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Level structure of ^{26}Si and its implications for the astrophysical reaction rate of ^{25}Al(p,γ)^{26}Si

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A study of the level structure of ^{26}Si using in-beam γ-ray spectroscopy is presented. A full level scheme is derived incorporating all states lying below the proton threshold energy. The results are in good agreement with shell model predictions and one-to-one correspondence is found with states in the mirror nucleus ^{26}Mg. Additionally, a γ-decay branch is observed from a state at 5677.0(17) keV, which is assigned to a 1^+ resonance important in the astrophysical reaction ^{25}Al(p,γ)^{26}Si. The newly derived resonance energy, E_r = 159.2(35) keV, has the effect of decreasing the reaction rate at the novae ignition temperature of ≈0.1 GK by a factor of ≈2 when compared with the previous most precise measurement of this state.

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Modern γ-ray spectroscopic techniques using large Ge detector arrays are providing a key alternative to studying the structure of astrophysically important proton-rich nuclei [1–4]. This approach gives very precise energies and relatively unambiguous assignments in comparison with traditional light ion transfer methods. Surprisingly, the fusion production method also proves to be relatively unselective for these nuclei. This allows complete level structure determinations below the particle threshold of interest for comparison with shell model calculations, and the observation of predominantly γ-decaying states of astrophysical interest just above this threshold [1,3]. The present paper describes such a study of the nucleus ^{26}Si. There are significant uncertainties in the nucleosynthesis of the important β-decaying cosmic γ-ray emitter, ^{26}Al [5], that are associated with the ^{25}Al(p,γ)^{26}Si reaction rate at novae temperatures [6]. This reaction is thought to be dominated by resonant capture on low lying 1^+ and 3^+ resonances above the proton threshold of 5517.8(31) keV in ^{26}Si [7–10]. The effect of this reaction is to remove flux from the ground-state of ^{26}Al, which is then bypassed by the ^{25}Al(p,γ)^{26}Si($\beta\nu$)^{26m}Al($\beta\nu$)^{26}Mg sequence. Presently, cosmic γ-ray emission from ^{26}Al is thought to be predominantly from massive stars [11], but novae may also contribute significantly to the flux.

The basic experimental technique has already been outlined in Ref. [3]. Here, an approximately 8 pnA beam of 58 MeV ^{16}O ions was used to bombard a stack of two 150 μg/cm^2 thick targets of ^{12}C for about 56 h with the object of producing ^{26}Si residues via the 2n fusion evaporation channel. Prompt γ rays were detected using the highly efficient Gammasphere array of Compton suppressed Ge detectors [12] in coincidence with $A = 26$, charge state 10^+ recoils detected at the focal plane of the Argonne Fragment Mass Analyzer (FMA) [13]. ^{26}Si, ^{26}Al and ^{26}Mg ions were cleanly resolved using $\Delta E - E$ information from an ionization chamber situated behind the FMA focal plane. An energy spectrum for recoil-coincident γ rays from ^{26}Si is shown in Fig. 1. The inset in Fig. 1 contains the high energy portion of the spectrum of γ rays observed in coincidence with the known 1797 keV, $2_1^+ \rightarrow 0_1^+$ transition in ^{26}Si [15]. A tabulation of the levels and γ-ray transitions observed for ^{26}Si in the present study is given in Table I. ^{152}Eu and ^{56}Co sources were used to calibrate the γ-ray detectors. Above 0.8 MeV, deviations from linearity were below 0.1 keV up to the maximum energy of 3.251 MeV in ^{56}Co. The intensities for strong transitions were fitted as a function of the detection angle with respect to the beam axis using the function: $W(\theta) = N(1 + a_2 \cdot P_2(\cos(\theta)) + a_4 \cdot P_4(\cos(\theta)))$. In the high-spin limit and assuming perfect alignment of an initial state, values of $(a_2, a_4) = (0.357, -0.107)$, $(-0.25, 0)$, $(0.5, 0)$ correspond to a pure $\Delta I = 2$ quadrupole, $\Delta I = \pm 1$ dipole, and $\Delta I = 0$ dipole transition, respectively. The proposed level structure and decay transitions of ^{26}Si are presented in Fig. 2. For orientation, the ^{26}Si levels are compared with the levels in the mirror nucleus ^{26}Mg, and shell-model calculations in Fig. 3. These results are discussed below.

