The ^{28}Si(p,t)^{26}Si*(p) reaction and implications for the astrophysical ^{25}Al(p,γ)^{26}Si reaction rate

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Several resonances in ^{25}Al(p,γ)^{26}Si have been studied via the ^{28}Si(p,t)^{26}Si reaction. Triton energies and angular distributions were measured using a segmented annular detector array. An additional silicon detector array was used to simultaneously detect the coincident protons emitted from the decay of states in ^{26}Si above the proton threshold in order to determine branching ratios. A resonance at 5927 ± 4 keV has been experimentally confirmed as the first $\ell = 0$ state above the proton threshold, with a proton branching ratio consistent with one.

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I. MOTIVATION

The rate of radiative proton capture on ^{25}Al is thought to greatly affect the production of galactic ^{26}Al in novae. The decay of the ^{26}Al^{gs} ($t_{1/2} = 7.17 \times 10^5$ yr) has been observed astronomically via a characteristic 1.809-MeV γ ray [1]. While diffuse, the intensity of this γ line has been catalogued as brighter near regions with more massive stars [2]. Additionally, the presence of ^{26}Al has been discovered in presolar grains, in surprisingly high abundance with respect to ^{27}Al [3]. Since the ^{25}Al(p,γ)^{26}Si($\beta^+\nu_e$)^{26}Al^m($\beta^+\nu_e$)^{26}Mg reaction sequence bypasses the production of ^{26}Al^{gs} [4] by populating the isomeric state, the rate of the ^{25}Al(p,γ)^{26}Si reaction (with respect to the beta decay of ^{25}Al, $t_{1/2} = 7.18$ s) will play a role in how much ^{26}Al^{gs} is produced via the ^{25}Al($\beta^+\nu_e$)^{25}Mg(p,γ)^{26}Al^{gs} sequence.

Evaluations of the ^{25}Al(p,γ)^{26}Si reaction rate (see, for instance, Ref. [4] and references therein) have concluded that the reaction is dominated at peak nova temperatures (0.15–0.4 GK) by an $\ell = 0$ resonance from the $5/2^+$ ^{25}Al ground state (a 3^+ level in ^{26}Si) with $E_{\mathrm{c.m.}} < 600$ keV. Direct capture and resonant capture through 1^+ states would play a lesser role. A host of recent measurements [4–10] have sought to find and characterize the resonances in the ^{25}Al(p,γ)^{26}Si reaction, in order to precisely determine the effect on the production of galactic ^{26}Al, focusing on an astrophysically interesting region around a resonance at 5914 keV [5] (an updated E_x has been determined; see below). The spin of this state has been hotly debated (see Ref. [5] and references therein), and its subsequent effect on the reaction rate is still contested as is evidenced by its ongoing study [9–12].

II. EXPERIMENT

In order to study the resonances of significant astrophysical interest, a beam of 40-MeV protons, typically between 1 and 2 nA, was delivered from the ORNL Holifield Radioactive Ion Beam Facility (HRIBF) into a target chamber which contained a 200-μg/cm^2 $^{\mathrm{nat}}$Si (∼92% ^{28}Si) target and two arrays of segmented silicon detectors; the experimental setup is shown in Fig. 1. A large aluminum plate with an aperture was situated just upstream of the target ladder and served to collimate the proton beam. Tritons from the resultant (p,t) reaction (ground-state Q value $= -22.013$ MeV, calculated from Ref. [10]) were detected at forward angles using the highly segmented SIlicon Detector ARray (SIDAR) [13] covering ∼18° to 50° (∼19°–54° in the center of mass), a configuration similar to previous (p,t) studies [4,5,14]. For particle identification, the SIDAR was arranged into ΔE-E telescopes with 100-μm ΔE detectors and 1000-μm E detectors, allowing for unambiguous triton identification. The radial strips of SIDAR allow detection of the tritons at several angles simultaneously, with an energy resolution between 65 and 115 keV (depending on the kinematic shift as a function of angle). A graphite beam stop was located downstream of the target chamber, with no line-of-sight to the silicon detectors, as a diagnostic. In addition, a modified implementation of the Oak Ridge Rutgers University Barrel Array (ORRUBA) [15] was used to cover laboratory angles between the edge of SIDAR (∼50°) and ∼90°. Six 65-μm non-resistive strip ORRUBA detectors formed a small "barrel" around the beam axis, covering roughly 6% of 4π steradians. The ORRUBA strips were aligned with the beam axis, providing no angular information on the decay protons detected. However, the detectors and accompanying electronics were sensitive, with 100% detection efficiency, down to the expected ∼400 keV of the lowest energy decay protons. Pulser tests indicated the detection threshold was just under 200 keV.

