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Resonances above the proton threshold in ^{26}Si

K. A. Chipps
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
and Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996

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^{26}Al remains an intriguing target for observational γ-ray astronomy, thanks to its characteristic decay. The $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ reaction is the crucial link in a sequence that bypasses the production of the observable $^{26}\text{Al}^{g}$ in favor of the short-lived isomeric state; determining its astrophysical reaction rate across a range of stellar environments has been the focus of many studies. A reanalysis of previous work, utilizing recent improvements in excitation energies and ground state masses, is presented to reduce the ambiguities in the literature and provide focus to future measurements.

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I. ASTROPHYSICAL IMPORTANCE

The astronomical observable ^{26}Al, the first radioisotope observed by detection of its γ ray in space, has long been recognized as a crucial indicator of the ongoing nucleosynthesis in the Milky Way Galaxy. Thanks to the unique properties of this radioactive isotope—its $\sim 700\,000$-yr half-life and its characteristic 1.809 MeV γ ray—it provides a direct link between astrophysical environment and nuclear physical properties, allowing us key insight into the depths of massive and exploding stars.

^{26}Al (cf. [1–5]) has been mapped across the Milky Way Galaxy, shown to be corotating with the galactic disk, is clumped near regions of massive stars, and is the cause of the ^{26}Mg overabundance in meteoritic presolar grains. While novae may not be the major contributors to the production of galactic ^{26}Al, they are suspected to produce up to 30% [6] of the ~ 2–3 solar masses of it in the Milky Way [3,7]. Indeed, nova explosions in the Milky Way are relatively frequent (an average of 40 annually [8]). The majority of the contributions likely arise from lower-temperature environments such as Wolf-Rayet and AGB stars (cf. [9]).

The observable γ ray results only from population of the ground state of ^{26}Al; the short-lived isomeric state produces no decay γs. Feeding through higher-excitation levels in ^{26}Al at certain astrophysical temperatures [5,10], due to potential communication between the ground state and isomer via γ-ray transitions, creates additional complications. Hence, understanding of the complete reaction network surrounding ^{26}Al is critical to our understanding of its net production in the Galaxy—and yet this goal has proved difficult to achieve.

One case in particular has seen significant interest over the years: the rate of the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ reaction, which bypasses the ^{26}Al ground state by preferentially populating the isomer. In fact, reducing the nuclear physics uncertainties in the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ reaction has been identified as critical for understanding nova astrophysics [11]. Multiple evaluations of this proton-capture cross section have concluded that the reaction rate is dominated at peak nova temperatures (0.15–0.4 GK) by the first $\ell = 0$ resonance from the $5/2^+$ ^{25}Al ground state (a $2^+/3^+$ level in ^{26}Si). Other resonances contribute across a wide temperature range; this work will focus on the first five resonances above the proton threshold in ^{26}Si, which would play a role in the astrophysical reaction rate for temperatures up to ~ 0.5–0.6 GK.

II. CURRENT KNOWLEDGE

A multitude of studies have sought to find, characterize, and determine the effect of resonances in the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ reaction, focusing preferentially on the astrophysically interesting region around a predicted 3^+, $\ell = 0$ level at $E_x = 5970 \pm 100$ keV [12] ($360 \lesssim E_r \lesssim 560$ keV). The exact E_x and J^π assignments for the relevant level have been intensely debated, however, as multiple levels in this energy range have been identified as candidates over the years [6,12–33]. Discrepancies in the way the reaction rate is treated in sensitivity studies also adds to the ambiguity, with a new Monte Carlo approach differing from the classical rate by nearly a factor of 4 [34]; it is unclear what portion of the variation is due to the new method versus newly included experimental inputs. Clearly, improved resonance information is needed.

In particular, five states within about half an MeV of the proton threshold are potentially of interest: 5517.8, 5677, 5892, 5913.8, and 5945.9 keV [35,36] (no levels are known between these and at least 6101 keV [35]). These levels would play a role in the cross section of the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ reaction at temperatures below ~ 0.5 GK.

Two major issues which have plagued measurements of ^{26}Si above the proton threshold are: 1) unavailability of the high-precision γ spectroscopy data of Ref. [22] prior to 2007, which affects any calibration made against "known" levels, and 2) a lack of inclusion of the updated, high precision mass measurement [37,38] prior to 2009, which affects any calibration done to calculated kinematics, or measurements relative to the Q value or proton threshold. Comparison between new measurements and older particle transfer have not taken these systematic shifts into account, including in some cases adoption of the new proton threshold, resulting in considerable ambiguity (see, for example, Refs. [39,40]).

