γ spectroscopy of states in ^{32}Cl relevant for the ^{31}S$(p,\gamma)^{32}$Cl reaction rate

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Background: The ^{31}S$(p,\gamma)^{32}$Cl reaction becomes important for sulfur production in novae if the ^{31}P$(p,\alpha)^{28}$Si reaction rate is somewhat greater than currently accepted. The rate of the ^{31}S$(p,\gamma)^{32}$Cl reaction is uncertain, primarily due to the properties of resonances at $E_{\text{c.m.}} = 156$ and 549 keV.
Purpose: We precisely determined the excitation energies of states in ^{32}Cl through high-resolution γ spectroscopy including the two states most important for the ^{31}S$(p,\gamma)^{32}$Cl reaction at nova temperatures.
Method: Excited states in ^{32}Cl were populated using the ^{10}B$(^{24}$Mg$,2n)^{32}$Cl reaction with a ^{24}Mg beam from the ATLAS facility at Argonne National Laboratory. The reaction channel of interest was selected using recoils in the Fragment Mass Analyzer, and precise level energies were determined by detecting γ rays with Gammasphere.
Results: We observed γ rays from the decay of six excited states in ^{32}Cl. The excitation energies for two unbound levels at $E_x = 1738.1$ (6) keV and 2130.5 (10) keV were determined and found to be in agreement with a previous high-precision measurement of the ^{32}S$(^3$He$,t)^{32}$Cl reaction [1].
Conclusions: An updated ^{31}S$(p,\gamma)^{32}$Cl reaction rate is presented. With the excitation energies of important levels firmly established, the dominant uncertainty in the reaction rate at nova temperatures is due to the strength of the resonance corresponding to the 2131-keV state in ^{32}Cl.

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I. INTRODUCTION

Classical nova explosions occur on the surface of a white dwarf and originate from the accretion of hydrogen-rich gas from a companion star. The rates of reactions on proton-rich nuclei are important for understanding both energy generation and the abundances of isotopes produced. Reactions on isotopes in the region of silicon-phosphorus-sulfur are of particular interest for understanding enrichments of sulfur that have been observed in ejecta from novae such as Nova Her 1991 [2,3], for using the ratios of elemental abundances as indicators of peak temperatures in novae [4], and for interpreting isotopic ratios measured in presolar grains [5].

We report on a study of states in ^{32}Cl by γ spectroscopy that correspond to resonances in the ^{31}S$(p,\gamma)^{32}$Cl reaction. Nova models show sulfur production having relatively little sensitivity to the ^{31}S$(p,\gamma)^{32}$Cl reaction rate, since cycling in the region is likely weak. The mean ^{31}P$(p,\gamma)^{32}$S reaction rate is about a factor of 5 larger than the ^{31}P$(p,\alpha)^{28}$Si reaction rate, and under these conditions either β decay of ^{31}S or proton capture on ^{31}S both lead to the formation of ^{32}S. However, there are still uncertainties in these reaction rates, and within 1σ, the ratio of the ^{31}P$(p,\gamma)^{32}$S reaction rate to the ^{31}P$(p,\alpha)^{28}$Si reaction rate is as small as a factor of 3.4 [6]. Within more conservative uncertainties, SiP cycling may not be very weak, and under such conditions the ^{31}S$(p,\gamma)^{32}$Cl reaction rate influences sulfur production. A reduction in the uncertainties of all these reaction rates is of interest for improving our understanding of sulfur production in novae.