A. Triton energy spectra and angular distributions

The states in ^{26}Si above the proton threshold populated in the present work are displayed in Fig. 2 and summarized in Table I. Triton energy spectra for each strip of the SIDAR were calibrated by using known levels in ^{26}Si with energies from Seweryniak *et al.* [16]. The proton threshold in ^{26}Si,

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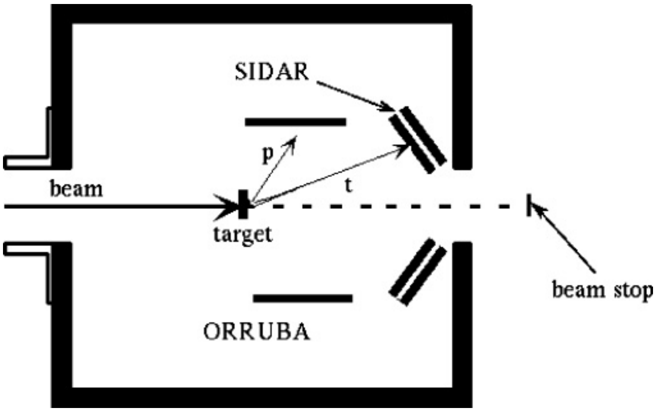

FIG. 1. Experimental setup for the (p,t) experiment. Both ORRUBA and SIDAR are symmetric (in ϕ) about the beam axis. The proton ("p") in the diagram is the decay proton from the ^{26}Si, not the beam. The aluminum beam collimator is not shown.

5513.7 ± 0.5 keV, and the updated (p,t) Q value were taken from a recent ^{26}Si mass measurement [10] (this new mass was confirmed later by Ref. [17]). A linear fit to the populated singlet states in ^{26}Si up to the proton threshold (9 total), with level energies taken from Table I of Seweryniak *et al.* [16], was used as an internal energy calibration for the triton spectra. The linear fit provided excellent agreement with the calibration levels ($R^2 = 1.000$), indicating higher order corrections were likely to be unnecessary. A few contaminant peaks from reactions on ^{12}C and ^{16}O [5] were identified by their different kinematics (as no other stable $A = 28$ isotopes exist, there can be no contaminants with the same kinematics). No evidence of tritons from (p,t) reactions on the contaminant ^{29,30}Si naturally occurring in the target was found. Owing to the use of thinner ΔE detectors compared to Ref. [4], tritons populating higher lying ^{26}Si excited states up to $\sim$10 MeV were observed, some of which do not appear in the literature. Additionally, this work

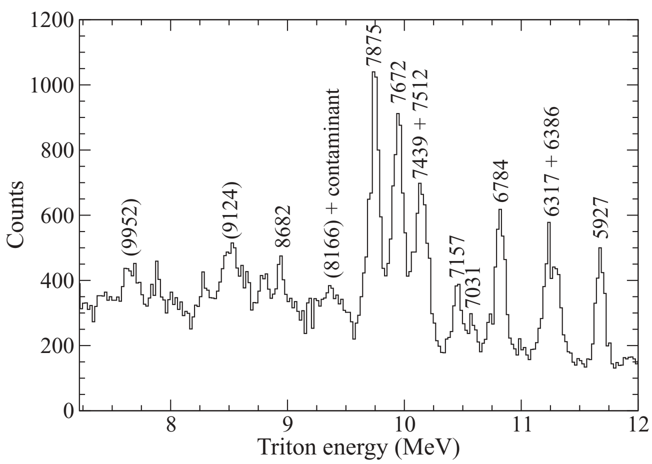

FIG. 2. Triton spectrum for the SIDAR strip at $\theta_{\mathrm{lab}} \approx 23^\circ$, showing levels above the proton threshold. Possible new levels are labeled in parentheses. The level at 8166 keV was discernible from the contaminant peak at other angles; however, the peak just below 8-MeV triton energy was too weakly populated to be discernible at all angles.

