$ and $3/2_1^+$ levels, as shown in Fig. 3(b). The 6941-keV γ ray was measured to have an angular distribution consistent with a $\Delta I = \pm 1$ transition, implying a 5/2 spin assignment for the 7899-keV state. From a comparison with the mirror nucleus, the $5/2^+$ 8097-keV level in ^{27}Al is the only state in the $E_x = 7.8$–8.3 MeV range that is known to exhibit γ-decay transitions to the $7/2^+_2$ and $3/2^+_1$ excited states. Consequently, 3425- and 6941-keV γ-ray transitions from a $5/2^+$ 7899-keV excited state in ^{27}Si were assigned.

C. $E_x = 7909$ keV ($E_r^m = 218$ keV)

As shown in Fig. 3(a), a 7127.1(7)-keV γ-decay branch to the $1/2^+_1$ level in ^{27}Si was observed, pointing to an excited state at 7909.1(7) keV in excellent agreement with the previously reported 7911(3) level energy [27]. The 7127-keV γ ray was measured to have angular distribution coefficients consistent with a mixed $M1 + E2$, $\Delta I = \pm 1$ transition, leading to a $3/2^+$ assignment for the observed 7909-keV state. In comparison with the mirror nucleus ^{27}Al in the $E_x = 7.9$–8.3 MeV energy range, the $3/2^+$ 8065-keV level is the only known $3/2^+$ state [27]. No decay transitions have been reported for this excited level. However, in the current ^{27}Al data, a 7217-keV γ-decay transition to the $1/2^+_1$ state from an excited level at 8065 keV was observed. Consequently, a $3/2^+$ 7909-keV excited state was assigned in ^{27}Si.

D. $E_x = 7966$ keV ($E_r^m = 275$ keV)

As shown in Fig. 3(b), a transition is observed at 7008.2(8) keV, establishing an excited state in ^{27}Si at 7966.3(8) keV. No other excited states were observed within ±40 keV of this level in ^{27}Si. Consequently, although our level energy measurement is in slight disagreement, we find this 7966-keV state to correspond with the previously reported 7972(3)-keV level [13]. The 7008-keV γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition, pointing to a 1/2 or 5/2 spin assignment. No additional γ-decay branches were observed from the 7966-keV level, and in comparison with the mirror nucleus ^{27}Al in the $E_x = 7.9$–8.4 MeV range, the $5/2^+$ 8324-keV excited state is the only unassigned level known to exhibit a single γ-decay branch, other than to the ground state, to the $3/2^+_1$ level [27]. Furthermore, the 8324-keV excited state in ^{27}Al is measured to have an effective lifetime of 10(5) fs, which is similar to the 11(8)-fs value obtained for the 7966-keV level and is larger than the lifetime obtained for the newly observed 7838-keV excited state in ^{27}Si. Such a measurement provides strong evidence for a mirror assignment between the 7966-keV and the 8324-keV excited state in ^{27}Si and ^{27}Al, respectively, and indicates that the 7966-keV level in ^{27}Si is unlikely to be the mirror of the $1/2^+$ 8130-keV state in ^{27}Al. Therefore, a $5/2^+$ 7966-keV excited state is assigned in ^{27}Si.

E. $E_x = 8032$ keV ($E_r^m = 340$ keV)

Schmalbrock *et al.* [11] reported an excited state in ^{27}Si at 8034(5) keV. This level was observed in this study at 8031.5(11) keV with 7071.6(19)- and 5384.2(9)-keV γ-decay branches to the $3/2^+_1$ and $5/2^+_2$ levels, respectively. An angular distribution analysis of the 7072-keV γ ray provides angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition, indicating a 1/2 or 5/2 spin assignment for the 8032-keV state. From a comparison with the mirror nucleus in the $E_x = 8.0$–8.7 MeV domain, only the $5/2^+$ 8537-keV state is known to exhibit a γ-decay transition to the $5/2^+_2$ level [27]. Furthermore, in our ^{27}Al data, this $5/2^+$ 8537-keV excited state also was observed to exhibit a previously unobserved 7520-keV γ-decay branch to the $3/2^+_1$ state. Consequently, 5384- and 7072-keV γ-ray transitions from a $5/2^+$ 8032-keV excited state were assigned in ^{27}Si.

