Thermonuclear $^{25}Al(p,\gamma)^{26}Si$ reaction rate in classical novae and Galactic ^{26}Al

C. Wrede*

Department of Physics, University of Washington, Seattle, Washington 98195, USA

(Received 12 November 2008; published 13 March 2009)

The nuclear physics uncertainty associated with the production of the Galactic β-delayed γ-ray emitter ^{26}Al in classical novae is currently dominated by the uncertainty in the thermonuclear $^{25}Al(p,\gamma)^{26}Si$ reaction rate. By combining the results of recent experiments with past work, the center-of-mass energy of the key $J^\pi = 3^+$, $^{25}Al(p,\gamma)^{26}Si$ resonance is determined to be 412(2) keV, and a lower limit of $\Gamma_p/\Gamma_\gamma > 5.6$ is set for this resonance. The resulting large reduction in the $^{25}Al(p,\gamma)^{26}Si$ rate uncertainty is expected to constrain uncertainties in the nova contribution to Galactic ^{26}Al.

DOI: 10.1103/PhysRevC.79.035803 PACS number(s): 26.30.Ca, 24.30.−v, 25.40.Lw, 27.30.+t

I. INTRODUCTION

The 1.809-MeV β-delayed γ ray from ^{26}Al ($t_{1/2} = 0.7$ Ma) constituted the first γ-ray line observed from radioactive decay in the Galaxy [1], an unprecedented probe of ongoing Galactic nucleosynthesis. Recent satellite-based observations of this line have been used to estimate that the Galaxy harbors 2.8 ± 0.8 $M_\odot$ of ^{26}Al [2]. Based on the spatial distribution of ^{26}Al, it has been concluded [3] that the primary sources of Galactic ^{26}Al are young, massive stars such as Wolf-Rayet stars and their core-collapse supernovae. However, it is possible that classical novae (hereafter, novae) make a secondary contribution of up to 0.4 $M_\odot$ [4]. Coupled with the discovery of fossil ^{26}Al in two candidate presolar-nova grains [5], the γ-ray observations motivate modeling of ^{26}Al nucleosynthesis in novae [6], which is facilitated by an experimental nuclear physics data set with few outstanding deficiencies [7]. Precise predictions of the nova contribution to Galactic ^{26}Al may also benefit studies [8] of nucleosynthesis in massive stars and supernovae that use the $^{60}Fe/^{26}Al$ γ-ray line flux ratio [9] as a benchmark.

At the peak temperatures of novae ($0.1 < T < 0.4$ GK), ^{26}Al may be produced by explosive hydrogen burning via the $^{24}Mg(p,\gamma)^{25}Al(\beta^+\nu_e)^{25}Mg(p,\gamma)^{26}Al$ reaction sequence [and destroyed via $^{26}Al(p,\gamma)^{27}Si$]. However, the ^{25}Al β decay ($t_{1/2} = 7.2$ s) and production of ^{26}Al are suppressed at the highest nova temperatures by competing sequences initiated by the $^{25}Al(p,\gamma)^{26}Si$ reaction [6]. Every reaction and decay above has been measured directly in the laboratory except for the $^{25}Al(p,\gamma)^{26}Si$ reaction. Uncertainties in the thermonuclear rate of this reaction span one to two orders of magnitude at peak nova temperatures [10]. A large reduction in these uncertainties would complement a recent measurement [11] of the $^{26}Al(p,\gamma)^{27}Si$ reaction by enabling conclusions on the contribution of novae to Galactic ^{26}Al that are not limited by uncertainties in these key rates [4,6,7,10–12]. To this end, many laboratories worldwide are in the process of developing radioactive ^{25}Al ion beams ([10] and references therein; [13]). Considering the prolonged absence of an intense beam, the present work integrates and reconciles available experimental data to reduce the $^{25}Al(p,\gamma)^{26}Si$ rate uncertainties to factors of two to three.

*wrede@u.washington.edu

II. BACKGROUND

In the stellar environment of novae, particles are usually assumed to have a Maxwell-Boltzmann distribution of energies characterized by temperature T, from which the resonant $^{25}Al(p,\gamma)^{26}Si$ reaction rate per particle pair for narrow, isolated resonances r may be derived [12]. The total resonant rate is described by an incoherent sum over these resonances,

$$\langle\sigma\upsilon\rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_r (\omega\gamma)_r e^{-E_r/kT}, \quad (1)$$

where $\hbar$ is the reduced Planck constant, k is the Boltzmann constant, μ is the reduced mass, and E_r is the resonance energy in the center-of-mass frame.

$$(\omega\gamma)_r = \frac{(2J_r+1)}{(2J_p+1)(2J_{Al}+1)}\left(\frac{\Gamma_p\Gamma_\gamma}{\Gamma}\right)_r, \quad (2)$$

is the resonance strength, where $J_p(=1/2)$, $J_{Al}(=5/2)$, and J_r are the spins of the reactants and the resonance, respectively. Γ_p and Γ_γ are the proton and γ-ray partial widths of the resonance, respectively, and $\Gamma = \Gamma_p + \Gamma_\gamma$ is the total width. No other decay channels are open to resonances at the energies considered herein. The direct capture (DC) to bound states of ^{26}Si is usually added to the resonant capture (RC) component under the assumption that the two do not interfere. Resonant contributions are expected to dominate the total rate at peak nova temperatures.

