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M. R. Hall *et al.*

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M.R. Hall,[1,2,*] D.W. Bardayan,[1] T. Baugher,[3] A. Lepailleur,[3] S.D. Pain,[2] A. Ratkiewicz,[3] S. Ahn,[4] J.M. Allen,[1] J.T. Anderson,[5] A.D. Ayangeakaa,[5] J.C. Blackmon,[6] S. Burcher,[7] M.P. Carpenter,[5] S.M. Cha,[8] K.Y. Chae,[8] K.A. Chipps,[2] J.A. Cizewski,[3] M. Febbraro,[2] O. Hall,[1,9] J. Hu,[1] C.L. Jiang,[5] K.L. Jones,[7] E.J. Lee,[8] P.D. O'Malley,[1] S. Ota,[10] B.C. Rasco,[6] D. Santiago-Gonzalez,[6] D. Seweryniak,[5] H. Sims,[3,9] K. Smith,[7] W.P. Tan,[1] P. Thompson,[2,7] C. Thornsberry,[7] R.L. Varner,[2] D. Walter,[3] G.L. Wilson,[6,11] and S. Zhu[5,12]

[1] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3] *Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903, USA*
[4] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[5] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[6] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[7] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[8] *Department of Physics, Sungkyunkwan University, Suwon 16419, South Korea*
[9] *Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[10] *Physics Division, Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[11] *Department of Physics and Applied Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[12] *National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York 11973, USA*

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Background: Nova explosions synthesize elements up to $A \simeq 40$, and discrepancies exist between calculated and observed abundances of Ar and Ca created in the explosion. The ^{38}K(p,γ)^{39}Ca reaction rate has been shown to be influential on these isotopic abundances at the endpoint of nova nucleosynthesis. The energies of the three most important resonances, corresponding to $J^\pi = 5/2^+$ excited states in the ^{39}Ca nucleus above the proton separation threshold, are uncertain and one has been measured with conflicting values (E_r = 679(2) versus E_r = 701(2) keV) in previous experiments.

Purpose: Reducing the uncertainties on the resonance energies would allow for a better understanding of the reaction rate. To improve these uncertainties, we searched for γ rays from the depopulation of the corresponding excited states in ^{39}Ca.

Methods: We report a new measurement of these resonance energies via the observation of previously unobserved γ-ray transitions. These transitions were observed by studying the ^{40}Ca(^{3}He,$\alpha\gamma$)^{39}Ca reaction with Gammasphere ORRUBA Dual Detectors for Experimental Structure Studies (GODDESS). The updated resonance energies were then used to calculate the ^{38}K(p,γ)^{39}Ca reaction rate and assess its uncertainties.

Results: In total, 23 new transitions were found, including three γ-ray transitions corresponding to the three $J^\pi = 5/2^+$ states of astrophysical interest at energies of 6156.2(16), 6268.8(22), and 6470.8(19) keV. These correspond to resonance energies in the ^{38}K(p,γ)^{39}Ca reaction of 386(2), 498(2), and 701(2) keV.

Conclusions: Updated ^{38}K(p,γ)^{39}Ca reaction rate calculations show a reduced upper limit at nova temperatures. However, the lower-than-previously-measured energy of the 498-keV resonance and uncertainty in its resonance strength increases the upper limit of the rate close to previous estimates at 0.4 GK.

I. INTRODUCTION

Classical novae occur in binary star systems that contain a white dwarf and a main sequence star that has filled its Roche lobe. Because of this, the white dwarf can accrete hydrogen-rich material from the main sequence star, eventually resulting in a thermonuclear runaway on its surface [1]. The composition of the white dwarfs involved in the explosion generally fall into two categories—carbon and oxygen (CO) or oxygen and neon (ONe)—depending on the mass of the original star. The nucleosynthesis that occurs during the nova explosion evolves through a series of proton-induced reactions and β^+ decays on the proton-rich side of stability.

* mhall12@alumni.nd.edu

Both theoretical calculations and observations of nova ejecta agree that the endpoint of nova nucleosynthesis on ONe white dwarfs is around ^{40}Ca, with maximum temperatures reaching ~ 0.4 GK [2, 3]. While the endpoint is generally agreed upon, discrepancies exist in the final abundances of isotopes estimated via theory and observation. Theoretical estimates find that the abundances of Ca and Ar isotopes created in the explosion should be similar to solar abundances [3]. However, estimates derived from observations point toward an enhancement of these isotopic abundances compared to their solar values [4], indicating higher temperatures than predicted may be reached.

The solution to this discrepancy may lie within the various statistical-model reaction rates used to calculate the synthesized abundances. Very little experimental information exists for the reaction rates of nuclei with mass $A > 34$ that are involved in the nucleosynthesis. Previously, the rates for the majority of these reactions were based solely on Hauser-Feshbach calculations [5]. Using these calculations, Illiadis *et al.* [5, 6] investigated the effect of various reaction-rate uncertainties on the final abundances of isotopes using different nova explosion models. In these sensitivity studies, the ^{38}K(p,γ)^{39}Ca reaction had a large effect on the abundances of ^{38}Ar, ^{39}K, and ^{40}Ca generated in the explosion. Iliadis *et al.* [6] assumed an uncertainty of a factor of 100 up and down from the mean calculated value. These uncertainties were determined based on comparisons of experimentally determined (p,γ) reaction rates to Hauser-Feshbach calculations, where the rates of reactions on $T_z = 0$ nuclei were found to differ by up to a factor of 10^3 [5]. Using these uncertainties, the maximum variations on the abundances of these three isotopes were factors of approximately 25, 136, and 58, respectively [6, 7].

