Identification of analog states in the $T = 1/2$ $A = 27$ mirror system from low excitation energies to the region of hydrogen burning in the $^{26}Al^{g,m}(p,\gamma)^{27}Si$ reactions

G. Lotay,[1] P. J. Woods,[1] D. Seweryniak,[2] M. P. Carpenter,[2] H. M. David,[1] R. V. F. Janssens,[2] and S. Zhu[2]
[1]*School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
(Received 9 March 2011; published 8 September 2011; publisher error corrected 20 September 2011)

The reactions $^{26}Al^{g}(p,\gamma)^{27}Si$ and $^{26}Al^{m}(p,\gamma)^{27}Si$ are important for influencing the galactic abundance of the cosmic γ-ray emitter $^{26}Al^{g}$ and for the excess abundance of ^{26}Mg found in presolar grains, respectively. Precise excitation energies and spin assignments of states from the ground state to the region of astrophysical interest in ^{27}Si, including the identification and pairing of key astrophysical resonances with analog states in the mirror nucleus ^{27}Al, are reported using γ rays observed in the $^{12}C + {}^{16}O$ fusion reaction. The detailed evolution of Coulomb energy differences between the states in ^{27}Si and ^{27}Al is explored, including the region above the astrophysical reaction thresholds.

DOI: 10.1103/PhysRevC.84.035802 PACS number(s): 23.20.Lv, 21.10.Dr, 26.50.+x, 27.30.+t

I. INTRODUCTION

In explosive stellar environments, such as classical novae and x-ray bursters, thermonuclear radiative capture reactions on unstable nuclei drive the path of nucleosynthesis toward the proton drip line. These processes are often dominated by resonant capture to excited states above the particle-emission threshold and, as such, depend critically on the nuclear properties of the levels involved. However, since the required spectroscopic information on proton-rich nuclei is intrinsically difficult to obtain through direct or indirect means, such properties are frequently unknown. Consequently, previous estimates of thermonuclear reaction rates in explosive stellar scenarios have often relied on adopting information for key resonant states from analog states in the better-studied stable mirror nucleus.

In particular, a theoretical study by Champagne *et al.* [1] investigated mirror states in the $T = 1/2$, $A = 27$ system in order to reduce uncertainties in the astrophysical $^{26}Al(p,\gamma)^{27}Si$ reaction. The $^{26}Al(p,\gamma)^{27}Si$ reaction is dominated by resonant capture to excited states above the ^{27}Si proton threshold of 7463.0(2) keV [2] and is expected to govern the destruction of the cosmic γ-ray emitter ^{26}Al in stellar environments. In Ref. [1], shell model calculations were used to predict the location of states in ^{27}Si analogous to well-studied states in the mirror nucleus ^{27}Al. From such an analysis, it was possible to propose direct mirror assignments for excited states in the $T = 1/2$ pair ^{27}Si and ^{27}Al up to an excitation energy of 4447 keV [1]. However, with almost no experimental information available on the nuclear properties of levels in ^{27}Si above this excitation energy [3] and with the increase in the level density of states, a unique matching of mirror pairs with $E_x > 4447$ keV was not possible. Consequently, in the excitation energy range 7.5–8.0 MeV, of relevance for key resonant states in ^{27}Si, rather than making direct mirror assignments, Champagne *et al.* adopted a global energy shift between mirror pairs, so that for each of the known levels in ^{27}Al, several states in ^{27}Si could be suggested as possible analogs. In Ref. [1], this shift was predicted to be ~200 keV, and by using such a methodology, Champagne *et al.* were able to restrict the assignments of proton-unbound states in ^{27}Si and evaluate the $^{26}Al(p,\gamma)^{27}Si$ reaction. However, each known state near the $^{26}Al + p$ threshold was still associated with several possible shell-model configurations, leaving considerable uncertainty in the rate.

The technique employed by Champagne *et al.* [1] is clearly a very powerful tool to estimate stellar reaction rates, for which the nuclear properties of key resonant states remain unknown. Nevertheless, it does suffer from a significant drawback in that, without experimental data, it is not possible to make unique mirror assignments for states at high excitation energies. Furthermore, it has yet to be established whether the use of a global mirror energy shift, as is used for low-lying bound states [1], is a valid approach for bound states of high excitation energy or for particle-unbound levels.

Recently, an experimental study performed at Argonne National Laboratory investigated the γ decay of astrophysically important proton-unbound states in ^{27}Si [4,5]. In that work [4,5], mirror assignments were used to help identify key resonant states in the $^{26}Al + p$ system by spin and parity J^{π}, significantly reducing uncertainties in the astrophysical $^{26}Al(p,\gamma)^{27}Si$ reaction rate. In this paper, using data taken at the same time as Refs. [4,5], the complete study of mirror states in the $T = 1/2$ $A = 27$ pair, ^{27}Si and ^{27}Al, is presented from low excitation energies into the energy region of importance for the astrophysical $^{26}Al(p,\gamma)^{27}Si$ reaction. In particular, the focus is on the evolution of the structure of excited states in ^{27}Al and ^{27}Si through a comparison with shell-model calculations and on an investigation of Coulomb energy differences between isobaric analog states and their dependence on spin and parity assignments.

II. EXPERIMENTAL DETAILS

This experiment forms part of a series of γ-ray spectroscopy studies of astrophysically important mirror systems using the Gammasphere detector array [6] in stand-alone mode or in combination with the Argonne Fragment Mass Analyzer (FMA) [7]; see Refs. [8–11].

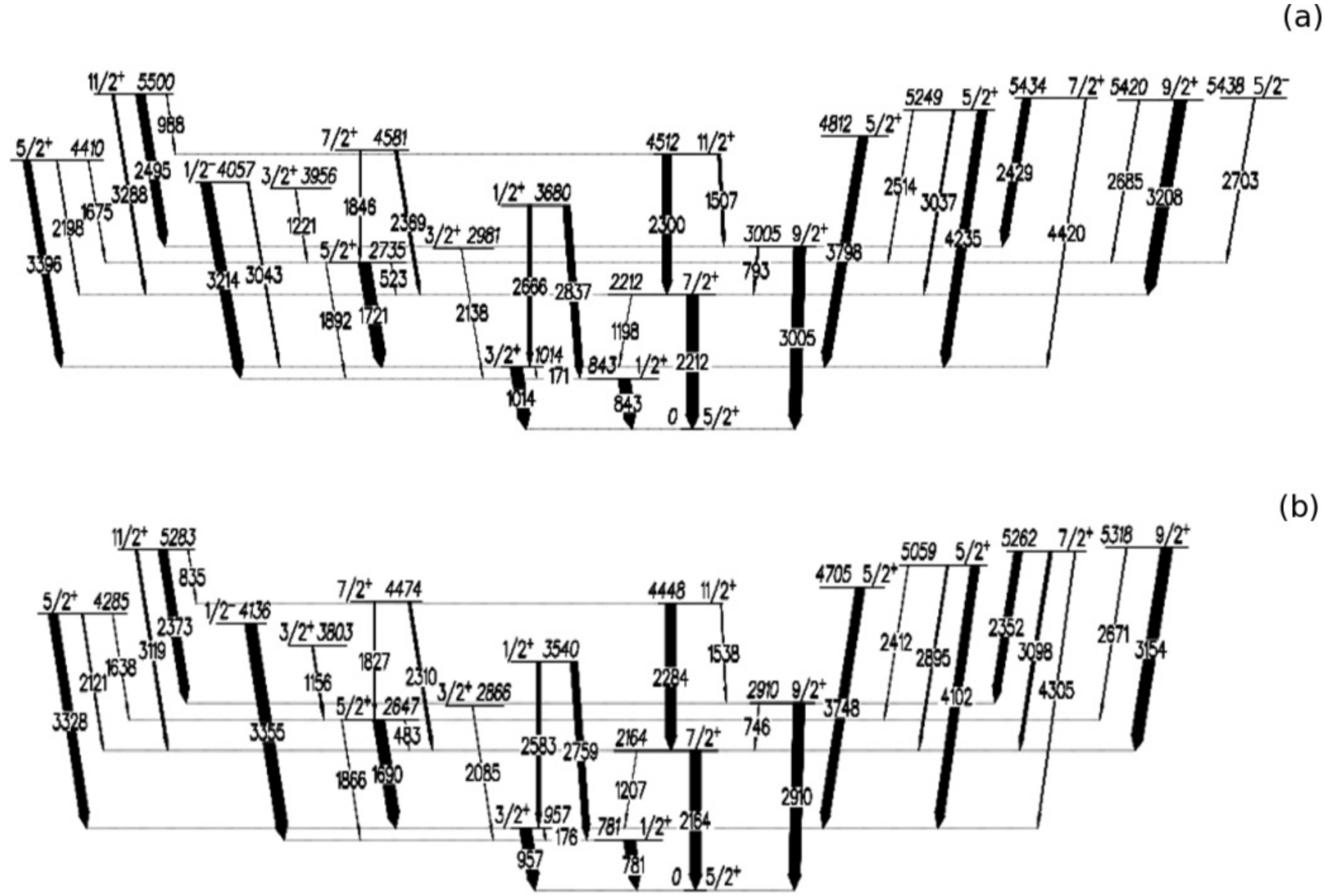

FIG. 1. (a) Observed low-lying level structure of ^{27}Al; relative intensities have been taken from Ref. [3]. (b) Observed low-lying level structure of ^{27}Si; relative intensities have been taken from Ref. [3].

Here, the Gammasphere array was used in stand-alone mode to detect γ decays resulting from heavy-ion fusion-evaporation. It consisted of 100 Compton-suppressed high-purity germanium (HPGe) detectors. A 6-pnA, 26-MeV beam of ^{16}O ions, produced by the Argonne ATLAS accelerator, was used to bombard a $\sim$150-μg/cm^2-thick ^{12}C target for 63 h in order to produce ^{27}Si and ^{27}Al nuclei via the single-neutron and single-proton evaporation channels, respectively. 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. A γ-ray singles spectrum, γ-γ coincidence matrix, and γ-γ-γ cube were produced and analyzed to obtain information on the ^{27}Si and ^{27}Al decay schemes. Lifetimes of the excited states observed were extracted using the fractional Doppler shift method [12].