γ-spectroscopy measurements are insensitive to the mass value shift; however, particle transfer measurements require knowledge of the masses involved to correctly calculate the reaction Q-value and resonance energies. Due to this shift, for instance, the level at 5517.8 keV [35] is now known to be slightly unbound [28,29]. Such changes can, if the conditions are right, have a significant effect on the ^{25}Al$(p,\gamma)^{26}$Si cross section at astrophysical energies.

Prior to about 2010, the consensus was that one of two levels around $E_r \simeq 400$ and 430 keV, one with a spin and parity of 3^+ and the other 0^+, would play the largest role in the astrophysical reaction rate; the literature at that point had largely reached agreement that the ~ 400 keV resonance is the 3_3^+, first $\ell = 0$ resonance in ^{25}Al$+p$.

Despite this consensus, the precise value of the resonance and excitation energy for this $\ell = 0$ resonance was not confirmed until recently [6], largely due to the difficulties mentioned previously—particularly, comparison to excitation energies which were calibrated based on outdated level energy values and resonance energies calculated from outdated mass values. Though some works did take one or more of these changes into account [6,25,28,29], these updated values have not been sufficiently disseminated and adopted. The discovery of a new level near $E_x = 5890$ keV [20,27,32,33] and its recent J^π assignment [32,33] has further complicated the situation by calling into question the 0^+ assignment of the higher energy resonance (~ 430 keV).

III. REANALYSIS OF PUBLISHED DATA

This work adopts the high precision level energies of Seweryniak *et al.* [22] and Doherty *et al.* [33], averaged, as calibration energies. The data from Komatsubara *et al.* [32], while reported with high precision, were not used in this analysis for the recalibration, due to several unexplained discrepancies with the other two high-precision sets [22,33]; the effect of this choice is minimal (see footnote 2 and Sec. IV), and it should be noted that there is reasonable agreement, below the proton threshold, amongst all three datasets. The ^{26}Si proton threshold (5513.8 ± 0.5 keV) from the 2012 Atomic Mass Evaluation [41] is adopted here. The 5928.7 keV level calculated from the γ energy in Bennett *et al.* [6] is also used as a calibration energy for those measurements which report an energy for Resonance D. The current work, by accounting for the new, high-precision mass [37,38,41], the additional high-precision excitation energy of Resonance D [6], and the significant amount of new experimental data published on ^{26}Si since 2009 [6,26–30,32,33,37], provides a substantial update to the previous reanalysis [25] and current evaluation [35].

A summary of the experiments up to now which populated one or more of the five levels just above the proton threshold in ^{26}Si is given in Table I. The resonances in ^{25}Al$(p,\gamma)^{26}$Si within the first half an MeV from the proton threshold will, for clarity, be referred to sequentially (in order of increasing E_x) as A, B, C, D, and E. Excitation energies, spins, and resonance energies are tabulated only if listed explicitly in the publication for each measurement; resonance energies are derived only for the compilation values. The information given in Refs. [19,21,23,25] are not listed here, as they did not measure the levels directly but instead adopted the values from other references.

Certain measurements reported only an excitation energy or resonance energy for the populated levels; however, some measurements also reported the S_p value assumed, allowing calculation of E_x from E_r and vice versa. The majority of works [15,16,18,20–22,24,26] adopted the old value of $S_p = 5518$ keV or something close to it; several [27,29,30,32,33] adopted the newer value of 5513.7 keV from Ref. [37], a 4.3 keV difference; the remainder adopted differing values (5517 [17], 5513 [19], 5512.3 [25,28], and the AME2012 value of 5513.8 [6]) or do not mention any value for S_p [13,14].

Based on the information given in each publication, an assessment was made as to whether the E_x or E_r values needed to be adjusted based on either the new calibration levels [6,22,33], the new mass [41], or both.

A. Excitation energies

The following measurements were reanalyzed with respect to their reported ^{26}Si excitation energies: ^{28}Si(p,t) [13], ^{24}Mg$(^3$He$,n)$ [14], ^{28}Si(p,t) [15], ^{29}Si$(^3$He$,^6$He$)$ [16], ^{24}Mg$(^3$He$,n)$ [18], ^{28}Si$(^4$He$,^6$He$)$ [20], ^{28}Si$(^4$He$,^6$He$)$ [24], ^{24}Mg$(^3$He$,n)$ [27], ^{28}Si(p,t) [28], and ^{27}Si(p,d) [30]. In each case, the level energies reported were compared against a "recalibration" set comprised of averaged level energies from Seweryniak *et al.* [22] and Doherty *et al.* [33], and a linear regression fit was calculated for the two sets. Certain reported peaks, such as doublets or peaks which do not seem to correspond to known levels, were not included in the recalibration fits.