The recent overview of the then known structure of ^{26}Si by Parpottas *et al.* [9] forms a very useful reference point for the present study, particularly Table I, which provides a comprehensive summary of level energies and assignments. The only γ-ray spectroscopic study of this nucleus was reported by Bell *et al.* in 1969 [14]. We note that the first four excited levels observed and assigned by Bell *et al.* are also detected here, the γ-ray angular distributions support previous spin assignments, but the level energies do not all agree within errors. These energies, and those of two other higher lying states measured by Bell *et al.*, were used by Parpottas *et al.* [9] to calibrate their (^{3}He,n) study of higher lying excited states. Hence, those data may need to be recalibrated at the ≈5 keV level. Bell *et al.* [14] reported also states at 3842 and 4093 keV that have not been observed in any subsequent studies of ^{26}Si [9], and they were not observed here either. We propose that they do not exist, because, as we shall

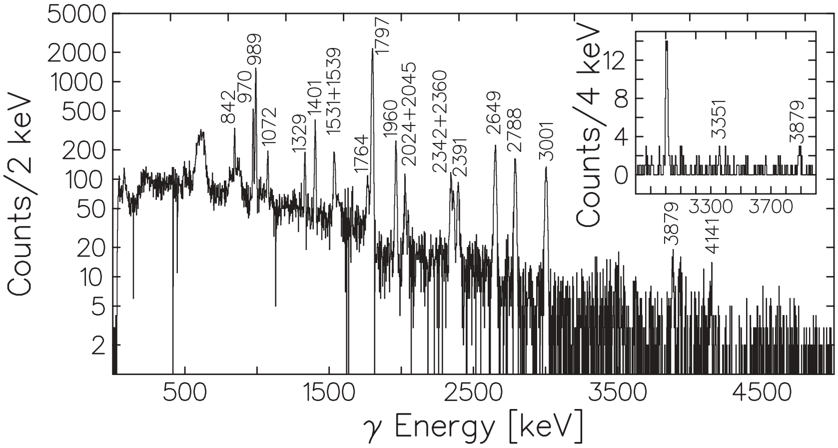

FIG. 1. Gamma-ray spectrum measured in coincidence with ^{26}Si residues. The inset contains the high-energy γ rays detected in coincidence with the 1797 keV, $2_1^+ \rightarrow 0_1^+$ transition.

demonstrate, we observe all expected states below the proton threshold based on the comparison with the mirror nucleus ^{26}Mg as well as shell-model calculations.

The state at 4139 keV has been widely reported before and uniformly assigned to a 2^+ level [9], and based on its decay pattern we agree with this assignment. The next state, at 4187 keV, has been variously assigned as either 3^+ or 4^+ [9]. The angular distributions for the γ-ray transitions from this level are consistent with a stretched, dipole character with quadrupole admixture, and, as the decay pattern of this state is similar to that of the 3^+ level at 4350 keV in the mirror nucleus ^{26}Mg, we assign 3^+ in agreement with the analysis of

TABLE I. The energies, intensities, angular distribution coefficients, and proposed assignments for the γ-ray transitions detected in coincidence with ^{26}Si nuclei produced in the ^{16}O+^{12}C reaction at 58 MeV. The deduced level energies included in the table were corrected for the recoil energy of ^{26}Si nuclei.