The ^{38}K(p,γ)^{39}Ca reaction rate is thought to be dominated by $\ell = 0$ resonances, which are associated with excited states in ^{39}Ca above the proton threshold (S_p = 5770.9(6) keV [8]). The $\ell = 0$ resonances in the ^{38}K+p system will have a spin-parity of $5/2^+$ or $7/2^+$ since the ground state spin-parity of ^{38}K is $J^\pi = 3^+$. Three $5/2^+$ levels have been previously identified above the proton threshold, with energies of 6157 ± 10, 6286 ± 10, and 6460 ± 10 keV [9], thereby having resonance energies of 386 ± 10, 515 ± 10, and 689 ± 10 keV. The 10-keV uncertainty alone results in the astrophysical reaction rate being uncertain by factors of 2-10 from T = 0.1-0.4 GK. It should also be noted that $\ell = 1$ resonances may also play an important role in the reaction rate due to the 2s orbital being full in the ^{38}K ground state, whereas the 2p orbitals are unoccupied. However, previous studies have only concentrated on excited states in ^{39}Ca corresponding to $\ell = 0$ resonances when calculating the ^{38}K(p,γ)^{39}Ca rate.

Recent experimental efforts have focused on measuring the resonance strengths and improving the resonance-energy uncertainties for the three $\ell = 0$ resonances to better understand the ^{38}K(p,γ)^{39}Ca reaction rate. Lotay *et al.* [7, 10] measured the reaction directly in inverse kinematics using the DRAGON recoil separator at TRIUMF. In this measurement, yield was observed for an apparent resonance at $E_r = 679^{+2}_{-1}$(stat)$\pm$1(sys) keV, with a corresponding resonance strength of 120^{+50}_{-30}(stat)$^{+20}_{-60}$(sys) meV. For the 386- and 515-keV resonances, the DRAGON gas target was tuned to cover center-of-mass energies of 386 ± 13 and 515 ± 13 keV [10]. However, these two resonances were unobserved, and upper limits were set for their resonance strengths of $\leqslant 2.54$ and $\leqslant 18.4$ meV, respectively. Using these resonance strengths, new constraints were placed on the ^{38}K(p,γ)^{39}Ca reaction rate, and the calculated uncertainty on the rate for $T > 0.3$ GK was reduced from a total factor of 10^4 to a factor of ~ 40 [7, 10].

Most recently, the ^{40}Ca(^{3}He,α)^{39}Ca reaction was measured by Setoodehnia *et al.* [11] using the TUNL high resolution Enge split-pole magnetic spectrograph to study the structure of ^{39}Ca. In addition to the many other levels observed in the experiment, two of the three important $5/2^+$ energy levels in ^{39}Ca were observed. The excitation energies (E_x) for these two levels were determined to be 6154(5) and 6472.2(24) keV (E_r = 383 and 701.3 keV). The energy measured for the 701-keV resonance was somewhat surprising when compared with the results of Refs. [7, 10], where $E_r = 679 \pm 2$ keV had been extracted. It is noted in Ref. [11] that a resonance at E_r = 701 keV would have occurred on the leading edge of the DRAGON gas target, meaning the measurement by Refs. [7, 10] may not have been able to accurately measure the strength of that resonance. Nevertheless, the ^{38}K(p,γ)^{39}Ca reaction rate was estimated by scaling the resonance strengths found by Refs. [7, 10] for the new resonance energies. It was found that the new reaction rate was up to a factor of 1.4 higher at low temperatures than previously estimated.

We report a measurement of the ^{40}Ca(^{3}He,$\alpha\gamma$)^{39}Ca reaction, which was performed to resolve some of the discrepancies in the previously measured resonance energies. By extension, this measurement aimed to reduce the uncertainty of the ^{38}K(p,γ)^{39}Ca reaction rate upper limit determined in previous measurements.

II. EXPERIMENTAL SETUP

To search for γ rays from the depopulation of the states of interest, the ^{40}Ca(^{3}He,$\alpha\gamma$)^{39}Ca reaction was studied. A 30-MeV ^{3}He beam was delivered by the ATLAS accelerator at Argonne National Laboratory onto a 938-μg/cm^2 CaF_2 target, used to simultaneously measure the ^{19}F(^{3}He,tγ)^{19}Ne reaction [12, 13]. The γ rays and reaction α particles were measured in coincidence using Gammasphere ORRUBA Dual Detectors for Experimental Structure Studies (GODDESS) [14–16], which couples the high-purity germanium detector array Gammasphere [17] with the Oak Ridge Rutgers University Barrel Array (ORRUBA) [18].

The charged particles produced in the experiment were measured by six ΔE-E telescopes in the ORRUBA barrel, which covered an angular range of approximately 45° to 90°. These telescopes consisted of a 65-μm-thick BB10 detector and a 1000-μm-thick Super X3 (SX3) detector. The SX3 detectors provided an angular resolution on the order of 1°, which aided in the Doppler reconstruction of the coincident γ-ray events. A particle identification (PID) spectrum showing the deposited energy in one of the BB10-SX3 detector telescopes at $\theta_{lab} \approx 50°$ is shown in Fig. 1. From these PID spectra, events corresponding to (^{3}He, α) reactions in the target could be separated from (^{3}He, p), (^{3}He, d), (^{3}He, t), and (^{3}He, ^{3}He).

