Structure of resonances in the Gamow burning window for the $^{25}Al(p,\gamma)^{26}Si$ reaction in novae

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(Received 8 July 2015; published 17 September 2015)

A γ-ray spectroscopy study of excited states in ^{26}Si has been performed by using the ^{24}Mg(^{3}He,n) reaction at a beam energy of 10 MeV. In particular, states have been studied above the proton threshold relevant for burning in the ^{25}Al$(p,\gamma)^{26}$Si reaction in novae. This reaction influences the amount of ^{26}Al injected into the interstellar medium by novae, which contributes to the overall flux of cosmic γ-ray emission from ^{26}Al observed in satellite missions. The present results point strongly to the existence of a 0^+ state at an excitation energy of 5890 keV lying within the Gamow burning window, which raises questions about the existence and properties of another, higher-lying state reported in previous experimental work. The existence of two such states within this excitation energy region cannot be understood within the framework of sd-shell-model calculations.

DOI: 10.1103/PhysRevC.92.035808 PACS number(s): 23.20.Lv, 21.10.Dr, 26.50.+x, 27.30.+t

I. INTRODUCTION

Novae are explosive astrophysical events for which the remaining nuclear physics uncertainties in the data required as input to model the explosions are now tightly circumscribed [1]. For example, the ^{30}P$(p,\gamma)^{31}$S reaction rate needs to be known more precisely to understand the abundances of elements up to Ca in novae ejecta and the ^{28}Si/^{30}Si abundance ratio in meteoritic inclusions [2]. The ^{25}Al$(p,\gamma)^{26}$Si reaction is also important to constrain since it influences the abundance of the cosmic γ-ray emitter ^{26}Al ($t_{1/2} = 7.2\times10^5$ yr) injected into the interstellar medium [3]. Most ^{26}Al material is currently thought to be associated with Wolf–Rayet stars and their subsequent explosions in core-collapse supernovae [4]. However, the high abundances of ^{26}Al observed relative to ^{60}Fe, when compared to core-collapse supernovae model predictions, suggest that there could be a significant additional contribution from novae [5,6]. The burning regime in novae occurs at temperatures of $\sim$0.1 to 0.4 GK, where the reaction rate is expected to be dominated by resonant reactions on 1^+, 0^+, and 3^+ states predicted by sd-shell-model calculations [7] to be located just above the proton threshold energy of 5513.7 (5) keV in ^{26}Si [8].

Considerable experimental efforts have gone into identifying and locating these resonant states [9–20]. The location of the 3^+ s-wave resonance, corresponding to a level at 5928.7 (6) keV in ^{26}Si, seems now to be unambiguously established from β-decay studies of ^{26}P [12,20], with $\sim$100% proton-decay branches reported for this state [11,17]. Richter *et al.* [7] compared sd-shell-model calculations with experimental results and assigned a state at $\sim$5675 keV to the 1_1^+ level and another level at $\sim$5946 keV to the 0_4^+ excitation. In a comment to this paper, Chipps *et al.* [21] noted that, in the Nuclei in the Cosmos Proceedings, NIC XI, from 2011, de Sereville *et al.* [18] had reported a new state at 5888 (2) keV, for which three γ-decay branches were observed. If correct, this new level implied the presence of an additional state in this region; e.g., one more than predicted by sd-shell-model calculations. De Sereville *et al.* themselves declined to speculate on the nature of this level which was observed in the ^{24}Mg(^{3}He,n) reaction at a beam energy of 8 MeV [18]. Komatsubara *et al.* [19] subsequently studied the same reaction at a beam energy of 10 MeV. They confirmed two of the three γ branches identified from Ref. [18] and measured an excitation energy of 5890.0 (10) keV consistent with that reported by de Sereville *et al.* [18]. Komatsubara *et al.* positioned one germanium detector at $+90^\circ$ and two others at -90° and 135°, and gating on the $2_1^+ \rightarrow 0^+$ ground-state transition, obtained angular correlation (so-called DCO) intensity ratios at 90/135 degrees for coincident transitions feeding the 2_1^+ level [19]. They deduced that the DCO ratios were consistent with the 5890.0 (10) keV level being a 0^+ state and the level at 5673.6 (10) keV having a spin parity of 1^+ [19]. They did not, however, speculate on the previously reported 0^+ level at $\sim$5946 keV of Parpottas *et al.* [9]. This latter measurement is particularly significant because it used the same ^{24}Mg(^{3}He,n) reaction as Refs. [18,19] at beam energies of 8 and 10 MeV and reported a 0^+ assignment. There is no theoretical prediction, or experimental evidence in the level structures of the $T = 1$ states in the analog nuclei ^{26}Al and ^{26}Mg for two closely neighboring 0^+ states in this region. The present paper describes a detailed study of the γ decays from levels in ^{26}Si, including the first full γ-ray angular distribution measurements for states above the proton threshold with the aim of clarifying the situation regarding these potentially important levels.