In 1996, Iliadis *et al.* showed [12] that the $J^\pi = 1_1^+, 4_4^+, 0_4^+$, and 3_3^+ shell-model levels of ^{26}Si potentially correspond to significant resonances in the $^{25}Al(p,\gamma)^{26}Si$ reaction ($Q_{p\gamma} =$ 5518 keV [14]) at nova temperatures. At that time experimental information on these levels was scarce, but the 4_4^+ level has since been measured [15] to lie at $E_x = 5517.2(5)$ keV, close to the proton-emission threshold where it does not contribute significantly as a $^{25}Al + p$ resonance at nova temperatures because of the Coulomb barrier. The 1_1^+ level has been measured [15] to lie at $E_x = 5677.0(17)$ keV, making it a probable contributor to the $^{25}Al(p,\gamma)^{26}Si$ reaction rate at temperatures below ≈0.15 GK [10]. At least two other levels have been identified at $E_x \approx 5914$ keV and ≈ 5946 keV, and these likely correspond to the 3_3^+ and 0_4^+ shell-model levels but there has been considerable discussion about which one is which [10,15–19]. A precise energy for the 3^+ resonance is crucial to the determination of the ^{25}Al$(p,\gamma)^{26}$Si reaction rate above ≈0.15 GK because it is expected to be much stronger than the 0^+ resonance [10] and because resonant contributions to the reaction rate depend on resonance energy exponentially.

Possible energies for the relevant 3^+ and 0^+ levels of ^{26}Si were discussed in the most recent evaluation [10] of the ^{25}Al$(p,\gamma)^{26}$Si reaction rate. In 2002, Bardayan *et al.* published measurements of ^{26}Si excitation energies using the (p,t) reaction and reported a level at $E_x = 5916(2)$ keV that they determined to have $J^\pi = 0^+$ based on an analysis of the triton angular distributions [16]. Later that year, Caggiano *et al.* published measurements of the ^{29}Si(^{3}He, ^{6}He)^{26}Si reaction and reported a level at $E_x = 5945(8)$ keV that they argued to be the important 3^+ level [17]. However, the ^{24}Mg(^{3}He, n)^{26}Si reaction was subsequently used by Parpottas *et al.* [18] to populate levels at 5912(4) and 5946(4) keV, and the authors compared the cross sections with Hauser-Feshbach predictions to determine that the J^π values were likely 3^+ and 0^+, respectively, in contradiction with Refs. [16,17] under the assumption that the same levels were being observed. That measurement prompted Bardayan *et al.* to extend their previous measurement [16] of the (p,t) angular distribution of their 5916-keV level to more forward angles [10]. By doing so they determined its spin and parity to be consistent with 2^+ or 3^+ [10] (rather than 0^+ [16]). The 3^+ assignment was deemed more likely because no 2^+, ^{26}Mg mirror levels are known in that energy region. Accordingly, in their calculation of the ^{25}Al$(p,\gamma)^{26}$Si reaction rate, the authors considered their 5916-keV level to have $J^\pi = 3^+$ and the 5946-keV level to have $J^\pi = 0^+$. However, the possibility that their 5916-keV level has $J^\pi = 2^+$ [and that the key 3^+ level independently lies in the broad region 5910(60) keV] was explored and incorporated in their estimate of the uncertainty in the rate, which consequently spanned one to two orders of magnitude at peak nova temperatures. The authors called for a definitive confirmation of the 3^+ resonance energy to reduce this uncertainty, and the uncertainties in the predicted nova yields of ^{26}Al.

In the present evaluation of the thermonuclear resonant ^{25}Al$(p,\gamma)^{26}$Si reaction rate, three important pieces of information are used to build on the evaluation of Bardayan *et al.* [10]. First, the previously measured excitation energies for the likely 3_3^+ and 0_4^+ ^{26}Si levels are adjusted because these are dependent on internal calibrations based on data [20] that have recently been shown [15] to be inaccurate. Second, a recent precision ^{26}Si mass-excess measurement [21] is used in the determination of resonance energies from the adjusted ^{26}Si excitation energies. Finally, a ^{26}P β-decay measurement [22] is shown to provide a direct measurement of the center-of-mass energy of the 3^+ resonance and is used to place a lower limit on the ratio of partial widths, Γ_p/Γ_γ, for that resonance. Together, this information is shown to produce a consistent picture of resonance parameters for the ^{25}Al$(p,\gamma)^{26}$Si reaction. These parameters are used to reevaluate the thermonuclear resonant ^{25}Al$(p,\gamma)^{26}$Si reaction rate and reduce its uncertainty substantially.

III. EXPERIMENTAL DATA EXTRACTION

A. Excitation energies of ^{26}Si

In 2007, Seweryniak *et al.* measured ^{26}Si γ-ray cascades using the ^{12}C(^{16}O, $2n$)^{26}Si fusion-evaporation reaction to determine a very precise, essentially complete, ^{26}Si-level scheme up to the $E_x = 5677.0(17)$ keV, 1^+ level [15]. The authors reported discrepancies with the previous γ-ray energy measurements of Bell *et al.* [20] at the ≈5-keV level and suggested that the ^{26}Si excitation energies from the ^{24}Mg(^{3}He, n)^{26}Si measurement of Ref. [18] may need to be recalibrated at the ≈5-keV level because the results of Ref. [20] were used for an internal energy calibration of the neutron spectra in that work. Bardayan *et al.* [10,16] and Kwon *et al.* [19] also used the data of Ref. [20] to calibrate their respective triton- and ^{6}He-energy spectra internally, and therefore adjustments to those results are needed as well.

Adjustments are particularly important for the excitation energy of the level at ≈5914 keV because the energy of that level depends entirely on the results of Refs. [10,16,18,19]. By applying linear, least-squares fits of the differences between the excitation energies of Seweryniak *et al.* [15] and those used for calibration in Refs. [18], [16], and [19] as functions of excitation energy, the adjustments in the calibrations are found to be described by the functions $\Delta E_x = 0.000928E_x(\chi^2/\nu = 9.1/5)$, $\Delta E_x = 0.00131E_x - 0.92$ keV $(\chi^2/\nu = 4.5/4)$, and $\Delta E_x = 0.000863E_x(\chi^2/\nu = 3.2/3)$, respectively. Accordingly, the values of $E_x = 5912(4)$ [18], 5916(2) [16], and 5918(8) keV [19] are adjusted by $\Delta E_x =$ 5.5(6), 6.8(30), and 5.1(7) keV, respectively, to yield $E_x =$ 5917.5(40), 5922.8(36), and 5923.1(80) keV, respectively. A weighted average of these three mutually consistent values is adopted: $E_x = 5920.7(26)$ keV.