F. $E_x = 8070$ keV ($E_r^m = 378$ keV)

Furthermore, Fig. 3(b) also shows that a low-intensity γ ray is observed at 7111.5(30) keV, establishing an excited level in ^{27}Si at 8069.6(30) keV in good agreement with the previously reported 8073(3)-keV state in Ref. [13]. An angular distribution analysis of the 7112-keV γ ray revealed coefficients consistent with a $\Delta I = 0$ transition, indicating a 3/2 spin assignment for the 8070-keV state. In comparison with the mirror nucleus in the $E_x = 7.9$–9.0 MeV region (in this case, a wider energy range was examined to allow for the possibility that the observed 8070-keV level is an odd-parity state, and currently, it is not known how large an energy shift should be expected between odd-parity ^{27}Al and ^{27}Si mirror pairs), there are no 3/2 states known to exhibit a γ-decay branch to the $3/2^+_1$ level [27]. The $3/2^-$ 8598-keV state in ^{27}Al is one of the 3/2 states located in the $E_x = 7.9$–9.0 MeV energy range. No γ-decay branches have been reported for this state, but its width has been measured to be 0.56 eV [27], corresponding to a lifetime of ~2 fs. A lifetime of 2 fs would be consistent with a fast $E1$ γ-decay transition from the 8598-keV level (as this state is proton-unbound in ^{27}Al, it also might exhibit a proton-decay branch). In our ^{27}Al data, the $3/2^-$ 8598-keV level was observed to exhibit a 7581-keV γ-decay branch to the $3/2^+_1$ state and was the only 3/2 excited level in ^{27}Al observed to exhibit such a branch in the $3/2^+_1$ gated $E_\gamma = 6.8$–7.9 MeV γ-ray spectrum. An angular distribution analysis of the 7581-keV ^{27}Al γ ray revealed $a_2 = 0.77(34)$ and $a_4 = 0.28(37)$ coefficients, consistent with a $\Delta I = 0$ transition and similar to those reported here for the 7112-keV γ ray in ^{27}Si. Thus, a 7112-keV γ-decay branch to the $3/2^+_1$ level from a $3/2^-$ 8070-keV state in ^{27}Si has been established.

G. $E_x = 8139$ keV ($E_r^m = 448$ keV)

In the proton-decay study of Ref. [22], a 4(1)% branch to the ^{26}Al^m level from an excited state at 8136(4) keV was observed and an l_{min} assignment of 0 was determined. In this study, this state was observed at 8139.0(6) keV and was found to exhibit a 7180.9(6)-keV γ-decay branch to the $3/2^+_1$ level, as shown in Fig. 3(b). The 7181-keV γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition, indicating a 1/2 or 5/2 spin assignment for the 8139-keV excited state. In addition to this observation, the lifetime of the 8139-keV state was measured to be <1 fs. Assuming a lifetime of ~0.7 fs for the 8139-keV state and given the 4% proton branch from this state to the isomeric level of ^{26}Al, we estimate a proton partial width Γ_p of 54^{+41}_{-25} meV. For present purposes, a 1/2 spin assignment is favored for this

8139-keV level as both $l_p = 2$ and 3 captures would imply a large corresponding proton spectroscopic factor for this state.

H. $E_x = 8168$ keV ($E_r^m = 477$ keV)

Buchmann *et al.* [12] reported γ decays to the $9/2_1^+$ and $11/2_1^+$ levels with 34% and 57% branches, respectively, from an excited state in ^{27}Si at 8165(2) keV. Here, we identify this excited state as being located at 8168.2(20) keV with 5261.0(40)-keV and 3724.9(14)-keV γ-decay branches to the $9/2_1^+$ and $11/2_1^+$ states, respectively. The 3719-keV γ ray was measured to have an angular distribution consistent with a $\Delta I = 0$ transition, indicating an 11/2 spin assignment for the observed 8168-keV level. In comparison with the mirror nucleus, the 11/2 8396-keV state in ^{27}Al is the only level in the excitation energy region $E_x = 8.0$–8.6 MeV known to exhibit a γ-decay branch to the $11/2_1^+$ and $9/2_1^+$ states [27]. Therefore, the observed 8168-keV excited state in ^{27}Si is the likely mirror analog of the 11/2 8396-keV level in ^{27}Al. Although the parity of the 8396-keV level is not known, the 8168-keV excited state in ^{27}Si has been previously given a $7/2^+$–$13/2^+$ assignment [27]. Consequently, 5261- and 3725-keV γ-decay transitions from an $11/2^+$ 8168-keV excited level in ^{27}Si were assigned. The observation of an $11/2^+$ state 709 keV above the threshold for proton emission to the ground state of ^{26}Al indicates that the 8168-keV level has a very small proton spectroscopic factor. This high-spin 8168-keV state will not have any significant impact on the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate and, as such, will not be considered in our analysis.