TABLE I. Excitation energy, spin, and parity assignments from this work for ^{26}Si levels above the proton threshold compared with previous data [4]; the difference is due to the calibration in this work being based upon more precise energies for bound levels obtained from a recent γ-ray measurement [16]. Note that the updated level scheme from Ref. [16] did not list energies above $\sim$5700 keV, and so cannot be used for comparison. The state at 5927 keV is discussed in detail below.

E_x, Ref. [4] (keV)	E_x, this work (keV)	J^π
5914 ± 2[a].	5927 ± 4	3^+
6300 ± 4[b] .	6317 ± 7	(2^+)[c].
6380 ± 4[b]	6386 ± 3	(2^+)[c]
6787 ± 4	6784 ± 3	3^-
7019 ± 10	7031 ± 5	$(0^+, 1^-)$[d].
7160 ± 5	7157 ± 4	2^+
7425 ± 7[b]	7439 ± 6	(2^+)[c]
7498 ± 4[b]	7512 ± 8	(2^+)[c]
7687 ± 22	7672 ± 2	3^-
7900 ± 22	7875 ± 2	1^-
8120 ± 20[e]		$(1^-, 2^+)$[e].
	$(8166) \pm 7$	
8570 ± 30[e]		$(1^-, 2^+)$[e]
8700 ± 30[e]	8682 ± 5	$(1^-, 2^+)$[e]
	$(9124) \pm 8$	
9170 ± 30[e]		$(1^-, 2^+)$[e]
	$(9952) \pm 17$	

[a]Ref. [5]; listed as 5916 ± 2 keV in Ref. [4].
[b]Doublet.
[c]Ref. [4], confirmed by this work.
[d]Assignment from this work.
[e]Ref. [19].

supports the (2^+) assignment [16] for the 4805 keV level. The 1^+ state at 5677.0 keV observed in Ref. [16] was not populated, and no evidence for a level around 5946 keV [8] was observed (as in the previous study [5]). In general, there is good agreement between this work and the previous results [4,5,16].

Angular distributions were also examined for the high-lying ^{26}Si levels, above the nova energy range. The solid-angle coverage of each strip was determined from calibration with a ^{244}Cm alpha source of known intensity, and angular distributions were then calculated by integrating the triton peaks. As the triton yield was measured at all angles simultaneously, the absolute beam-current normalization was unimportant for spin and parity assignments or branching ratios. Angular distributions for previously studied levels agreed well with those in Ref. [4]. The angular distribution of tritons populating the 7031-keV level has been extracted for the first time, and is plotted in Fig. 3. This state was seen previously (at 7019 ± 10 keV with the previous energy calibration) [4], but only within a limited angular range, preventing a spin and parity assignment. Distorted wave calculations with DWUCK5 [18] using the optical model parameters of Ref. [4] suggest that this level is populated by either an $\ell = 0$ or 1 transfer, as displayed in Fig. 3. Angular distributions for populating levels at 8166 and 8682 keV were also extracted but were not sufficiently distinctive to determine the transferred angular momentum.

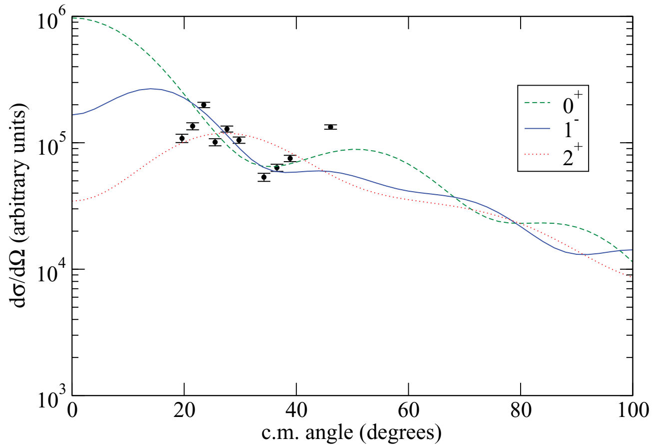

FIG. 3. (Color online) The observed triton angular distribution populating the 7031-keV ^{26}Si level. DWUCK5 calculations for 0^+ (green dashed) and 1^- (solid blue) assignments are shown. Assignments greater than $\ell = 2$ (red dotted) were ruled out.

