Properties of ^{20}Na, ^{24}Al, ^{28}P, ^{32}Cl, and ^{36}K for studies of explosive hydrogen burning

C. Wrede,[1,2] J. A. Clark,[2,3] C. M. Deibel,[2,3,4] T. Faestermann,[5] R. Hertenberger,[6] A. Parikh,[5] H.-F. Wirth,[6] S. Bishop,[5] A. A. Chen,[7,8] K. Eppinger,[5] B. M. Freeman,[1] R. Krücken,[5] O. Lepyoshkina,[5] G. Rugel,[5] and K. Setoodehnia[7]

[1]*Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[2]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Physik Department E12, Technische Universität München, D-85748 Garching, Germany*
[6]*Fakultät für Physik, Ludwigs-Maximilians-Universität München, D-85784 Garching, Germany*
[7]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada*
[8]*DFG Cluster of Excellence Origin and Structure of the Universe, Technische Universität München, D-85748 Garching, Germany*

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The radiative proton-capture reactions ^{19}Ne$(p,\gamma)^{20}$Na, ^{23}Mg$(p,\gamma)^{24}$Al, ^{27}Si$(p,\gamma)^{28}$P, ^{31}S$(p,\gamma)^{32}$Cl, and ^{35}Ar$(p,\gamma)^{36}$K potentially influence energy generation and/or nucleosynthesis during explosive hydrogen burning in classical novae and/or type I x-ray bursts. The thermonuclear rates of these reactions are dependent on resonance energies $E_r = E_x - Q$ and strengths $\omega\gamma$. The ^{20}Ne(^{3}He,t)^{20}Na, ^{24}Mg(^{3}He,t)^{24}Al, ^{28}Si(^{3}He,t)^{28}P, ^{32}S(^{3}He,t)^{32}Cl, and ^{36}Ar(^{3}He,t)^{36}K reactions have been measured using a 32-MeV, ^{3}He^{2+} beam; ion-implanted carbon-foil targets developed at the University of Washington; and the Munich Q3D magnetic spectrograph. This experiment has already yielded precision mass measurements of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl [C. Wrede *et al.*, Phys. Rev. C **81**, 055503 (2010)], which are used presently to constrain the corresponding (p,γ) reaction Q values. The new ^{24}Al and ^{28}P masses resolve a discrepancy in the energy of the lowest-energy resonance in the ^{23}Mg$(p,\gamma)^{24}$Al reaction and better constrain a direct measurement of its strength. Excitation energies in ^{32}Cl and ^{36}K have also been measured. An important new proton-unbound level has been found at $E_x = 2196.9(7)$ keV in ^{36}K and the uncertainties in ^{36}K excitation energies have been reduced by over an order of magnitude. Using the new data on ^{36}K, the $A = 36$, $T = 1$ triplets have been reassigned. The thermonuclear ^{35}Ar$(p,\gamma)^{36}$K reaction rate is found to be much higher than a commonly adopted rate and this could affect energy generation in type I x-ray bursts.

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I. INTRODUCTION

Explosive hydrogen burning is thought to cause outbursts on the surfaces of compact stars that are accreting hydrogen-rich material from companion stars [1]. For example, classical novae and type I x-ray bursts occur on the surfaces of accreting white dwarf stars and neutron stars, respectively, where networks of proton- or α-particle-induced reactions and β decays produce energy and synthesize heavier elements. A knowledge of thermonuclear radiative proton-capture reaction rates for nuclei involved in these explosions is needed to accurately model the associated nucleosynthesis and nuclear energy generation.