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II. EXPERIMENTAL DETAILS

The experiment was performed using the ATLAS accelerator facility at Argonne National Laboratory. The nucleus ^{26}Si was produced with the ^{24}Mg(^{3}He,n) reaction at a beam energy of 10 MeV. A ^{24}Mg target, of thickness $\sim$840 μg/cm^2, was bombarded for $\sim$3 days with a typical beam current of $\sim$5 pnA. Gamma rays were measured with almost 4π coverage with the Gammasphere array [22,23]. Energy and efficiency calibrations were performed with the standard ^{152}Eu and ^{60}Co γ-ray sources as well as with an additional, 6.129 MeV line in ^{16}O, from the ^{13}C(α,n)^{16}O reaction to improve the energy calibration at the highest energies. For the present experiment, the angular-distribution analysis was performed with coincidence matrices where the energies of γ rays detected at specific Gammasphere angles (measured with respect to the beam direction), $E_\gamma(\theta)$, were incremented on one axis, while the energies of coincident γ rays detected at any angle, E_γ(any), were placed on the other axis. In order to improve statistics, angles symmetric with respect to 90° in the forward and backward hemispheres were summed leading to a total of eight matrices (corresponding to angles 17.3°, 31.7°, 37.4°, 50.1°, 58.3°, 69.8°, 80.0°, and 90.0°). After gating on the E$_\gamma$(any) axis, efficiency-corrected spectra