It is clear that in most cases, the necessary adjustment is small, on the order of 0.3% or less. However, even this minimal variation is enough to result in a change of up to 16 keV at the upper end of the astrophysically important region. The largest shift was in the ^{28}Si$(^4$He$,^6$He$)^{26}$Si data of Ref. [20], which suffered from low statistics for peaks above the proton threshold. The majority of the adjustments were on the order of 5 keV or less in the excitation energy region of interest (as anticipated by Ref. [22]), as can be seen in Fig. 1. Most of the updated excitation energies show good consistency, particularly for Resonances A, B, and D.

A comparison may be made with the earlier reanalysis of Ref. [25], which also adjusted several measurements (those of Refs. [15,18,24]). Though that reanalysis did not have the benefit of the 5928.7 keV level of Bennett *et al.* [6] as a calibration point, this work agrees quite well with Wrede's recalibration [25]: adjusted excitation energies from all three of the reanalyzed measurements agree between Ref. [25] and this work to within about 2 keV, less than Wrede's adopted uncertainties. This demonstrates again that the choice of calibration levels has a small, but non-negligible, effect.

B. Resonance energies

The following measurements were reanalyzed with respect to their reported resonance energies: ^{26}P decay [17] and ^{25}Al(d,n) [26]. In these two measurements, the resonance energy (or decay Q value) was measured directly, but in each the adopted proton threshold S_p differs from the updated, most precise value [37,41].

Accounting for the new value of $S_p = 5513.8$ keV, the 412 keV resonance energy measured by Thomas *et al.* [17] produces an excitation energy of 5925.8 keV, reduced from

TABLE I. The first five levels above the proton threshold in ^{26}Si, with energies in keV, according to the current literature. References (other than the ENSDF compilation) are listed in chronological order. If only the excitation energy or resonance energy were published, only these are shown below (ie no values were calculated based on an implicit or explicit S_p). See text for more discussion.

Resonance: →		**A**			**B**			**C**			**D**			**E**	
Measurement: ↓	E_x	J^π	E_r	E_x	J^π	E_r	E_x	J^π	E_r	E_x	J^π	E_r	E_x	J^π	E_r
Compilation [35]	5517.8 ± 0.4[a]	4^+	4[b]	5677.0 ± 1.7	1^+	163.2[b]	5892 ± 4		378.2[b]	5913.8 ± 2.0	3^+	400[b]	5945.9 ± 4.0	0^+	432.1[b]
^{28}Si(p,t) [13]	5562 ± 28												5960 ± 22		
^{24}Mg(^{3}He,n) [14]										5910 ± 30[c]	0^++(4^+)				
^{28}Si(p,t) [15]	5515 ± 5	(4^+)								5916 ± 2	0^+[d]				
^{29}Si(^{3}He,^{6}He) [16]	5526 ± 8	4^+		5678 ± 8									5945 ± 8	3^+	
^{26}P decay [17]										5929 ± 5		412 ± 2			
^{24}Mg(^{3}He,n) [18]	5515 ± 4			5670 ± 4						5912 ± 4	3^+		5946 ± 4	0^+	
^{28}Si(^{4}He,^{6}He) [20]							5892 ± 4								
^{12}C(^{16}O,2n) [22]	5517.2 ± 0.5	4^+		5677.0 ± 1.7	1^+										
^{28}Si(^{4}He,^{6}He) [24]	5508 ± 3									5918 ± 8					
^{25}Al(d,n) [26][e]												360 ± 70			(360 ± 70)
^{24}Mg(^{3}He,nγ) [27][f]	5517			5677			5888 ± 2								
^{28}Si(p,t) [28]	5517.2 ± 1.6	4^+								5921 ± 12	3^+		5944 ± 20	0^+	
^{28}Si(p,t) [29]	5516 ± 3									5927 ± 4	3^+	413 ± 4			
^{27}Si(p,d) [30]	5511 ± 10			5659 ± 22											
^{26}P decay [6]										5928.7 ± 0.6[g]	3^+	414.9 ± 0.6[g]			
^{24}Mg(^{3}He,nγ) [32]	5517.8 ± 1.1	4^+		5673.6 ± 1.0	1^+		5890.0 ± 1.0	0^+							
^{24}Mg(^{3}He,nγ) [33]	5517.0 ± 0.1	4^+		5675.9 ± 1.1	1^+		5890.1 ± 0.6	0^+							

[a] ENSDF lists the level as 5513.8 ± 0.5 keV, but then specifies that this value corresponds to the adopted proton emission threshold from the 2012 Atomic Mass Evaluation [41], and determines the least-squares fit to γ data gives the value listed in this Table [35].

