Astrophysically important ^{26}Si states studied with the ^{28}Si$(p, t)^{26}$Si reaction. II. Spin of the 5.914-MeV ^{26}Si level and galactic ^{26}Al production

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The ^{28}Si$(p, t)^{26}$Si reaction has been studied to resolve a controversy surrounding the properties of the ^{26}Si level at 5.914 MeV and its contribution to the ^{25}Al$(p, \gamma)^{26}$Si reaction rate in novae, which affects interpretations of galactic ^{26}Al observations. Recent studies have come to contradictory conclusions regarding the spin of this level (0^+ or 3^+), with a 3^+ assignment implying a large contribution by this level to the ^{25}Al$(p, \gamma)^{26}$Si reaction rate. We have extended our previous study [Bardayan *et al.*, Phys. Rev. C **65**, 032801(R) (2002)] to smaller angles and find the angular distribution of tritons populating the 5.914-MeV level in the ^{28}Si$(p, t)^{26}$Si reaction to be consistent with either a 2^+ or 3^+ assignment. We have calculated reaction rates under these assumptions and used them in a nova nucleosynthesis model to examine the effects of the remaining uncertainties in the ^{25}Al$(p, \gamma)^{26}$Si rate on ^{26}Al production in novae.

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I. INTRODUCTION

The origin of galactic ^{26}Al has been a key question in nuclear astrophysics since its observation via detection of 1.809-MeV γ rays [1–3]. Its spatial distribution has been interpreted to imply a massive star origin [4], but this explanation is not completely accepted, in part, because ^{60}Fe should be produced in similar amounts to ^{26}Al but surprisingly has not been observed by the γ-ray telescopes [5]. Novae may also be an important source of ^{26}Al, but it is difficult to estimate the nova contribution because of uncertainties in the ejected envelope mass [6], in the occurrence rate of novae [7], and in the nova nucleosynthesis of ^{26}Al [8]. Recent studies have found that an important uncertainty in the nucleosynthesis of ^{26}Al comes from the uncertain rate of the ^{25}Al$(p, \gamma)^{26}$Si reaction at nova temperatures [8,9]. This reaction bypasses ^{26}Al$^{g.s.}$ production via the sequence ^{25}Al$(p, \gamma)^{26}$Si$(\beta^+\nu)^{26m}$Al$(\beta^+\nu)^{26}$Mg$^{g.s.}$, which produces no 1.809-MeV γ rays. Because of its importance, the ^{25}Al$(p, \gamma)^{26}$Si reaction rate is or is proposed to be the subject of numerous studies at both stable [10,11] and radioactive ion beam facilities [12–20].

The ^{25}Al$(p, \gamma)^{26}$Si reaction rate has been evaluated in Ref. [21] with recent updates in Refs. [10,11]. These studies have concluded that the reaction rate is dominated by direct capture and by resonant capture through low-energy 1^+ and 3^+ resonances, with the 3^+ resonance providing the largest contribution in the peak novae temperature range 0.15–0.4 GK. The estimated 3^+ contribution is rather uncertain, however, as its resonance energy has not been determined, and the thermonuclear reaction rate depends exponentially upon its value. The energy of the 3^+ resonance was estimated in Ref. [21] to be $E_{c.m.} = 452 \pm 100$ keV ($E_x = 5970 \pm 100$ keV) from Coulomb displacement energy calculations. Guided by this estimate, a newly-observed ^{26}Si level at 5945 ± 8 keV was suggested to be the 3^+ resonance in Ref. [10]. Parpottas *et al.* [11], however, found from a comparison of ^{24}Mg$(^3$He$, n)^{26}$Si cross sections with Hauser-Feshbach calculations that the spin of the 5945-keV level is low and is most likely a 0^+. Additionally, they concluded that the ^{26}Si level at 5914 keV has higher spin, and the magnitude of their observed cross section was consistent with a 3^+ assignment and calculated reaction rates based on this assumption. This would seem to be in contradiction to the results obtained in Ref. [14], however, where the angular distribution of tritons populating the 5914-keV state in the ^{28}Si$(p, t)^{26}$Si reaction was found to be consistent with a 0^+ assignment. Parpottas *et al.* [11] argued that the angular distribution measured in Ref. [14] was not conclusive because it was not measured at the most forward angles where the angular distribution for a 0^+ would be the most distinctive. Furthermore, since it was believed that only natural parity states were being observed in Ref. [14], multistep processes were not considered as a possible explanation for the measured angular distributions. The goal of the present work was to measure the triton angular distribution populating the 5914-keV level in the ^{28}Si$(p, t)^{26}$Si reaction at more forward angles ($\theta_{c.m.} = 12°$–$23°$) and to consider a coupled-channels analysis of the angular distribution to examine these previous spin assignments and the possibility that the level has $J^\pi = 3^+$.