The γ rays produced in the depopulation of ^{39}Ca excited states were detected by Gammasphere, in coincidence with the α particles produced in the reaction. Due to the very short lifetimes ($\tau < 1$ ps) of most of the excited states in ^{39}Ca, the Gammasphere spectra needed to

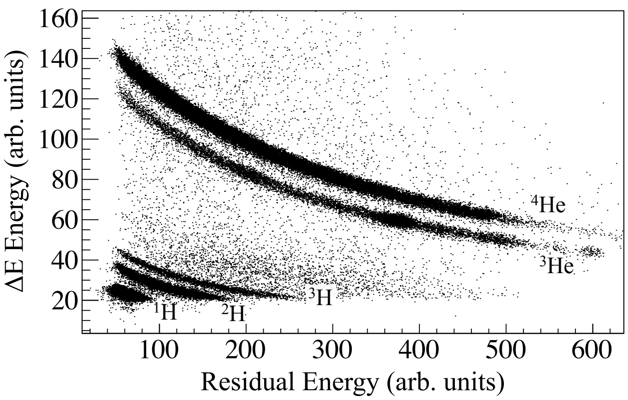

FIG. 1. Particle identification spectrum plotting the particle energy detected in one strip of the BB10 (y-axis) and Super X3 detectors (x-axis) at $\theta_{lab} \approx 50^\circ$. The reaction channel of interest was selected by gating on the ^{4}He nuclei in this spectrum.

be Doppler corrected, since the ^{39}Ca recoils were moving when they decayed. The Doppler angle was determined by comparing the recoil angle to the Gammasphere detector angle for each event, where the recoil angle was reconstructed using the detected α particle energy and angle. The velocities of the ^{39}Ca nuclei ranged between $\beta = 0.01$ and 0.015 for α particles detected close to 45° and 90°, respectively. When applying the Doppler correction, γ-ray peaks from all other sources were smeared out relative to the peaks of interest in the spectra. This allowed the transitions from short-lived ^{39}Ca states to be uniquely identified.

III. RESULTS

A. ^{39}Ca γ rays and level energies

The energy levels and γ rays observed in the present experiment are summarized in Table I. All of the reported transitions were determined by leveraging α-γ-γ coincidences, unless the transition was direct to the ground state. For transitions to the ground state, the γ-ray multiplicity in the event was required to be exactly one. That is, for any detected α particle it was required that only one γ ray was detected within the specified timing window. Doing so greatly reduced the random γ ray background, allowing weak transitions to be identified. For levels where more than one transition was observed, the level energy was calculated by taking the average of the level energy from each cascade, inversely weighted by their uncertainties. Each of the excitation energies also included a recoil correction given by

$$E_{Recoil} = \frac{E_\gamma^2}{2Mc^2}, \quad (1)$$

where E_γ is the γ-ray energy and M is the ^{39}Ca mass in keV/c^2. In this case, the recoil correction ranged from 0.1 to 0.7 keV for γ-ray energies between 2000 and 7000 keV.

TABLE I. Level energies important in the ^{38}K(p,γ)^{39}Ca reaction rate are shown in bold.

$E_x{}^a$ (keV)	$J^{\pi\, b}$	E_γ (keV)	I_γ	E_f (keV)
2466.6(5)	$1/2^+$	2466.5(5)	100	0
2795.7(6)	$7/2^-$	2795.6(6)	100	0
3024.5(7)	$3/2^-$	3024.4(7)	100	0
3638.6(6)	$(9/2^-)$	842.9(3)	70.0(30)	2796
		3638.5(13)	30.0(30)	0
3820.3(10)	(1/2,3/2,5/2)	3820.1(10)	100	0
3890.1(5)	$(11/2^-)$	251.5(4)	30.1(12)	3639
		1094.4(3)	69.3(12)	2796
3937.5(8)	$(3/2^-)$	1470.8(10)†	17.7(10)	2467
		3937.4(11)	82.3(10)	0
3949.9(7)	$(3/2^-)$	1154.2(3)	100	2796
4017.0(7)	$1/2^+$	1550.4(4)	100	2467
4340.3(7)	$(9/2^-)^c$	451.0(14)†	13.5(30)	3890
		701.2(5)†	86.5(30)	3639
5070.5(15)	$3/2^+,5/2^+$	5070.1(15)†	100	0
5125.3(13)	$5/2^+$	5124.9(13)†	100	0
5153.9(24)	$(11/2^-)$	1263.7(24)	100	3890
5226.0(22)	$3/2^+,5/2^+$	5225.7(22)†	100	0
5396.0(14)	$(13/2^-)$	1595.8(14)	100	3890
5483.4(14)	$5/2^+$	5483.0(14)†	100	0
5589.9(22)	$3/2^+,5/2^+$	5589.5(22)†	100	0
5682.9(18)	$3/2^+,5/2^+$	5682.5(18)†	100	0
5735.8(36)	$(5/2^-,7/2^-)$	5735.3(36)†	100	0
5786.1(24)	$1/2^-,3/2^-$	5785.6(24)†	100	0
5849.9(19)	$1/2^-,3/2^-$	5849.4(19)†	100	0
6093.7(19)	$(1/2^+)$	6093.2(19)†	100	0
6156.7(16)	$5/2^+$	6156.2(16)†	100	0
6174.1(12)†	$(11/2^-,13/2^+)^c$	2283.9(11)†	100	3890
6269.3(22)	$5/2^+$	6268.8(22)†	100	0
6407.5(14)	$5/2^-,7/2^-$	3612.9(10)†	95.2(10)	2796
		6401.1(53)†	4.8(10)	0
6424.3(18)	$(15/2^+)$	1028.5(12)	100	5396
6471.4(19)	$5/2^+$	6470.8(19)†	100	0
6509.2(27)	$3/2^+,5/2^+$	6508.6(27)†	100	0
6591.1(66)	$5/2^-,7/2^-$	6590.5(66)†	100	0
6793.4(30)	$3/2^+,5/2^+$	6792.8(30)†	100	0
6901.2(26)	$1/2^+$	6900.5(26)†	100	0

†Newly observed levels and transitions in this work.
^{a}Excitation energies determined in this work.
^{b}Spin-parities from Ref. [19].
^{c}Updated spin-parities based on transitions and branching ratios observed in the mirror nucleus.