[b] Derived from ENSDF S_p value of 5513.8 ± 0.5, which is adopted from the AME2012 value [41].

[c] Reported in Ref. [14] as 5.91 MeV with "20 or 30 keV" uncertainty.

[d] In a later publication [21], additional data plus a new DWBA analysis led to an assignment for this level of 3^+.

[e] Ref. [26] reported a proton decay Q value of 0.36(7) MeV for the first $\ell = 0$ level about the proton threshold, consistent with either Resonance D or E. They assign 3^+ to Resonance D based on the interpretation from Ref. [18].

[f] It is unclear from Ref. [27] whether the authors measure the values given for Resonances A and B, or whether they are giving the values used in their calibration. Uncertainties of ±2 keV are adopted in this work, for consistency with their third level energy.

[g] Ref. [6] gives the uncertainty on the excitation energy as $\pm 0.6(stat) \pm 0.3(sys) \pm 0.3(literature)$ and on the resonance energy as $\pm 0.6(stat) \pm 0.3(sys) \pm 0.6(literature)$.

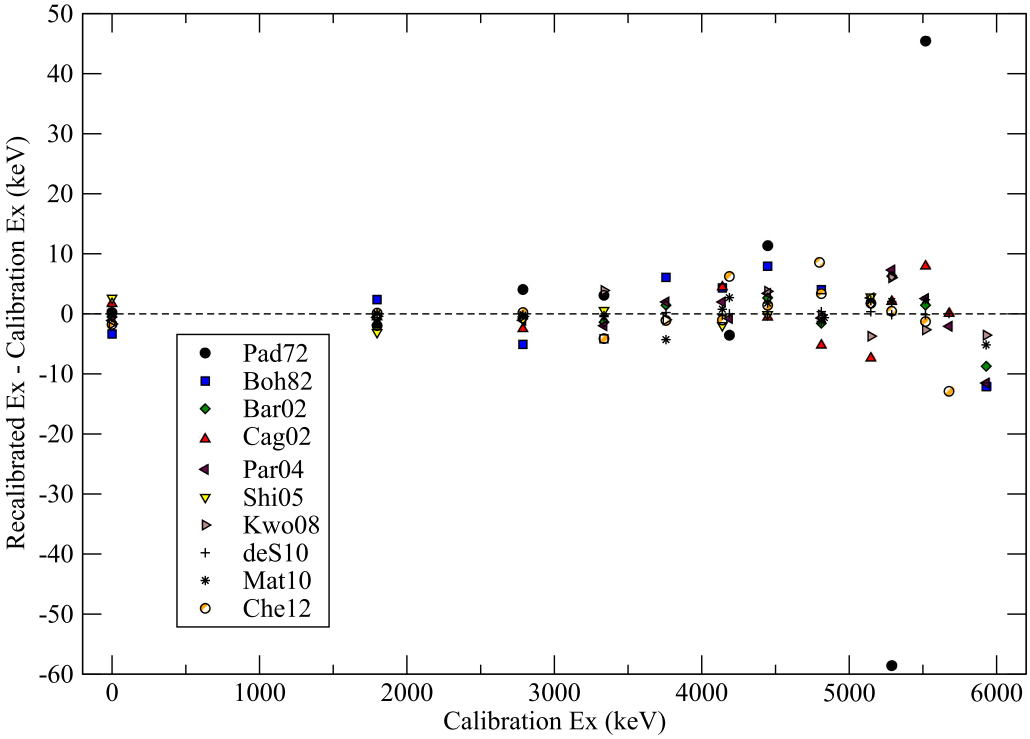

FIG. 1. Residuals from the recalibration fit for excitation energies, in keV. The references are listed as first three letters of first author's last name followed by the last two digits of the publication year.

5929 keV. In the proton decay Q-value measurement of Peplowski *et al.* [26], the shift in S_p results in a new E_x of 5873.8 keV, reduced from 5878 keV (this E_x is not reported explicitly, but is calculated from the reported $Q = 0.36$ MeV and $S_p = 5518$ keV which the measurement adopts).