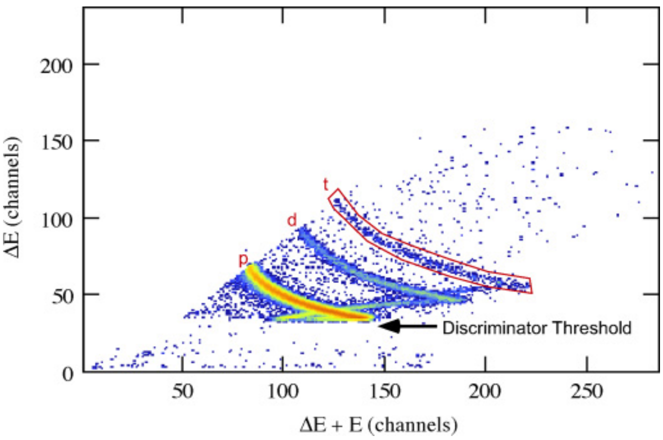

FIG. 1. (Color online) A typical particle-identification plot used to distinguish tritons from other reaction products.

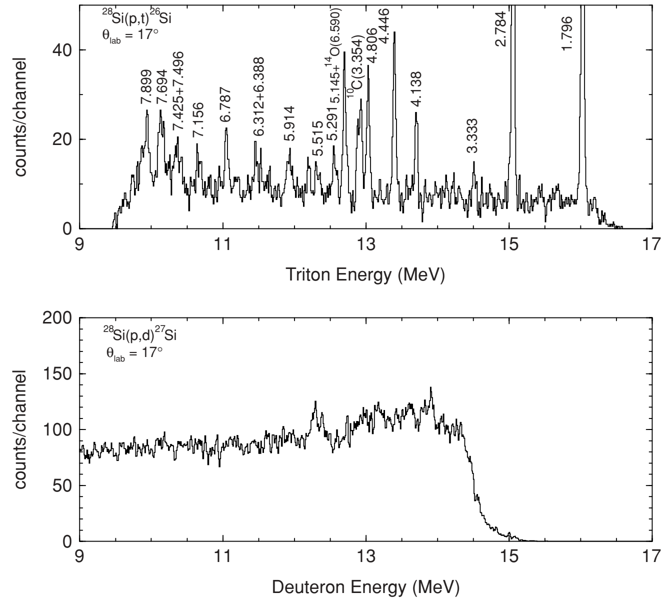

FIG. 2. The triton energy spectrum from the ^{28}Si$(p,t)^{26}$Si reaction observed at 17°. Peaks are labeled with excitation energies from Refs. [11,14,23]. The bottom plot shows the deuteron energy spectrum observed at the same angle and demonstrates that our conclusions concerning the 5914-keV level are not influenced by any possible deuteron contamination of our spectra.