The rate of the ^{31}S$(p,\gamma)^{32}$Cl reaction depends upon the properties of resonances corresponding to excited states in ^{32}Cl above the proton threshold, $S_p = 1581.3(6)$ keV [7]. The uncertainty in the reaction rate spans as much as an order of magnitude in the nova temperature range and arises from uncertainties in resonance energies and resonance strengths [8]. Direct information on energy levels in ^{32}Cl comes mostly from the ^{32}S$(^3$He$,t)^{32}$Cl reaction. Two recent measurements of this reaction differ systematically by about 4 keV on average for the resonance energies [1,8]. There has been a previous measurement of the $(^3$He$,t\gamma)$ reaction for the most important levels at 1738 and 2131 keV (likely $J^\pi = 3^+$), but with an uncertainty of 2 keV, and with mean values between that of Refs. [1] and [8]. A precise value for the energy of the 2209-keV level was also determined following ^{32}Ar β^+ decay [9–11]. Previous results for excitation energies in ^{32}Cl are summarized in Table I. The purpose of this experiment was to determine the decay scheme for states in ^{32}Cl and precise excitation energies that are most important for the ^{31}S$(p,\gamma)^{32}$Cl reaction rate.

II. EXPERIMENT

The experimental approach closely followed one applied in several previous studies (e.g., [12,13]). A beam of ^{24}Mg from ATLAS at 75 MeV with a current of about 10 pnA bombarded a 200-μg/cm^2 ^{10}B target to produce states in ^{32}Cl via the ^{10}B$(^{24}$Mg$,2n)^{32}$Cl reaction channel. Gamma rays emitted from recoiling heavy nuclei were detected by Gammasphere, which at the time of this measurement consisted of 98 Compton-suppressed high-purity Ge detectors covering nearly 4π. Ions recoiling from the target were separated from the beam and dispersed by the Argonne Fragment Mass Analyzer (FMA), which selects recoils according to their mass-to-charge (M/Q) ratio [14]. An xy position-sensitive, parallel-grid avalanche counter (PGAC) was located at the focal plane of the FMA to

TABLE I. Previous results from the $^{32}S(^{3}He,t)^{32}Cl$ reaction (columns 2–6) and from β-decay measurements with high resolution γ spectroscopy (summarized in column 7) are compared to excitation energies (E_x) determined from this measurement (column 8). Observed γ-ray energies (E_γ) and relative intensities (I_γ) are given in the last two columns, respectively.

^{32}Cl levels from previous work							This work		
			$^{32}S(^{3}He,t)^{32}Cl$			$^{32}Ar(\beta^+)$			
J^π [15]	[8]	[16]	[17]	[1]	[18][a]	[15]	E_x	E_γ	I_γ
$(2)^+$						89.1(1)	89.65 (5)	89.65 (5)	100 (4)
$(0)^+$	462 (1)	447 (7)				461.1(1)	460.80 (14)	460.80 (14)	9 (1)
1^+	1167 (2)	1157 (5)				1168.55 (13)	1168.8 (6)	708.0 (5)	3 (1)
$(2)^+$	1327 (3)	1326 (5)	1329 (3)	1331.2 (5)			1332.3 (6)	1332.3 (6)	15 (2)
								1242.7 (9)	10 (1)
(3^+)	1734 (1)	1719 (4)	1735 (3)	1736.7 (6)	1736 (2)		1738.1 (6)	1648.5 (6)	24 (3)
$(3)^+$	2127 (2)	2122 (5)	2129 (3)	2131.1 (4)	2130 (2)		2130.5 (10)	2040.9 (10)	33 (3)
(1^+)	2203 (3)	2193 (7)	2213 (3)	2209.5 (5)		2209.3 (11)[b]			
$(2)^+$	2279 (3)	2270 (5)	2281 (3)	2283.5 (5)					

[a]Excitation energies determined from detection of γ rays in coincidence with tritons.
[b]From Ref. [9].

determine M/Q of the reaction products by their measured horizontal positions. Only nuclei with $M/Q \approx 2.46$ (e.g., $A = 32$ and $Q = 13^+$) reached the focal plane through the mass slits of the FMA. After passing through the PGAC, ions were stopped in an ionization chamber (IC) filled with isobutane gas at 13 Torr. The IC was divided into three segments (5, 5, and 20 cm long, respectively) to facilitate particle identification by energy loss (ΔE) and total energy (E) measurements. Well-separated groups corresponding to Mg, Al, Si, P, S, and Cl recoil ions were identified, as illustrated in Fig. 1. Gating on the group corresponding to Cl ions allowed recoil-γ and recoil-$\gamma\gamma$ coincidence events to be studied in order to determine the level structure of ^{32}Cl.