Similarly, the energy of the $E_x = 5946(4)$-keV level observed by Parpottas *et al.* [18] may be adjusted to yield $E_x = 5952(4)$ keV. Caggiano *et al.* [17] used internal calibration points together with external calibration points to measure $E_x = 5945(8)$ keV so an adjustment is necessary, but nontrivial, in this case. $E_x = 5952(4)$ keV is adopted for the excitation energy of this level because of the higher precision and simpler interpretation of the adjusted value from Parpottas *et al.*.

B. Mass excess of ^{26}Si

The ^{25}Al$(p,\gamma)^{26}$Si resonance energies are currently determined by the relation $E_r = E_x - Q_{p\gamma}$ [10], so the mass excess of ^{26}Si is important. In 2005, Parikh *et al.* measured [21] the Q value of the ^{28}Si$(p,t)^{26}$Si reaction and determined the mass excess of ^{26}Si to be −7139.5(1.0) keV: nearly a 2σ difference from the compilation [14] value of −7145(3) keV (and from a recently recalibrated value of −7145.5(30) [23]) that was also based on a (p,t) measurement [24]. The measurement of Parikh *et al.* has not been cited in subsequent work on

TABLE I. ^{25}Al$(p,\gamma)^{26}$Si resonance parameters from Ref. [10].

E_x (keV)	$E_r = E_x - Q_{p\gamma}$ (keV)[a]	J^π	Γ_p (meV)	Γ_γ (meV)
5673(4)[b]	155	1^+	1.3×10^{-6}	110
5914(2)[c]	396	3^+	2300	33
		or		
5910(60)	392	3^+	$\Gamma_p(E_r)$	33
5914(2)[c]	396	2^+	<180	20
5946(4) [18]	428	0^+	19	8.8

[a]Using E_x from column 1 and $Q_{p\gamma}$ from Ref. [14].
[b]Weighted average of 5670(4) [18] and 5678(8) [17].
[c]Average of 5912(4) [18] and 5916(2) [10].

the ^{25}Al$(p,\gamma)^{26}$Si reaction rate [10,15,19]. Using the more precise value from Ref. [21] for the mass excess of ^{26}Si (together with mass excesses from Ref. [14] for ^{25}Al and ^{1}H) yields a new $Q_{p\gamma}$ value for the ^{25}Al$(p,\gamma)^{26}$Si reaction of 5512.3(11) keV [21] that is adopted.

The most recent evaluation [10] of the ^{25}Al$(p,\gamma)^{26}$Si rate employed the unadjusted excitation energies and the $Q_{p\gamma}$ value derived from Ref. [14] to yield the resonance energies in Table I. Using instead the more precise excitation energy [15] for the 1^+ level, the presently adjusted excitation energies for the other two levels of interest, and the precise $Q_{p\gamma}$ value [21] yields resonance energies that are 9, 12, and 12 keV higher, respectively (Table II).

C. β decay of ^{26}P

The β decay of ^{26}P [$J^\pi = (3^+)$] to ^{26}Si provides an excellent means for determining parameters for the astrophysically important 3^+, ^{25}Al$(p,\gamma)^{26}$Si resonance and appears to have been overlooked in that context. The shell model predicts the 3^+_3, ^{26}Si level to lie at $E_x = 6.15$ MeV and have a β-decay feeding of 8.2%: the strongest feeding predicted for any level above $E_x = 4.4$ MeV [22]. Indeed a ^{26}Si level with a very strong (18%) feeding from the β decay of ^{26}P has been observed at $E_x \approx 5.93$ MeV by Thomas *et al.* [22], and it decays predominantly by proton emission to the ground state of ^{25}Al with a center-of-mass energy of 412(2) keV. This value is not in close agreement with the ^{25}Al + p resonance energies inferred from unadjusted transfer-reaction data for either of the candidate 3^+ levels (Table I). The β-decay work has not been cited in subsequent work on the ^{25}Al$(p,\gamma)^{26}$Si reaction rate [10,15,18,19,21].

Two pieces of evidence are considered to identify the (3^+), 412(2) keV, ^{25}Al + p resonance observed in the β-decay experiment [22] with one of the resonances inferred from transfer-reaction data. First, the adjusted center-of-mass resonance energies inferred from transfer-reaction data are 408.4(28) and 440(4) keV (Table II), making the 408-keV resonance the only consistent candidate based on its energy. Second, the spin of the 408-keV resonance has been determined to be 3^+ by Parpottas *et al.* [18] and 2^+ or 3^+ by Bardayan *et al.* [10], whereas the spin of the 440-keV resonance has been determined to be 0^+ by Parpottas *et al.* [18], making the 408-keV resonance the only consistent candidate based on its spin. This evidence leads to the conclusion that the 412-keV proton resonance observed in the β-decay experiment is the same resonance as the 408-keV resonance inferred from transfer-reaction data and that its spin and parity is 3^+. A resonance energy of 412(2) keV is adopted for the 3^+ resonance in the ^{25}Al$(p,\gamma)^{26}$Si reaction because Ref. [22] is the only direct measurement of its center-of-mass proton energy.