I. $E_x = 8184$ keV ($E_r^m = 492$ keV)

As shown in Fig. 3(a), a 7401.7(4)-keV γ ray was observed to decay to the $1/2_1^+$ level, placing an excited state at 8183.5(4) keV in ^{27}Si, which is in excellent agreement with the previously reported level energy of 8184(4) keV [27]. The observed 7402-keV γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition, producing a 3/2 spin assignment for the 8184-keV excited state. An examination of the mirror nucleus reveals that the $3/2^-$ 8182-keV level in ^{27}Al is the only state, in the 7.9–9.0 MeV range, known to exhibit a γ-decay branch to the $1/2_1^+$ level. Thus, a 7402-keV γ-decay transition from a $3/2^-$ 8184-keV excited state in ^{27}Si was assigned.

J. $E_x = 8200$ keV ($E_r^m = 509$ keV)

Returning to Fig. 3(b), we observe a 7241.7(7)-keV γ-decay branch to the $3/2_1^+$ level, establishing a newly observed excited state in ^{27}Si at 8199.8(7) keV. No additional decays were observed, and an angular distribution analysis of the 7242-keV γ ray indicates a $\Delta I = \pm 1$ character, suggesting a 1/2 or 5/2 spin assignment. If we assume a ~200-keV energy shift between mirror states in ^{27}Si and ^{27}Al, the observed 8200-keV level is most likely a mirror analog of an excited state in ^{27}Al above the proton threshold energy of $E_p = 8271.3(2)$ keV [23]. Because proton emission begins to compete with γ decay above the threshold, γ-decay transitions from many proton-unbound excited states in ^{27}Al remain unknown. Consequently, no other restrictions can be placed on the spin-parity assignment of the 8200-keV excited state.

K. $E_x = 8209$ keV ($E_r^m = 518$ keV)

In this study, a 5298.3(22)-keV γ-decay transition to the $9/2_1^+$ level in ^{27}Si, originating from an excited state at 8209.0(22) keV, is in good agreement with previous studies [14,21,27]. Vogelaar [14] reported γ decays from this state to the $9/2_1^+$ and ground-state levels with 20% and 60% branches, respectively. Furthermore, a resonance strength of 206(31) meV was determined for the 8209-keV state, pointing to an $l_p = 0$ or 1 capture to the ^{26}Al ground state. In comparison with the ^{27}Al mirror nucleus, in the excitation energy range 8.0–9.0 MeV, only the ($5/2^+$, 7/2, $9/2^+$) 8043- and 7/2 8442-keV states are known to exhibit strong γ-decay branches to both the $9/2_1^+$ and ground-state levels. In this work, no negative energy shifts have been observed between even-parity mirror analog states, and the large resonance strength measured in Ref. [14] indicates a maximum $l_p = 1$ proton capture to the ^{26}Al$^g(p,\gamma)^{27}$Si reaction rate. Consequently, a $7/2^-$ spin assignment is favored for the observed 8209-keV excited state in ^{27}Si. Again, a high-spin state such as this is unlikely to contribute to the ^{26}Al$^m(p,\gamma)^{27}$Si reaction and has consequently been omitted in the rate analysis.

L. $E_x = 8345$ keV ($E_r^m = 653$ keV)

Vogelaar [14] reported γ decays to the $9/2_1^+$ and $7/2_1^+$ levels from an excited state at 8348(3) keV in ^{27}Si. Here, we identify an excited level in ^{27}Si at 8344.5(10) keV with 5434.0(19)- and 6180.6(7)-keV γ-decay transitions to the $9/2_1^+$ and $7/2_1^+$ states, respectively. The 6181-keV γ ray has angular distribution coefficients consistent with a $\Delta I = 0$ or ± 2 transition, indicating a 7/2 or 11/2 spin assignment for the 8345-keV excited state. In comparison with the mirror nucleus ^{27}Al, both the 7/2 8586-keV and ($7/2, 9/2^+$) 8675-keV excited levels are the only states in the $E_x = 8.3$–8.8 MeV region known to exhibit strong γ-decay branches to the $7/2_1^+$ state. Consequently, a 7/2 spin assignment is favored for the 8345-keV excited state in ^{27}Si. Again, this state is not considered when evaluating the reaction rate.