The data obtained in the present work for the γ-decay schemes of low-lying states in ^{27}Al and ^{27}Si are entirely consistent with previously published work [3] and are presented in Figs. 1(a) and 1(b). No previous information exists on the γ-decay modes of excited states in ^{27}Si above the energy region displayed in Fig. 1(b) [3]. As can be seen in Fig. 1, there is excellent agreement in the γ-decay modes and branching ratios of analog states in the $T = 1/2$ $A = 27$ mirror pair, confirming the power of isospin symmetry. However, it should be noted that small differences are observed in the γ-decay branches of several mirror analog states. Specifically, the $7/2^+_3$, 5262-keV excited state in ^{27}Si is observed to exhibit a γ-decay branch to the $7/2^+_1$ level, whereas no such transition is observed from its analog $7/2^+_3$, 5434-keV state in ^{27}Al. Furthermore, the $1/2^-_1$, 4057-keV excited state in ^{27}Al is observed to exhibit a γ-decay branch, not observed from its corresponding isobaric mirror $1/2^-_1$, 4136-keV level in ^{27}Si, to the $3/2^+_1$ level. Similar differences between the γ-decay modes of mirror states in sd-shell nuclei have been previously reported [13].

III. EXCITED STATES IN ^{27}Al

In general, previous structural data reported on the nucleus ^{27}Al are of an extensive and detailed nature [3,14], and results obtained in the present study are in agreement with Fig. 3 of Ref. [14] up to 7.5 MeV. However, there is uncertainty regarding the γ-decay branches of excited states in ^{27}Al in the region of high excitation energy, $E_x > 7.5$ MeV, in which the level density is high and excited levels are in close proximity to the the proton-emission threshold energy of 8271.32(16) keV [2]. It is important to obtain a detailed knowledge of the level structure of ^{27}Al in order to propose analog assignments in the much less well studied proton-rich mirror nucleus ^{27}Si. In particular, states at high excitation energies are important, as

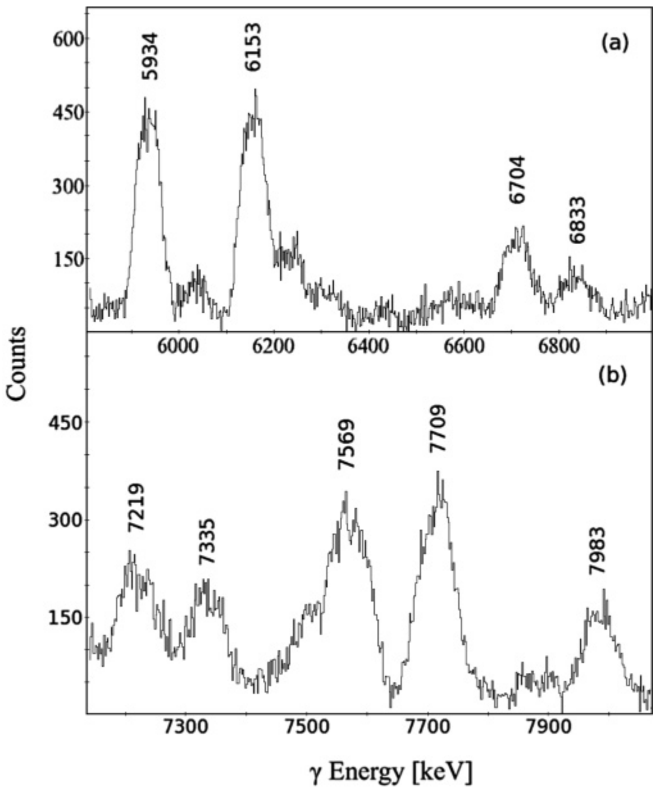

FIG. 2. (a) The γ-γ coincidence spectrum gated on the 843-keV transition in ^{27}Al showing the energy range 5.8–7.0 MeV. (b) The γ-γ coincidence spectrum gated on the 843-keV transition in ^{27}Al showing the energy range 7.1–8.1 MeV.

levels in this region are analogs of key resonant states in ^{27}Si, relevant for the determination of the ^{26}Al$(p,\gamma)^{27}$Si reaction rate. Consequently, in the following sections, the γ-decay transitions observed in this study from excited states in ^{27}Al with E_x>7.5 MeV are discussed in some detail.

A. E_x = 8063, 8179, 8413, 8553, and 8827 keV

Figure 2 displays the presently observed high-energy γ-ray transitions in coincidence with the lowest-lying $1/2^+$, 843.2(1)-keV excited state in ^{27}Al.

The 7335.1(22)-keV γ decay from the known $3/2^-$, 8179.4(16)-keV level in ^{27}Al, seen in Fig. 2(b), has been reported previously [3,14]. This γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition. As such, the current indicated spin assignment for the 8179-keV excited state in ^{27}Al and measured γ-decay transition energy to the $1/2_1^+$ level are in agreement with Ref. [3].

In contrast to the 7335-keV γ ray, the 7218.5(9)-, 7568.6(13)-, 7709.0(12)-, and 7982.5(12)-keV transitions from the known 8062.7(9)-, 8412.9(13)-, 8553.4(12)-, and 8827.0(12)-keV states in ^{27}Al [3] [Fig. 2(b)] are newly observed in this study. An angular distribution analysis of the 7219-, 7566-, and 7709-keV γ rays revealed a_2/a_4 coefficients consistent with $\Delta I = \pm 1$ transitions, indicating $3/2^+$, 3/2, and 3/2 assignments for the 8063-, 8413-, and 8553-keV excited levels in ^{27}Al.

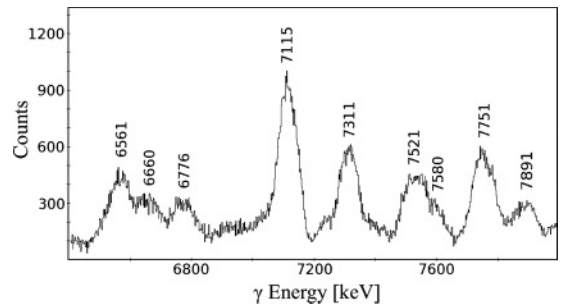

FIG. 3. The γ-γ coincidence spectrum gated on the 1014-keV transition in ^{27}Al.

B. E_x = 7676, 7790, 8130, 8766, and 8906 keV

Figure 3 displays the presently observed high-energy γ-ray transitions in coincidence with the lowest-lying $3/2^+$, 1014.0(1)-keV excited state in ^{27}Al.

As can be seen in Fig. 3, previously reported γ-decay branches to the $3/2_1^+$ level at 6561.2(6)-, 6660.3(10)-, 7115.0(8)-, 7310.8(12)-, 7521.0(9)-, and 7580.2(18)-keV were observed, resulting from the deexcitation of known states in ^{27}Al at 7576.0(6)-, 7676.0(10)-, 8130.1(8)-, 8325.9(12)-, 8536.2(9)-, and 8595.3(18)-keV [3]. In the present work, the 7676-keV state was also observed to exhibit a new 6832.7(9)-keV γ-decay branch to the $1/2_1^+$ level, as shown in Fig. 2(a). The 7676-keV excited state in ^{27}Al had been previously assigned $(3/2, 5/2)^+$ [3]. However, in Ref. [14], the same state was given a $(1/2–5/2)^+$ assignment. Here the observed 6660- and 6833-keV γ rays were measured to have a_2/a_4 angular distribution coefficients of $-0.09(7)/-0.09(9)$ and $-0.04(10)/-0.11(11)$, respectively. From these measurements, a $3/2^+$ assignment may be ruled out for the 7676-keV state in ^{27}Al, but $1/2^+$ and $5/2^+$ assignments remain possible, in agreement with Ref. [14]. Consequently, the 7676-keV excited level in ^{27}Al has been reassigned as $(1/2, 5/2)^+$ here. In addition, in Ref. [3], the 8130-keV level in ^{27}Al was reported as a $1/2^+$ state, with γ-decay branches to the $3/2_1^+$ and ground states. However, in Ref. [14], no such γ-decay branches were reported for a $1/2^+$ 8130-keV state in ^{27}Al. Instead, in that work [14], γ-decay branches to the $3/2_1^+$ and ground states were reported for a 5/2 state at 8136 keV. Here the 7115-keV γ ray was measured to have a_2 and a_4 coefficients of $-0.13(2)$ and $-0.03(3)$, respectively, ruling out a 1/2 assignment. Furthermore, shell-model calculations suggest a $5/2^+$ assignment for this state [15]. Hence, the known 8130-keV excited state in ^{27}Al has been reassigned as a $5/2^+$ level.

Considering Fig. 3 further, 6775.5(7)-, 7750.5(14)-, and 7891.0(30)-keV γ-decay branches to the $3/2_1^+$ level were observed, indicating previously unobserved excited states in ^{27}Al at 7790.4(7) and 8765.7(14) keV and a previously unobserved branch to the $3/2_1^+$ level from the known 8906.2(30)-keV state in ^{27}Al [3]. An angular distribution analysis of the 6776- and 7751-keV γ rays revealed nonzero a_2/a_4 coefficients consistent with $\Delta I = \pm 1$ transitions, indicating 5/2 assignments for the 7790- and 8766-keV excited states in ^{27}Al. In contrast, the 7891-keV γ ray was measured to have a_2 and a_4 angular distribution coefficients consistent with zero, indicating a 1/2 assignment for the 8906-keV state in ^{27}Al. The 8906-keV level has been previously assigned as a $(1/2, 3/2)^-$ state [3]. Consequently, a 7891-keV γ-decay branch to the $3/2^+_1$ level from a $1/2^-$, 8906-keV excited state in ^{27}Al was assigned.