III. ANALYSIS

To extract precise energies for the states of interest required good energy calibration of the Gammasphere detectors. To achieve this, we collected spectra for each germanium detector using a series of standard γ-calibration sources (^{243}Am, ^{152}Eu, ^{182}Ta, and ^{56}Co) located at the target position. The peak areas and positions were extracted (and background subtracted) using the RADWARE software package [19]. From the well-known energies and intensities of these sources, the deposited energies were calibrated and the relative efficiency as a function of γ-ray energy was determined. A γ-ray energy spectrum measured in coincidence with ^{32}Cl ions detected at the focal plane of the FMA is presented in Fig. 2 using a Doppler correction (with ion velocity of $v/c = 0.0564$ corresponding to the average velocity of ^{32}Cl recoils selected by the FMA) applied to each detector, based upon the angle of the detector. With these calibrations and Doppler corrections, the excitation energies for levels in ^{32}Cl were determined to better than 1-keV accuracy. The energies of γ rays detected in coincidence with ^{32}Cl residues are summarized in Table I together with the determined level excitation energies and branching ratios.

The strongest observed transition at 89.65 (5) keV corresponds to the transition from the first-excited level to the ground state in ^{32}Cl. Most higher-energy states decay by a cascade through this state, and we built the ^{32}Cl level scheme

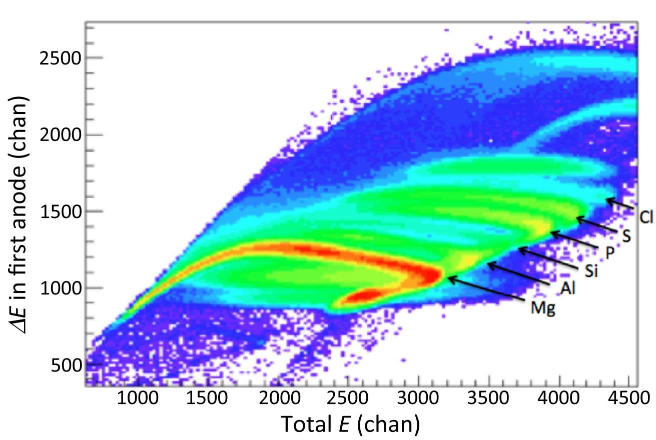

FIG. 1. Particle identification plot (ΔE vs. total E) from the ionization chamber at the focal plane of the FMA.

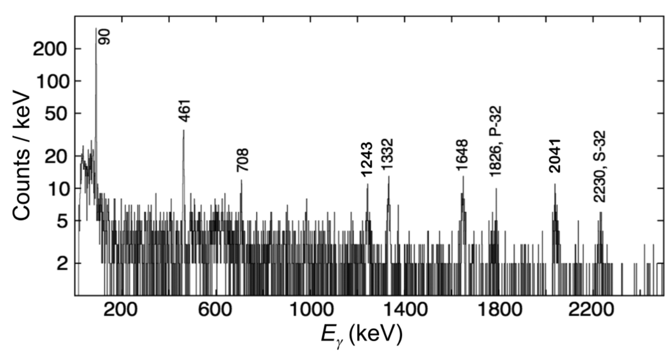

FIG. 2. The γ-ray energy spectrum from Gammasphere gated on ^{32}Cl recoils at the focal plane of the FMA. Transitions in ^{32}Cl are indicated by energy (in keV) as well as two contaminant transitions in ^{32}P and ^{32}S.