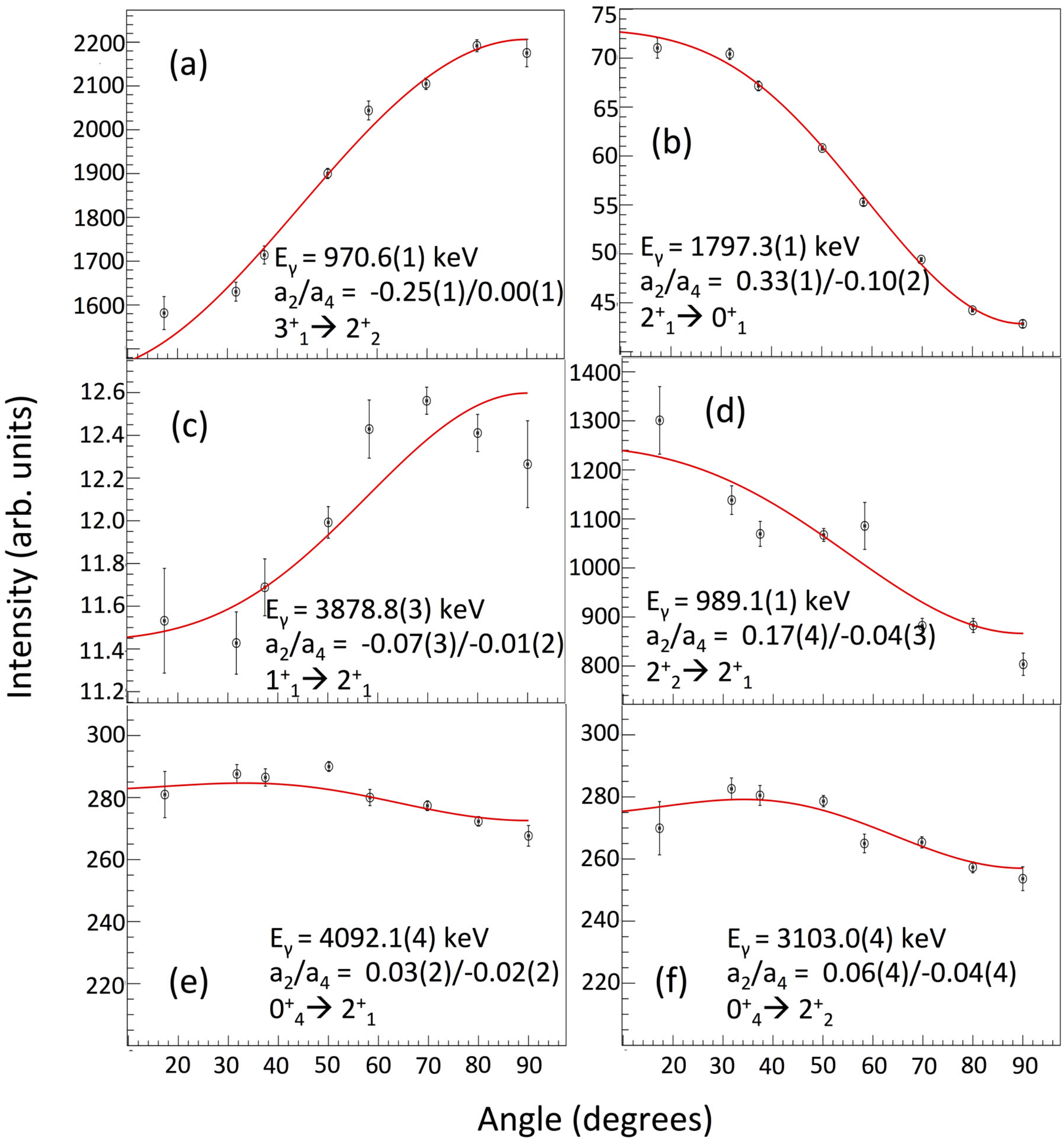

FIG. 1. (Color online) Representative γ-ray angular distributions obtained in the present work. (a) Example of a $\Delta J = 1$ transition between 3^+ and 2^+ states. (b) Example of a $\Delta J = 2$ transition between 2^+ and 0^+ levels. (c) An example of a $\Delta J = 1$ transition between 1^+ and 2^+ states. (d) Example of a $\Delta J = 2$ transition linking two 2^+ levels. Panels (e) and (f) show examples of isotropic distributions from the decay of the 0^+_4 state. Corrections for the detection efficiency of various rings of the Gammasphere array were taken into account.

were generated from which the intensities of transitions of interest could be extracted. A fit to the measured yields at each angle was subsequently performed with the standard angular distribution function $W(\theta) = a_0[1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)]$, where P_2 and P_4 are Legendre polynomials. The extracted coefficients, a_2 and a_4, contain information on the multipolarity of the transitions. Representative fits for several key transitions are provided in Fig. 1.

III. RESULTS AND DISCUSSION

The level scheme for ^{26}Si can be found in Fig. 2, together with the observed decay cascades. Table I gives the energies, branching ratios, angular distributions, and spin assignments for the observed transitions (note singles transitions to the ground state are not observed because only γ-γ coincidence events were recorded). In general, good agreement is observed between the present work and the ^{26}Si spectroscopic information reported in the latest Nuclear Data Sheets [24], with several transitions observed by Seweryniak *et al.* [13], but not reported in the most recent work of Komatsubara *et al.* [19] being confirmed. The following discussion will, therefore, focus on the astrophysically important states just above the proton threshold. Figures 3 and 4 display γ-energy spectra gated on the 1797 keV transition for two different energy regions. These were chosen to highlight transitions from the key states above the proton threshold observed in the present work. Considering first the level at 5676 keV, two deexcitation branches were observed to the two lowest lying 2^+ states; the weaker one, to the 2_2^+ level, is reported here for the first time (see Fig. 4). The angular distribution parameters for the strongest transition to the 2_1^+ state are consistent with a $\Delta J = 1$ transition, and in turn are consistent with a 1^+ assignment for this 5676 keV level. This distribution, seen in Fig. 1(c), compares well with that of the known $\Delta J = 1$ decay between the 3_1^+ and 2_1^+ levels [Fig. 1(a)]. This assignment now appears solid, with no contradictory evidence reported in previous experiments suggesting possible alternative assignments (see Table 2 in Ref. [19]) and is consistent with *sd*-shell-model calculations predicting a 1_1^+ state at this excitation energy [7].