C. $E_x = 7807$, 7998, and 8046 keV

In addition to the new information obtained on the γ-decay scheme of high-energy, low-spin excited states in ^{27}Al, newly observed γ-ray transitions are also reported here for the known 7807.2(10)-, 7997.6(8)-, and 8046.2(13)-keV high-spin excited levels in ^{27}Al [3]. The $9/2^+$, 7807-keV state is known to exhibit γ-decay branches to the $7/2^+_2$, $11/2^+_1$, and $7/2^+_1$ levels [3]. In the present work, an additional 1847.1(14)-keV decay transition to the $7/2^+_4$ level was observed. Moreover, the $9/2^+$, 7998-keV level, previously reported to have γ-decay branches to the $9/2^+_1$ and $7/2^+_1$ states, was also observed to exhibit 2497.7(21)- and 2578.0(40)-keV γ decays to the $11/2^+_2$ and $9/2^+_2$ states, respectively. In Ref. [3], the excited level at 8046 keV in ^{27}Al is listed with possible $5/2^+$, 7/2, and $9/2^+$ assignments. However, in this work, 2377.0(40)- and 2608.7(22)-keV γ-decay branches from the 8046-keV state in ^{27}Al to the $9/2^+_3$ and $5/2^-_1$ levels were observed, as indicated in Figs. 4 and 5, respectively, together with 2612.4(3)- and 5040.3(14)-keV γ-decay branches to the $7/2^+_3$ and $9/2^+_1$ excited states, respectively. These observations indicate that this level should be assigned as a possible $9/2^-$ state rather than $9/2^+$. The unlabeled γ rays that appear at 2212 and 2299 keV in Figs. 4 and 5 are contaminant transitions from the $11/2^+_1 \rightarrow 7/2^+_1 \rightarrow 5/2^+_1$ cascade.

D. $E_x = 7950$ keV

As a final note on information obtained in this study on excited states in ^{27}Al, an outstanding issue in the previously reported level structure [3] is addressed here. The most recent compilation on excited states in ^{27}Al lists $(9/2, 11/2)^-$ and $(9/2, 11/2)^+$ excited levels at 7935(3) and 7948(2) keV, respectively [3]. The 7935-keV state is reported to exhibit 3424- and 4930-keV γ-decay branches to the $11/2^+_1$ and $9/2^+_1$ levels, respectively, whereas the 7948-keV state is reported to

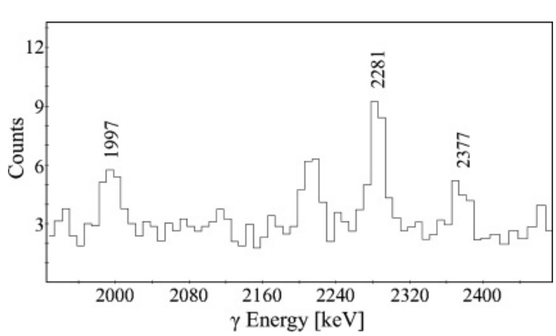

FIG. 4. The γ-γ-γ coincidence spectrum gated on the 3005- and 2663-keV transitions in ^{27}Al.

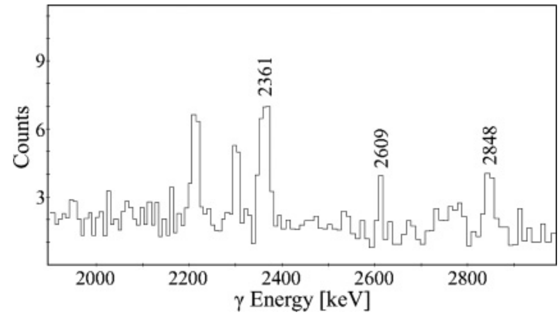

FIG. 5. The γ-γ-γ coincidence spectrum gated on the 1014- and 2703-keV transitions in ^{27}Al.

exhibit 2448-, 2527-, 3437-, and 4943-keV γ-decay branches to the $11/2^+_2$, $9/2^+_2$, $11/2^+_1$, and $9/2^+_1$ levels, respectively [3]. It has been previously suggested that both excited states may potentially be important mirror analogs to key resonant states in ^{27}Si [1], but, to date, only the 7948-keV state has been specifically assigned as a mirror to an astrophysically significant resonance [4].

In the present data, no evidence was found for γ-decay transitions to the $11/2^+_1$ or $9/2^+_1$ levels from an excited state in ^{27}Al at 7935 keV. However, 2448.7(7)-, 2529.1(2)-, 3437.9(3)-, and 4943.2(4)-keV γ-decay transitions were measured to the $11/2^+_2$, $9/2^+_2$, $11/2^+_1$, and $9/2^+_1$ levels, respectively, from an excited state in ^{27}Al at 7949.5(3) keV, together with an additional 2281.1(5)-keV γ-decay branch to the $9/2^+_3$ level, as seen in Fig. 6. Here the 3438-keV γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = 0$ transition, indicating an $11/2^+$ assignment for the presently observed 7950-keV level in ^{27}Al. Consequently, γ-decay branches to the $9/2^+_3$, $11/2^+_2$, $9/2^+_2$, $11/2^+_1$, and $9/2^+_1$ levels were assigned from a $11/2^+$, 7950 excited state in ^{27}Al, and γ-decay branches to the $11/2^+_1$ and $9/2^+_1$ levels from an excited state at 7935 keV in ^{27}Al have been ruled out. It should also be noted that no γ-decay transitions were listed from an excited level at 7935 keV in ^{27}Al in Fig. 3 of the most recent previous γ-ray study by Lickert *et al.* [14].

The data acquired in the present study, together with earlier work [3], have provided a comprehensive level structure of the nucleus ^{27}Al. Figure 6 displays the expected level structure of even-parity states in ^{27}Al as a function of spin. The results of shell-model calculations [15] are given as well. It can be seen that all even-parity states predicted by the shell model up to high excitation energy have now been identified and associated with experimentally observed levels in ^{27}Al. Such a complete level structure determination of ^{27}Al is important for the assignment of excited levels in the proton-rich nucleus ^{27}Si. In the following section the assignment of excited states in ^{27}Si is presented with specific focus on proton-unbound levels for which the assignments depend critically on the nuclear properties of high-lying excited states in ^{27}Al.

IV. EXCITED STATES IN ^{27}Si

In this work, 55 previously unassigned excited states in ^{27}Si were identified and matched to their mirror analog

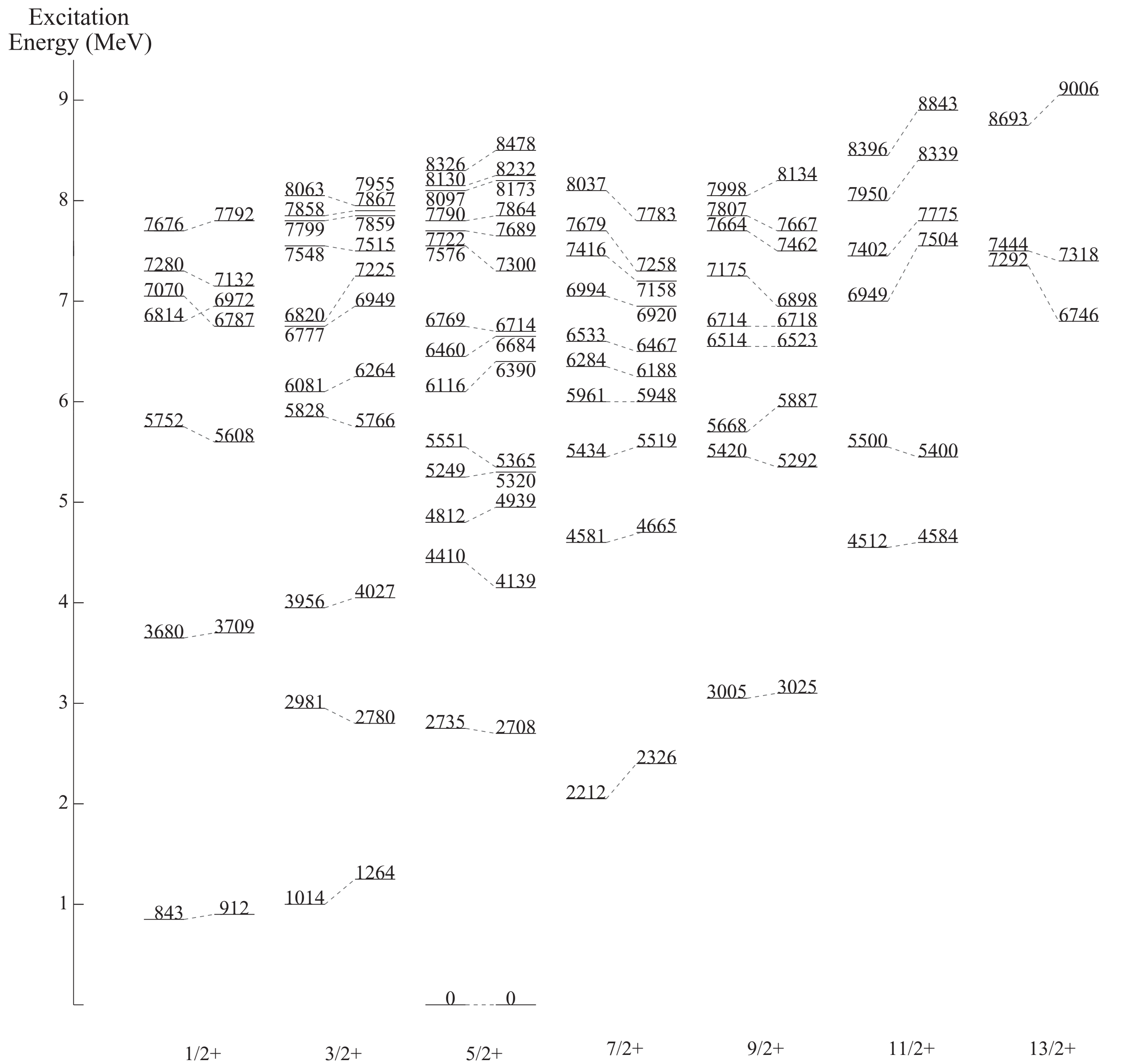

FIG. 6. (Color online) Even-parity excited states in ^{27}Al (left value in each pair) together with a comparison to shell-model calculations [15] (right value in each pair).

states in ^{27}Al. Table I presents the level energies, spin-parity assignments, γ-ray energies, angular distribution coefficients, and lifetime information for excited states in ^{27}Si, together with a comparison with previous studies.

An example is given below of the approach undertaken in the assignment of mirror analog states in this work.