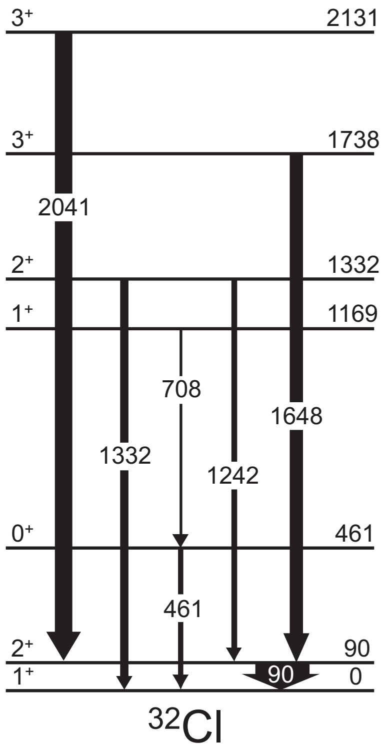

FIG. 3. Excitation energies of levels (in keV), with observed γ-ray transition energies in ^{32}Cl (also in keV). The relative strength of the γ-ray transitions is indicated by the width of the arrows connecting levels.

using ^{32}Cl-$\gamma\gamma$ coincidence relationships with the 89.65-keV transition. The proposed ^{32}Cl level scheme is given in Fig. 3.

We accurately determined excitation energies for the two unbound states in ^{32}Cl at 1738.1 (6) keV and 2130.5 (10) keV that correspond to the two most important resonances for the ^{31}S(p,γ) ^{32}Cl reaction rate at nova temperatures. The 1738-keV and 2131-keV levels are observed to decay to the 89.65-keV state by emission of 1648.5 (6) keV and 2040.9 (11) keV γ rays, respectively. The 1738-keV level energy measured in this work is 1.4 keV higher than from the (^{3}He,t) measurement of Ref. [1] (slightly more than a 1σ difference), but the energies measured for the 2131-keV level are in good agreement. On the other hand, our results are about 4 keV higher than those of Ref. [8] for both states of astrophysical interest, though we find good agreement for the lower energy bound states. In addition to the unbound states of interest for astrophysics, we observed the decay of the 1168.8 (6)-keV state by emission of a 708.0 (5)-keV γ ray cascading through the 460.80 (15)-keV level.

It should be noted that spin/parity assignments in ^{32}Cl are based largely on comparisons with the mirror nucleus ^{32}P, and the 1332.3 (6)-keV state in ^{32}Cl presumably corresponds to the 1322-keV (2)$^+$ state in ^{32}P. In ^{32}P this level decays both to the ground state and to the first-excited (2)$^+$ state. Mirror symmetry suggests that a similar decay pattern should be observed for the 1332-keV level in ^{32}Cl, and indeed, we observe decays both to the ground state and via the 1242.7 (9)-keV transition to the 89-keV state in ^{32}Cl. This transition has not been observed previously. The relative intensity of the decay to the first-excited state relative to the ground-state branch is 2 : 3 and is in good agreement with that observed in the mirror nucleus.

We did not observe the 2209-keV or 2283-keV states in ^{32}Cl in this measurement. By gating on ^{32}P in the ionization chamber, we also searched for, but did not observe, γ rays from the decay of states at 2217 keV (2$^+$) and 2230 keV (1$^+$) in ^{32}P that would have been populated in the mirror reaction. These nonyrast states were not observed in another in-beam, γ-ray study using the fusion evaporation reaction ^{18}O(^{16}O,np)^{32}P [20], so we can draw no limitations on the γ branching ratios of the mirror states in ^{32}Cl from their nonobservation in this measurement.

IV. DISCUSSION

We precisely determined excitation energies in ^{32}Cl through γ-ray spectroscopy focusing on two states corresponding to resonances at 156 and 549 keV that dominate the ^{31}S(p,γ) ^{32}Cl reaction rate at nova temperatures. We summarize values for important resonances in Table II. Energies of the 156-keV and 549-keV resonances are taken as a weighted average of those from this work and from Ref. [1] using the proton separation energy of 1581.3 (6) keV [10], with uncertainties in the level energy and proton separation energy added in quadrature. Energies for the 628-keV and 702-keV resonances are taken from the previous work of Refs. [1,9].