The βp and $\beta\gamma$ data from Ref. [22] may also be used to constrain Γ_p/Γ_γ for the 412(2) keV, 3^+ resonance. Because the experimental ^{26}Si level scheme of Ref. [15] matches 1:1 with the shell model (and with the well-studied level scheme of ^{26}Mg [25]), it is clear that the 5921-keV 3^+ ^{26}Si level corresponds to the 3^+_3 shell-model level (and to the 6125.5 keV 3^+ ^{26}Mg mirror level, which has a 70.9%, γ-ray decay branch to the 3^+_2 level [25]). The Evaluated Nuclear Structure Data File includes an assumed γ-ray multipolarity of [$M1$] for this transition that is adopted. One would expect a similar $3^+_3 \rightarrow 3^+_2$ γ-ray transition in ^{26}Si of energy $5921 - 4187 = 1734$ keV [15]. Assuming identical partial widths for mirror transitions, the 1734-keV γ-ray branch from the 5921-keV level is estimated to be 71^{+13}_{-19}% (the other 29% is highly fragmented in ^{26}Mg with unknown multipolarities [25]). This assumption is likely to work well for $M1$ transitions, which are dominated by the isovector component [26]. For $E2$ transitions the assumption is weaker, but because the weaker transitions are fragmented it is highly unlikely that all of these transitions would be enhanced in the same direction. The uncertainty is estimated by assigning a factor of 1.7 uncertainty to the partial width of each transition [25], based on mirror-level comparisons in the $21 \leqslant A \leqslant 44$

TABLE II. Present ^{25}Al$(p,\gamma)^{26}$Si resonance parameters.

E_x (keV)	$E_r = E_x - Q_{p\gamma}$ (keV)[a]	E_r (keV) [22]	E_r (keV) adopted	J^π	Γ_p (meV)	Γ_γ (meV)
5677.0(17) [15]	164.7(20)		164.7(20)	1^+	$4.6^{+9.3}_{-3.1} \times 10^{-6}$	$\gg\Gamma_p$
5920.7(26)[b]	408.4(28)	412(2)	412(2)	3^+	$>5.6\Gamma_\gamma$[c]	31^{+31}_{-15}
5952(4)[d]	440(4)		440(4)	0^+	25^{+50}_{-17}	$6.2^{+6.2}_{-3.1}$

[a]Using E_x from column 1 and $Q_{p\gamma}$ from Ref. [21].
[b]Adjustment of Refs. [16,18,19] using Ref. [15] (see text).
[c]Deduced from Ref. [22]; adopted $\Gamma_p/\Gamma = 0.99^{+0.01}_{-0.14}$ (see text).
[d]Adjustment of Ref. [18] using Ref. [15] (see text).

mass region [27]. An upper limit on the sensitivity of the experiment [22] to β-delayed γ-ray branches near the γ-ray energy of 1734 keV is estimated to be 1.32(34)% using the 1960-keV line. The hypothetical 1734-keV line is weaker than the clearly observed 1960-keV line, so its $\beta\gamma$ branching is estimated to be less than 1.32(34)%. Using this information, an upper limit on the total $\beta\gamma$ branch through the 3_3^+ ^{26}Si level of $1.32^{+0.34}/0.71_{-0.19} = 1.86^{+1.33}$% is calculated. The ratio of the βp branch [18.0(9) %] to the upper limit on the $\beta\gamma$ branch (3.2 %) yields an experimentally based lower limit of $\Gamma_p/\Gamma_\gamma > 5.6$ for the 412-keV ^{25}Al$(p,\gamma)^{26}$Si resonance.

IV. RATE CALCULATION

Considering the new information extracted in Sec. III, the resonance parameters are reevaluated to recalculate the thermonuclear resonant ^{25}Al$(p,\gamma)^{26}$Si reaction rate (Eq. (1)) using experimental information wherever possible.

Proton widths may be parameterized by the formula [28],

$$\Gamma_p = C^2 S \Gamma_{\mathrm{SP}} = \frac{2\hbar^2}{\mu R_n^2} P_\ell(E_r, R_n) C^2 S \theta^2_{\mathrm{s.p.}}, \qquad (3)$$

where $R_n = 1.25(1^{1/3} + 25^{1/3})$ fm is the interaction radius, $P_\ell(E_r, R_n) = kR_n/(F_\ell^2 + G_\ell^2)$ is the penetration factor that may be calculated by computing the regular (F_ℓ) and irregular (G_ℓ) Coulomb wave functions [29], C is an isospin Clebsch-Gordan coefficient, S is the spectroscopic factor, k is the wave number, Γ_{SP} is the single-particle partial width, and $\theta^2_{\mathrm{s.p.}}$ is the single-particle reduced width. Equation (3) is used in the present work to scale values of Γ_p from past work using the energy dependence of the penetration factor.

The partial width for a γ-ray transition i of definite multipolarity may be calculated using perturbation theory to be [28],

$$\Gamma_\gamma^i = \hbar\lambda(\bar{\omega}L) = \frac{8\pi}{L[(2L+1)!!]^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\bar{\omega}L), \qquad (4)$$

where E_γ, L, and $\bar{\omega}$ denote the energy, multipolarity, and electric (E) or magnetic (M) character of the radiation, respectively. $\lambda(\bar{\omega}L)$ is the decay constant and $B(\bar{\omega}L)$ is the reduced transition probability. Equation (4) is used in the present work to extract Γ_γ values for ^{26}Si levels by scaling the partial widths of corresponding γ-ray transitions in the mirror nucleus ^{26}Mg for the E_γ^{2L+1} energy dependence and assuming that $B(\bar{\omega}L)$ is equal for corresponding mirror transitions [27]. The possibility that each transition has mixed multipolarity introduces an uncertainty to this assumption that is accounted for [27].