A typical γ-decay spectrum obtained for such states in this study is given in Fig. 7, which shows γ-γ coincidence relationships with the $11/2_1^+$ excited level in ^{27}Si. In Fig. 7, a γ-decay transition appears at 1099.9(1) keV, indicating a high-spin excited state in ^{27}Si at 5547.3(1) keV, which is in agreement with the previously reported value of 5547(4) keV [3]. The 1100-keV γ ray was measured to have angular distribution

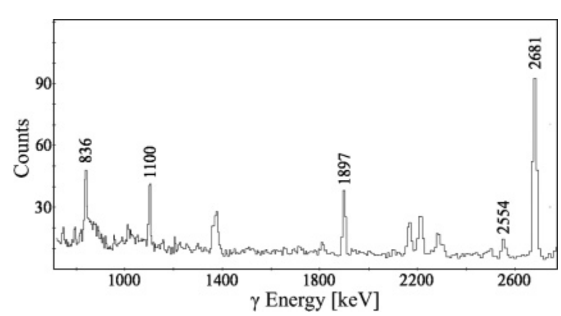

FIG. 7. The γ-γ-γ coincidence spectrum gated on the 2164- and 2284-keV transitions in ^{27}Si.

TABLE I. Properties of excited states in ^{27}Si.

E_x (keV) [3]	$J^\pi; T$ [3]	E_x (keV)	$J^\pi; T$	E_γ (keV)	a_2/a_4	$t_{1/2}$
780.9(2)	$1/2^+$	780.8(1)	$1/2^+$	780.8(1)		35 ps 4[a]
957.4(2)	$3/2^+$	957.1(1)	$3/2^+$	176.3(1)	−0.10(1)/−0.02(2)	1.20 ps 8[a]
				957.1(1)		
2163.6(2)	$7/2^+$	2163.6(1)	$7/2^+$	1205.9(1)	0.29(5)/−0.12(6)	44 fs 5[a]
				2163.5(1)	−0.77(1)/0.11(5)	
2647.6(3)	$7/2^+$	2647.2(1)	$5/2^+$	484.5(1)		15 fs 3
				1690.1(1)	−0.29(1)/−0.03(1)	
				1866.5(1)	0.19(5)/−0.12(6)	
2866.3(3)	$(3/2, 5/2)^+$	2866.0(3)	$3/2^+$	2085.1(3)		<3 fs[a]
2909.9(2)	$9/2^+$	2910.1(1)	$9/2^+$	746.3(1)	−0.19(1)/−0.05(4)	52 fs 6[a]
				2909.9(1)		
3540.2(11)	$1/2^+$	3539.8(1)	$1/2^+$	2582.5(1)	−0.07(3)/0.06(3)	10 fs 2
				2758.9(1)	0.04(2)/−0.03(2)	
3803.6(11)	$3/2^+$	3803.1(2)	$3/2^+$	1155.5(2)	0.13(7)/0.04(9)	<1 fs
4138.1(14)	$(1/2, 3/2)^-$	4136.1(2)	$1/2^-$	3355.1(2)	−0.01(3)/0.00(4)	8 fs 2
4289.2(9)	$5/2^+$	4284.8(2)	$5/2^+$	1637.4(1)		4 fs 2
				2121.0(3)		
				3327.6(1)	0.03(2)/0.02(3)	
4447.3(5)	$11/2^+$	4447.5(1)	$11/2^+$	1536.9(1)	0.59(2)/0.06(2)	390 fs 40[a]
				2283.9(1)	0.31(1)/−0.11(1)	
4474.8(7)	$(7/2, 9/2)^+$	4473.9(2)	$7/2^+$	1826.7(1)	−0.31(2)/0.01(3)	11 fs 3
				2310.2(2)		
				3516.7(3)		
4703.8(11)	$5/2^+$	4705.1(2)	$5/2^+$	3747.6(1)	0.09(2)/0.04(3)	7 fs 2
5062(2)	$5/2^+$	5059.4(7)	$5/2^+$	2410.0(30)		21 fs 6[a]
				2896.6(2)		
				4101.9(2)	−0.27(2)/0.00(2)	
5208(2)	$3/2^-$	*unobserved*	$3/2^-$			<35 fs[a]
5262.0(5)	$(5/2^+, 7/2, 9/2^+)$	5262.1(3)	$7/2^+$	2351.7(1)	−0.13(2)/0.03(3)	10 fs 2
				3098.8(6)	0.27(5)/0.02(7)	
				4304.3(14)	0.29(9)/0.05(12)	
5282.8(4)	$(7/2, 11/2)^+$	5283.2(2)	$11/2^+$	835.6(6)		9 fs 3
				2372.9(1)	−0.64(1)/0.04(1)	
				3119.6(1)	0.28(2)/−0.10(3)	
5316.7(5)		5317.8(2)	$9/2^+$	2670.0(7)		7 fs 2
				3154.0(1)	−0.67(1)/0.03(1)	
5391.7(16)	$(3/2, 5/2)^+$	5392.9(6)	$5/2^+$	4435.4(6)		<30 fs[a]
5497(2)		5500.4(2)	$5/2^-$	2853.1(2)	0.40(6)/0.04(8)	8 fs 2
5547(4)		5547.3(1)	$9/2^+$	1099.9(1)	−0.34(6)/0.05(8)	14 fs 3
				2637.1(1)	0.32(2)/−0.05(3)	
5580(4)		5573.7(3)	$1/2^+$	2033.8(3)		<3 fs
				4792.3(3)	0.05(4)/−0.06(5)	
5613(4)		5607.0(3)	$3/2^+$	2066.6(3)	−0.29(12)/−0.05(7)	5 fs 2
				4649.6(2)		
5783(6)		5785.8(2)	$7/2^+$	2875.0(4)		7 fs 2
				3137.8(1)	−0.31(3)/0.07(3)	
				3622.0(1)	0.33(2)/0.00(3)	
New level		5850.3(11)	$3/2^+$	4892.7(11)	0.17(7)/0.01(9)	
5897(3)		5893.1(3)	$5/2^+$	4935.5(3)	−0.13(2)/−0.03(3)	8 fs 2
6028(4)		6027.3(3)	$3/2^-$	3379.1(12)		<1 fs
				5246.1(2)	−0.08(3)/−0.03(3)	
6059(4)		6059.1(3)	$7/2^+$	1775.5(12)		<4 fs
				3410.9(3)		
				3895.0(2)	0.17(7)/−0.15(9)	
6323(4)		6319.0(15)	$7/2^+$	3670.5(4)	−0.08(7)/0.22(9)	<1 fs
				4155.6(20)	0.10(7)/0.05(10)	

TABLE I. (Continued).

E_x (keV) [3]	J^π; T [3]	E_x (keV)	J^π; T	E_γ (keV)	a_2/a_4	$t_{1/2}$
New level		6339.2(9)	$5/2^+$	5381.5(9)	0.00(6)/0.12(8)	<1 fs
6346(4)		6344.0(4)	$9/2^+$	1870.0(30)		10 fs 2
				1896.7(2)	−0.07(5)/−0.01(6)	
				3433.5(2)	0.22(3)/−0.04(3)	
				4179.7(6)		
New level		6381.8(4)	$3/2^-$	2841.5(8)		<1 fs
				5425.4(16)		
				5600.5(1)	−0.27(2)/−0.05(3)	
6398?		6388.8(24)	$7/2^-$	3741.3(24)		
6457(3)		6449.8(10)	$5/2^-$	5492.1(10)		
6513(4)		*unobserved*	$3/2^+$			
New level		6559.0(2)	$3/2^+$	3019.1(4)	−0.15(3)/0.05(5)	6 fs 2
				5777.5(2)		
6572(3)		6576.5(3)	$9/2^+$	2102.4(15)		10 fs 2
				3666.1(1)	0.31(2)/−0.04(3)	
6587(6)		6586.4(9)	$5/2^+$	2112.4(12)		<3 fs
				5628.6(8)		
6626(3)	$1/2^+$; T=3/2	*unobserved*	$1/2^+$; T=3/2			
6715(3)		6720.7(9)	$1/2^-$	5939.2(9)	0.01(5)/−0.07(7)	6 fs 2
6743(3)		6734.0(2)	$11/2^+$	1450.2(6)		<1 fs
				3823.6(1)	−0.32(2)/−0.04(3)	
				4570.1(4)	0.37(4)/−0.26(5)	
New level		6767.2(4)	$7/2^+$	4603.2(4)	0.38(5)/−0.01(5)	<1 fs
6780(4)		6776.3(8)	$1/2^+$	5818.5(8)	0.03(5)/−0.03(6)	< 1 fs
7005(8)		7000.7(22)	$9/2^+$	2526.0(40)		6 fs 2
				2554.0(30)		
				4090.7(2)	0.21(3)/0.00(4)	
7059(5)		*unobserved*	$1/2^+$			
7080(3)		7070.2(4)	$9/2^-$	1752.1(10)		<1 fs
				4160.1(9)	0.36(5)/−0.09(6)	
				4906.0(3)	−0.30(2)/0.04(2)	
7134(5)		7129.0(2)	$13/2^+$	2681.3(1)	−0.81(1)/0.00(2)	10 fs 2
				4219.2(4)	0.39(6)/−0.06(8)	
7223(4)		7222.4(2)	$13/2^+$	1939.0(1)	−0.15(7)/0.17(9)	6 fs 2
				4311.9(2)	0.12(3)/0.06(3)	
7239(4)		7245.4(5)	$11/2^+$	668.8(1)		17 fs 3
				1962.2(1)		
				2771.0(3)	0.35(6)/−0.14(7)	
				2797.3(14)		
				4335.3(7)		
7260(4)		7252.5(2)	$7/2^+$	5088.4(2)	0.31(3)/−0.16(4)	9 fs 2
7276(3)		*unobserved*				
7324(4)		7325.4(18)	$3/2^+$	6367.1(15)		<2 fs
				6543.8(18)	−0.28(10)/−0.08(11)	
7341(4)		7346.6(9)	$7/2^-$	4436.1(9)		
7383(4)		7380.4(15)	$5/2^+$	6422.5(15)		4 fs 3
7428(4)		*unobserved*	$7/2^+$			
7436(3)		7433.3(6)	$9/2^+$	1647.7(15)		3 fs 2
				2985.6(5)		
				4522.8(10)		
				4785.8(2)	0.39(3)/−0.24(4)	
				5269.1(2)	0.59(4)/0.08(5)	
7468(3)		7468.8(8)	$(1/2, 5/2)^+$	6511.1(6)	−0.64(25)/0.39(24)	
				[6685.0(30)]	[0.05(41)/−0.14(46)]	
New level		[7493.1(40)]	$(3/2^+)$	[1993.0(40)]		
7532(3)		7531.3(7)	$5/2^+$	4883.5(5)		<4 fs
				6573.5(9)	−0.85(9)/0.20(13)	

TABLE I. (Continued)