J^π	Level energy (keV)	γ energy (keV)	γ intensity	a_2/a_4	Assignment
2_1^+	1797.3(1)	1797.2(1)	100.0(15)	0.18(4)/−0.08(4)	$2_1^+ \rightarrow 0_1^+$
2_2^+	2786.4(2)	988.8(1)	26.4(7)	0.14(5)/0.01(7)	$2_2^+ \rightarrow 2_1^+$
		2787.5(3)	12.9(7)	0.36(12)/−0.22(14)	$2_2^+ \rightarrow 0_1^+$
0_2^+	3336.4(6)	1539.1(5)	2.6(5)		$0_1^+ \rightarrow 2_1^+$
3_1^+	3756.9(2)	970.4(1)	8.1(4)	−0.30(9)/0.07(11)	$3_1^+ \rightarrow 2_2^+$
		1960.4(2)	10.6(6)	−0.15(11)/0.01(15)	$3_1^+ \rightarrow 2_1^+$
2_3^+	4139.3(7)	1355(2)			$2_3^+ \rightarrow 2_2^+$
		2341.9(6)	6.8(6)		$2_3^+ \rightarrow 2_1^+$
		4141(3)	0.8(4)		$2_3^+ \rightarrow 0_1^+$
3_2^+	4187.1(3)	1400.7(2)	10.1(6)	0.41(13)/0.09(15)	$3_2^+ \rightarrow 2_2^+$
		2391.4(5)	5.8(6)	0.52(18)/0.20(20)	$3_2^+ \rightarrow 2_1^+$
4_1^+	4446.2(4)	1657(2)			$4_1^+ \rightarrow 2_2^+$
		2648.8(3)	17.3(8)	0.32(11)/−0.15(13)	$4_1^+ \rightarrow 2_1^+$
4_2^+	4798.5(5)	3001.0(4)	12.4(8)	0.12(11)/−0.37(14)	$4_2^+ \rightarrow 2_1^+$
(2_4^+)	4810.7(6)	2024.2(5)	4.3(5)		$2_4^+ \rightarrow 2_2^+$
(0_2^+)	4831.4(10)	2044.9(9)	1.2(4)		$0_2^+ \rightarrow 2_2^+$
2_5^+	5146.7(9)	2360.2(8)	3.6(5)	0.42(24)/0.17(26)	$2_5^+ \rightarrow 2_2^+$
		3351(2)			$2_5^+ \rightarrow 2_1^+$
4_3^+	5288.2(5)	842.1(3)	3.6(4)		$4_3^+ \rightarrow 4_1^+$
		1531.1(5)	4.8(5)		$4_3^+ \rightarrow 3_1^+$
		2503(2)			$4_3^+ \rightarrow 2_2^+$
4_4^+	5517.2(5)	1071.8(4)	2.9(4)		$4_4^+ \rightarrow 4_1^+$
		1329.4(3)	3.9(4)		$4_4^+ \rightarrow 3_2^+$
		1764.4(8)	4.0(7)		$4_4^+ \rightarrow 3_1^+$
		2733(3)			$4_4^+ \rightarrow 2_2^+$
1_1^+	5677.0(17)	3879.4(17)	1.4(4)		$1_1^+ \rightarrow 2_1^+$