II. EXPERIMENT

The ^{28}Si$(p,t)^{26}$Si reaction was studied at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF). A 40-MeV proton beam of average intensity ~2 nA was used to bombard a 50-μg/cm^2 natural Si target. Beam currents were integrated from a graphite beam stop placed downstream of the target chamber. Tritons were detected and identified using the Silicon Detector Array (SIDAR) [22] with 300-μm-thick (ΔE) detectors backed by 500-μm-thick (E) detectors. Tritons were distinguished from other charged particles using standard energy loss techniques (Fig. 1). Triton identification was done on a strip by strip basis and was quite clean with no evidence for contamination from other particle groups. Since the SIDAR array is segmented, the yields of tritons were measured at all angles in this study simultaneously. Many of the experimental details are the same as in Ref. [14] except in this case the detector elements were placed perpendicular to the beam direction and further away from the target so that smaller angles would be covered in the laboratory ($\theta_{\rm lab} = 11°$–$21°$). This increase in distance also resulted in smaller solid angle coverage resulting in reduced statistics compared with the previous measurement.

The triton energy spectrum measured at $\theta_{\rm lab} = 17°$ is shown in Fig. 2. Owing to the smaller angular width of the strips, the center of mass energy resolution was improved to 45 keV compared with 75 keV in the previous experiment [14]. This allowed for the better resolving of certain levels (e.g., the 5145- and 5291-keV levels were cleanly separated) and for the clear identification of the triton energy peak at 13.7 MeV in Fig. 2 with the 4138-keV level in ^{26}Si. Also shown in Fig. 2 is the deuteron energy spectrum observed at the same angle. There is no indication that any of the observed triton peaks arose from deuteron contamination in our triton gate.

Owing to the high level density in the region of interest, care was taken to elminate any confusion of level identification between our experiments and the (^{3}He, n) work of Ref. [11]. An internal energy calibration was performed at each angle using the strongly-populated levels at 2784, 4446, 5145, and 6787 keV, for which energies are known accurately from previous measurements [11,23]. This procedure resulted in excitation energies which agree with the averages of the previously-measured high precision values listed in Ref. [11] to, on average, ±5 keV. We label the peaks in Fig. 2 with energies from Ref. [23] for levels below 5 MeV and with the average of the values from Refs. [11,14] for levels higher than this. The only exception was for the doublet at 6312 and 6388 keV, which was not completely resolved in Ref. [14], for which we just used Ref. [11]. The ^{26}Si peaks labeled in Fig. 2 were observed over a large range of angles, and there was no significant shifting of their extracted excitation energies with angle. We show in Fig. 3, for example, the extracted excitation energies as a function of angle for the 5914-keV level from this work and Ref. [14]. Noting the angular dependence of the extracted energies allowed the ^{26}Si peaks to be clearly distinguished from contaminant peaks from reactions on ^{12}C and ^{16}O. There was no evidence for peaks resulting from reactions on the small amount of ^{29,30}Si in the target. The peak between the 5515 and 5914 keV levels was only observed at two angles but may be the 5673-keV level observed in Refs. [10,11]. This use of an internal calibration minimizes any effects of uncertainties in beam energy, target thickness, detector angles, pulse height defect, and detector energy calibrations on the extracted excitation energies. While, in principle, our resolution was not sufficient to resolve the levels observed at 5912 and 5946 keV in Ref. [11], we find no evidence that we are populating a level at 5946 keV. As can be seen in Fig. 3, there is no systematic trend that would suggest the centroid is shifting, and no indication that two levels are being populated.

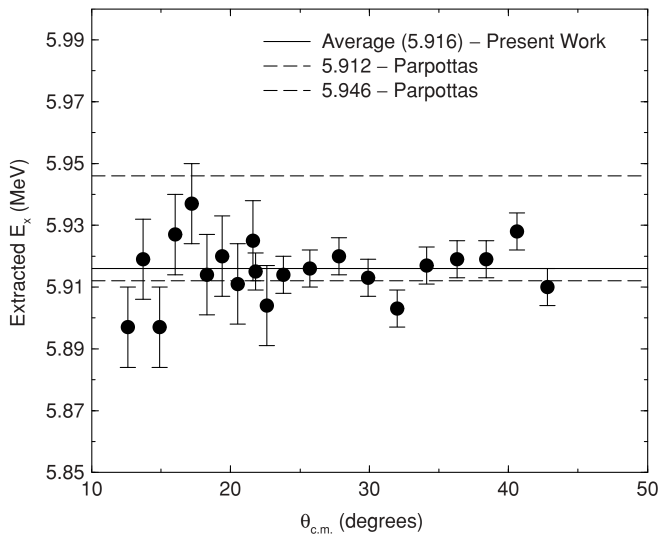

FIG. 3. The excitation energy extracted for the 5914-keV level is plotted vs. angle for the data obtained in this work and Ref. [14]. Lines have been drawn at the average energy from this work and the energies reported in Ref. [11].