A level is established at 5890 keV and transitions are observed to the 2_1^+, 2_2^+, and 2_3^+ states, as first reported by de Sereville *et al.* [18]. No branching ratios or intensities were reported in Ref. [18], but the overall γ-ray singles intensities (gated on neutrons) shown in Fig. 3 of Ref. [18] appear to be broadly consistent with the values reported in Table I. Komatsubara *et al.* [19] only observed the more intense transitions to the 2_1^+ and 2_2^+ states, and the intensities given are consistent with the approximately equal decay branches reported here. Therefore, it is concluded that all three experiments observed the same state, and herewith confirm its existence. Angular distributions for the two most intense transitions from this 5890 keV level are provided in Figs. 1(e) and 1(f). The results are consistent with isotropic distributions, as expected from a $J = 0$ state, and consistent with the assignment by Komatsubara *et al.* from their DCO measurements [19]. This implies a 0^+ assignment because there is no evidence for 0^- analog states in ^{26}Al and ^{26}Mg. Shell-model calculations performed by Richter *et al.* [25] predict the strongest deexcitation paths from the 0_4^+ level to be to the the three lowest 2^+ states (59%, 35%, 4% in increasing order of excitation energy), in good qualitative and fair quantitative agreement with experiment. Richter *et al.* also predict that, for the γ decay of the 0_4^+ analog state at 6256 keV in ^{26}Mg, there is a large mirror asymmetry and that the 2_1^+ transition is dominant, as observed by experiment [25].