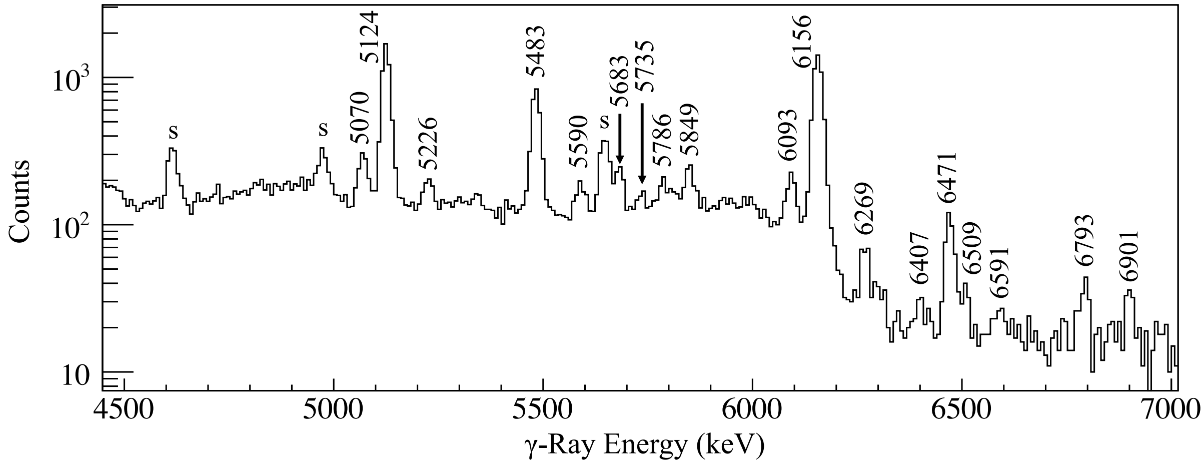

FIG. 2. Summed, Doppler-corrected Gammasphere spectrum gated on the detected ^{4}He nuclei, timing between the silicon and germanium detectors, and a γ-ray multiplicity of 1. Single-escape peaks (s) and direct ground state transitions are shown in the spectrum, with the transitions labeled by their energies.

In total, 37 transitions from 32 energy levels were identified. Of the 37 transitions observed, 23 of them are first observed in this work. The only levels with lifetimes long enough such that their transitions did not require a Doppler correction were the states at 2795.7, 3638.6, 3890.1, and 3949.9 keV. All of the levels requiring a Doppler correction are therefore constrained as having a lifetime less than 1 ps. A Doppler-corrected spectrum showing candidate ground state transitions, from excited states with energies greater than 5000 keV, identified in the experiment is shown in Fig. 2. These transitions are likely to be directly to the ground state due to the first excited state in ^{39}Ca being relatively high in energy (E_x = 2467 keV), and since these transitions do not appear in coincidence with γ rays from the first few excited states. The majority of the observed level energies and transitions agree well with previous measurements. Those levels that differ from previous measurements are outlined below, as well as observations for the three $J^\pi = 5/2^+$ states important in the ^{38}K(p,γ)^{39}Ca reaction rate.

1. *Notable energy levels*

***E_x* = 4340.3(7) keV:** This level was previously reported as having an energy of 4332(10) keV and spin-parity of $5/2^-$ or $7/2^-$ [19]. Two new low-energy transitions were observed for this level to the 3639-keV [$J^\pi = (9/2^-)$] and 3890-keV [$J^\pi = (11/2^-)$] levels. The 4520-keV [$J^\pi = 9/2^-$] level in the mirror nucleus, ^{39}K, exhibits similar decays to the 3944-keV [$J^\pi = 11/2^-$] and 3597-keV [$J^\pi = 9/2^-$] states. Therefore, we have tentatively assigned a new spin-parity of $J^\pi = (9/2^-)$ to this state.

***E_x* = 5589.9(22) keV:** This state was first observed by Matoba *et al.* [9] with an excitation energy of E_x = 5588(10) keV. A state with a similar excitation energy was also found at four angles in the ^{40}Ca(^{3}He,α)^{39}Ca experiment by Setoodehnia *et al.* [11]; however, the excitation energy was measured to be much lower, at 5537(6) keV. Both of these measurements tentatively assigned spin-parities of $3/2^+$ or $5/2^+$. We observe a ground state transition with an energy of 5589.5(22) keV, which agrees well with the energy measured by Matoba *et al.* [9]. The transition to the ground state ($J^\pi = 3/2^+$) also supports either of the previously assigned spin-parities.

***E_x* = 6093.7(19) keV:** This level was observed by Matoba *et al.* [9] with an energy of 6094(10) keV and tentatively assigned a spin and parity of $1/2^+$. This state was also observed in the measurement by Setoodehnia *et al.* [11] with an excitation energy of 6083(7) keV. In that measurement, spin-parities of $7/2^+$ or $9/2^+$ were determined based on DWBA fits to α angular distributions from the ^{40}Ca(^{3}He,α)^{39}Ca reaction. It is noted in Ref. [11] that this state could be important in the ^{38}K(p,γ)^{39}Ca reaction rate based on these updated spin-parities.