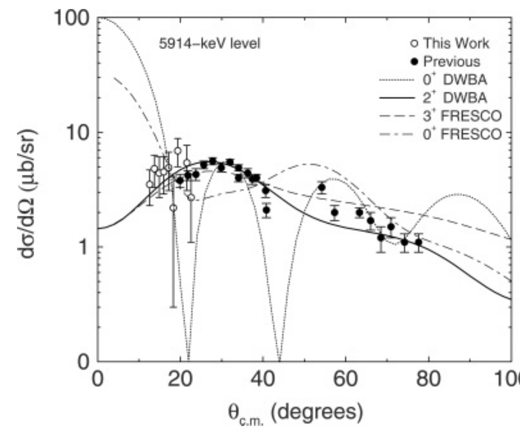

FIG. 4. The angular distribution for the 5914-keV level is plotted. Open circles are from this work while filled circles are from Ref. [14]. The dotted and solid curves are DWBA calculations for the population of 0^+ and 2^+ levels, respectively. The dashed line is a FRESCO calculation of the expected angular distribution for populating a 3^+ through a multistep process. The dot-dashed line shows the multistep calculation for populating a 0^+ after reducing the normalization by a factor of ten to directly compare with the data.

III. ANGULAR DISTRIBUTIONS

Angular distributions have been extracted for the strongly populated levels with an emphasis on obtaining the 5914-keV angular distribution at the most forward angles. The angles and solid angles subtended by the detector strips were calculated from the known detector geometry. A calibrated ^{244}Cm α source was used to check the solid angle calculations and agreement was achieved with only a $\sim$1 mm adjustment of the target to detector distance ($\sim$266 mm) used in the solid angle calculation. The calculated angles were also checked by noting the angular dependence of triton energies populating known levels in the $^{28}\mathrm{Si}(p,t)^{26}\mathrm{Si}$ and $^{12}\mathrm{C}(p,t)^{10}\mathrm{C}$ reactions, and good agreement was observed. The angular distribution extracted for the 5914-keV level is shown in Fig. 4. The cross sections extracted from this experiment had to be increased by $\sim$10% to agree in normalization with the previous data [14] at the same angles as a result of using a different beam stop in this experiment. This does not represent a significant uncertainty for our measurement since the triton yield is measured simultaneously at all angles covered in this experiment, and thus the shape of the angular distribution is determined quite accurately.

We also show in Fig. 4 distorted-wave Born approximation (DWBA) calculations using the finite range code DWUCK5 [24] for populating 0^+ and 2^+ levels at this energy using the same parameters as described in Ref. [14]. We find, as suggested in Parpottas *et al.* [11], that the angular distribution at forward angles does not agree with a 0^+ assignment and, in fact, that the calculated 0^+ cross section is larger than the data by a factor of 4–5 at the lowest angles measured, and a 0^+ contribution is constrained to be less than 25% of the total at angles greater than $\sim 18^\circ$. This lends support to the contention in Parpottas *et al.* that the 5946-keV ^{26}Si level (and not the 5914-keV level) is a 0^+ and the mirror to the ^{26}Mg level at 6256 keV. We find that the angular distribution for the 5914-keV level is fit well by the DWBA calculation describing transfer to a 2^+ state. We had not considered this possibility in Ref. [14] because of the strong evidence from Bohne *et al.* [25] that a 0^+ level had to be present to account for the observed $^{24}\mathrm{Mg}(^3\mathrm{He},n)^{26}\mathrm{Si}$ angular distribution. As suggested in Parpottas *et al.*, it now appears that the measurement in Bohne *et al.* could not resolve the 5914/5946-keV doublet, and that their angular distribution is best described by a combined population of levels.