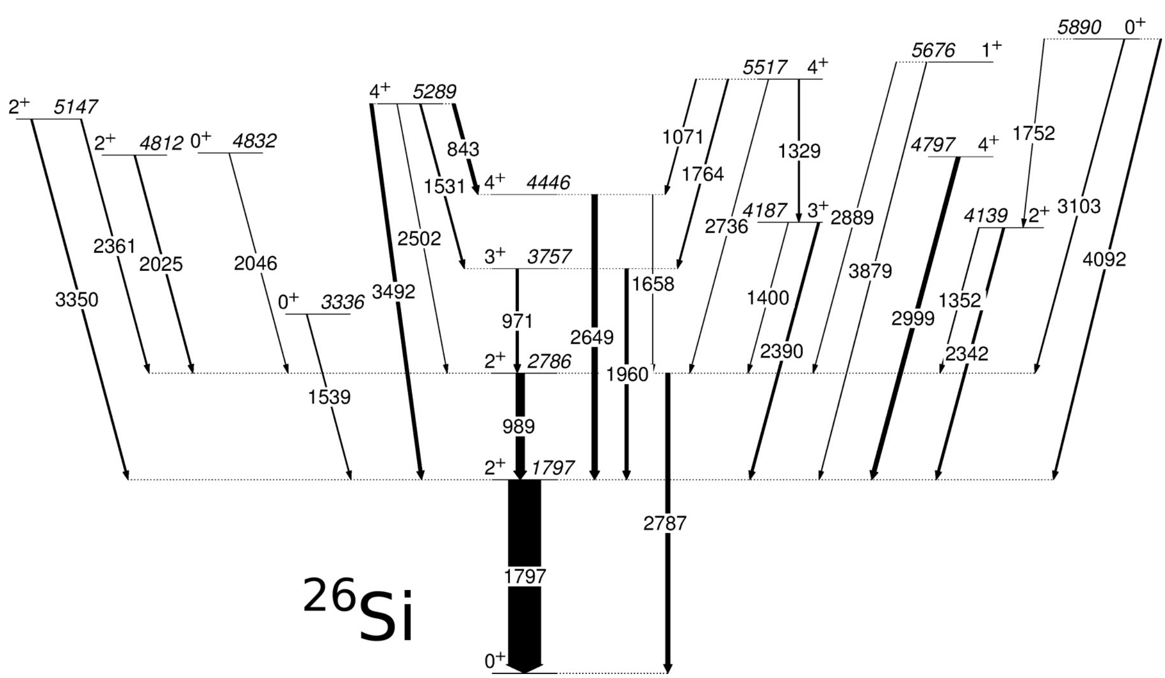

FIG. 2. Full γ-decay scheme for the nucleus ^{26}Si observed in this work. The γ-ray energies are given in keV, while the width of the arrows represents the measured intensity of the transitions.

TABLE I. Properties of excited states in ^{26}Si determined in the present work. Excitation energies E_x are corrected for the recoil of the compound nucleus. The † labels a_2 and a_4 coefficients that are consistent with an isotropic angular distribution.

E_x [keV]	E_γ [keV]	Branch [%]	a_2/a_4	ΔJ	J^π	^{26}Mg mirror-energy assignment
1797.3(1)	1797.2(1)	100	0.33(1)/−0.10(2)	2	2_1^+	1809
2786.4(2)	989.1(1)	60(2)	0.17(4)/−0.04(3)	0	2_2^+	2938
	2786.6(2)	40(3)	0.24(2)/−0.08(3)	2		
3336.4(2)	1539.1(2)	100	0.05(4)/0.02(3)†	2	0_2^+	3589
3757.1(3)	970.6(1)	45(2)	−0.25(1)/0.00(1)	1	3_1^+	3942
	1959.8(2)	55(2)	−0.16(2)/0.01(2)	1		
4138.8(13)[a]	1351.9(12)	9(4)			2_3^+	4333
	2341.8(2)	81(4)	0.14(2)/0.02(3)	0		
4187.2(4)	1400.4(2)	38(3)	−0.14(4)/0.03(4)	1	3_2^+	4350
	2390.0(3)	62(3)	−0.19(6)/0.01(5)	1		
4445.5(12)	1658.3(14)	9(4)			4_1^+	4319
	2648.9(2)	91(2)	0.21(4)/−0.09(4)	2		
4796.7(4)	2999.1(3)	100	0.16(5)/−0.05(4)	2	4_2^+	4901
4811.9(4)	2025.4(3)	100	0.09(2)/0.02(3)	0	2_4^+	4835
4832.1(4)	2045.6(3)	100			0_3^+	4972
5147.4(8)	2360.8(2)	84(3)	0.11(4)/−0.02(5)	0	2_5^+	5292
	3350.3(8)	16(4)				
5288.5(7)	842.5(1)	26(3)	0.10(3)/0.01(4)	0	4_3^+	5476
	1531.1(6)	49(3)	−0.09(2)/−0.02(3)	1		
	2501.9(10)	4(4)				
	3492.0(2)	21(4)	0.12(3)/−0.08(2)	2		
5517.0(5)	1071.4(2)	24(4)			4_4^+	5716
	1329.4(3)	35(4)	−0.09(5)/0.01(4)	1		
	1764.2(4)	37(4)	−0.08(4)/−0.02(3)	1		
	2736.3(10)	4(5)				
5675.9(11)	2888.9(9)	14(6)				
	3878.8(3)	86(4)	−0.07(3)/−0.01(2)	1	1_1^+	5691
5890.1(6)	1751.9(10)	28(5)			0_4^+	6256
	3103.0(4)	35(5)	0.06(4)/−0.04(4)†	2		
	4092.1(4)	37(5)	0.03(2)/−0.02(2)†	2		

[a]The known ground-state transition [13] is not observed in the present work because only γ-γ coincident events were recorded.