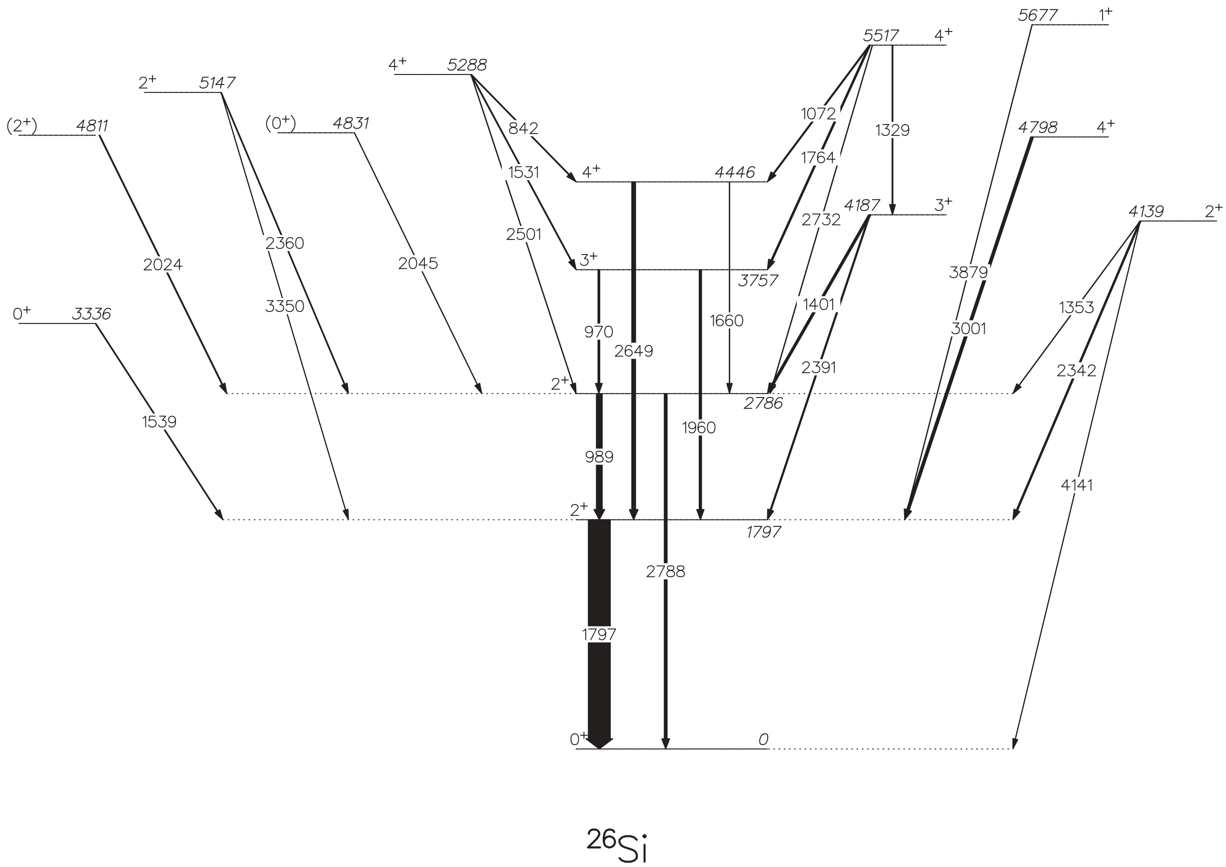

FIG. 2. The γ-decay scheme of ^{26}Si obtained in this work.

Ref. [9]. The 4446 keV level has been widely observed before, but with varying 2^+, 3^+, 4^+ assignments [9]. Here, the angular distribution of the 2649 keV transition is consistent with that of a stretched quadrupole, thus suggesting a 4^+ assignment. Moreover, the γ-ray transition strengths to the 2_1^+ and 2_2^+ levels are consistent with those observed for the 4^+ mirror state at 4318 keV [15]. Therefore, we assign the 4446 keV level to a 4^+ state, again in agreement with the analysis of Ref. [9]. It should be noted that the energy of the mirror 4^+ state is lower, in contrast to all other analog pairs observed in ^{26}Si and ^{26}Mg. In the shell model analysis of Illiadis *et al.* [7] the spins for the 4187 keV and 4446 keV states were interchanged, which led to a large positive energy shift for the 3^+ state.

Nearly degenerate 0^+, 2^+, 4^+ states are expected around ≈ 4.8 MeV in ^{26}Si [7]. However, these levels have not been resolved in previous studies [9]. The 3001 keV transition deexciting the state at 4798 keV is in strong coincidence with the $2_1^+ \rightarrow 0_1^+$ transition and has an angular distribution consistent with a stretched quadrupole character. In all respects it is analogous to the state 4_2^+ at 4901 keV in ^{26}Mg, also produced in this experiment. Therefore, we assign this level to the 4_2^+ state in ^{26}Si. Weaker transitions are observed at 2024 and 2045 keV feeding the 2_2^+ state at 2786 keV. These are analogous to the decays of the 0_2^+ and 2_4^+ levels in the ^{26}Mg mirror. In the present experiment, the 2^+ state in ^{26}Mg is significantly more strongly populated than the 0^+ level. Hence, we tentatively assign the relatively stronger 2024 keV transition in ^{26}Si to the decay of the 2_4^+ state at 4810 keV, and, correspondingly, the 2045 keV transition to the decay of the 0_2^+ level at 4831 keV.