We also show in Fig. 4 the results of a FRESCO [26] calculation describing the multistep process $^{28}\mathrm{Si}(p,d)^{27}\mathrm{Si}(\frac{1}{2}{}^+_1)(d,t)^{26}\mathrm{Si}(3^+)$. Such multistep processes have been found to be important in other (p,t) studies populating unnatural parity levels [27]. Additional multistep processes involving inelastic excitation of ^{28}Si and ^{26}Si levels were also considered but were thought to be much weaker. Optical model parameters were taken from Ref. [27] and good agreement was observed for the first step $[^{28}\mathrm{Si}(p,d)^{27}\mathrm{Si}]$ between the FRESCO calculation and the experimental data of Kozub [28] using the spectroscopic factor 0.64 for population of the first excited state of ^{27}Si from Ref. [28]. The spectroscopic factor for the second step $^{27}\mathrm{Si}(\frac{1}{2}{}^+_1)(d,t)^{26}\mathrm{Si}(3^+)$ was left as a free parameter. The best fit to our angular distribution data shown in Fig. 4 was for a spectroscopic factor of 3.1, which seems reasonable considering the maximum spectroscopic factor for neutron pickup from the $1d_{5/2}$ orbital from the first excited state of ^{27}Si is 4 if one assumes the ^{16}O core to be closed [29]. As can be seen in Fig. 4, the multistep process also seems to provide a reasonable description of the data. Other possibilities were considered such as a multistep population of 0^+ (shown in Fig. 4) and 1^+ levels or direct transfer to 1^-, 3^-, and 4^+ levels, but none produced results consistent with the data.

While both a direct population of a 2^+ level and a multistep population of a 3^+ are reasonable interpretations of the angular distribution, the 3^+ scenario seems somewhat more likely. The mirror to a 2^+ ^{26}Si level at 5914 keV would be expected in the range 5.8–6.3 MeV in ^{26}Mg. Despite years of study [30], no such 2^+ level has ever been observed in ^{26}Mg and none are predicted by shell-model calculations [21,31]. For these reasons, we calculate our recommended ^{25}Al$(p,\gamma)^{26}$Si reaction rate based on the assumption that the 5914-keV level has $J^\pi = 3^+$ but consider the 2^+ possibility as an alternative, since a $2p$ pickup experiment has not been performed on ^{28}Si which might be required to reveal the ^{26}Mg mirror level.

IV. ASTROPHYSICAL REACTION RATE

We show our updated ^{25}Al$(p,\gamma)^{26}$Si reaction rate calculation in Fig. 5. We took the direct capture rate from Ref. [21] and added to it contributions from resonances with $E_{\mathrm{c.m.}} < 500$ keV with resonance properties listed in Table I. Higher energy resonances were found to make only negligible contributions to the reaction rate at nova temperatures [21], and so we have not included them. We take partial widths for the 1^+ 155-keV and 0^+ 428-keV resonances from Ref. [11]. It appears, however, that a numerical mistake in Ref. [11] resulted in the contribution from the 0^+ resonance being overestimated by a factor of 10 and erroneously making it a large component of the total reaction rate shown in Fig. 7 of Ref. [11]. For the 396-keV 3^+ resonance, we take the γ width from Ref. [21] and scale the proton width based on the change in resonance energy. The resulting reaction rate is shown as a solid line in the bottom plot of Fig. 5.