E_x (keV) [3]	$J^\pi; T$ [3]	E_x (keV)	$J^\pi; T$	E_γ (keV)	a_2/a_4	$t_{1/2}$
7557(3)		*unobserved*	$3/2^+; T = 3/2$			
7592(3)		7590.1(9)	$9/2^+$	1804.5(23)		14 fs 2
				3115.6(14)		
				3142.6(27)		
				5425.9(1)	−0.52(2)/0.01(3)	
7652(3)		7651.9(6)	$11/2^+$	2104.3(1)	−0.21(5)/−0.07(7)	8 fs 2
				2334.0(40)		
				2371.0(40)		
				3204.1(1)	0.40(3)/−0.01(4)	
7690(3)?		7693.8(9)	$5/2^+$	5530.1(9)	0.50(7)/0.24(9)	<3 fs
7702(2)		7704.3(2)	$7/2^-$	5056.7(1)	−0.21(7)/0.09(9)	<1 fs
7740.8(9)	$(9/2, 11/2^+)$	7739.3(4)	$9/2^+$	2421.6(4)		15 fs 3
				2455.9(4)		
				3291.3(1)		
				4828.7(5)	0.25(12)/−0.25(17)	
				5575.7(2)	−0.10(4)/0.11(5)	
7792(3)		7794.8(19)	$7/2^+$	5631.0(19)	0.86(26)/−0.26(28)	
7831(3)	$(9/2, 11/2^+)$	7831.5(5)	$9/2^-$	2284.0(40)		6 fs 4
				2329.8(8)		
				2568.0(15)		
				3383.8(2)		
				4921.0(4)	0.18(7)/0.05(9)	
				5668.0(3)		
New level		7837.6(2)	$5/2^+$	6879.6(2)	−0.29(3)/0.03(1)	<1 fs
7893(4)		7899.0(8)	$5/2^+$	3424.9(8)		10 fs 7
				6941.1(8)	−0.14(9)/−0.02(12)	
7911(3)		7909.1(7)	$3/2^+$	7127.1(7)	−0.14(16)/0.46(19)	
7972(3)		7966.3(8)	$5/2^+$	7008.2(8)	−0.08(10)/−0.03(13)	8 fs 6
8036(3)		8031.5(11)	$5/2^+$	5384.2(9)		
				7071.6(19)	−0.18(17)/0.12(21)	
8074(3)		8069.6(30)	$3/2^-$	7111.5(30)	0.51(49)/0.28(54)	
8140(4)		8139.0(6)	1/2	7180.9(6)	−0.05(7)/0.20(9)	<1 fs
8157(2)		*unobserved*	(7/2–11/2)			
8165(2)	$(7/2–13/2)^+$	8168.2(20)	$11/2^+$	3719.4(12)	0.21(7)/0.04(9)	
				5261.0(40)		
8176(2)	$(1/2, 3/2)^+$	*unobserved*	$(1/2, 3/2)^+$			
8184(4)		8183.5(4)	$3/2^-$	7401.7(4)	−0.04(9)/0.00(12)	3 fs 2
New level		8199.8(7)	5/2	7241.7(7)	−0.27(9)/−0.09(11)	9 fs 5
8207(3)		8209.0(22)	(7/2)	5298.3(22)		
8226(3)	$7/2^+$	*unobserved*	$7/2^+$			
8289(3)	$(7/2–13/2)^+$	*unobserved*	$(7/2–13/2)^+$			
8328(2)	$(1/2, 3/2)^+$	*unobserved*	$(1/2, 3/2)^+$			
New level		8344.5(10)	(7/2)	5434.0(19)		
				6180.6(7)	0.33(9)/−0.11(13)	
8358(2)	$(3/2–9/2)^+$	*unobserved*	$(3/2–9/2)^+$			
New level		8375.5(9)	$5/2^+$	7417.3(9)	0.52(16)/0.22(17)	<4 fs

[a]Taken from Ref. [3].

coefficients consistent with a $\Delta I = \pm 1$ transition, indicating a 9/2 or 13/2 assignment for the 5547-keV state. This level was also observed to exhibit a 2637.1(1)-keV γ-decay branch to the $9/2^+_1$ excited state in ^{27}Si. An angular distribution analysis of the 2637-keV γ ray revealed a $\Delta I = 0$ character, indicating a 9/2 assignment for the presently observed 5547-keV excited level in ^{27}Si. In comparison with the mirror nucleus, ^{27}Al, the $9/2^+$, 5668-keV level is the only 9/2 state in the energy range 4.5–6.0 MeV known to exhibit γ decays to the $11/2^+_1$ and $9/2^+_1$ excited states, respectively [3]. Furthermore, the presently measured half-life for the 5547-keV state in ^{27}Si of 14(3) fs is broadly consistent with the known 11(3) fs half-life of the 5668-keV level in ^{27}Al. Consequently, 1100- and 2637-keV γ decays to the $11/2^+_1$ and $9/2^+_1$ excited levels in ^{27}Si were assigned as originating from a $9/2^+$, 5547-keV state.

A similar procedure to that discussed above was performed for all states in ^{27}Si when making mirror assignments. A

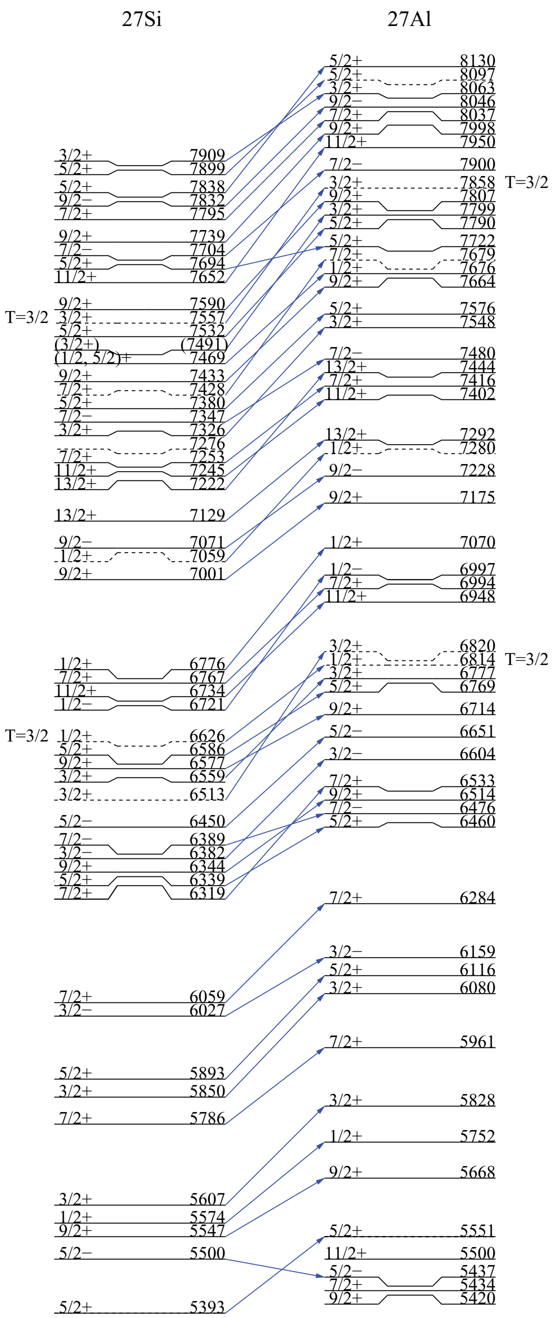

FIG. 8. (Color online) Mirror assignments of excited states in ^{27}Si in the energy range 5.392–7.909 MeV. Dashed lines indicate excited states not observed in the present work.

full overview of the mirror assignments made in this study for excited states in ^{27}Si in the energy range $E_x = 5.392$–7.909 MeV is proposed in Fig. 8.

The identification of excited states located above the proton-emission threshold in ^{27}Si of 7463.0(2) keV [2], which are expected to be of importance for the astrophysical $^{26}\mathrm{Al}^g(p,\gamma)^{27}\mathrm{Si}$ and $^{26}\mathrm{Al}^m(p,\gamma)^{27}\mathrm{Si}$ reactions, has already been discussed in Refs. [4,5]. However, from the new assignments of bound states in ^{27}Si made in this work, it has been possible to identify additional γ-ray transitions from previously identified astrophysically important proton-unbound excited states. Consequently, in the following sections, the identification of newly observed γ-decay branches from astrophysically important resonant states is discussed in the order of increasing excitation energy, together with the mirror assignments of proton-unbound levels that have not been discussed in earlier work [4].

A. $E_x = 7469$ and 7531 keV

In Ref. [4], 6511.1(6)- and 6573.5(9)-keV, $\Delta I = \pm 1$ γ-ray transitions to the $3/2_1^+$ level from excited states at 7469.0(6) and 7531.3(7) keV in ^{27}Si were reported. In the present work, a further γ-decay transition to the $1/2_1^+$ level from the 7469-keV state was tentatively observed. In comparison with the mirror nucleus, ^{27}Al, in the energy range 7.1–7.9 MeV, the $(1/2, 5/2)^+$ 7676-keV state is the only 1/2 or 5/2 level known to exhibit γ-decay branches to the $1/2^+$ and $3/2_1^+$ excited states. Consequently, a $(1/2, 5/2)^+$ assignment is adopted here for the 7469-keV state in ^{27}Si. In contrast, the 6574-keV γ ray from the 7531-keV level in ^{27}Si was measured to have nonzero angular distribution coefficients consistent with a mixed $M1 + E2$ character, giving a $5/2^+$ assignment. In the energy region 7.1–7.9 MeV in the mirror nucleus ^{27}Al, both the $5/2^+$, 7576-keV and newly observed $5/2^+$, 7790-keV states are potential mirror analogs. However, from the presently observed trends of mirror energy differences and the extremely large ~400-keV shift that would otherwise be implied for the $5/2^+$ 7380-keV state in ^{27}Si, the $5/2^+$ 7531-keV level has been paired with the newly observed 7790-keV state in ^{27}Al.

B. $E_x = 7590$ keV

From the new level structure information obtained in this study on bound states in ^{27}Si, it was possible to identify new γ-decay transitions from previously reported astrophysically important resonant states [4]. In particular, the key $9/2^+$, 7590-keV level was observed to exhibit a 1804.5(23)-keV γ-decay branch to the newly identified $7/2_4^+$ state, as demonstrated in Fig. 9.