All previous studies observing the 5147 keV state have reported a 2^+ assignment [9] and our results are consistent with this conclusion as well, since its decay pattern is similar to that of the mirror 2_5^+ state in ^{26}Mg. Similarly, a level is observed at 5288 keV and is assigned to a 4^+ state in agreement with all previous work [9]. We observe a state at 5517 keV very close to the proton threshold. Parpottas *et al.* [9] and Caggiano *et al.* [8] proposed a 4^+ assignment, whereas Illiadis *et al.* [7] suggested 1^+ based on a comparison with the shell model. As seen from the decay scheme, a transition is observed to a 4^+ level, which rules out the 1^+ assignment. The decay characteristics are also found to be analogous to those of the known 4_4^+ state in the ^{26}Mg mirror, also observed here. Consequently, the 5517 keV level is given a 4^+ assignment, which would correspond to the calculated shell-model 4^+ state at 6009 keV [7]. On the other hand, we associated the calculated 1^+ state at 5833 keV [7] with the 5677 keV level above the proton emission threshold (see below). This exhausts all the predicted shell model states near/below the threshold [7] and all the observed mirror states [15] (see Fig. 3).

In Fig. 1 one can see a γ-ray line at 3879 keV, which is in coincidence with the $2_1^+ \rightarrow 0_1^+$ transition (see inset). This corresponds to a level excitation energy of 5677.0(17) keV, consistent with the energy reported by Caggiano *et al.* of

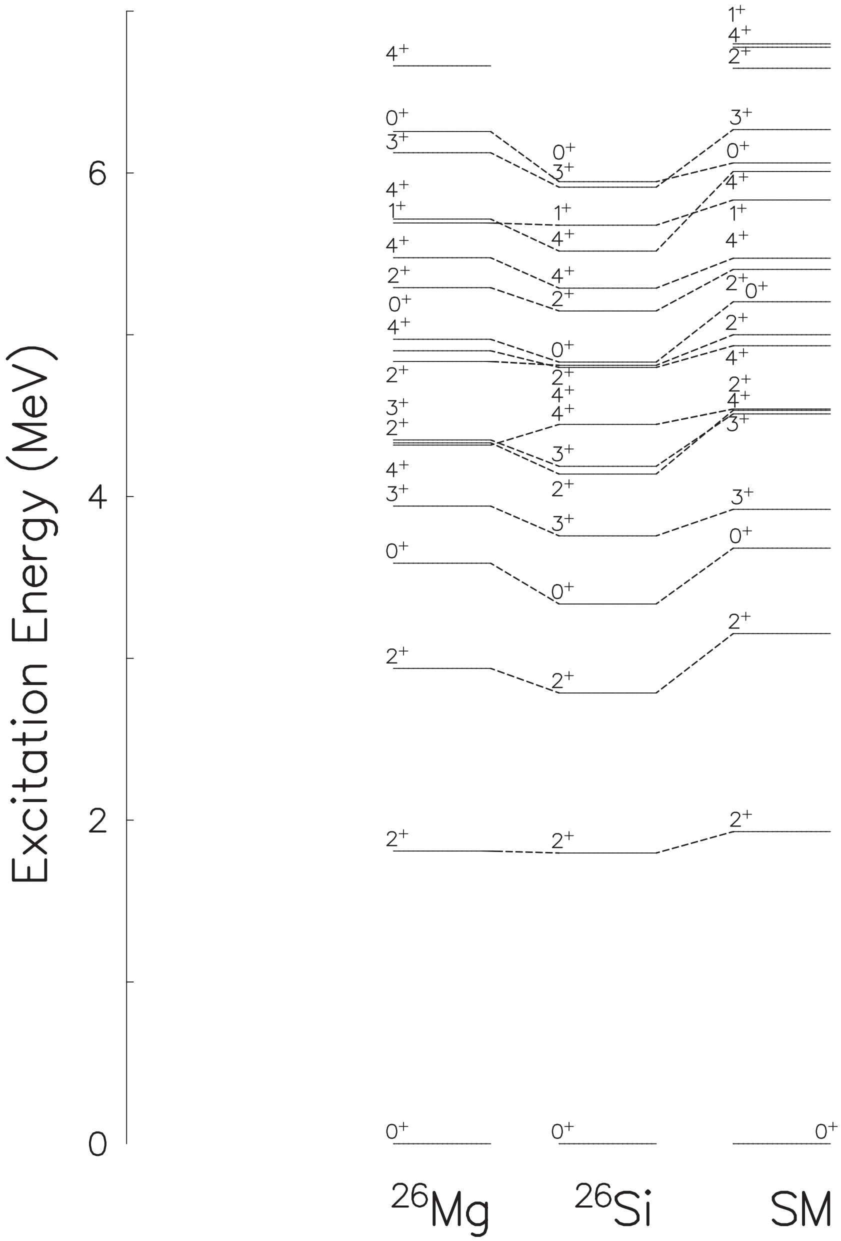

FIG. 3. Comparison between the ^{26}Si levels, the states in ^{26}Mg, and the results of shell-model calculations [7].