B. Proton branching ratios

In addition to detecting tritons in the forward-angle SIDAR detectors, decay protons from the excited ^{26}Si levels were detected in coincidence by the non-resistive-strip ORRUBA detectors. These events are clearly visible in a plot of recorded ORRUBA energy versus SIDAR energy, as shown in Fig. 4. This is similar to the methodology of Deibel *et al.* [20,21], but represents the first such measurement of the proton-unbound states of ^{26}Si. Specifically, in the Deibel *et al.* measurement [20,21], tritons or alpha particles from the reaction studied were detected at the focal plane of a magnetic spectrograph, in coincidence with decay protons detected in a silicon detector array around the target; in the current work, both reaction tritons and decay protons were detected in silicon detector arrays around the target without the use of magnetic separation. By examining the triton spectra as gated on the proton-coincident events shown in Fig. 4 and correcting for efficiency, the branching ratios of the proton-unbound states in ^{26}Si could be determined. Figure 5 shows both the ungated and the gated triton spectra for one angle in SIDAR.

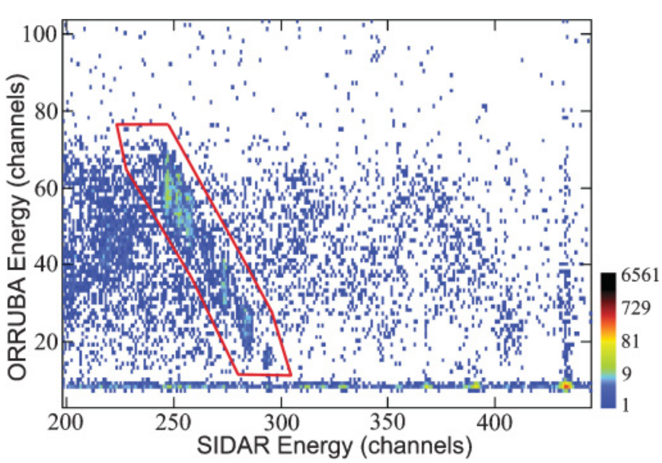

FIG. 4. (Color online) ORRUBA energy (decay protons) vs. SIDAR energy (reaction tritons) for all proton-triton coincident events. The red box, indicating the gate used, has been drawn around events associated with proton decay from excited ^{26}Si levels.

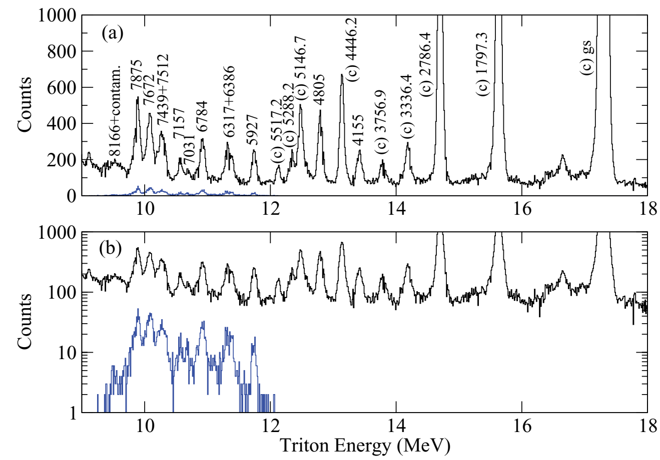

FIG. 5. (Color online) (a) Triton energy spectrum for the SIDAR strip at $\theta_{\rm lab} \approx 23^\circ$ without (black) and with (blue, lower histogram) a coincident decay proton. The rightmost triton peak (black) is the ^{26}Si ground state. Energies used for the calibration are labeled with a "c" and the E_x values from Refs. [16]. (b) Same as (a), but on a log scale to highlight the coincident spectrum.