For the 1^+ resonance at 164.7 keV, Γ_p is many orders of magnitude less than Γ_γ due to the low resonance energy, and therefore $\Gamma_p\Gamma_\gamma/\Gamma = \Gamma_p$ for the present purposes. Γ_p was evaluated in Ref. [18] based on a shell-model calculation of the spectroscopic factor [12] and an optical-model calculation of the single-particle partial width [12]. Under the assumption of constant reduced width, Γ_p is scaled from Ref. [18] by the barrier-penetration factor using the new resonance energy, and a factor of three uncertainty is adopted [10].

For the 3^+ resonance at 412 keV, Γ_γ is scaled from the ^{26}Mg mirror level by E_γ^3 of the dominant transition, which is assumed to be $M1$ [25]. A factor of two uncertainty was assigned to Γ_γ in Ref. [10], where it was extracted directly from the lifetime of the ^{26}Mg mirror level. If the $M1$ multipolarity assumption for the $3_3^+ \rightarrow 3_2^+$ transition is relaxed, then it might be argued that the uncertainty in Γ_γ (and, hence, the uncertainty in the contribution of the 3^+ resonance to the total rate) needs to be inflated for reasons discussed Sec. III. Nevertheless, the work in Ref. [27] indicates that the factor of two uncertainty assigned for Γ_γ in Ref. [10] is sufficiently conservative regardless of multipolarity, and therefore it is adopted. Using the present limit $\Gamma_p/\Gamma_\gamma > 5.6$ and the relation $\Gamma = \Gamma_p + \Gamma_\gamma$, a proton-branching ratio of $\Gamma_p/\Gamma = 0.99^{+0.01}_{-0.14}$ is deduced, where the central value is again estimated by scaling Γ_p from Ref. [18] by the penetration factor using the new resonance energy under the assumption of constant reduced width. In this case the spectroscopic factor was obtained from the neutron spectroscopic factor of the mirror level in ^{26}Mg [12].

For the 0^+ resonance at 440 keV, Γ_γ is scaled from the ^{26}Mg mirror level by E_γ^5 of the dominant $E2$ transition [25] and a factor of two uncertainty is adopted [10,27]. Γ_p was evaluated in Ref. [18] based on a shell-model calculation of the spectroscopic factor [12], and an optical-model calculation of the single-particle partial width [12]. Under the assumption of constant reduced width, Γ_p is scaled from Ref. [18] by the barrier-penetration factor using the new resonance energy, and a factor of three uncertainty is adopted [10].

Nonresonant DCs to all bound states of ^{26}Si were considered in Ref. [12] to calculate the total DC cross section, which was converted into an astrophysical S factor of 27.0 keV b that is roughly constant below a proton energy of 1 MeV. This S factor is adopted to calculate the DC rate using equation 3.94 in Ref. [28], but the DC rate is found to be slightly lower—particularly at lower temperatures. The difference is attributed to rounding of the atomic masses of ^{1}H and ^{25}Al to the nearest a.m.u. in Ref. [12]. The DC component was determined to carry a 30% uncertainty in Ref. [30] that is adopted.

The resonant ^{25}Al$(p,\gamma)^{26}$Si reaction rate is recalculated using the values summarized in the final four columns of Table II. To determine the total rate, The DC rate is added to the RC rate under the assumption that they do not interfere; uncertainties are approximated by varying the input parameters within their uncertainties. Inflating all partial-width uncertainties associated with known or potential $E2$ mirror transitions (besides the $3_3^+ \rightarrow 3_2^+$ transition) to a factor of five scarcely affects the uncertainties in the total reaction rate. The rates and uncertainties are summarized in Table III.

The DC component is found to dominate the rate in the temperature range $0.010 \lesssim T \lesssim 0.054$ GK and makes a significant, but minor, contribution up to $T \approx 0.185$ GK. The 1^+ resonance dominates the rate in the range $0.054 \lesssim T \lesssim 0.174$ GK. The 3^+ resonance dominates the rate in novae

TABLE III. Thermonuclear ^{25}Al$(p,\gamma)^{26}$Si reaction rate, $N_A\langle\sigma\upsilon\rangle$, in units of cm^3 s^{-1} mol^{-1} as a function of stellar temperature, T, including resonant capture (RC) contributions from individual resonances denoted by J^π and direct capture (DC). N_A is the Avogadro number. The column labeled "Total RC + DC" is the recommended rate, and the final two columns are the rates at the "Low" and "High" uncertainty limits, respectively.