The 7590-keV state was previously paired to the $9/2^+$, 7807-keV level in ^{27}Al [4]. In the present work, the 7807-keV level in ^{27}Al was also observed to exhibit a γ-decay branch

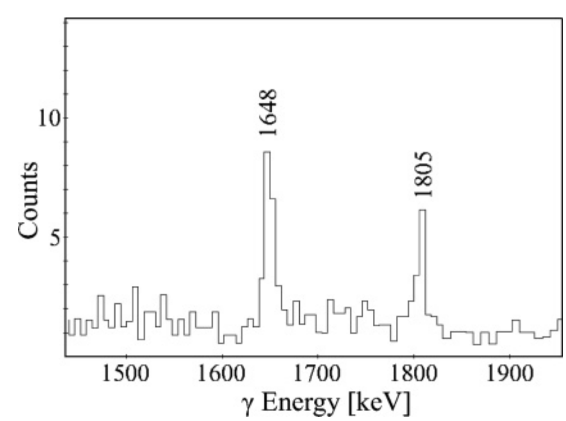

FIG. 9. The γ-γ-γ coincidence spectrum gated on the 2164- and 3622-keV transitions in ^{27}Si.

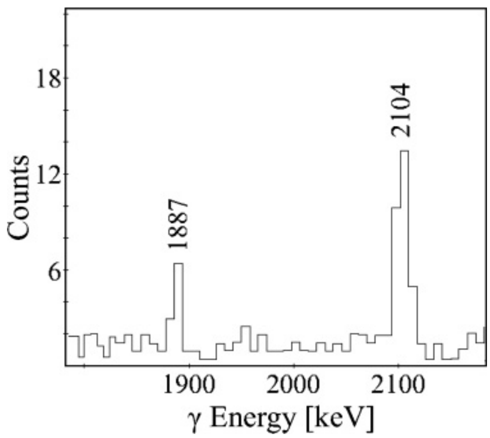

FIG. 10. The γ-γ-γ coincidence spectrum gated on the 2910- and 2637-keV transitions in ^{27}Si.

to the $7/2_4^+$ state. Consequently, the newly observed transition from the 7590-keV state in ^{27}Si has further solidified the mirror assignment proposed in Ref. [4].

C. $E_x = 7652$ keV

The $11/2^+$, 7652-keV state in ^{27}Si has been previously reported to exhibit γ-decay branches to the $11/2_2^+$ and $11/2_1^+$ excited levels with a $t_{1/2}$ of 8(2) fs. Here additional 2104.3(1)- and 2334.0(40)-keV branches from this state to the $9/2_3^+$ and $9/2_2^+$ excited levels are reported (see Fig. 10).

The 2104-keV γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition, affirming the 11/2 spin assignment made in Ref. [4]. Furthermore, in comparison with the mirror nucleus, ^{27}Al, in the energy range 7.5–8.3 MeV, the $11/2^+$, 7950-keV state, measured to have a $t_{1/2}$ of 8(3) fs in this work, is the only 11/2 one known to exhibit γ-decay branches to the $9/2_3^+$, $11/2_2^+$, $9/2_2^+$, and $11/2_1^+$ levels. Consequently, the conclusions made on the parity of the 7652-keV state in Ref. [4] are reinforced here. It should be noted that although the 7652- and 7950-keV mirror states were observed to exhibit four similar γ-decay branches, the 7950-keV excited level in ^{27}Al was observed to exhibit a γ-ray transition to the $9/2_1^+$ state, a decay branch that was not observed from the 7652-keV state in ^{27}Si. However, as stated previously, some differences in the γ-decay modes of analog states in this mirror system have been observed in the present data. As such, the 7652-keV state in ^{27}Si is still assigned as the mirror analog of the 7950-keV level in ^{27}Al.

D. $E_x = 7694$ and 7704 keV

In Ref. [4], 5530.1(9)- and 5056.7(1)-keV γ-decay transitions to the $7/2_1^+$ and $5/2_2^+$ levels in ^{27}Si from excited states at 7693.8(9) and 7704.3(2) keV, respectively, were reported. Both the 7694- and 7704-keV excited states have been previously reported as resonant levels in the ^{26}Al $+ p$ system with relative strengths of $\leqslant$0.010 and 0.010(5) meV [16], indicating l_p transfers $\leqslant$2 from these states. An angular distribution analysis of the 5530-keV γ ray revealed a mixed $M1 + E2$ character, indicating a $5/2^+$ or $9/2^+$ assignment for the 7694-keV state. In the present work, all even-parity excited states in ^{27}Si are observed to exhibit positive energy shifts with respect to mirror analog states in ^{27}Al. An examination of the mirror nucleus, ^{27}Al, in the energy region 7.7–8.1 MeV reveals that the $5/2^+$, 7722-keV excited state is the only unassigned 5/2 or 9/2 level to exhibit a γ-decay branch to the $7/2_1^+$ state [3]. Furthermore, in this study, the γ-ray transition to the $7/2_1^+$ state from the 7722-keV level in ^{27}Al was the only decay observed from this state. Consequently, the 7694-keV state in ^{27}Si was paired with the 7722-keV level in ^{27}Al and assigned as $5/2^+$. In contrast, the 5057-keV γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = \pm 1$ transition, indicating a 3/2 or 7/2 spin assignment for the 7704-keV state in ^{27}Si. In comparison with the mirror nucleus, the $7/2^-$, 7900-keV excited state is the only 3/2 or 7/2 level known to exhibit a γ-decay branch to the $5/2_2^+$ state in the energy range 7.4–8.1 MeV [3]. As such, the observed 7704-keV excited state in ^{27}Si was paired with the 7900-keV level in ^{27}Al and assigned as $7/2^-$.

E. $E_x = 7739$ keV

The proton-unbound excited state at 7739.3(4) keV in ^{27}Si was recently identified to exhibit γ-decay branches to the $9/2_2^+$, $11/2_2^+$, $11/2_1^+$, $9/2_1^+$, and $7/2_1^+$ levels [4]. From new information on excited states in ^{27}Al presented in this paper, the $9/2^+$, 7998-keV state is the only 9/2 state in the $E_x = 7.5$–8.1 MeV range to exhibit γ-decay branches to the $9/2_2^+$, $11/2_2^+$, $9/2_1^+$, and $7/2_1^+$ excited levels. Consequently, the $9/2^+$, 7739-keV state in ^{27}Si is assigned as the mirror partner of the $9/2^+$, 7998-keV state in ^{27}Al.

F. $E_x = 7795$ keV

In Ref. [4], a 5631.0(19)-keV γ decay to the $7/2_1^+$ level from an excited state at 7794.8(19) keV in ^{27}Si was reported. This γ ray was measured to have angular distribution coefficients consistent with a $\Delta I = 0$ transition, indicating a 7/2 assignment for the 7795-keV level. An examination of the mirror nucleus reveals that the $7/2^+$, 8037-keV excited state in ^{27}Al is the only 7/2 state in the $E_x = 7.5$–8.3 MeV range to exhibit a γ-decay branch to the $7/2_1^+$ state. As such, the $7/2^+$, 7795-keV excited state in ^{27}Si is assigned as the mirror analog of the 8037-keV state in ^{27}Al.

G. $E_x = 7832$ keV

The astrophysically important 7831.5(5)-keV resonant state in ^{27}Si has been assigned as a $9/2^-$ state and was reported to γ decay to the $5/2_1^-$ level (see Fig. 11), $11/2_1^+$, $9/2_1^+$, and $7/2_1^+$ states [4].

In the present work, additional 2284.0(40)- and 2568.0(15)-keV γ-ray transitions to the $9/2_3^+$ and $7/2_3^+$ excited states were observed from the 7832-keV level. In comparison with the mirror nucleus, ^{27}Al, the $9/2^-$, 8046- and 8287-keV excited states are the only $9/2^-$ states known to exhibit γ-decay branches to the $9/2_3^+$, $5/2_1^-$, $7/2_3^+$, and $9/2_1^+$ levels [3]. It should be noted that the 8287-keV state in ^{27}Al is the only $9/2^-$ state also known to exhibit a γ-decay branch to the $7/2_1^+$ excited level [3], similar to the presently reported 7832-keV state in ^{27}Si (the 8046-keV state in ^{27}Al does not exhibit such a decay mode). However, pairing the $9/2^-$, 7832-keV state in

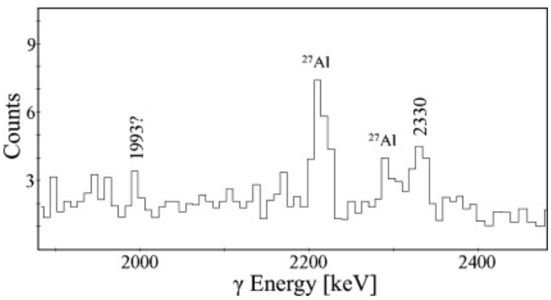

FIG. 11. The γ-γ-γ coincidence spectrum gated on the 957- and 2853-keV transitions in ^{27}Si. The question mark indicates a tentatively observed peak.

^{27}Si to the 8287-keV state in ^{27}Al would imply an extremely large mirror energy shift (~500 keV). Consequently, the $9/2^-$, 7832-keV level in ^{27}Si is assigned as the mirror analog of the 8046-keV state in ^{27}Al.

H. $E_x = 7838$ keV

In Ref. [5], the 7838-keV excited state in ^{27}Si was reported to exhibit a 6879.6(2)-keV γ-decay branch to the $3/2^+_1$ level and was matched to the 8130-keV level in ^{27}Al. However, a recent reanalysis of the angular distribution of the 6880-keV γ ray indicated a 5/2 assignment for the 7838-keV state in ^{27}Si [17], implying the mirror assignment made in Ref. [5] was incorrect. At the time of Ref. [5], the 8130-keV level in ^{27}Al was incorrectly assigned as $1/2^+$ [3], as discussed earlier in Sec. III C, which in turn led to an incorrect assignment of the 7838-keV state in ^{27}Si. From the present analysis of excited states in ^{27}Al, the 8130-keV level in ^{27}Al has been reassigned as a $5/2^+$ state. As such, the presently observed $5/2^+$, 7838-keV excited state in ^{27}Si is still assigned as the mirror analog of the 8130-keV state in ^{27}Al.