Because of the high counting rate in the SIDAR detectors ($\sim$5 kHz) and the relatively long hardware timing gate ($\sim$4 μs), there were a significant number of random coincidences between the SIDAR and ORRUBA detectors (as is evident in Fig. 4). By requiring a proper energy correlation via implementation of a two-dimensional gate around the correlated events (demonstrated by the red box in the figure), much of the random background could be excluded from subsequent analysis. The number of additional random background events that fall within this gate were estimated by gating on events in the proton-bound region of Fig. 4. Doing this, the probability of a random coincidence was found to be $\sim$1%, and this random background was subsequently subtracted from later analysis. Once this background was accounted for, the extracted branching ratios were insensitive to small variations in the construction of the gate.

The extracted proton branching ratios for excited states in ^{26}Si are summarized in Table II. The calculated B_p values assume decay to the ground state of ^{25}Al, which is energetically favorable; decays to excited states, however, cannot be ruled out, but they would seem to be considerably weaker and may be obscured by the random background. Because the ORRUBA detectors were not sensitive to the angle of the detected decay protons, the calculated proton-branching ratios relied upon theoretical angular correlation functions [22]. Angular correlation curves were deduced [23] using scattering amplitudes calculated with the code FRESCO [24] and the adopted spin-parity and ℓ-transfer information for the measured proton-unbound states (as summarized in Table I). The unbound 2^+ and 3^+ states in ^{26}Si decay isotropically via $\ell = 0$ transfers to the $5/2^+$ ground state of ^{25}Al, and display direction-independent angular correlations. However,

TABLE II. Proton branching ratios for excited states in ^{26}Si from proton-triton coincidences. The spin and parity assignments used for the angular correlation calculations are also given. For doublet states that could not be resolved in the proton-gated spectra, branching ratios were calculated as though the doublet was a singlet. The uncertainties are dominated by the proton statistics.

E_x (keV)	J^π	$B_p = \Gamma_p/(\Gamma_p + \Gamma_\gamma)$
5927	3^+	0.91 ± 0.10
6317 + 6386	2^+	0.88 ± 0.20
6784	3^-	1.21 ± 0.24[a].
7031 + 7157	2^+	1.04 ± 0.25
7439 + 7512	2^+	1.31 ± 0.27[b].
7672	3^-	1.18 ± 0.23[a]
7875	1^-	1.11 ± 0.22[a]

[a]Anisotropic decay ($\ell > 0$).
[b]It is likely that one of the two states in this unresolved doublet is 4^+, which accounts for the slight anisotropy in the branching ratio.

branching ratios for states with other J^π assignments, and thus anisotropic decay curves, had to be adjusted for the angle-dependent detection efficiency. The calculated angular correlations for anisotropic decays are shown in Fig. 6. The dominant uncertainty in the branching ratios arises from statistics, although uncertain ℓ-transfer values would introduce a systematic uncertainty. That the observed proton branching ratios are consistent with unity is in agreement with the earlier theoretical work by Iliadis *et al.* [11].

C. First $\ell = 0$ resonance in ^{25}Al$(p,\gamma)^{26}$Si

The first $\ell = 0$ resonance in the ^{25}Al + p system to fall within the Gamow window would dominate the ^{25}Al$(p,\gamma)^{26}$Si reaction rate at astrophysical energies. The level at 5517.2 keV [16], which was previously thought to fall just below the proton threshold, has been shown by the updated ^{26}Si mass measurement [10,12] to actually be unbound by ∼4 keV. However, such a low-energy resonance is likely to have little