Since there is little direct experimental information, γ-ray partial widths, Γ_γ, are inferred based upon properties of mirror states in ^{32}P, and are the same as those presented in Ref. [8]. The proton partial width for the 156-keV resonance was determined based upon mirror properties, as was done in Ref. [8] using neutron spectroscopic factors from measurements of the (d,p) reaction [21,22]. However, the resonance strength for the 156-keV resonance is now about 50% higher than that recommended in [8] due to the higher resonance energy found in this work.

There is somewhat contradictory evidence regarding the partial widths of the states corresponding to resonances at 549, 628, and 702 keV. The 549-keV resonance dominates the ^{31}S(p,γ) ^{32}Cl reaction rate near peak nova temperatures, $T \approx$ 0.25–0.35 GK. With the resonance energy precisely determined, the uncertainty in the ^{31}S(p,γ) ^{32}Cl reaction rate

TABLE II. Properties of states in ^{32}Cl that are important resonances for the ^{31}S(p,γ) ^{32}Cl reaction rate in novae. We recommend adopting an average strength for the 549-keV resonance consistent with properties of the mirror and that of Ref. [8], but with uncertainties reflecting the relatively loose experimental constraints.

E_x [keV]	E_r [keV]	J^π	Γ_γ [meV]	Γ_p [meV]	$\omega\gamma$ [meV]	$\sigma(\omega\gamma)$ [meV]
1737	156.3(7)	(3$^+$)	1.0	4.2×10^{-8}	7.4×10^{-8}	1.5×10^{-8}
2131	549.9(8)	(3)$^+$	8	<8	1.4	<6
2209	628.4(8)	(1$^+$)	16	>19	10	3
2283	702.4(8)	(2)$^+$	3.1	>6	3	1

in novae now hinges on the strength of this resonance. Gamma branching ratio measurements indicate $\Gamma_p \approx \Gamma_\gamma$, but with large uncertainties [$\Gamma_p/\Gamma = 50(30)\%$] [18]. However, the mirror to this level is weakly populated in the (d,p) reaction, with a single particle spectroscopic factor of about 0.002 [22], indicating an expected proton partial width of $\Gamma_p \approx 0.9$ meV, about 9 times smaller than the expected γ width based upon the mirror nucleus. Previously, the proton branching ratio was directly measured to be $\Gamma_p/\Gamma = (7 \pm 4)\%$ [8], in agreement with expectations from the mirror nucleus.

The 628- and 702-keV resonances may contribute to the ^{31}S$(p,\gamma)^{32}$Cl rate at the highest ONe nova temperatures (especially if the 549-keV resonance strength is closer to the value suggested from the direct proton-branching ratio measurements of Ref. [8]). Gamma-ray branching ratio measurements for the 628-and 702-keV states indicate that the proton branching ratios (Γ_p/Γ) are approximately 1 [9]. This is supported by neutron spectroscopic factors from the mirror states, which indicate that proton partial widths are expected to be about 25–30 times larger than the γ partial widths for these levels. A direct measurement [8] resulted in $\Gamma_p/\Gamma = 54(7)\%$ and 66(13)% for the 628- and 702-keV states, respectively, indicating a smaller proton width that would decrease the resonance strengths for these two states by about 40%. We recommend adopting a proton partial width that is 4 times larger than the γ width for both of these states, while adopting an uncertainty that is consistent with both the proton and γ-ray branching ratio measurements. This results in only about a 20% uncertainty in the contribution of these resonances, which likely only make a small contribution at nova temperatures.