I. Tentatively observed state $E_x = 7493$ keV

Considering Fig. 11 further, a γ-decay transition is tentatively observed at 1993.0(40) keV, indicating a newly observed proton-unbound excited state at 7493.1(40) keV in ^{27}Si. In comparison with the mirror nucleus, ^{27}Al, the $3/2^+$, 7798-keV level remains unassigned to a mirror analog in ^{27}Si. This state is the only one known to exhibit a single γ-decay branch to the $5/2^-_1$ level [3]. Consequently, a $3/2^+$, 7493-keV excited state was tentatively assigned in ^{27}Si. It should be noted that, should this state exist, its resonance energy of 30.1(40) keV and low spin would make its contribution to the ^{26}Al$(p,\gamma)^{27}$Si reaction rate negligible.

Considering the levels listed above, it is the level at 7652 keV that is expected to be the dominant source of destruction of the cosmic γ-ray emitter ^{26}Al^g in novae via the ^{26}Al$^g(p,\gamma)$ reaction. The strength of the resonance has been measured by Vogelaar *et al.* [16] and more recently by Ruiz *et al.* [18] with reasonably good agreement. Combining this information with the present assignment of an $11/2^+$ level gives a proton spectroscopic factor $C^2S \sim 0.1$ for $l_p = 0$ capture. This is consistent with the observation of Vogelaar *et al.*, in a ^{26}Al^g(^{3}He,d) study [19], that the 7652-keV level is of a strong single-particle character. The measurement of new γ-decay branches from this level further reinforces our earlier conclusions on its assignment [4] and, along with new information on the intermediate level energies in the γ-ray cascades reported here, provides a new more precise excitation energy of 7651.9(6) keV, corresponding to a resonance energy of 188.9(6) keV, consistent with our earlier value reported in Ref. [4]. Recent observations by the RHESSI and INTEGRAL satellites indicate that Wolf-Rayet stars, which achieve peak temperatures ~0.05 GK, are likely to make the most dominant contribution to the observed galactic abundance of ^{26}Al [20]. In such environments, the $5/2^+$, 7531.3(7)-keV and $9/2^+$, 7590.1(9)-keV excited states in ^{27}Si, corresponding to $l_p = 2$ and $l_p = 0$ resonances in the ^{26}Al$^g + p$ system at 68.3(7) and 127.1(9) keV, respectively, are expected to dominate the ^{26}Al$^g(p,\gamma)^{27}$Si reaction rate. The proton spectroscopic factor C^2S is entirely unknown for the 68-keV resonance, and to date, only an upper limit of 0.02 has been set for the 127-keV state [19], leading to large uncertainties in the strength of the two resonances. Thus, further constraints on the astrophysical ^{26}Al$^g(p,\gamma)^{27}$Si reaction rate require a determination of the proton spectroscopic factors of the 68- and 127-keV resonances [4].

The ^{26}Al$^m(p,\gamma)^{27}$Si reaction is expected to occur in high-temperature astrophysical environments such as oxygen-neon (ONe) novae and supernovae, which are thought to be the astrophysical sites responsible for the production of excess ^{26}Mg observed in presolar grains [21]. In such environments the 0^+ isomeric state at 228.31(3) keV can be thermally excited or fed via the superallowed β decay of ^{26}Si following the ^{25}Al(p,γ) reaction [for completeness, proton radiative capture on the stable isotope ^{25}Mg can also lead to its population]. Here it is relatively higher-energy, low-spin resonances in ^{27}Si that are most influential in determining the reaction rate. Spectroscopic information for such states has recently been reported by Lotay *et al.* [5] and Deibel *et al.* [22]. In particular, excited states in ^{27}Si at 8069.6(30) and 8139.0(6) keV [5,22] have been identified as $l_p = 1$ and $l_p = 0$ resonances at 378.3(30) and 477.7(6) keV in the ^{26}Al$^m + p$ system, respectively, and are expected to dominate the rate over the temperature range $T = 0.2$–1.5 GK. The strength of the 378- and 478-keV resonant levels represents the key remaining uncertainty in estimating the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate in ONe novae and supernovae [5]. A direct measurement of the strength of these resonances using a radioactive isomeric ^{26}Al beam has been approved for the DRAGON separator at TRIUMF [23].

V. MIRROR ENERGY DIFFERENCES

The observed mirror energy differences (MEDs) as a function of excitation energy between all excited states in the $T = 1/2$ pair ^{27}Si and ^{27}Al are presented in Fig. 12(a). As can be seen, there is a general trend of increasing MEDs with increasing excitation energy. In particular, the mean MED in the excitation energy region of interest for explosive hydrogen

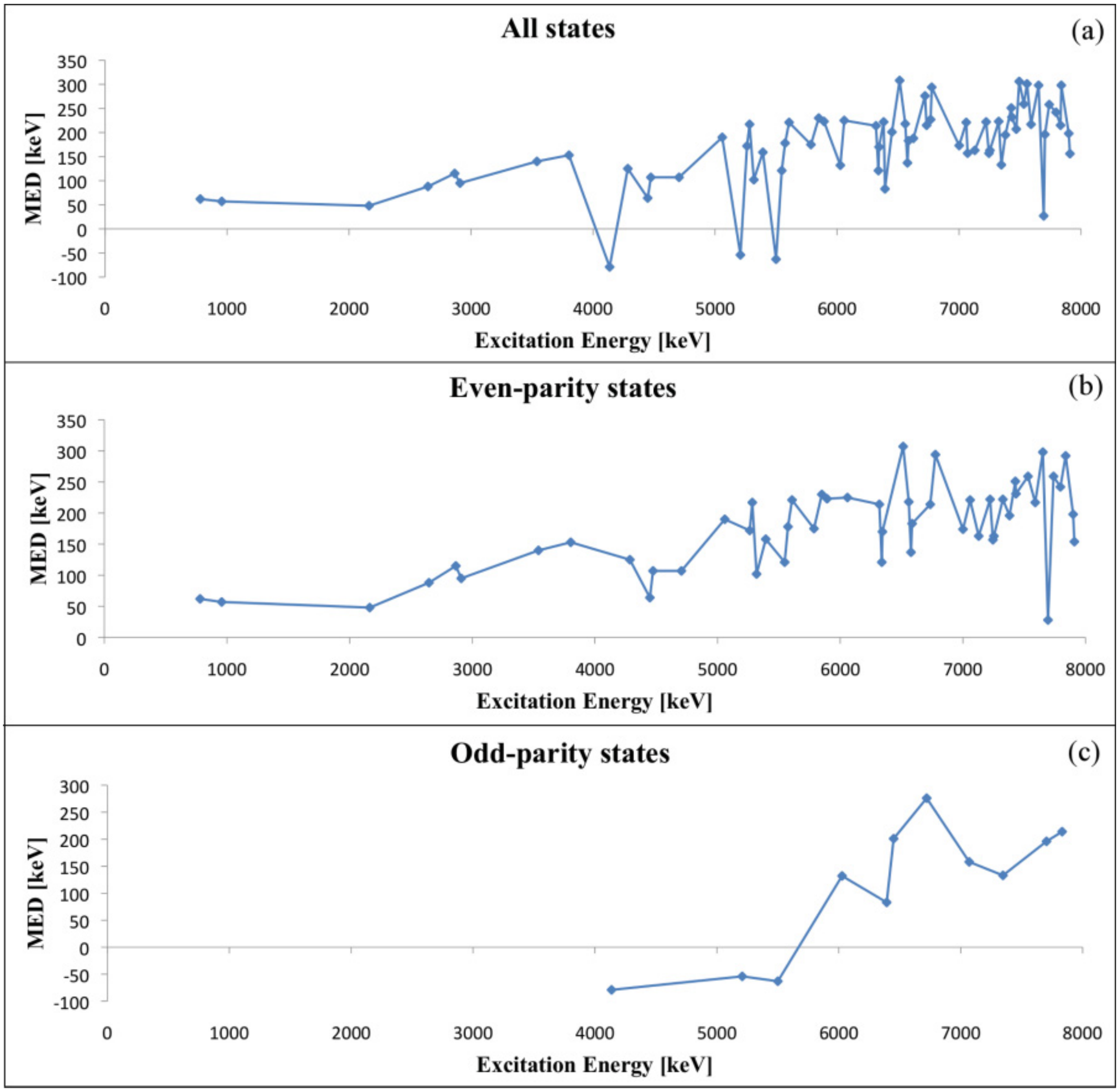

FIG. 12. (Color online) Mirror energy differences between all states in the $T = 1/2$ pair ^{27}Si and ^{27}Al in the energy region 0–7.909 MeV.

burning was observed to be ∼230 keV, in good agreement with the predictions of Champagne *et al.* [1]. However, it can also be seen in Fig. 12(a) that there are several distinct breaks from this trend in which either very small or even negative energy shifts are observed between mirror analog states. Figures 12(b) and 12(c) display MEDs for even-parity and odd-parity states in ^{27}Si and ^{27}Al. It is clear from Fig. 12(c) that all stark breaks from the general trend of increasing MEDs with excitation energy, with the exception of one isobaric analog pair, are caused by odd-parity excited states. The shifts between odd-parity mirror pairs do not seem to follow any particular pattern. These pairs can exhibit both negative-energy and positive-energy shifts as large as ∼270 keV. However, it should be noted that despite the marked breaks from the trend caused by several states, the general rise keeps fairly steady, even in the proton-unbound excitation energy region. This is not too unexpected given that the proton-unbound excited states in ^{27}Si paired to mirror levels in ^{27}Al in this study are located relatively close to the proton threshold and are mainly high-spin states.