5678(8) keV [8], where possible 1^+ or 3^+ assignments were considered, and the former was proposed, based on the comparison with the calculated Coulomb displacement energies. More recently, the (^{3}He,n) differential cross section measurements by Parpottas *et al.* [9] led to a specific 1^+ assignment to this state, with corresponding energy of 5670(4) keV. Based on mirror symmetry, from the known level scheme and γ decays of ^{26}Mg [15], the dominant γ decay of the 1^+ level is expected to be to the 2_1^+, consistent with what is found here, supporting the previous assignments. Conversely, a 3^+ assignment is clearly ruled out as a dominant 1490 keV transition to the 4187 keV 3_2^+ level is expected [15], which is not observed here. The transition to the 2_1^+ state in this case is expected to be about 20 times weaker. The 3^+ level is in fact observed at 5912(4) keV by Parpottas *et al.* [9], and this assignment has been supported by a recent (p,t) transfer experiment, which is strongly indicative of a 3^+ state at 5914(2) keV [16]. Such a level would predominantly proton decay, and would thus not be observed in the present experiment. Parpottas *et al.* [9] report the only other state expected around this energy, a 0^+ level, to be at 5946(4) keV. Based on these results, Bardayan *et al.* [16] predicted a dominating proton decay branch, although the γ-decay to the 2_1^+ state is expected to be of comparable strength. No such γ-ray transition was observed. This is not surprising since the 0^+ analog state in the much more strongly produced ^{26}Mg mirror nucleus is only weakly populated in the present experiment. Combined with the competing proton decay branch, we would not expect to observe this transition with the present experimental detection sensitivity.

The present results suggest that the complete detailed structure of ^{26}Si below, and in the region of the proton threshold, can be well reproduced by comparisons with the shell model [7], although some states were reassigned in the present work when compared to Ref. [7]. In addition, a one to one correspondence is found with all known levels in the mirror nucleus ^{26}Mg [15]. This would reinforce the most recent assumptions about the location and nature of the key astrophysical resonances in ^{26}Si [9,16], and would further make unlikely the replacement of the important 3^+ level at 5914 keV with a 2^+ assignment, a possibility explored by Bardayan *et al.* when analyzing uncertainties in the ^{25}Al$(p,\gamma)^{26}$Si reaction rate [16]. Our results suggest that the precise calibration of excitation energies in the key study of Parpottas *et al.* [9], including that of the 3^+ at 5914 keV, may need be reconsidered. This study used γ-ray energies from a single work in 1969 [14] with which we report discrepant values at the $\approx$5 keV level. The 1^+ excitation energy measured here with improved precision gives a resonance energy in the center of mass of 159.2(35) keV, limited by the precision of the proton threshold energy of 5517.8(3) keV [17]. Compared to the most recent precise measurement, by Parpottas *et al.* [9], this would have the effect of increasing the ^{25}Al$(p,\gamma)^{26}$Si reaction rate at the novae ignition temperature of ≈ 0.1 GK by a factor of ≈ 2. This will result in a slight increase in the predicted yield of the cosmic γ-ray emitter ^{26}Al in novae modeling calculations [16]. Ideally, the key resonance strengths influencing the ^{25}Al$(p,\gamma)^{26}$Si reaction rate should ultimately be determined directly. In such approaches using radioactive beams, it is important to have accurate and precise resonance energies to facilitate measurements (see for example Ref. [18]).

In summary, we have completed a detailed study of the structure of levels below and in the region of the proton threshold. The results agree well with shell model calculations and the mirror nucleus ^{26}Mg, and further constrain likely uncertainties in the ^{25}Al$(p,\gamma)^{26}$Si reaction rate.

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