A transition to the ground state is observed in the data corresponding to an excitation energy of E_x = 6093.7(19) keV, which agrees well with the previous measurements for the energy of this state. Since the spin-parity of the ^{39}Ca ground state is $3/2^+$, the spin-parity of $9/2^+$ suggested by Ref. [11] can be confidently ruled out. However, a spin-parity of $7/2^+$ is possible, since the observed transition would be of E2 character. Further studies targeting the spin of this state are necessary to assess its importance to the ^{38}K(p,γ)^{39}Ca reaction rate.

***E_x* = 6174.1(12) keV:** This level has not been observed in previous measurements. One transition was found for this level to the 3890-keV state with an energy of E_γ = 2283.9(11) keV. The mirror of the 3890-keV state is most likely the 3944-keV state [$J^\pi = 11/2^-$] in ^{39}K.

In the mirror nucleus, only three levels between 6.0 and 6.5 MeV have been observed to depopulate to the 3944-keV state—the 6006-, 6192-, and 6434 keV states [19]. The 6006- [$J^\pi = 11/2^-$] and 6434-keV [$J^\pi = 13/2^+$] levels decay exclusively to the 3944-keV state, whereas the 6192-keV [$J^\pi = (7/2^-)$] state has been observed to have an additional, larger branch to the 4520-keV state. A second branch was searched for in the current data to the 4340-keV state but was not found. Therefore, we assign spin-parities of $11/2^-$ or $13/2^+$ to this state based on the previous observations in the mirror.

2. *Energy levels important for* ^{38}K(p,γ)^{39}Ca

***E_x* = 6156.7(16) keV:** The first of the three $J^\pi = 5/2^+$ states was observed at 6156.7(16) keV via a transition directly to the ground state. This level energy corresponds to a resonance energy of 386 keV in the ^{38}K+p system. The measured excitation energy is in good agreement with previous studies. Prior to this experiment, the most precise measure of this level energy came from Setoodehnia *et al.* [11], who measured an energy of $E_x = 6154(5)$ keV. Constraining the uncertainty of this level energy to 1.6 keV reduces the rate uncertainty due to the resonance energy from a factor of ~ 3 to a factor of ~ 1.2 at low temperatures.

***E_x* = 6269.3(22) keV:** The location of the second of the three $5/2^+$ states has been the least certain in previous measurements. The energy of this $5/2^+$ state was first measured at 6286(10) keV [9]. This state was not found in the measurements of Refs. [10, 11]; however, Setoodehnia *et al.* [11] did observe a large peak near this energy at multiple angles, and its α angular distribution from the ^{40}Ca(^{3}He,α)^{39}Ca reaction agreed with a $3/2^+$ or $5/2^+$ assignment. A weighted average energy of 6226(10) keV was adopted for this state, but due to large, correlated shifts in energy at various detection angles it was determined that this state could have been from a contaminant.

The only γ-ray transition observed in the present experiment in this region is a transition to the ground state, with an energy of 6268.8(22) keV, most likely depopulating the aforementioned $J^\pi = 5/2^+$ state. This supports the hypothesis in Ref. [11] that their 6226-keV peak was from a contaminant. The resonance energy for this $\ell = 0$ resonance is $E_r = 498(2)$ keV. The gas target of Refs. [7, 10] covered center-of-mass energies of $E_{\rm c.m.} = 515\pm13$ keV, and therefore could not have set an upper limit on this resonance strength.

***E_x* = 6471.4(19) keV:** The third $\ell = 0$ resonance in the ^{38}K(p,γ)^{39}Ca reaction rate arises from the $E_x =$ 6471.4-keV level in ^{39}Ca ($E_r = 701$ keV). This level was previously measured with excitation energies of 6450(30) keV [20] and 6467(10) keV [9]. Based on these measurements, the gas target of Refs. [7, 10] covered a center-of-mass energy of $E_{\rm c.m.} = 689\pm13$ keV [$E_x = 6460(13)$ keV]. They observed a resonance at $E_r = 679(2)$ keV, which corresponds to an excitation energy of $E_x = 6450(2)$ keV in ^{39}Ca and were able to get a measure of the resonance strength. However, in the experiment by Setoodehnia *et al.* [11], this level was measured with an excitation energy of 6472.2 keV, which disagrees with the measurement made by Refs. [7, 10].

We measure a γ ray with an energy of 6470.8(19) keV, which most likely corresponds to a depopulation of the state to the ground state. This level energy is in good agreement with that measured by Setoodehnia *et al.* [11]. It is noted in Ref. [11] that this resonance would have been in the entrance of the DRAGON target, rather than the center as intended. The gas density is not homogenized in this region, and the calculated resonance strength, which depends on the gas density via the stopping power, may not have been accurately measured.

B. ^{38}K(p,γ)^{39}Ca reaction rate calculations

Due to the limited information available on the energy levels of the ^{39}Ca nucleus, estimates of the ^{38}K(p,γ)^{39}Ca reaction rate and its uncertainties are difficult to assess. Since the energies found for the 386- and 701-keV resonances are in good agreement with previous measurements, the resonance strengths used in Ref. [11] were also used in the following calculations. However, for the 498-keV resonance, a different approach was taken, since the resonance could not have been observed in the DRAGON measurement [7, 10].