C. Spin assignments

Assignment of spin to each of the five resonances A–E is based on experimental data where available, with mirror arguments also playing a role. In Ref. [12], shell model calculations for $A = 26$ were compared with the known levels in ^{26}Mg, ^{26}Al, and ^{26}Si, with the astrophysically-important $\ell = 0$ resonance in $^{25}\mathrm{Al} + p$ being predicted at 5970 keV via Coulomb displacement calculations. Around this 3_3^+ level are also the 1_1^+, 0_4^+, 4_4^+, and 4_5^+ levels predicted by the shell model (see Tables VIII and IX of Ref. [12]).

The shell model predictions of Iliadis *et al.* [12] order these five levels, in increasing excitation energy, as 1_1^+, 4_4^+, 0_4^+, 3_3^+, 4_5^+ for the $A = 26$ isospin triplets. In the known level structure of the mirror ^{26}Mg, these five levels are ordered, in increasing excitation energy, 1_1^+, 4_4^+, 3_3^+, 0_4^+, 4_5^+. Reference [12] gives several possibilities for the mirror assignments, resulting in multiple possible values for the Coulomb displacement of these levels.

The high precision gamma spectroscopy data of Seweryniak *et al.* [22] assigns Resonances A and B as the 4_4^+ and 1_1^+ levels, respectively. A transition from Resonance A to another 4^+ level was observed, conclusively ruling out the 1^+ assignment; the level's decay scheme matched that of the 4_4^+ mirror in ^{26}Mg. This verified the tentative 4^+ DWBA assignment of Bardayan *et al.* [15]. The expected transition from the purported 1_1^+ level, Resonance B, to the 2_1^+ level was observed, supporting the 1^+ spin assignment. Resonance B was also assigned 1^+ in Refs. [16] and [18], though little discussion of the details leading to the assignment are given in those works. The recent γ spectroscopy of Komatsubara *et al.* [32] and Doherty *et al.* [33] confirm the 1^+ for Resonance B with an angular correlation measurement.

Resonance D has, by far, received the most attention [6,15,17,18,21,24,26,28,29]. These measurements have generally converged on the spin assignment of this level being 3^+; those measurements with a particular sensitivity to this important $\ell = 0$ resonance have verified this assignment beyond a reasonable doubt [6,17,26,29] (see also Sec. III D).

Resonance C has only been reported a few times [20,27,32,33], and only the most recent measurements have assigned a spin: 0_4^+. In the Komatsubara measurement, this assignment is based on only one γ-ray transition, and their data (see Fig. 7 of Ref. [32]) are also consistent within uncertainties with a 2^+ assignment. Shimizu *et al.* [20] used the (^{4}He, ^{6}He) reaction and therefore preferentially populated natural parity states, which would support either a 0, 2, or 4^+ assignment. Reference [27] reports that the level, Resonance C, was observed to decay to the 4139, 2784, and 1797 keV levels, all of which are 2^+; not enough to constrain the spin. However, the recent Gammasphere measurement of ^{24}Mg(^{3}He$,n$) [33] confirmed this level to be a 0^+, an assignment which would match the ordering of levels proposed by Iliadis [12]. The authors of Ref. [33] explicitly call into question the assignment of Resonance E, and, in fact, its existence as a separate resonance, as they do not report any evidence of populating Resonance E. However, Resonance E was reported in two separate measurements as observed in conjunction with Resonance D, making it unlikely that the two are in fact one potentially misreported level.

The ^{24}Mg(^{3}He,n) measurement of Parpottas *et al.* [18] is often singled out, as it is one of the few experiments which observed both Resonances D and E (see Table I) simultaneously. Matic *et al.* [28] also populated both levels, though only weakly. Hence, the Matic measurement was unable to make spin assignments, noting only that assignments of 3^+ and 0^+, respectively, were consistent with several other measurements.[1] In Ref. [18], comparison of the experimental differential cross sections at two different energies with Hauser-Feshbach calculations gave clear indication of a $J = 0$ assignment for Resonance E [18]. Figure 6 of that publication shows that Resonance E is definitely not consistent with $J = 4$. This information is surprising, as one of these two states is expected to be 4^+ based on mirror arguments, and there are no remaining "missing" levels from the mirror assignments. No 2^+ resonances are expected in this particular excitation energy region, but some of the 2^+ assignments at lower excitation energies are only tentative. A 0^+ assignment is possible for both Resonances C and E, however, if one is due to particles being excited into a different shell. It does not appear that any theoretical study of ^{26}Si which takes such particle excitations into account has been done to date, though there is evidence such intrusions into lower shells can be seen down to $\sim$ 5 MeV in excitation energy in this mass range [42].