T (GK)	1^+ RC	3^+ RC	0^+ RC	DC	Total RC + DC	Low	High
0.01	1.85×10^{-84}	6.58×10^{-202}	1.18×10^{-217}	1.57×10^{-37}	1.57×10^{-37}	1.10×10^{-37}	2.04×10^{-37}
0.015	4.70×10^{-57}	5.85×10^{-133}	5.32×10^{-144}	1.00×10^{-31}	1.00×10^{-31}	7.01×10^{-32}	1.30×10^{-31}
0.02	2.08×10^{-43}	1.53×10^{-98}	3.14×10^{-107}	4.56×10^{-28}	4.56×10^{-28}	3.19×10^{-28}	5.93×10^{-28}
0.03	7.74×10^{-30}	3.38×10^{-64}	1.55×10^{-70}	1.75×10^{-23}	1.75×10^{-23}	1.22×10^{-23}	2.27×10^{-23}
0.04	4.15×10^{-23}	4.41×10^{-47}	3.04×10^{-52}	1.34×10^{-20}	1.35×10^{-20}	9.45×10^{-21}	1.75×10^{-20}
0.05	4.20×10^{-19}	7.60×10^{-37}	2.66×10^{-41}	1.51×10^{-18}	1.93×10^{-18}	1.40×10^{-18}	2.88×10^{-18}
0.06	1.87×10^{-16}	4.82×10^{-30}	4.98×10^{-34}	5.52×10^{-17}	2.42×10^{-16}	1.16×10^{-16}	6.16×10^{-16}
0.07	1.40×10^{-14}	3.36×10^{-25}	7.53×10^{-29}	9.73×10^{-16}	1.50×10^{-14}	5.65×10^{-15}	4.31×10^{-14}
0.08	3.49×10^{-13}	1.40×10^{-21}	5.62×10^{-25}	1.04×10^{-14}	3.59×10^{-13}	1.27×10^{-13}	1.06×10^{-12}
0.09	4.15×10^{-12}	9.01×10^{-19}	5.66×10^{-22}	7.65×10^{-14}	4.23×10^{-12}	1.46×10^{-12}	1.25×10^{-11}
0.10	2.97×10^{-11}	1.56×10^{-16}	1.41×10^{-19}	4.27×10^{-13}	3.01×10^{-11}	1.03×10^{-11}	8.94×10^{-11}
0.11	1.46×10^{-10}	1.04×10^{-14}	1.26×10^{-17}	1.92×10^{-12}	1.48×10^{-10}	5.06×10^{-11}	4.40×10^{-10}
0.12	5.45×10^{-10}	3.43×10^{-13}	5.31×10^{-16}	7.24×10^{-12}	5.53×10^{-10}	1.89×10^{-10}	1.64×10^{-9}
0.13	1.65×10^{-9}	6.51×10^{-12}	1.24×10^{-14}	2.37×10^{-11}	1.68×10^{-9}	5.79×10^{-10}	4.97×10^{-9}
0.14	4.21×10^{-9}	8.06×10^{-11}	1.84×10^{-13}	6.92×10^{-11}	4.36×10^{-9}	1.55×10^{-9}	1.28×10^{-8}
0.15	9.44×10^{-9}	7.08×10^{-10}	1.89×10^{-12}	1.83×10^{-10}	1.03×10^{-8}	4.03×10^{-9}	2.92×10^{-8}
0.16	1.90×10^{-8}	4.71×10^{-9}	1.44×10^{-11}	4.44×10^{-10}	2.42×10^{-8}	1.13×10^{-8}	6.24×10^{-8}
0.17	3.50×10^{-8}	2.50×10^{-8}	8.58×10^{-11}	1.00×10^{-9}	6.11×10^{-8}	3.43×10^{-8}	1.35×10^{-7}
0.18	6.00×10^{-8}	1.09×10^{-7}	4.18×10^{-10}	2.13×10^{-9}	1.72×10^{-7}	1.02×10^{-7}	3.34×10^{-7}
0.19	9.68×10^{-8}	4.08×10^{-7}	1.71×10^{-9}	4.29×10^{-9}	5.11×10^{-7}	2.88×10^{-7}	9.62×10^{-7}
0.20	1.48×10^{-7}	1.33×10^{-6}	6.08×10^{-9}	8.23×10^{-9}	1.49×10^{-6}	7.88×10^{-7}	2.85×10^{-6}
0.21	2.17×10^{-7}	3.85×10^{-6}	1.91×10^{-8}	1.51×10^{-8}	4.11×10^{-6}	2.08×10^{-6}	7.99×10^{-6}
0.22	3.06×10^{-7}	1.01×10^{-5}	5.37×10^{-8}	2.68×10^{-8}	1.05×10^{-5}	5.20×10^{-6}	2.06×10^{-5}
0.23	4.18×10^{-7}	2.43×10^{-5}	1.38×10^{-7}	4.58×10^{-8}	2.50×10^{-5}	1.22×10^{-5}	4.93×10^{-5}
0.24	5.54×10^{-7}	5.43×10^{-5}	3.26×10^{-7}	7.60×10^{-8}	5.53×10^{-5}	2.68×10^{-5}	1.10×10^{-4}
0.25	7.17×10^{-7}	1.13×10^{-4}	7.18×10^{-7}	1.23×10^{-7}	1.15×10^{-4}	5.56×10^{-5}	2.28×10^{-4}
0.26	9.07×10^{-7}	2.23×10^{-4}	1.49×10^{-6}	1.93×10^{-7}	2.26×10^{-4}	1.09×10^{-4}	4.49×10^{-4}
0.27	1.13×10^{-6}	4.16×10^{-4}	2.91×10^{-6}	2.96×10^{-7}	4.21×10^{-4}	2.03×10^{-4}	8.37×10^{-4}
0.28	1.37×10^{-6}	7.42×10^{-4}	5.40×10^{-6}	4.46×10^{-7}	7.49×10^{-4}	3.61×10^{-4}	1.49×10^{-3}
0.29	1.65×10^{-6}	1.27×10^{-3}	9.62×10^{-6}	6.59×10^{-7}	1.28×10^{-3}	6.16×10^{-4}	2.55×10^{-3}
0.30	1.95×10^{-6}	2.09×10^{-3}	1.64×10^{-5}	9.56×10^{-7}	2.11×10^{-3}	1.01×10^{-3}	4.20×10^{-3}
0.31	2.28×10^{-6}	3.33×10^{-3}	2.71×10^{-5}	1.36×10^{-6}	3.36×10^{-3}	1.61×10^{-3}	6.68×10^{-3}
0.32	2.64×10^{-6}	5.13×10^{-3}	4.32×10^{-5}	1.92×10^{-6}	5.18×10^{-3}	2.49×10^{-3}	1.03×10^{-2}
0.33	3.02×10^{-6}	7.71×10^{-3}	6.69×10^{-5}	2.66×10^{-6}	7.78×10^{-3}	3.75×10^{-3}	1.55×10^{-2}
0.34	3.42×10^{-6}	1.13×10^{-2}	1.01×10^{-4}	3.63×10^{-6}	1.14×10^{-2}	5.49×10^{-3}	2.27×10^{-2}
0.35	3.85×10^{-6}	1.62×10^{-2}	1.48×10^{-4}	4.91×10^{-6}	1.63×10^{-2}	7.85×10^{-3}	3.25×10^{-2}
0.36	4.29×10^{-6}	2.26×10^{-2}	2.13×10^{-4}	6.56×10^{-6}	2.29×10^{-2}	1.10×10^{-2}	4.55×10^{-2}
0.37	4.75×10^{-6}	3.11×10^{-2}	3.00×10^{-4}	8.67×10^{-6}	3.14×10^{-2}	1.51×10^{-2}	6.25×10^{-2}
0.38	5.23×10^{-6}	4.20×10^{-2}	4.15×10^{-4}	1.13×10^{-5}	4.24×10^{-2}	2.04×10^{-2}	8.44×10^{-2}
0.39	5.72×10^{-6}	5.57×10^{-2}	5.63×10^{-4}	1.47×10^{-5}	5.63×10^{-2}	2.71×10^{-2}	1.12×10^{-1}
0.40	6.23×10^{-6}	7.29×10^{-2}	7.52×10^{-4}	1.89×10^{-5}	7.37×10^{-2}	3.55×10^{-2}	1.47×10^{-1}
0.42	7.27×10^{-6}	1.20×10^{-1}	1.28×10^{-3}	3.04×10^{-5}	1.21×10^{-1}	5.84×10^{-2}	2.41×10^{-1}
0.44	8.34×10^{-6}	1.87×10^{-1}	2.08×10^{-3}	4.75×10^{-5}	1.89×10^{-1}	9.14×10^{-2}	3.77×10^{-1}
0.46	9.42×10^{-6}	2.81×10^{-1}	3.22×10^{-3}	7.23×10^{-5}	2.84×10^{-1}	1.37×10^{-1}	5.66×10^{-1}
0.48	1.05×10^{-5}	4.07×10^{-1}	4.80×10^{-3}	1.07×10^{-4}	4.12×10^{-1}	1.99×10^{-1}	8.18×10^{-1}
0.50	1.16×10^{-5}	5.70×10^{-1}	6.91×10^{-3}	1.56×10^{-4}	5.77×10^{-1}	2.78×10^{-1}	$1.15 \times 10^{+0}$