The ^{31}S$(p,\gamma)^{32}$Cl reaction rate is tabulated in Table III and plotted in Fig. 4 using the values in Table II with higher energy resonances included using parameters from Ref. [8]. The individual contributions from the 156- and 549-keV resonances to the reaction rate are indicated in Fig. 4. Also shown in Fig. 5 is the ratio of the rate from Refs. [6,8] to the rate from this work. The increased ^{31}S$(p,\gamma)^{32}$Cl reaction rate for $T \approx$ 0.1–0.25 GK results primarily from the improved

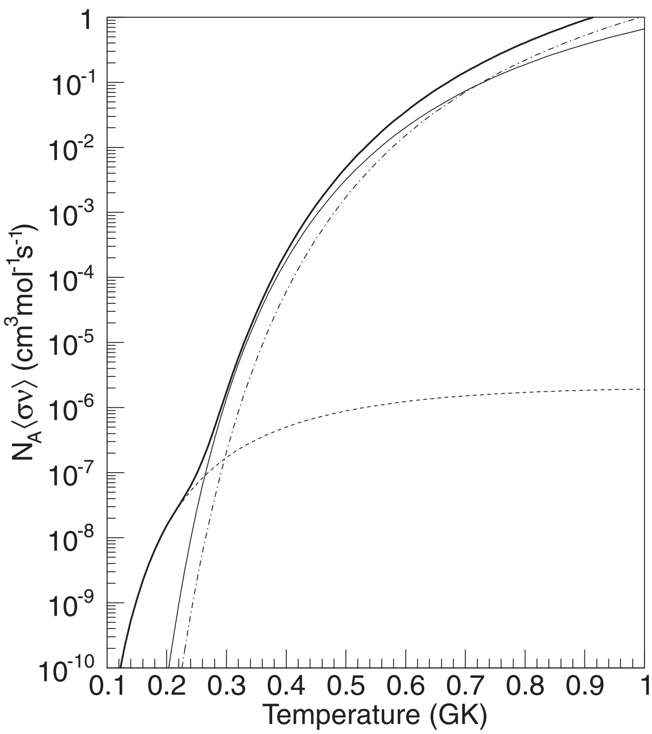

FIG. 4. Recommended ^{31}S$(p,\gamma)^{32}$Cl reaction rate as a function of the stellar temperature, T, using $\omega\gamma = 1.4$ meV for the 549-keV resonance (thick solid line). Contributions to the rate from the 156-keV resonance (dashed line), 549-keV resonance (thin solid line), and all other resonances (dot-dashed line) are also shown.

TABLE III. Recommended ^{31}S$(p,\gamma)^{32}$Cl astrophysical reaction rate as a function of temperature T. Low and high rates cover the 68% confidence level.

Temperature T [GK]	Recommended rate $N_A\langle\sigma v\rangle$ [cm^{3}mol^{-1}s^{-1}]	Low rate $N_A\langle\sigma v\rangle$ [cm^{3}mol^{-1}s^{-1}]	High rate $N_A\langle\sigma v\rangle$ [cm^{3}mol^{-1}s^{-1}]
0.10	4.9×10^{-12}	3.9×10^{-12}	6.0×10^{-12}
0.15	1.1×10^{-9}	0.91×10^{-9}	1.4×10^{-9}
0.20	1.5×10^{-8}	1.2×10^{-8}	1.8×10^{-8}
0.25	8.4×10^{-8}	6.6×10^{-8}	10.1×10^{-8}
0.30	1.2×10^{-6}	0.68×10^{-6}	1.7×10^{-6}
0.35	2.0×10^{-5}	1.1×10^{-5}	2.9×10^{-5}
0.40	1.8×10^{-4}	1.1×10^{-4}	2.5×10^{-4}
0.45	1.0×10^{-3}	0.63×10^{-3}	1.4×10^{-3}
0.5	4.0×10^{-3}	2.6×10^{-3}	5.3×10^{-3}
0.6	3.1×10^{-2}	2.1×10^{-2}	4.0×10^{-2}
0.7	1.3×10^{-1}	9.1×10^{-2}	1.7×10^{-1}
0.8	3.8×10^{-1}	2.7×10^{-1}	4.8×10^{-1}
0.9	8.6×10^{-1}	6.2×10^{-1}	10.1×10^{-1}
1.0	1.6	1.2	2.0