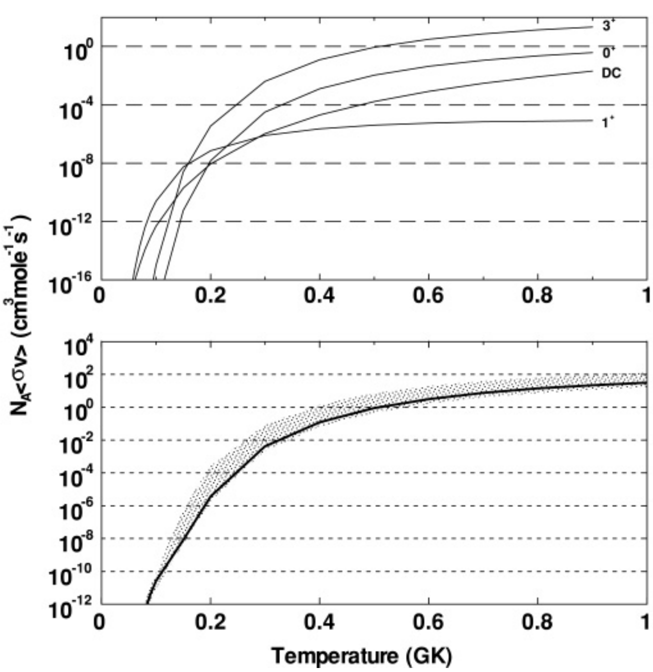

FIG. 5. The top figure shows the contributions of resonances and direct capture to the ^{25}Al$(p,\gamma)^{26}$Si reaction rate. The bottom figure shows the sum of these contributions along with an estimated uncertainty.

TABLE I. Resonance parameters for ^{26}Si levels used in the calculation of the ^{25}Al$(p,\gamma)^{26}$Si reaction rate. See the text for explanation.

E_x (keV)	$E_{\mathrm{c.m.}}$ (keV)	J^π	Γ_p (eV)	Γ_γ (eV)
5673(4)	155	1^+	1.3×10^{-9}	0.11
5914(2)	396	3^+	2.3	0.033
5946(4)	428	0^+	1.9×10^{-2}	8.8×10^{-3}

To estimate the uncertainty in the rate, we consider a variety of contributions including the possibility that the 5914-keV level has $J^\pi = 2^+$. We have then estimated its maximum contribution based on the nonobservation of a 2^+ analog level in the ^{25}Mg$(d,p)^{26}$Mg reaction [32]. From a comparison of the level energy shifts going from ^{26}Si to ^{26}Mg [21], the mirror to a 5914-keV 2^+ ^{26}Si level would be expected roughly to be in the energy range 5.8–6.3 MeV in ^{26}Mg. There were no 2^+ levels clearly observed in Ref. [32] in this energy range, but the existence of several contaminant lines may have hindered the observation. We estimate that the spectroscopic factor to populate such a 2^+ level in ^{26}Mg must be less than was extracted for the observed 2^+ level at 6.74 MeV in ^{26}Mg. Spectroscopic factors of 0.008 and 0.11 were extracted in Ref. [32] for $L = 0$ and $L = 2$ neutron transfers, respectively, and we thus use these as upper limits to calculate a maximum proton width [$\Gamma_p(2^+) < 0.18$ eV]. We take as a γ partial width the average of γ partial widths tabulated in Ref. [21] with an uncertainty large enough to cover the range [i.e., $\Gamma_\gamma(2^+) = 0.02 \pm 0.01$ eV]. A remaining uncertainty would then be the location of the 3^+ resonance. We assume that the 3^+ level should have been observed in at least one of the recent high-resolution studies [10,11,14], and thus we take the excitation energy as 5910±60 keV, which is the average energy observed for all peaks in the relevant energy range in those studies. We also assume factor of 2 uncertainties for partial widths based on measured quantities in the mirror nucleus, ^{26}Mg, and factor of 3 uncertainties for those based on shell model calculations [21]. The uncertainty in Γ_p for the 3^+ resonance was dominated by the uncertainty in the resonance energy which was explicitly taken into account. For the possible 2^+ resonance, we used 100% uncertainties on Γ_p reflecting the upper limit on its strength. The uncertainty in the direct capture calculation was estimated as 30% in Ref. [33]. To calculate the uncertainty range at each temperature, the deviations produced by varying each contribution by its uncertainty were added in quadrature. The resulting rate band is also shown in Fig. 5. The upper end of the rate band occurs when the 5914-keV level is assigned 2^+ and the 3^+ resonance energy is at its lower limit. The lower end of the rate band occurs when the 5914-keV level is assigned 3^+ and no 2^+ resonance is included.