for $T \gtrsim 0.174$ GK. The 0^+ resonance makes only a minor ($\lesssim 1\%$) contribution to the rate in novae and only at the highest temperatures.

The present thermonuclear ^{25}Al$(p,\gamma)^{26}$Si reaction rate differs from that in Ref. [10] by up to a factor of 2.5 at peak nova temperatures of $0.1 < T < 0.4$ GK (Fig. 1, top). Considering the uncertainties this is good agreement. Most importantly, the ratios of upper-to-lower uncertainty limits in the rate are reduced by factors as large as 30 at peak nova temperatures (Fig. 1, bottom).

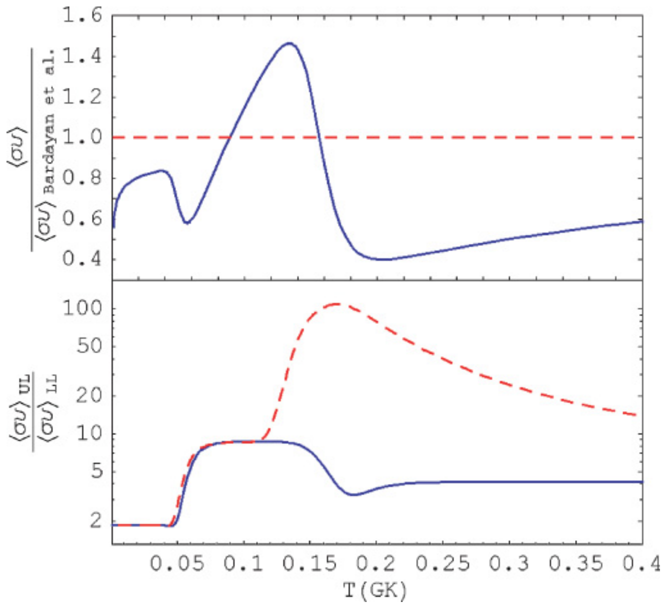

FIG. 1. (Color online) (Top panel) Ratios of the ^{25}Al$(p,\gamma)^{26}$Si reaction rates per particle pair, $\langle\sigma\upsilon\rangle$, from the present work (solid; blue online) and Ref. [10] (dashed; red online) to $\langle\sigma\upsilon\rangle$ from Ref. [10]. (Bottom panel) Ratio of the upper-to-lower uncertainty limits of $\langle\sigma\upsilon\rangle$ estimated in the present work (solid; blue online), and estimated from Ref. [10] (dashed; red online).

V. CONCLUSIONS

By integrating all available information on the ^{25}Al$(p,\gamma)^{26}$Si reaction, the energy of the important $J^{\pi}=3^{+}$ resonance is determined to be 412(2) keV. This results in a large reduction in the thermonuclear reaction-rate uncertainty that is expected to introduce a stringent constraint on the nuclear-physics uncertainty affecting ^{26}Al yields from nova-nucleosynthesis models [6,10,31]. Other uncertainties in the modeling of novae, such as the process of mixing between the white-dwarf core and the accreted envelope [4,7] may dominate the remaining ^{25}Al$(p,\gamma)^{26}$Si reaction-rate uncertainties in this respect. If so, updated predictions of the nova contribution to Galactic ^{26}Al are enabled [6,11]. Such predictions will require extensive astrophysical modeling and are beyond the scope of the present work. Further progress on the ^{25}Al$(p,\gamma)^{26}$Si rate in novae will require reductions in the resonance-strength uncertainties.

ACKNOWLEDGMENTS

The author is grateful to T. A. D. Brown, A. García, and S. Hoedl for careful readings of the manuscript and A. García for discussions on electromagnetic transition strengths. This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Grant No. DE-FG02-97ER41020.