Therefore, it is concluded that 5890 keV level is the 0_4^+ state predicted by shell-model calculations and expected based on mirror-symmetry considerations. This state was not observed in a previous Gammasphere study of the level structure of ^{26}Si [13]. However, the statistics were much lower in this previous investigation, and a heavy-ion fusion reaction was used, which is less likely to populate non-yrast states. Here, a light-ion reaction was chosen because it is likely to favor the feeding of low-spin states as, for example, was found in the study of ^{31}S [2].

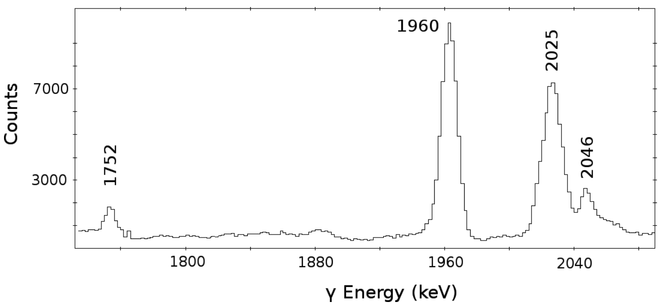

FIG. 3. Portion of the γ-ray spectrum gated on the 1797 keV transition in ^{26}Si. Energies of observed transitions are labeled in keV.

These observations then raise the issue of the 0^+ level at 5946 keV reported by Parpottas *et al.* [9]. This is an important issue to resolve because the present results indicate that all the predicted sd-shell-model states have been observed from the ^{26}Si ground state up to the region of interest for hydrogen burning in novae. It has been pointed out that the properties of the 3^+ state at 5927 keV are the most critical for novae burning conditions [3]. However, if a state is present at 5946 keV which predominantly decays by proton emission

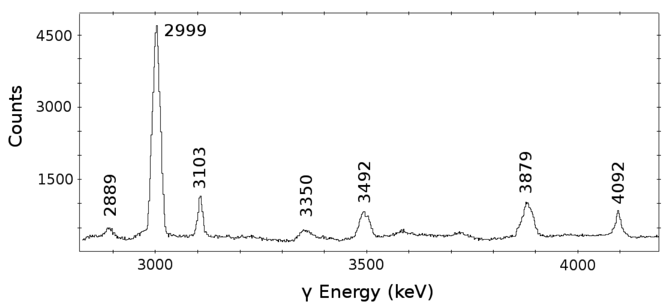

FIG. 4. Another part of the γ-ray spectrum gated on the 1797 keV transition in ^{26}Si. Energies of observed transitions are labeled in keV.

(but is not observable by γ decay) and has a larger γ-decay partial width, Γ_γ, than the 3^+ level, then it can potentially strongly influence, or even dominate, astrophysical burning. Considering states outside the sd-shell basis, the lowest-lying known negative-parity state in the stable mirror nucleus ^{26}Mg is a 3^- level at 6876 keV which already has a natural mirror partner at 6787 keV in ^{26}Si, and a $T = 1$ partner at 6964 keV in ^{26}Al [24]. The next highest negative-parity state listed in the latest Nuclear Data Sheets [24] is at 7062 keV in ^{26}Mg. It was assigned a 1^- spin parity (and has a lifetime <7 fs). However, a study of the ^{28}Si$(p,t)^{26}$Si reaction in which the level is strongly populated suggests a 0^+ assignment, consistent with an intruder $(f_{7/2})^2$ configuration [26]. No analog $T = 1$ state is observed in the structure of ^{26}Al, but none of the reaction mechanisms used to investigate the latter nucleus to date would selectively populate such a state. The analog of this 7062 keV state is probably the best non-sd-shell candidate for the purported 5946 keV level in ^{26}Si, however this conjecture would require a very large Thomas–Ehrmann shift. Although perhaps unlikely, this possibility cannot be entirely ruled out.