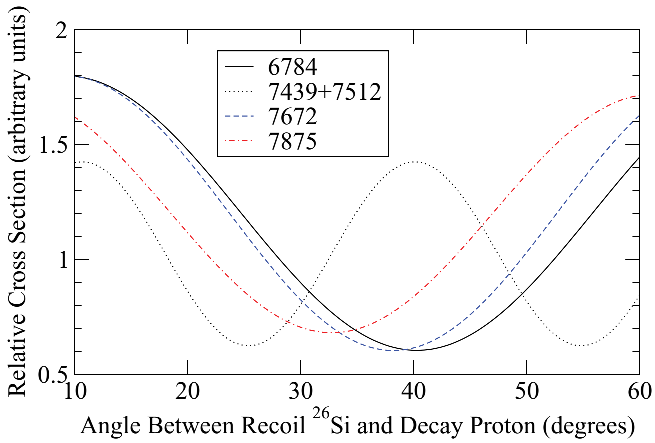

FIG. 6. (Color online) Theoretical angular correlation curves calculated for the three anisotropically decaying levels at 6784, 7672 (both $\ell = 1$), and 7875 keV ($\ell = 3$), as well as the doublet at 7439 + 7512 keV ($\ell = 0 + 2$), as a function of angle between the decay proton and the ^{26}Si parent.

effect on the astrophysical reaction rate in novae. Therefore, the focus is on the 5927 ± 4-keV state ($E_r = 413 \pm 4$ keV) as the most likely candidate for the first $\ell = 0$ resonance. A recent in-beam γ-ray-spectroscopy study [16] suggested that the location of this level, accounting for updated transition energies, should shift by ∼5 keV from previous placements. Accounting for this, a recent reanalysis [12] assigned a new energy of $E_x = 5920.7 \pm 2.6$ keV ($E_r = 412 \pm 2$ keV). The energy measured in the current work, using the more accurate level energies as defined in Ref. [16] and the updated Q value from Ref. [10], is consistent with this reanalysis. (Using the same Q value and calibration levels as in Ref. [4] resulted in an E_x consistent with the previous measurement, indicating the change in E_x in this work is due entirely to the updated Q value and calibration levels.)

Matic *et al.* [25] recently reported concurrent results from another ^{28}Si$(p,t)^{26}$Si measurement using the spectrometer at the Research Center for Nuclear Physics (RCNP), which also sought to confirm level energies and spin-parity assignments for states of astrophysical interest in ^{26}Si. While the authors of this measurement only observed a weak population of this most important lowest $\ell = 0$ level (although at an E_x consistent with the current work), the excitation energies measured for other levels are generally in agreement with the present results.

The angular distribution of tritons corresponding to the observed triton peak in this work agrees well with the previously measured distribution for this state [5], which yielded an angular distribution that was compatible with a J^π assignment of either 2^+ (population by a single-step process) or 3^+ (via a multistep process). However, a 3^+ assignment was preferred, due to a lack of both experimental observation and theoretical prediction of 2^+ states within this energy region in the mirror nucleus ^{26}Mg. Moreover, a recent γ-ray-spectroscopy measurement [16] failed to observe the decay of the 5927 keV state, while finding a one-to-one correspondence with all known levels in the mirror nucleus ^{26}Mg, further favoring a 3^+, rather than 2^+, assignment.

In the present work, the proton-decay branching ratio for the 5927 ± 4-keV state was measured to be $B_p = 0.91 \pm 0.10$. This is in good agreement with the predicted branching ratio [5,9] for a 3^+ level, providing further evidence for a 3^+ spin and parity assignment. Therefore, this work adopts a 3^+ assignment for the 5927 keV state, making it the first $\ell = 0$ resonance above the proton threshold in ^{26}Si.

III. CONCLUSION

The ^{28}Si$(p,t)^{26}$Si*(p) reaction was utilized to study astrophysically interesting resonances in ^{25}Al$(p,\gamma)^{26}$Si. By examining not only the tritons but the coincident decay protons as well, the proton branching ratios for several of the states above the proton threshold in ^{26}Si were determined. This work represents the first measurement of proton-decay branching ratios for unbound ^{26}Si levels, and provides further evidence that the ^{26}Si level at 5927 ± 4 keV is indeed the first 3^+ ($\ell = 0$) resonance above the proton threshold, which significantly influences the astrophysical ^{25}Al$(p,\gamma)^{26}$Si reaction rate. Additionally, this work is in agreement with the recently published measurements and analyses [5,9,10,12], and supports the astrophysical conclusions in those studies. Further reductions in the uncertainties of the astrophysical rate will require further elucidation of the proton and γ partial widths of the low-lying levels above the ^{26}Si proton threshold.

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