We have used the calculated ^{25}Al$(p,\gamma)^{26}$Si reaction rate in a nova nucleosynthesis model looking at the effect of the uncertainties on the produced amount of ^{26}Al. We first parametrized the rate using the tool set available from the

TABLE II. The 21 coefficients, a_{ij}, used to parametrize the ^{25}Al$(p,\gamma)^{26}$Si rate via a fit of Eq. (1) to the calculated rate. The parametrization is valid over the temperature range 0.01–1.5 GK and reproduces the rate within 0.5% over this range.

i\j	1	2	3	4	5	6	7
1	0.115811×10^3	-0.401060×10^{-2}	-0.181651×10^2	-0.178991×10^3	0.262227×10^3	-0.413948×10^3	0.172493×10^2
2	0.477043×10^2	-0.129178×10^1	-0.373031×10^2	-0.852627×10^2	0.148315×10^3	-0.107987×10^3	-0.209633×10^2
3	0.267979×10^1	-0.448947×10^1	-0.509549×10^1	0.115811×10^2	-0.146263×10^1	0.238122×10^0	-0.587637×10^1

Computational Infrastructure for Nuclear Astrophysics [34]. The parametrized rate was of the form

$$N_A\langle\sigma v\rangle = \sum_{i=1}^{3} \exp\left[a_{i1} + \sum_{j=2}^{6} a_{ij} T^{2j/3-7/3} + a_{i7}\ln T\right], \quad (1)$$

where the reaction rate is given in cm^3/mole/s and the temperature, T, is in GK with coefficients listed in Table II. The parametrization is valid over the temperature range 0.01–1.5 GK and deviated by no more than 0.5% from the calculated rate over this range. The element synthesis calculation was also done in the framework employed in the Computational Infrastructure. Similar to Ref. [35], a nuclear reaction network [36] containing 169 isotopes from ^{1}H to ^{54}Cr was used with nuclear reaction rates from the REACLIB [37] database. Thermodynamic histories (time histories of the temperature and density) from one-dimensional hydrodynamic calculations with a limited reaction rate network were extracted for nova outbursts on a 1.35 $M_\odot$ ONeMg white dwarf [38]. Reaction rate variations for the ^{25}Al$(p,\gamma)^{26}$Si reaction do not appreciably change the nuclear energy generation, and thus this decoupling of nuclear and hydrodynamical effects is valid. The ejected envelope is divided into 28 zones, each with its own thermodynamic history. Separate reaction network calculations with the full complement of nuclei and reactions were carried out within each zone, and the final abundances determined by summing each zone's contribution to the total mass. We find that the uncertainty in the ^{25}Al$(p,\gamma)^{26}$Si reaction rate results in a factor of 3.4 variation in the ejected amount of ^{26}Al. To further reduce this uncertainty, confirmation of the 3^+ ^{25}Al$(p,\gamma)^{26}$Si resonance energy needs to be made.

V. CONCLUSIONS

In conclusion, we have studied the ^{28}Si$(p,t)^{26}$Si reaction to determine the spins of unbound ^{26}Si levels important for the ^{25}Al$(p,\gamma)^{26}$Si reaction. We find that the triton angular distribution for the 5914-keV ^{26}Si level is consistent with either a multi-step process populating a 3^+ state or a direct population of a 2^+ level. From a comparison with the mirror nucleus, ^{26}Mg, it appears that the 3^+ scenario is more likely as no 2^+ mirror levels are known or expected. We additionally find that the contribution to the rate of the 0^+ resonance at 428 keV was overestimated in Ref. [11] by a factor of 10. Using this information, we have investigated production of ^{26}Al in a nova nucleosynthesis model and find that the uncertainties in the ^{25}Al$(p,\gamma)^{26}$Si rate result in roughly a factor of 3 uncertainty in the amount of ^{26}Al that was ejected in the model. Further reduction of these uncertainties would come from a definitive confirmation of the 3^+ resonance energy, possibly requiring the utilization of an ^{25}Al beam at a radioactive beam facility.

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