Considering shifts between even-parity excited states in more detail, Fig. 13 displays the observed MEDs between even-parity levels in ^{27}Si and ^{27}Al as a function of spin J. There does not appear to be any specific dependence on the spin of the mirror pair with regard to the observed MEDs but simply a reiteration of the general trend of increasing MEDs as a function of excitation energy. However, one may expect outlying exceptions to the general trend to appear if one or both of the analog states is particle unbound, and as stated previously, one such case is observed in this study between the $5/2^+$ mirror pair at 7694 and 7722 keV in ^{27}Si and ^{27}Al, respectively, where a shift of only ∼30 keV is reported. The 7694-keV excited state in ^{27}Si was observed to exhibit a single mixed $M1 + E2$ transition to the $7/2^+_1$ level, indicating a $5/2^+$ or $9/2^+$ assignment. In comparison with the mirror nucleus ^{27}Al in the energy region 7.5–8.2 MeV, the $5/2^+$, 7722-keV

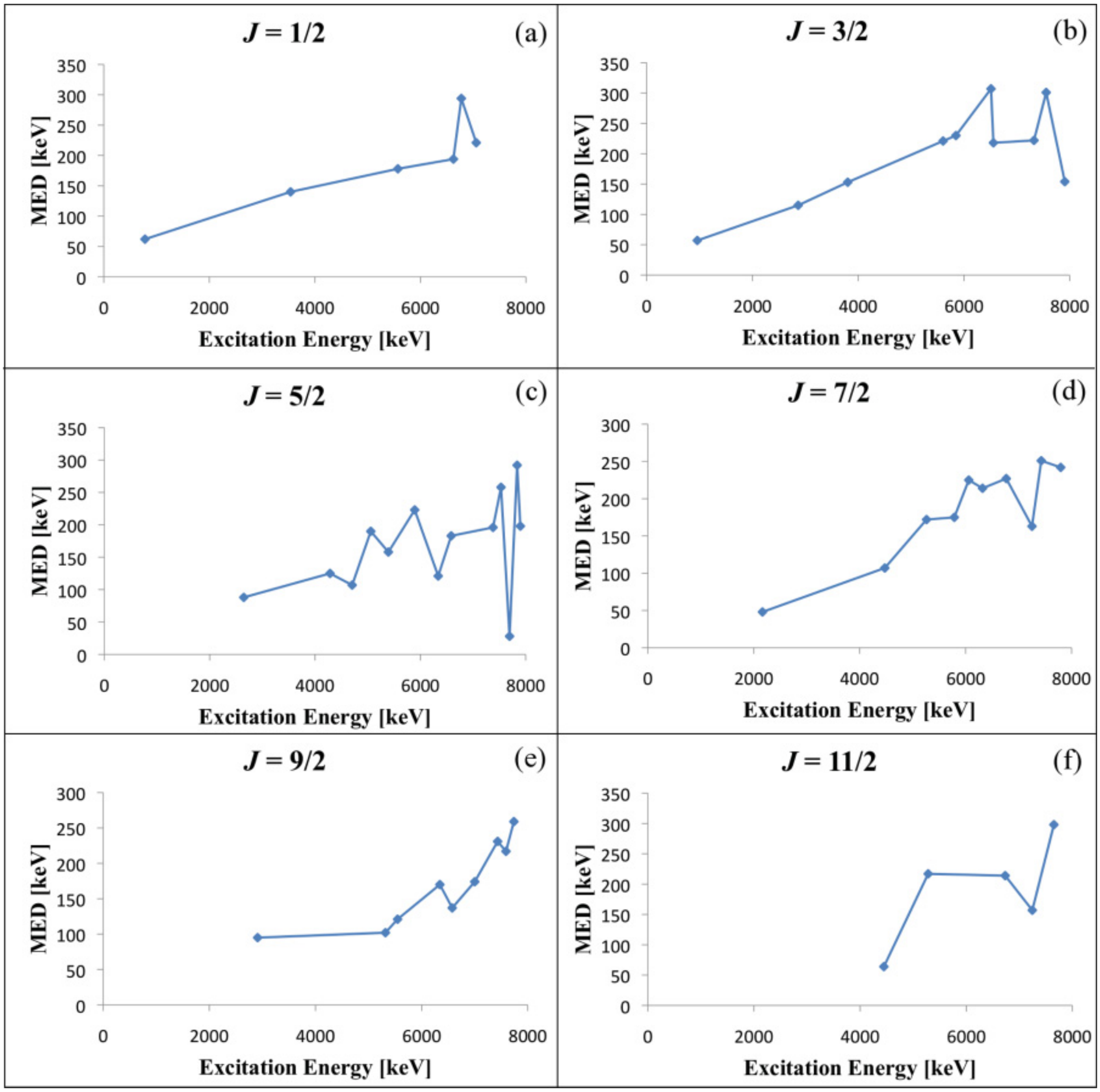

FIG. 13. (Color online) Mirror energy differences between positive-parity states in the $T = 1/2$ pair ^{27}Si and ^{27}Al in the energy region 0–7.909 MeV.

level is the only 5/2 or 9/2 state known to exhibit a single γ-decay branch to the $7/2^+_1$ level [3].

It is clear that while the global energy shift prediction of Champagne *et al.* [1] is in good agreement with the mean MED value obtained in this study, there are large variations from the mean for individual states. Consequently, the present study indicates that although the use of a global energy shift to assign mirror pairs is a good general guide in the absence of experimental data, spectroscopic information is essential for the direct assignment of isobaric analog states, especially when the parity of the level is unknown. This is of particular significance for the assignment of astrophysically important $l_p = 1$ resonant states, which can have strong proton spectroscopic factors and dominate astrophysical reaction rates over large temperature ranges.

On the other hand, the present study has highlighted the power of the shell model in predicting the location of excited states in sd-shell nuclei. Indeed, all states predicted by shell-model calculations up to very high excitation energies have now been identified in ^{27}Al and matched to excited levels in ^{27}Si.

VI. CONCLUSIONS

Mirror assignments have been proposed for all excited states in ^{27}Si from the ground state to 7.909 MeV, incorporating the identification of 55 previously unassigned levels with all assignments being consistent with shell-model predictions. Five excited states in ^{27}Si were newly observed in this work at 5850.3(11), 6339.2(9), 6392.5(4), 6559.0(2) and 6767.2(4) keV with $3/2^+$, $5/2^+$, $7/2^-$, $3/2^+$, and $7/2^+$ spin-parity assignments, respectively, and a previously unobserved proton-unbound excited state in ^{27}Si has been tentatively reported at 7493.1(40) keV.

A general trend of increasing MEDs with increasing excitation energy has been observed between even-parity analog states in the $T = 1/2$ mirror pair ^{27}Si and ^{27}Al. The mean MED value obtained in this study for excited states in ^{27}Si in the energy range of interest for the $^{26}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ reaction is ∼230 keV. While this average value is in good agreement with the ∼200-keV global energy shift predicted by Champagne *et al.* [1], stark variations from the mean are observed on an individual state-by-state basis. This is particularly evident in the case of odd-parity states, which have been observed to exhibit both negative and large positive energy shifts with no noticeable trend. Consequently, in order to make direct analog assignments and investigate Coulomb energy differences for excited states in mirror pairs of nuclei, experimentally obtained spectroscopic information is important.

Furthermore, future direct measurements of the astrophysical $^{26}\mathrm{Al}(p,\gamma)^{g\,27}\mathrm{Si}$ and $^{26}\mathrm{Al}^m(p,\gamma)^{27}\mathrm{Si}$ reactions depend on the experimental spectroscopic data acquired for analog states in the $T = 1/2$, $A = 27$ mirror system. In particular, such information identifies precisely the location of excited states expected to be strong resonances in the $^{26}\mathrm{Al}^g + p$ and $^{26}\mathrm{Al}^m + p$ systems, which is an important requirement in the direct measurement of such states using radioactive ion beams. Moreover, the pairing of excited states in ^{27}Al to $^{26}\mathrm{Al}^g + p$ and $^{26}\mathrm{Al}^m + p$ resonant states in ^{27}Si is important to extract proton spectroscopic factors from the $^{26}\mathrm{Al}(d,p)^{27}\mathrm{Al}$ transfer reaction for low-lying resonances in the astrophysical $^{26}\mathrm{Al}^g(p,\gamma)^{27}\mathrm{Si}$ and $^{26}\mathrm{Al}^m(p,\gamma)^{27}\mathrm{Si}$ reactions.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357. UK personnel were supported by the Science and Technologies Facilities Council.

[1] A. E. Champagne *et al.*, Nucl. Phys. A **556**, 123 (1993).
[2] G. Audi and A. H. Wapstra, Nucl. Phys. A **729**, 337 (2003).
[3] P. M. Endt, Nucl. Phys. A **521**, 1 (1990).
[4] G. Lotay, P. J. Woods, D. Seweryniak, M. P. Carpenter, R. V. F. Janssens, and S. Zhu, Phys. Rev. Lett. **102**, 162502 (2009).
[5] G. Lotay, P. J. Woods, D. Seweryniak, M. P. Carpenter, R. V. F. Janssens, and S. Zhu, Phys. Rev. C **80**, 055802 (2009).
[6] I. Y. Lee, Nucl. Phys. A **520**, 641c (1990); R. V. F. Janssens and F. S. Stephens, Nucl. Phys. News **6**, 9 (1996).
[7] C. N. Davids *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. B **70**, 358 (1992).
[8] G. Lotay *et al.*, Phys. Rev. C **77**, 042802(R) (2008).
[9] D. Seweryniak *et al.*, Phys. Rev. Lett. **94**, 032501 (2005).
[10] D. Seweryniak *et al.*, Phys. Rev. C **75**, 062801(R) (2007).
[11] D. Seweryniak *et al.*, Phys. Lett. B **590**, 170 (2004).
[12] B. Cederwall *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **354**, 591 (1995).
[13] J. Ekman *et al.*, Phys. Rev. Lett. **92**, 132502 (2004).
[14] M. Lickert *et al.*, Z. Phys. A **331**, 409 (1988).
[15] B. A. Brown [http://www.nscl.msu.edu/∼brown/resources/SDE.HTM].
[16] R. B. Vogelaar, Ph.D. thesis, Caltech, 1989.
[17] G. Lotay, P. J. Woods, D. Seweryniak, M. P. Carpenter, R. V. F. Janssens, and S. Zhu, Phys. Rev. C **81**, 029903(E) (2010).
[18] C. Ruiz *et al.*, Phys. Rev. Lett. **96**, 252501 (2006).
[19] R. B. Vogelaar *et al.*, Phys. Rev. C **53**, 1945 (1996).
[20] R. Diehl *et al.*, Nat. Lett. **439**, 45 (2006).
[21] D. D. Clayton and L. R. Nittler, Annu. Rev. Astron. Astrophys. **42**, 39 (2004).
[22] C. M. Deibel, J. A. Clark, R. Lewis, A. Parikh, P. D. Parker, and C. Wrede, Phys. Rev. C **80**, 035806 (2009).
[23] G. Lotay, C. Ruiz *et al.*, TRIUMF proposal S989 (unpublished).