M. $E_x = 8376$ keV ($E_r^m = 684$ keV)

The highest energy γ-ray transition observed in our data appears at 7417.3(9) keV and was found to be coincident with the $3/2_1^+$ level, establishing an excited state in ^{27}Si at 8375.5(9) keV, which is in good agreement with the previously reported 8375(3)-keV state by Deibel *et al.* [22]. An angular distribution analysis of the 7417-keV γ ray provides angular distribution coefficients consistent with a mixed $M1 + E2$, $\Delta I = \pm 1$ transition, leading to a $1/2^+$ spin or $5/2^+$ spin assignment for the 8376-keV level. In Ref. [22], a minimum l-transfer of 1 was determined for proton decay from the 8376-keV state to the ^{26}Al metastable level. Consequently, a $5/2^+$ 8376-keV excited state was assigned in ^{27}Si. Here, an effective lifetime of 3(2) fs was obtained for this 8376-keV state, and in Ref. [22], a 31(8)% proton-decay branch to the isomeric level of ^{26}Al was measured. This indicates a proton partial width of 98^{+273}_{-54} meV for the 8376-keV state, corresponding to a proton spectroscopic factor, $C^2S \sim 0.03$ for $l_p = 2$ capture to the $^{26}\text{Al}^m$ level.

N. Unobserved high-spin levels: $E_x = 8157, 8226, 8289$, and 8358 keV ($E_r^m = 465, 535, 603$, and 665 keV)

Previously reported strong $^{26}\text{Al}^g + p$ resonances in the direct (p,γ) studies of Buchmann *et al.* [12] and Vogelaar [14] at 8157(2), 8226(3), 8289(3), and 8358(2) keV were not observed in the present work. It is expected that all four states exhibit dominant proton decay branches and, as such, would be unlikely to be observed in the current study. The 8226- and 8289-keV excited states have been previously given $7/2^+$ and $(7/2^+\text{–}13/2^+)$ spin-parity assignments and, consequently, will not make significant contributions to the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate. Buchmann *et al.* [12] reported a γ-decay branch to the $11/2_2^+$ level in ^{27}Si from the 8157-keV excited state, which is consistent with a minimum spin assignment of $7/2$. Furthermore, Deibel *et al.* [22] measured a proton decay branch to the ^{26}Al ground state of 22(4)% from the 8157-keV state. Thus, this 8157-keV level also is unlikely to contribute significantly to the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate. Finally, although no definitive spin-parity restrictions can be placed on the unobserved 8358-keV level, other than those already presented in Ref. [27], Deibel *et al.* [22] observed a 39(6)% proton-decay branch to the ^{26}Al ground state from the 8358-keV level. An l_{min}-transfer assignment of 0 was determined [22], pointing to a high-spin assignment for the 8358-keV state. Therefore, for present purposes, this 8358-keV level is not expected to influence the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate.

O. Unobserved level: $E_x = 8176$ keV ($E_r^m = 485$ keV)

A possible $(1/2, 3/2)^+$ excited state at 8176(3) keV was reported in a β-delayed proton study by Ognibene *et al.* [32] but was not observed in the current study. This excited state was also not observed in any study prior to Ref. [32] or in the recent work by Deibel [21], despite lying within the investigated energy range. Therefore, we do not include this state in Table I, although it would certainly be worthwhile for a future study of β-delayed proton emission from ^{27}P to elucidate whether it exists.

P. Unobserved level: $E_x = 8323$ keV ($E_r^m = 632$ keV)

In Ref. [21], a 53(10)% proton-decay branch to the $^{26}\text{Al}^m$ level from an excited state at 8318(3) keV in ^{27}Si was observed and an l_{min}-transfer of 0 was assigned. This state was not observed in the current study but has been previously assigned as a $(1/2, 3/2)^+$ state [27]. The non-observation of this state is consistent with a dominant proton decay branch to the isomeric state in ^{26}Al.

The analysis thus far completes the assignment of excited states in ^{27}Si above the $^{26}\text{Al}^m + p$ threshold of importance for the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction.