To calculate the reaction rate contribution and its uncertainties from the 498-keV resonance, the resonance strength, $\omega\gamma$, must be theoretically estimated. The resonance strength for the ^{38}K(p,γ)^{39}Ca reaction is given by

$$\omega\gamma = \frac{2J_{^{39}\mathrm{Ca}}}{(2J_{^{38}\mathrm{K}}+1)(2J_p+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma_p+\Gamma_\gamma}, \quad (2)$$

where $J_{^{39}\mathrm{Ca}}$, $J_{^{38}\mathrm{K}}$, and J_p are the spins of the resonant state in ^{39}Ca, the ground state of ^{38}K, and the proton, respectively. Γ_p and Γ_γ are the proton and γ partial widths of the resonant state in the compound nucleus, ^{39}Ca. Since information regarding the partial widths and mirror state of the 498-keV resonance were not available, it was assumed in the following calculations that $\Gamma_\gamma \gg \Gamma_p$. This assumption means that the resonance strength only depends on Γ_p, which can be estimated theoretically [21] via

$$\Gamma_\ell(E) = \frac{2\hbar c}{R_n}\left[\frac{2E}{\mu c^2}\right]^{1/2} P_\ell(E,R_n)\theta_\ell^2, \quad (3)$$

where R_n is the radius, E is the excitation energy, μ is the reduced mass of the ^{38}K+p system, θ_ℓ^2 is the reduced width, and P_ℓ is the penetration factor given by

$$P_\ell = \frac{1}{F_\ell^2+G_\ell^2}. \quad (4)$$

In the above equation, F_ℓ and G_ℓ are the regular and irregular Coulomb wave functions, respectively.

Using this method, the resonance strength was calculated for the 498-keV resonance for spectroscopic factors (and hence, θ_ℓ^2) ranging between 0.01 and 0.1, which is a measure of the single-particle nature of the state. These spectroscopic factors were chosen based on those estimated in Ref. [7]. Doing so yields resonance strengths between 2.46 and 24.6 meV. Since the resonances are narrow and isolated, the reaction rate for the ^{38}K(p,γ)^{39}Ca reaction can be calculated analytically [in units of cm^3·s^{-1}·mol^{-1}] via

$$N_A\langle\sigma v\rangle_r = \frac{1.5399\times10^{11}}{T_9^{3/2}}\left(\frac{M_0+M_1}{M_0M_1}\right)^{3/2} \times\sum_i(\omega\gamma)_i\exp\left(\frac{-11.605E_i}{T_9}\right), \quad (5)$$

where T_9 is the temperature in GK, M_0 and M_1 are the atomic masses of the proton and ^{38}K, E_i is the resonance energy in MeV, and $(\omega\gamma)_i$ is the resonance strength for that resonance in MeV.

The contributions of the individual resonances were explored, as well as the effect that the current measurement has on the overall reaction rate. The upper limits of the reaction rate presented in previous measurements did not consider the energy uncertainties associated with the resonances, which in some cases were large and considerably affected the rate. Therefore, these uncertainties are considered in the following discussions.

1. *The 386-keV resonance*

The contribution of the 386-keV resonance to the ^{38}K(p,γ)^{39}Ca reaction rate is the most important of the three resonances; therefore, constraining its energy has a large effect on the total rate. The relatively large uncertainties on the resonance energy in previous measurements were considered and compared to the new uncertainty determined in the present experiment.

Figure 3 shows the individual contributions from the 1σ upper limit of the 386-keV resonance energy to the ^{38}K(p,γ)^{39}Ca reaction rate, compared to the upper limit reported in Ref. [7], which did not include resonance-energy uncertainties (i.e. the mean upper limit). At low temperatures, the 10- and 5-keV uncertainties on the resonance energy from Refs. [7, 11], respectively, contribute an additional factor of $\sim$2.8 to the upper limit of the rate, whereas at high temperatures this is reduced to an additional factor of $\sim$1.4. The reduced uncertainty on the resonance energy in the present measurement (σ_E = 2 keV) improves these factors to 1.2 at low temperatures and 1.05 at high temperatures.

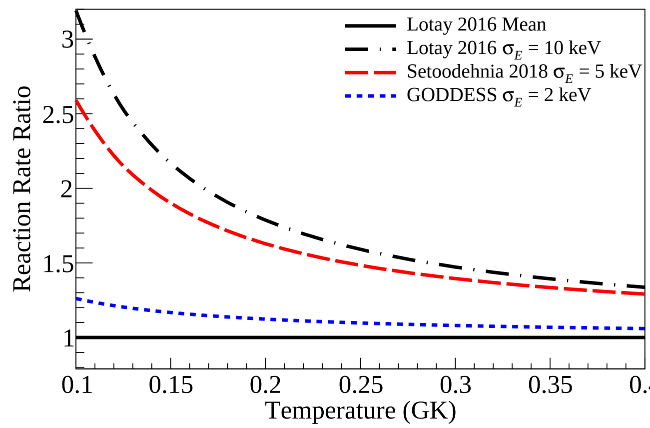

FIG. 3. The ratios of the individual contribution of the 386-keV resonance to the mean value of the contribution calculated from Refs. [7, 10] (Lotay 2016). The 1σ upper limit of the contribution is reduced to less than a factor of 1.3 with the resonance strength held constant in the present study.

2. *The 498-keV resonance*

Using the calculated resonance strengths ranging between 2.47 and 24.7 meV, the upper and lower limit of the fractional contribution of the 498(2)-keV resonance to the ^{38}K(p,γ)^{39}Ca reaction rate was calculated. In the calculations for the present work, resonance energies of 386 and 701 keV and resonance strengths of 2.54 and 126 meV, respectively, were used for the other two resonances considered. Figure 4 shows the upper and lower limit of the calculated fractional contribution compared to the mean upper limit contribution in Refs. [7, 10]. Since this state was measured with a much lower resonance energy (498 keV versus 515 keV), the upper limit of the fractional contribution is much higher than previously considered. At high temperatures, the fractional contribution from this resonance has a large variation based on the chosen energy and resonance strength. The upper and lower limit of the fractional contribution ranges between 3% and 28% at temperatures of 0.4 GK. In the following discussion of the overall reaction rate, only the upper limit of the resonance strength is used for this resonance to meaningfully compare these results with the upper limits from previous publications [7, 11].