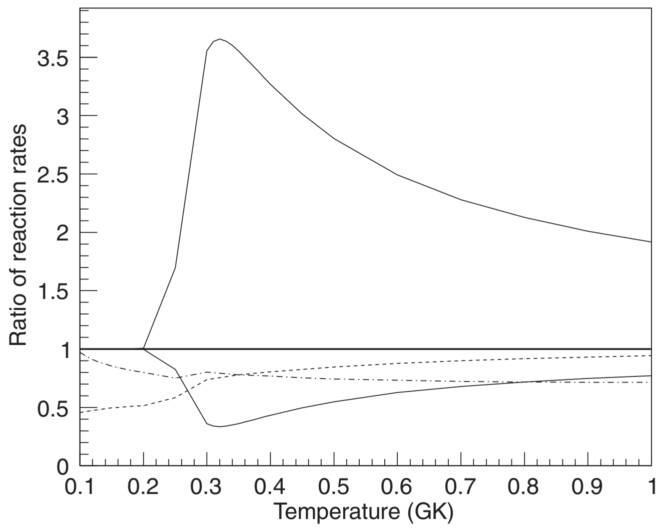

FIG. 5. Ratio of the ^{31}S$(p,\gamma)^{32}$Cl reaction rate from Ref. [6] (dashed line) to the recommended rate in this work, and ratio of Ref. [8] to this work (dot-dashed line). Ratio of rates using $\omega\gamma =$ 7 meV and $\omega\gamma = 0$ meV for the 549-keV resonance to that using $\omega\gamma = 1.4$ meV, as recommended, are given as the upper and lower thin solid lines, respectively.

energy determination for the 156-keV resonance and increased resonance strength.

The uncertainty in the resonance strength of the 549-keV level dominates the uncertainty in the ^{31}S$(p,\gamma)^{32}$Cl reaction rate near peak nova temperatures. This is illustrated in Fig. 5, where the ratio of the reaction rate using $\omega\gamma = 7$ meV ($\Gamma_\gamma \approx \Gamma_p$ [18]) to the reference rate from Table III (and Fig. 4) is plotted, along with the ratio of the reaction rate using $\omega\gamma = 0$ to the reference rate. A Monte Carlo analysis of the reaction rate was conducted following the approach of Ref. [6] with Gaussian error distributions assumed for the resonance energies and log-normal distributions for the resonance strengths. For the 549-keV resonance a mean value for the resonance strength of $\omega\gamma = 1.4$ meV was used with an uncertainty of $\sigma(\omega\gamma) = 1.4$ meV. Energies and strengths of other resonances are taken from Table II and from Ref. [8] for higher energy resonances. The low and high rates given in Table III span the 68% confidence level. The uncertainty in the reaction rate at peak nova temperatures (approximately 45% at $T = 0.35$ GK) arises primarily from the uncertainty assumed for the 549-keV resonance strength. The proton width of the 1737-keV level (156-keV resonance) contributes to the uncertainty in the rate at $T \lesssim 0.25$ GK, and the uncertainties in the γ widths of levels at $E_x > 2200$ keV contribute primarily to uncertainties in the rate at $T \gtrsim 1$ GK.

V. CONCLUSION

We precisely measured γ-ray transitions in ^{32}Cl following the ^{10}B(^{24}Mg$,2n)^{32}$Cl reaction using Gammasphere and the FMA. The measured γ-ray energies were used to determine the resonance energies for two resonances that likely dominate the ^{31}S$(p,\gamma)^{32}$Cl reaction rate at nova temperatures. Our results reduce two uncertainties in the ^{31}S$(p,\gamma)^{32}$Cl reaction rate. An updated reaction rate is presented. As illustrated in Fig. 5, the uncertainty in the reaction rate is now dominantly due to the strength of the 549-keV resonance. A precise experimental determination of the proton or γ branching ratio for the 2131-keV level in ^{32}Cl is important if the ^{31}P$(p,\alpha)^{28}$Si reaction rate is higher than the currently accepted rate.

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