D. Additional data

Data from the ^{28}Si(p,t)^{26}Si*(p) measurement [29] were reexamined in an effort to further elucidate the properties of these five levels. That work observed decay protons from the excited ^{26}Si level at 5927 ± 4 keV, calculating a proton decay branching ratio of ~ 1, consistent with an $\ell = 0$ transfer. The triton singles peak for this level was fit with a Gaussian curve plus linear background for each of the angles measured, and the process was repeated for the decay-proton-gated triton peaks, in order to determine whether a systematic offset existed between the excitation energy derived from the tritons alone and that derived from the proton-gated tritons. Any difference could indicate that the peak observed in the triton singles was in fact a doublet (within the resolution of the measurement), and that the decay protons were originating from only one of the levels within such a doublet. The average centroid of the proton-gated events was found to lay 6 keV above the average triton singles centroid; however, due to the low statistics of the proton-gated events, there was a $\sim$ factor of 3 larger spread in the calculated excitation energies from the centroids of these peaks compared to the scatter of the triton singles peaks. Taking this scatter into account, no statistically significant systematic offset could be said to be observed between the triton singles and proton-gated triton spectra. The events gated on the decay protons from the 5927 keV level could not be attributed to any of the other resonances (Resonance E being 22 keV away), and hence only Resonance D can be given a 3^+ assignment by that work.

IV. ADOPTED VALUES

The adopted values for the five resonances above the proton threshold in ^{26}Si are listed in Table II. The final values adopted by this work are weighted averages of those measurements which remained after a careful selection process; weighting was based on reported uncertainties. Only a few measurements were not included in the average, one due to known background issues in the data (Ref. [13]) and the other due to the inability to definitively assign the measured value to a single resonance (Ref. [26]). The adopted value for Resonance B differs from the Seweryniak *et al.* energy of 5677.0 keV [22] (used in the recalibrations described in this work) mainly because the quoted uncertainty on the Komatsubara *et al.* [32] value of 5673.6 is only 1 keV, increasing its weight in the average; the authors of Ref. [32] do not discuss the discrepancy with the value from Ref. [22] in the de-excitation γ energy for this level.[2] In addition to these two high-precision excitation energy measurements [22,32], a new measurement [33] provides a value for the excitation energy between the original values, but closer to the Gammasphere result, supporting the adoption of a value closer to 5677 keV. It is possible that the uncertainty on the Komatsubara *et al.* [32] measurement is underestimated, as it does not seem to account for sources of uncertainty other than the extrapolation of their calibration fit to higher energies.

The process of weighting by the uncertainty may seem to unfairly represent the high-precision spectrometer (p,t) data from Matic *et al.* [28], as the authors do not have the benefit of adopting the uncertainty of multiple simultaneous measurements as do, for example, Ref. [15] or [29]. The resolution of the experimental device is, of course, superior in the Matic *et al.* case. However, this should not have much detrimental effect on the weighted averages presented here, for several reasons. First, the Matic observation of Resonances D and E suffered from weak population of those levels, so though it is high-resolution charged-particle data, it will not factor strongly into the average. Second, in the case of Resonance E,

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[1] Caggiano *et al.* [16] assigned Resonance E as 3^+, based on the argument that other 0^+ states were only weakly populated in their measurement and therefore the Resonance E peak could not be 0^+. This discrepancy, while perhaps not resolved, has been dismissed by the overwhelming evidence from other measurements. In fact, the energy reported by Caggiano *et al.* for this peak, adjusted for the updated calibration level energies ($\sim$ 5944 keV), would be consistent with population of Resonances D+E as a doublet, which could explain why the authors' argument was ultimately inconsistent with further measurement.

[2] The effect of using the 5673.6 keV value of Ref. [32] in the recalibration in this work instead of the 5677 keV value from Ref. [22] is minimal; for all five resonances A–E, the maximum difference in the adopted E_x value due to this extrapolation was less than 0.55 keV. This work adopts the average of the Gammasphere values [22,33] in the calibration set for consistency.

TABLE II. Adopted values for the five excited states above the proton threshold in ^{26}Si. The measurements included in each weighted average are listed explicitly. The weighted uncertainty in the excitation energy comes only from the reported uncertainties of included measurements; the uncertainty in the resonance energy includes the uncertainty in the new S_p value.