IV. EVALUATION OF THE STELLAR REACTION RATE

Figure 4 displays individual contributions of astrophysical resonances to the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ stellar reaction rate, together with the predicted total reaction rate of the NACRE Collaboration [19]. In this section, we will discuss the features of the rate and the assumptions made in its determination for each astrophysically important $^{26}\text{Al}^m + p$ resonance in order of increasing resonance energy. The 2.5(8)-, 11.2(3)-, 48.0(4)-, 103.5(19)-, and 140.2(4)-keV resonances previously identified in Ref. [18] were found either to be too low in energy or to exhibit minimum $l_p = 4$ and 5 captures to the isomeric state of ^{26}Al and, as a result, have no noticeable effect on the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate. As such, these states will not be discussed in this section. For all resonances identified in this work, we have assumed that the lowest possible l_p will dominate the proton partial width.

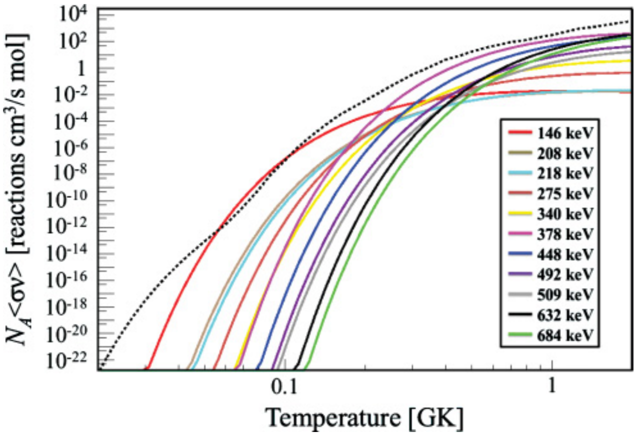

FIG. 4. (Color online) Contribution of individual resonances to the $^{26m}\text{Al}(p,\gamma)^{27}\text{Si}$ stellar reaction rate. Inset: Key of plotted resonances in terms of energy with respect to the $^{26}\text{Al}^m + p$ threshold. The dashed line represents the total analytical rate presented by Angulo [19]. The direct capture component to the reaction rate is expected to be insignificant for $T \geqslant 0.02$ GK and, as such, was not included in the analysis.

A $1/2^+$ resonant state has been newly identified in the $^{26}\text{Al}^m + p$ system at 146.3(3) keV. The width of this $l_p = 0$ resonance is dominated by γ decay, and its effective lifetime has been measured to be <1 fs, leading to a resonance strength estimate of $\sim$0.66 μeV. Uncertainties in the strength of the 146-keV resonance are dominated by uncertainties in Γ_p, and in this work, we have assumed a proton spectroscopic factor C^2S of 0.05 for this state. This value is in the typical range of C^2S obtained in previous work studying proton-unbound states in the excitation energy region of interest [15,33].

Low-energy $l_p = 2$ resonances have been identified in the $^{26}\text{Al}^m + p$ system at 207.7(8), 217.8(7), 275.0(8), and 340.2(11) keV. At these resonance energies, $\Gamma_\gamma \gg \Gamma_p$ and the strengths of the 208-, 218-, 275-, and 340-keV resonant states are determined by Γ_p. Again, a proton spectroscopic factor C^2S of 0.05 was assumed for these states, and it is observed that the strengths of the $l_p = 2$ resonances are too weak to make such states astrophysically important.

The 378.3(30)-keV resonance has been identified as a $3/2^-$ state, indicating an $l_p = 1$ capture to the $^{26}\text{Al}^m$ level. Here, we adopt a value of $C^2S = 0.05$ and estimate a proton partial width of $\sim$30 meV. The lifetime of this resonant state remains unknown, but we assume a typical γ-ray lifetime of $\sim$1 fs for a high-energy $E1$ transition. Such a lifetime would imply a $\sim$3% proton-decay branch from the 378-keV state to the ^{26}Al isomeric level.

In the proton-decay study of Deibel *et al.* [22], a 4% branch to the isomeric state of ^{26}Al was observed from a resonant state in ^{27}Si at 445(4) keV. We observed this state in this study at 447.7(6) keV, and it was measured to have a lifetime of <1 fs. Assuming a lifetime of 0.7 fs and a spin-parity assignment of $1/2^+$, we estimate a resonance strength of 52 meV for the 448-keV resonance.