Parpottas *et al.* [9] used the same reaction, ^{24}Mg(^{3}He,n), and beam energies of 8 and 10 MeV as the γ-ray studies identifying the 5890 keV level in ^{26}Si. In this work of Ref. [9], high resolution neutron time-of-flight measurements were used to investigate the level structure of ^{26}Si at two different angles, 0° and 60°, for 8 MeV and 0° for 10 MeV. Two neighboring states are clearly resolved in the 8 MeV data, with excitation energies of 5912 (4) and 5948 (4) keV, while a 5912-5946 keV doublet is observed at 10 MeV [9]. These levels are clearly resolved in Fig. 2 of Ref. [9], with no evidence for a peak at 5890 keV. In the present γ-ray study, and also that of Komatsubara *et al.* [19], the γ-ray intensity of the decays observed from the 5890 keV level are comparable to that from the 1^+_1 state at 5675 keV (see Fig. 4). This latter state is also observed in the Parpottas work for all three experimental settings. Its intensity is comparable, but somewhat smaller than that seen for the 5912 keV state, assigned as 3^+, in the spectrum of Fig. 1 in Ref. [9]. The state at 5890 keV should, therefore, have been clearly seen by Parpottas *et al.* [9]. Hence, it is difficult to reconcile the experimental results from Ref. [9] with the data from the γ-ray studies.

In a detailed study of neutron differential cross sections for the ^{24}Mg(^{3}He,n) reaction by Bohne *et al.* [14], performed at a slightly higher beam energy of 13 MeV, a structure was observed at 5.91 (3) MeV. By using a DWBA analysis, this structure was deduced to be consistent with a dominant $l = 0$, two-neutron-transfer component at forward angles, and a weaker $l = 4$ one at more backward angles (the resolution was insufficient to resolve the states—inspecting the spectrum of Fig. 1 in Ref. [14], a tail can be noticed on the high-energy side of the 5.91 MeV peak). The results of Bohne *et al.* [14] are consistent with a strongly populated natural-parity 0^+ state at 5890 keV and a weaker unnatural-parity 3^+ level at 5927 keV. Parpottas *et al.* [9] assumed a dominant compound-nucleus mechanism at their slightly lower beam energies and used a comparison of the cross section with Hauser–Feshbach calculations (at each of three individual angle or energy settings) to assign 3^+ and 0^+ quantum numbers to states at 5912 and 5948 keV, respectively [9]. It should be noted that the dominant component seen in the earlier (^{3}He,n) study of Ref. [14] is 0^+ at ~5910 keV, whereas in contrast in Parpottas *et al.* [9], the (higher excitation energy) state assigned as 0^+ is produced significantly more weakly than the neighboring state. Finally, a state at 5945 (8) keV was reported in a multinucleon transfer reaction by Caggiano *et al.* [10]. However, the authors state that this level cannot be associated with a 0^+ state (based on the much weaker population of other 0^+ levels) and tentatively propose a 3^+ assignment. The latter would be consistent with relating this state with the now-well-established 3^+ level at 5928.7 (6) keV, agreeing at the $\sim 2\sigma$ level in energy.

Based on the present data and on the discussion above, it is concluded that the majority of experimental evidence argues against a 5946 keV, 0^+ level as proposed in Ref. [9], but favors instead a 0^+_4 assignment to the 5890 keV state. As such, the data agree with expectations based on sd-shell-model calculations as well as with arguments based on mirror-symmetry considerations. A final resolution of this issue would require a repeat of the experiment of Ref. [9]. It is important to confirm or refute the existence of the possible state around 5946 keV and, if it exists, identify its structure because it could strongly influence the ^{25}Al$(p,\gamma)^{26}$Si burning rate in novae environments.

In summary, new information on the level structure of ^{26}Si has been reported with a specific focus on the region above the proton threshold relevant for novae burning. In particular, these results firmly establish the existence of a 0^+ state at 5890 keV.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-O6CH11357. This research used resources of ANL's ATLAS facility which is a DOE office of Science User Facility. D.T.D., P.J.W., A.K., and C.L. would like to thank the STFC for support, C.L. acknowledges support from the Austrian Science Fund (FWF): J3503. UMCP personnel acknowledge support from DoE Grant No. DE-FG02-94ER40834. P.J.W. would like to thank Alex Brown for many stimulating remarks on issues raised in this paper.

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