Resonance:	**A**	**B**	**C**	**D**	**E**
E_x (keV)	5517.3 ± 0.8	5675.2 ± 1.4	5890.0 ± 0.8	5927.6 ± 1.0	5949.7 ± 5.3
J^π	4^+_4	1^+_1	(0^+_4)	3^+_3	$(4^+_5,0^+_4)$
E_r (keV)	3.5 ± 0.9	161.4 ± 1.5	376.2 ± 1.0	413.8 ± 1.1	435.9 ± 5.3
Refs. included	[15,16,18,22,24,27–30,32,33]	[16,18,22,27,32,33,43]	[20,27,32,33]	[6,14,15,17,18,24,28,29]	[16,18,28]

there are fewer observations and none of them are particularly strong, so that the weighted average is not highly biased toward any one measurement. In all relevant cases, any gamma spectroscopy measurements are most highly weighted due to the comparatively small uncertainties. Measurements with larger uncertainties, such as Bohne [14] or Chen [43], are included in the weighted average, but due to their large uncertainties cause very little shift.

V. OPEN QUESTIONS

The astrophysical implications of the updated level structure of ^{26}Si above the proton threshold have yet to be fully determined, as several questions remain.

First, the spin assignments of Resonances C and E need to be resolved. When comparing shell model predictions [12,25] against the data [18,32], confusion arises regarding Resonances C and E. Naively, one of these two levels should be 4^+_5 and the other 0^+_4, yet the data suggest that neither are compatible with a 4^+ assignment. Shifting the location of the 0^+_4 level alters the total reaction rate, as demonstrated by the example in Fig. 2, by as much as ∼ 14% at 0.2 GK. Theoretical calculations of possible configurations which could account for two 0^+ levels in this region should be undertaken, but experimental confirmation of the spins of these levels is necessary to fully understand the $^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}$ astrophysical reaction rate. Study of a reaction which will populate all five levels simultaneously could be ideal in helping to resolve this issue. A measurement of single-particle transfer could help to reduce any uncertainties in the analysis of angular distributions, assuming sufficient experimental resolution is achieved; such a measurement could also provide some idea of the single particle (i.e., single proton) structure of these resonances. Additional γ-spectroscopy measurements

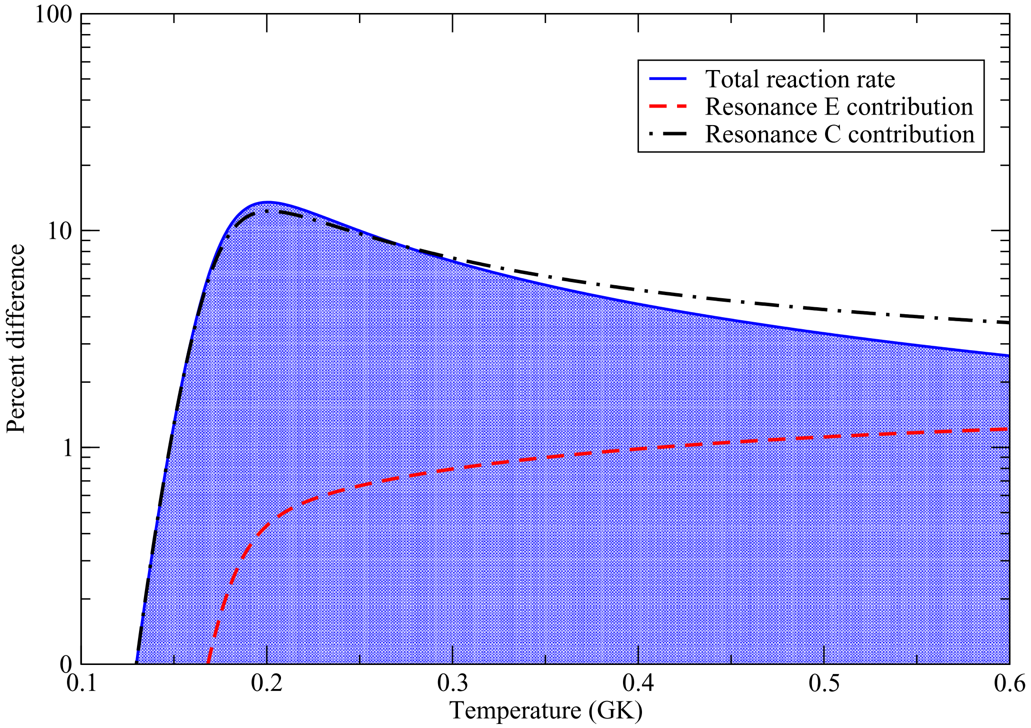

FIG. 2. The percent difference, as a function of temperature, between two calculated reaction rates ($N_A < \sigma v >$) with different assignments for the 0^+_4 level. The calculations are for an idealized case of three main resonant components (the 1^+, 3^+, and 0^+ resonances), utilizing the resonance parameters from Matic *et al.* [28]. Only the location of the 0^+ assignment has changed, shifting from Resonance E to Resonance C (normalized to Resonance E). The blue solid curve shows the percent change in the total reaction rate due to this difference in assignment; the red dashed curve shows the percent of the total reaction rate from the contribution of Resonance E as the only 0^+; the black dot-dashed curve shows the percent of the total reaction rate from the contribution of Resonance C as the only 0^+.