3. *Total reaction rate*

All three of the above resonances were used to calculate the total reaction rate using Eq. 5. To compare the upper limit of the ^{38}K(p,γ)^{39}Ca reaction rate from Refs. [7, 11], the 1σ upper limit was used for each of the resonance energies and resonance strengths that had a quantified uncertainty. The 1σ upper limit was chosen to ensure consistency with the resonance strength determined in the DRAGON measurements [7, 10]. Note that the lower

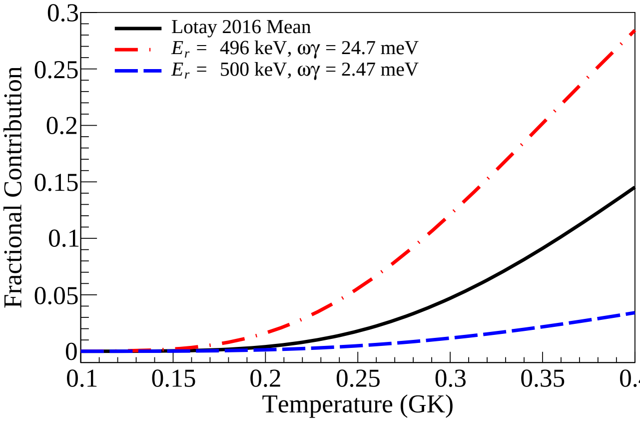

FIG. 4. The fractional contribution of the 498-keV resonance to the overall reaction rate. The resonance strengths used in the present work were estimated theoretically with assumed proton spectroscopic factors of 0.01 and 0.1. The upper limit of the fractional contribution from this resonance is much higher than shown in Refs. [7, 10] (Lotay 2016).

limit of the rate is experimentally unconstrained.

Table III shows the excitation energies, resonance energies, and resonance strengths from the present work and those reported in Refs. [7, 11]. In the present work, the resonance strengths for the 386- and 701-keV resonances were assumed from prior analyses, whereas the resonance strength for the 498-keV resonance was calculated as explained in Section III B.

TABLE II. Resonance parameters used in the calculation of the total ^{18}K$(p,\gamma)^{39}$Ca reaction rate are shown. The resonance strengths reported in Ref. [11] were scaled from those of Ref. [7].

Ref.	E_x (keV)	E_r (keV)	$\omega\gamma$ (meV)
	6157(10)	386(10)	$\leqslant$2.54
Christian *et al.* [7]	6286(10)	515(10)	$\leqslant$18.4
	6450(2)	679(2)	120(25)
	6154(5)	383(5)	$\leqslant$2.6
Setoodehnia *et al.* [11]	6286(10)	515(10)	$\leqslant$18.4
	6472.2(24)	701.3(25)	126(39)
	6156.7(16)	386(2)	$\leqslant$2.54^a
Present Work	6269.3(22)	498(2)	2.47 - 24.7
	6471.4(19)	701(2)	126(39)^b

^{a}Resonance strength from Ref. [7]
^{b}Resonance strength from Ref. [11].

The upper limits of the ^{38}K$(p,\gamma)^{39}$Ca reaction rate including the resonance-energy uncertainties and resonance strength uncertainties from Refs. [7, 11] and the present work can be seen in Fig. 5, compared to the mean upper limit calculated in Refs. [7, 10]. Also shown are the uncertainties on the Hauser-Feshbach calculations by Iliadis *et al.* [5]. Figure 6 shows the ratios of the three upper limits to the mean of the upper limit calculated by Christian *et al.* [7]. The uncertainties on the resonance energies and resonance strengths in Refs. [7, 11] result in an additional factor of 1.9-2.2 at low temperatures and $\sim$ 1.2 at high temperatures.

In the present analysis, including the new resonance-energy uncertainties and parameters for the 498-keV resonance reduces these additional uncertainties at low temperatures to a factor less than 1.3. At higher temperatures, the upper limit approaches that of Refs. [7, 11] as a result of the 498-keV resonance playing a larger role in the reaction rate due to its lower resonance energy (see Fig. 4). At these temperatures, the additional factor on the reaction rate upper limit rises to 1.2. Therefore, this resonance could be more important than previously thought and should be a focus of future measurements.

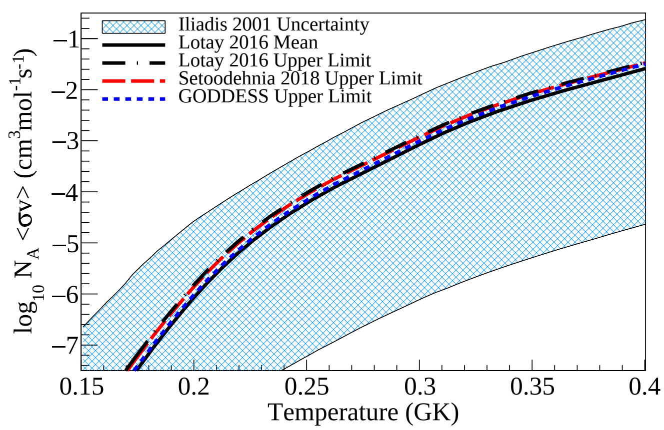

FIG. 5. Upper limits of the total ^{38}K$(p,\gamma)^{39}$Ca reaction rate from the present work and Refs. [7, 10] (Lotay 2016) and [11] (Setoodehnia 2018). Energy uncertainties that were previously neglected were included in the calculation of the upper limits. Also shown are the mean rate from Ref. [7] and Hauser-Feshbach rate uncertainty band [6] (Iliadis 2001) as presented in Refs. [7, 10], for comparison.