The presently observed 492.2(4)-keV resonant state has been given a $3/2^-$ spin-parity assignment, corresponding to $l_p = 1$ capture to the ^{26}Al^m level, and has been measured to have a lifetime of 4(3) fs. However, this state was not observed in the delayed proton-decay study of Deibel *et al.* [22] and no information on the proton-decay branch is known. In the study of Ref. [22], proton-decay branches as low as 4(1)% were reported. As such, to be consistent with its non-observation in Ref. [22], an upper limit of $\sim$3% is assumed for the branch of the 492-keV state (although the background could vary with proton energy in Ref. [22]). Given this upper limit, a proton partial width of $\sim$7 meV, corresponding to an implied spectroscopic factor $C^2S \sim 0.001$, is estimated for the 492-keV resonance.

A newly observed resonant state in the ^{26}Al$^m + p$ system has been identified at 508.5(7) keV and has been measured to have a lifetime of 13(7) fs. In this study, a (1/2, 5/2) spin assignment restriction has been placed on this 509-keV resonance, indicating possible $l_p = 0$, 1, 2, or 3 captures to the ^{26}Al metastable state. No proton-decay branch has been observed from this state. As with the 492-keV state described above, the non-observation of a proton-decay branch from a ^{26}Al$^m + p$ resonant state at 509 keV in Ref. [22] is suggestive of a maximum branch of $\sim$3%. Given the measured 13-fs lifetime, a proton partial width of $\sim$2 meV is estimated for the 509-keV state. This would imply very low spectroscopic factors for both $l_p = 0$ and 1 captures and a $C^2S \sim 0.01$ for the $l_p = 2$ capture. Here, we assume the $l_p = 2$ capture to a $5/2^+$ level with $C^2S = 0.01$.

The unobserved ^{26}Al$^m + p$ resonant state at 631.7(25) keV has been measured to have a proton-decay branch to the ^{26}Al^m level of 53(10)% [22]. Excited states in ^{27}Si in this energy region are expected to have γ-decay partial lifetimes of $\sim$1–10 fs. Here, we assume a 1-fs lifetime for the 8323-keV level, corresponding to a γ-ray partial width of $\sim$1 eV. This can be viewed as the limiting case. Given the measured 53% branch to the isomeric state from the 8323-keV level, a proton partial width of $\sim$530 meV is expected. This would indicate a proton spectroscopic factor of $\sim$0.002 for the $l_p = 0$ capture and $C^2S \sim 0.2$ for the $l_p = 2$ capture. Although no definitive spin-parity assignment can be placed on the 8323-keV state, we assume a $1/2^+$ spin-parity assignment.

The highest energy resonant state to be observed in this study appears at 684.2(5) keV. This level has been measured to have a lifetime of 3(2) fs and has been measured to have a 31(8)% proton-decay branch to the ^{26}Al^m level. From these measurements, a resonance strength of 157 meV is predicted for the 684-keV state.

At astrophysical temperatures $T = 0.02$–0.20 GK, such as those found in Wolf-Rayet stars ($T_{\text{peak}} \sim 0.05$ GK), AGB stars ($T_{\text{peak}} \sim 0.10$ GK), and carbon-oxygen (CO) novae ($T_{\text{peak}} \sim 0.20$ GK), the abundance of the isomeric state of ^{26}Al is expected to be significantly less than that of the ground state. Nevertheless, the ^{26}Al$^m(p,\gamma)^{27}$Si reaction is expected to affect the isotopic abundance of ^{26}Mg synthesized in such environments, which has been identified as a distinctive signature of ^{26}Al nucleosynthesis in many presolar grains attributed to AGB stars and classical novae. As shown in Fig. 4, the newly observed $1/2^+$ 7838-keV excited state in ^{27}Si, corresponding to a low-energy $l_p = 0$ resonance at $E_r^m = 146.3(3)$ keV in the ^{26}Al$^m + p$ system, clearly dominates the rate for $T = 0.02$–0.20 GK. The contribution of the newly observed $l_p = 0$ resonance brings the predicted rate into agreement with the analytical rate of Ref. [19] for $T = 0.05$–0.10 GK. Without its influence, the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate would most likely be three orders of magnitude lower than that reported in the NACRE compilation [19]. Uncertainties in the rate in this temperature range now depend critically on the uncertainties in the strength of the 146-keV resonance.