TABLE III. Sources of spectroscopic information for each of the five resonances discussed in the existing literature on the $^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}$ reaction rate, if a reaction rate is calculated. Falling into the "theory" category are calculations from coupled channels, USD interactions, the shell model, values derived from mirror assignments, and adjustments made to values adopted from earlier works. The "experiment" category only includes values which have been directly measured and values derived from those direct measurements.

Resonance:	**A**	**B**	**C**	**D**	**E**
Theory	[19]	[6,12,16,18,19,21,23,25,26,28,32,44]	[32]	[12,16,18,19,21,23,25,26,28,32,44]	[6,12,16,18,19,21,23,25,26,28,44]
Experiment				βp branching ratio 17.96 ± 0.90% [17] $\sigma[\text{resonant } ^{25}\mathrm{Al}(d,n)] = 8.7 \pm 3$ mb [26] $\Gamma_p/\Gamma_\gamma < 5.6$ [25][a] $\Gamma_p/(\Gamma_p+\Gamma_\gamma) = 0.91 \pm 0.10$ [29] $\omega\gamma = 23 \pm 6$(stat) meV [6][b]	

[a] Derived from data in Thomas *et al.* [17].

[b] The case of Bennett *et al.* [6] does not fall cleanly into these categories. The ratio $\Gamma_\gamma/\Gamma_p = 0.014$ is derived from the measured value of the ^{26}P β-delayed proton decay intensity from Thomas *et al.* [17], the measured value of the ^{26}P β-delayed γ intensity for the 1742 keV γ, and the theoretical partial γ-decay branch of the 3_3^+ level (where the values for this last component are equivalent whether they are derived from the shell model or from the mirror). The resonance strength is derived from this ratio and the "experimentally determined value of Γ_p" from Peplowski *et al.* [26].

which focused on the excitation energy region above the proton threshold, though difficult, would also be highly beneficial.

A second open question pertains to the proton and γ widths (and resonance strengths) of these five levels. Table III summarizes all of the existing spectroscopic information in the literature. While significant effort has been focused on Resonance D [6,17,25,26,29], properties of the other states, in particular the lesser known Resonances C and E, are not well constrained. This lack of experimental information on the spectroscopic information for these resonances continues to contribute a large—likely the largest remaining—uncertainty to the astrophysical reaction rate. For example, the proton partial width of Resonance E is unknown to within a factor of two [25]; for Resonance C it is completely unmeasured, and has only been calculated assuming that Resonance E does not exist [32] (cf. Fig. 2). Uncertainties in the resonance strengths manifest almost one to one in the resonant contributions to the total rate. As mentioned, a single-proton transfer measurement would help to fill in this missing information. Measurements to reduce the current ~ 30% uncertainty contribution from the direct capture component are also needed.

Further effort to understand ^{26}Si through indirect measurements is ongoing; in particular, results from additional γ spectroscopy [45] and a high-statistics repeat of $^{25}\mathrm{Al}(d,n)$ [46] are anticipated. Of course, a direct measurement of the $^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}$ reaction cross section at the relevant astrophysical energies would provide the best, most reliable information on this reaction rate. Such a measurement requires significant investment in infrastructure, however: considerable beam development, a dense hydrogen gas target, and a dedicated recoil separator. At least one letter of intent to perform such a study [47] already exists.

Finally, future evaluations of the rate need to include contributions from potentially five resonances instead of the three or four typically assumed. While the contributions to the astrophysical reaction rate from 0^+ or 4^+ levels will be small, they should be fully considered. The adopted values from this work for these five resonances above the proton threshold in ^{26}Si will be invaluable in assessing the astrophysical impact of the $^{25}\mathrm{Al}(p,\gamma)$ reaction rate on the ^{26}Al cosmic abundance.

Extensive indirect studies of the $^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}$ astrophysical reaction have resulted in a number of discrepancies in the parameters of the resonances that dominate this important reaction rate. This study has used updated, high precision level energies and mass values to resolve a number of these discrepancies, and elucidates the remaining gaps in our understanding. The new resonance parameters adopted in this work will be useful in further studies of the galactic abundance of ^{26}Al.

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