[1] W. A. Mahoney, J. C. Ling, W. A. Wheaton, and A. S. Jacobson, Astrophys. J. **286**, 578 (1984).
[2] R. Diehl, H. Halloin, K. Kretschmer, G. G. Lichti, V. Schönfelder, A. W. Strong, A. von Kienlin, W. Wang, P. Jean, J. Knödlseder *et al.*, Nature (London) **439**, 45 (2006).
[3] N. Prantzos and R. Diehl, Phys. Rep. **267**, 1 (1996).
[4] J. José, M. Hernanz, and A. Coc, Astrophys. J. Lett. **479**, L55 (1997).
[5] J. José, M. Hernanz, S. Amari, K. Lodders, and E. Zinner, Astrophys. J. **612**, 414 (2004).
[6] J. José, A. Coc, and M. Hernanz, Astrophys. J. **520**, 347 (1999).
[7] J. José and M. Hernanz, J. Phys. G **34**, R431 (2007).
[8] M. Limongi and A. Chieffi, Astrophys. J. **647**, 483 (2006).
[9] W. Wang, M. J. Harris, R. Diehl, H. Halloin, B. Cordier, A. W. Strong, K. Kretschmer, J. Knödlseder, P. Jean, G. G. Lichti *et al.*, Astron. Astrophys. **469**, 1005 (2007).
[10] D. W. Bardayan, J. A. Howard, J. C. Blackmon, C. R. Brune, K. Y. Chae, W. R. Hix, M. S. Johnson, K. L. Jones, R. L. Kozub, J. F. Liang *et al.*, Phys. Rev. C **74**, 045804 (2006).
[11] C. Ruiz, A. Parikh, J. José, L. Buchmann, J. A. Caggiano, A. A. Chen, J. A. Clark, H. Crawford, B. Davids, J. M. D'Auria *et al.*, Phys. Rev. Lett. **96**, 252501 (2006).
[12] C. Iliadis, L. Buchmann, P. M. Endt, H. Herndl, and M. Wiescher, Phys. Rev. C **53**, 475 (1996).
[13] P. N. Peplowski, L. T. Baby, I. Wiedenhöver, S. E. Dekat, E. Diffenderfer, D. L. Gay, O. Grubor-Urosevic, P. Höflich, R. A. Kaye, N. Keeley *et al.*, Phys. Rev. C **79**, 032801(R) (2009).
[14] G. Audi, O. Bersillon, J. Blachot, and A. H. Wapstra, Nucl. Phys. **A729**, 3 (2003).
[15] D. Seweryniak, P. J. Woods, M. P. Carpenter, T. Davinson, R. V. F. Janssens, D. G. Jenkins, T. Lauritsen, C. J. Lister, J. Shergur, S. Sinha *et al.*, Phys. Rev. C **75**, 062801(R) (2007).
[16] D. W. Bardayan, J. C. Blackmon, A. E. Champagne, A. K. Dummer, T. Davinson, U. Greife, D. Hill, C. Iliadis, B. A. Johnson, R. L. Kozub *et al.*, Phys. Rev. C **65**, 032801(R) (2002).
[17] J. A. Caggiano, W. Bradfield-Smith, R. Lewis, P. D. Parker, D. W. Visser, J. P. Greene, K. E. Rehm, D. W. Bardayan, and A. E. Champagne, Phys. Rev. C **65**, 055801 (2002).
[18] Y. Parpottas, S. M. Grimes, S. Al-Quraishi, C. R. Brune, T. N. Massey, J. E. Oldendick, A. Salas, and R. T. Wheeler, Phys. Rev. C **70**, 065805 (2004).
[19] Y. K. Kwon, C. S. Lee, J. Y. Moon, J. H. Lee, J. Y. Kim, M. K. Cheoun, S. Kubono, N. Iwasa, K. Inafuku, H. Yamaguchi *et al.*, J. Korean Phys. Soc. **53**, 1141 (2008).
[20] R. A. I. Bell, J. L'Ecuyer, R. D. Gill, B. C. Robertson, I. S. Towner, and H. J. Rose, Nucl. Phys. **A133**, 337 (1969).
[21] A. Parikh, J. A. Caggiano, C. Deibel, J. P. Greene, R. Lewis, P. D. Parker, and C. Wrede, Phys. Rev. C **71**, 055804 (2005).
[22] J.-C. Thomas, L. Achouri, J. Äystö, R. Béraud, B. Blank, G. Canchel, S. Czajkowski, P. Dendooven, A. Ensallem, J. Giovinazzo *et al.*, Eur. Phys. J. A **21**, 419 (2004).
[23] J. C. Hardy and I. S. Towner, Phys. Rev. C **71**, 055501 (2005).
[24] J. C. Hardy, H. Schmeing, W. Benenson, G. M. Crawley, E. Kashy, and H. Nann, Phys. Rev. C **9**, 252 (1974).
[25] P. M. Endt, Nucl. Phys. **A633**, 1 (1998), www.nndc.bnl.gov/ensdf.
[26] E. K. Warburton and J. Weneser, *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North Holland, Amsterdam, 1969).

[27] C. Iliadis, P. M. Endt, N. Prantzos, and W. J. Thompson, Astrophys. J. **524**, 434 (1999).
[28] C. Iliadis, *Nuclear Physics of Stars* (Wiley-VCH, Weinheim, 2007).
[29] A. R. Barnett, Comput. Phys. Commun. **27**, 147 (1982).
[30] C. Iliadis, J. M. D'Auria, S. Starrfield, W. J. Thompson, and M. Wiescher, Astrophys. J. Suppl. Ser. **134**, 151 (2001).
[31] C. Iliadis, A. Champagne, J. José, S. Starrfield, and P. Tupper, Astrophys. J. Suppl. Ser. **142**, 105 (2002).