C. Nucleosynthesis Simulations

To investigate how the uncertainties on the ^{38}K$(p,\gamma)^{39}$Ca reaction rate affect the final abundances of ^{38}Ar, ^{39}K, and ^{40}Ca produced in nova explosions, nucleosynthesis simulations were performed. The simulations were carried out using the Computational Infrastructure for Nuclear Astrophysics [22, 23] on ONeMg white dwarfs (WD) with masses of 1.15, 1.25, and 1.35 solar masses ($M_\odot$) [24]. All other reaction rates in the reaction network were taken from the REACLIB v2.0 library [25].

The abundances found using the upper limits of the ^{38}K$(p,\gamma)^{39}$Ca reaction rate from Lotay *et al.* [10] (i.e. in-

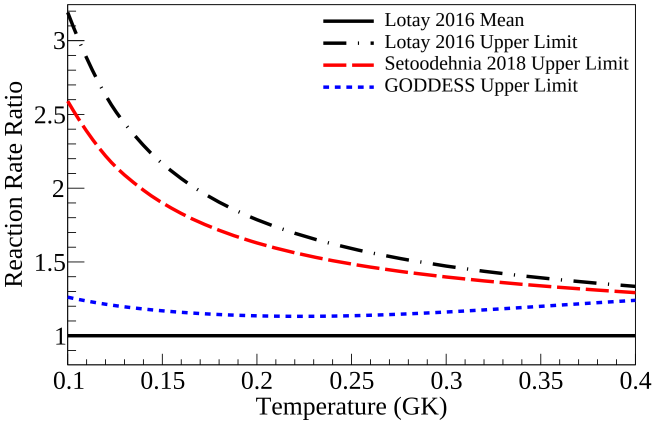

FIG. 6. Ratios of the 1σ upper limits from Fig. 5 to the mean value presented in Refs. [7, 10]. The upper limit from the present work is smaller than previous measurements due to the reduction in uncertainty on energy of the 386-keV resonance. However, at higher temperatures the current upper limit approaches the previous limits due to the lower energy of the 498-keV resonance and resonance-strength uncertainty.

cluding the resonance-energy uncertainties) and the current analysis were compared to those found using the mean reaction rate upper limit presented in Ref. [10]. Based on the reaction network, a higher ^{38}K(p,γ)^{39}Ca rate should reduce the ^{38}Ar abundance, since less ^{38}K will be available to β^+ decay, and the ^{39}K and ^{40}Ca abundances should increase.

Table III shows the percent differences of the final abundances for the two upper limits of the rate to those found using the mean upper limit of Ref. [10]. As expected, the abundances calculated assuming the present upper limit of the rate are close to those calculated using the mean upper limit of the rate from Refs. [7, 10]. The most significant differences are in the abundances of ^{38}Ar and ^{39}K produced in the nova explosion, however, these differences are only on the order of 7% and do not resolve the aforementioned discrepancies regarding the observed abundances [2, 3].

TABLE III. Approximate percent differences of the final abundances calculated for the ^{38}K(p,γ)^{39}Ca upper limits of Ref. [10] and the present work to the mean upper limit presented in Ref. [10]. The percent differences of the abundances for ^{38}Ar, ^{39}K, and ^{40}Ca are presented for each WD mass assumed in the simulation. A negative percent difference implies a decrease in the abundance, whereas positive implies an increase.

WD Mass ($M_\odot$)	Ref.	^{38}Ar	^{39}K	^{40}Ca
1.15	Lotay *et al.* [10]	-1	4	< 1
	Present Work	< 1	1	< 1
1.25	Lotay *et al.* [10]	-4	8	< 1
	Present Work	-2	3	< 1
1.35	Lotay *et al.* [10]	-16	16	2
	Present Work	-7	7	1

IV. CONCLUSIONS

The ^{38}K(p,γ)^{39}Ca reaction has been shown to influence the abundances of isotopes created at the endpoint of nova nucleosynthesis. The current uncertainties in the reaction rate are attributed to uncertainties in the energies, resonance strengths, and angular momentum transfer for three resonances, corresponding to excited states in ^{39}Ca. The ^{40}Ca(^{3}He,α)^{39}Ca reaction was studied using GODDESS at Argonne National Laboratory to constrain these three astrophysically important levels and search for their γ decays.

In total, 23 new γ-ray transitions were identified from ^{39}Ca levels across a wide range of excitation energies, with three of these transitions corresponding to these astrophysically important states. The resonance energies for these states were constrained to 386(2), 498(2), and 701(2) keV. Only one of these resonance energies (E_r = 386 keV) was within the sensitive energy range in the measurement made by Refs. [7, 10]. In particular, the 498-keV resonance was measured 17 keV lower than previous measurements. This reduction in resonance energy means that the previously reported estimations of the upper limit of its resonance strength need to be reconsidered.

The ^{38}K(p,γ)^{39}Ca reaction rate was reevaluated including the new resonance energies and the theoretically estimated resonance strength for the 498-keV resonance. Also included in the calculations were the resonance energy uncertainties and resonance strength uncertainties, which were not included in previous evaluations of the reaction rate. It was concluded that the reduction in resonance-energy uncertainties reduced the 1σ upper limit of the rate from a factor of $\sim$2 to a factor of $\sim$1.2 when compared to the mean upper limit in Refs. [7, 10]. At high nova temperatures, the reduced resonance energy of the 498-keV resonance and additional uncertainty in its resonance strength increases the upper limit of the rate higher than previously thought. Therefore, this resonance strength should be re-measured to further reduce the uncertainty of the ^{38}K(p,γ)^{39}Ca reaction rate in nova explosions.

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