At astrophysical temperatures $T = 0.30$–1.00 GK, such as those found in ONe novae ($T_{\text{peak}} = 0.40$ GK) and CCSN, the ^{25}Al$(p,\gamma)^{26}$Si reaction competes significantly with the β^+ decay of ^{25}Al, leading to a sizable population of the ^{26}Al isomeric state. The increased abundance of ^{26m}Al present at these temperatures in comparison with the $T = 0.02$–0.20 GK regime is likely to make the ^{26}Al$^m(p,\gamma)^{27}$Si reaction important in determining the isotopic abundance of ^{26}Mg synthesized in these environments. As shown in Fig. 4, the ($l_p = 1$) 378-keV resonance is most likely to be the main contributor to the rate for $T = 0.30$–1.00 GK. The strength of this resonant state is largely uncertain and, as such, dominates uncertainties in the rate for the $T = 0.30$–1.00 GK range.

At astrophysical temperatures $T > 1.00$ GK, such as those found in CCSN, the ^{25}Al$(p,\gamma)^{26}$Si reaction continues to compete significantly with the β^+ decay of ^{25}Al, leading to a large abundance of isomeric ^{26}Al. However, in this instance, the metastable state of ^{26}Al can communicate with the ground state [8] through thermal excitations. Consequently, the ^{26}Al$^m(p,\gamma)^{27}$Si stellar reaction rate may play a key role in the net isotopic abundance of ^{26}Al synthesized in CCSN [8]. This is of significant importance for γ-ray astronomy studies as CCSN have been identified as a potential source of characteristic 1.809-MeV γ rays associated with the decay of ^{26}Al^g. From Fig. 4, we see that the 378-, 448-, 632-, and 684-keV resonances all contribute to the rate. Both the lifetimes and proton branching ratios have now been measured for the 448- and 684-keV resonant states, and consequently, the contribution to the rate from these resonances is relatively well defined for $T > 1.00$ GK. The 378- and 632-keV resonances are likely to make the most notable contributions to the rate for $T > 1.00$ GK. The strengths of these states remain largely uncertain and, as such, dominate rate uncertainties in this temperature range.

The results of this work indicate that the ^{26}Al$^m(p,\gamma)^{27}$Si stellar reaction rate is likely to be lower than that predicted by the NACRE compilation for large portions of the temperature range 0.02–2.00 GK. This may significantly affect the isotopic abundances of ^{26}Mg and ^{26}Al produced in astrophysical environments. At high astrophysical temperatures, when several resonances are observed to make contributions to the rate, the Hauser-Feshbach approach [19] becomes comparable with the current estimate, although we still suggest a lower rate based on our experimental data. However, it is clear that a Hauser-Feshbach approach is particularly inappropriate to model the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ stellar reaction rate for the temperature range $T = 0.02$–0.20 GK, where only a single resonance is expected to dominate.

V. CONCLUSION AND OUTLOOK

In summary, this article reports the first γ-decay information on astrophysically important states in ^{27}Si relevant for the determination of the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate. Excitation energies have been measured with improved precision over previous studies. In addition, the first J^π assignments and lifetime information have been obtained. In this work, a new ($l_p = 0$) 146-keV resonance has been identified and is expected to dominate the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate for $T =$ 0.02–0.20 GK, corresponding to the combined temperature range of Wolf-Rayet stars, AGB stars, and CO novae. At higher astrophysical temperatures, $T = 0.30$–1.00 GK, found in ONe novae and CCSN, the ($l_p = 1$) 378-keV resonance is likely to make the most notable contribution to the rate. In the very high temperature regime of $T > 1.00$ GK, such as is found in CCSN, several resonances contribute to the rate.

The results of this study, therefore, point to the need to make more accurate estimates of the strengths of the 146- and 378-keV resonances to constrain uncertainties in the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate. A direct measurement of the cross section of the lower lying resonance reaction using a radioactive $^{26}\text{Al}^m$ beam does not seem to be feasible in the near future. In the case of the higher lying resonance, a direct measurement of the reaction strength could be feasible with $^{26}\text{Al}^m$ beams $\sim 10^6$ pps, depending on the value of the unknown proton spectroscopic factor. An alternative avenue for future study in reducing uncertainties in the $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ reaction rate would be to measure the proton-decay branches of the 146- and 378-keV resonant states. This may be achieved by adopting a similar approach to that of Ref. [22] and by employing lower threshold detectors for the measurement of coincident protons.

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