The radiative proton-capture reactions on the even-Z, $T_z = -1/2$ nuclei ^{19}Ne, ^{23}Mg, ^{27}Si, ^{31}S, and ^{35}Ar provide the means to bypass their slow β decays and the subsequent weak nucleosynthesis cycling that may be triggered by the (p,α) reactions on their β-decay daughters [2–5]. For example, following the ^{15}O$(\alpha,\gamma)^{19}$Ne bottleneck in type I x-ray bursts, the ^{19}Ne$(p,\gamma)^{20}$Na reaction is expected to provide an efficient path for breakout from the hot carbon-nitrogen-oxygen (CNO) nucleosynthesis cycles to the NeNa mass region and beyond [3]. Indeed, all of the reactions of interest to the present work are expected to be fast enough in type I x-ray bursts to overcome the corresponding β decays due to the relatively high temperatures ($T \lesssim 2.0$ GK) involved [5]. Variations of the ^{27}Si$(p,\gamma)^{28}$P, ^{31}S$(p,\gamma)^{32}$Cl, and ^{35}Ar$(p,\gamma)^{36}$K reaction rates within their current uncertainties [5] may affect the nuclear energy generation [6], thereby influencing the predicted light curves and nucleosynthesis. Conversely, the proton-capture reactions of interest are unlikely to affect the energy generation in classical novae, but the lower temperatures ($T \lesssim 0.4$ GK) make the β decays more competitive with the proton captures and this competition may influence nucleosynthesis. For example, the ^{23}Mg$(p,\gamma)^{24}$Al and ^{27}Si$(p,\gamma)^{28}$P reaction rates are comparable to the corresponding β decay rates in oxygen-neon (ONe) novae based on their currently accepted uncertainties [4,5]. The ^{23}Mg$(p,\gamma)^{24}$Al reaction provides a path connecting the NeNa mass region to the MgAl mass region in ONe novae, influencing the production of the γ-ray astronomy targets ^{22}Na and ^{26}Al [4,7,8]. The ^{31}S$(p,\gamma)^{32}$Cl and ^{35}Ar$(p,\gamma)^{36}$K reactions are expected to be too slow to compete with the corresponding β decays in novae based on their currently accepted rates [5]. However, variations in the thermonuclear rates of these two reactions beyond those explored in Ref. [5] could influence the competitions between the β decays and the proton captures, and the possibility of temperatures above 0.4 GK in some classical novae [9] would certainly increase the influence of the proton captures on the nucleosynthesis of heavier species.

The thermonuclear rates of the ^{19}Ne$(p,\gamma)^{20}$Na, ^{23}Mg$(p,\gamma)^{24}$Al, ^{27}Si$(p,\gamma)^{28}$P, ^{31}S$(p,\gamma)^{32}$Cl, and ^{35}Ar$(p,\gamma)^{36}$K reactions are expected to be dominated by contributions from narrow, isolated resonances at the

temperatures of interest. Consequently, these reaction rates are dependent on resonance energies E_r and strengths $\omega\gamma$. Because these reactions have low Q values ($\lesssim$2.2 MeV), the density of states corresponding to potential (p,γ) resonances is too low to reliably employ statistical methods to approximate the total reaction rates. Instead, the energies and strengths of the few resonances that may contribute to each rate must be determined by experimental methods. In favorable cases the reactions can be measured directly using radioactive ion beams. In the absence of such beams, the energies and strengths must be determined using experimental information on related quantities such as nuclear masses, excitation energies, spins, and partial widths. This indirect information on potential resonances may be supplemented by comparisons with the shell model or properties of isobaric analog levels.

Measurements of the $(^3\mathrm{He},t)$ and (p,n) reactions have indirectly identified potential resonances in the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction [10–14]. Direct measurements with ^{19}Ne beams have led to a 90% C.L. upper limit of $\omega\gamma < 15.2$ meV on the lowest-energy resonance [3,15] and an upper limit on the average cross section for the second-, third-, and fourth-lowest energy resonances combined [3]. Measurements of the $(^3\mathrm{He},t)$ [16–20] and $(^{16}\mathrm{O},2n\gamma)$ [21] reactions have indirectly identified potential resonances in the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$ reaction, and the strength of the most important resonance has recently been measured directly to be $\omega\gamma = 37.8^{+20.5}_{-15.4}$ meV [8] with a ^{23}Mg beam. This value could be constrained further by a precise independent measurement of the ^{24}Al mass because the resonance strength measurement is correlated with the resonance energy [8]. Experimental information on all other potential resonances in these five reactions is indirect, being from measurements of excited states in the product nuclides together with the adopted Q values [5]. Uncertainties in the masses of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl currently dominate the uncertainties in the Q values of the (p,γ) reactions leading to them [22]. In the case of ^{32}Cl there is a systematic discrepancy of $\approx$11 keV [23,24] between the excitation energies reported in Refs. [25] and [26] (Table II) that has motivated at least one independent measurement [27]. In the case of ^{36}K the excitation energies are only known to relatively poor precisions of 20 to 30 keV [23] (Table III), mostly from a single study of the $^{36}\mathrm{Ar}(^3\mathrm{He},t)^{36}\mathrm{K}$ reaction with a resolution of 100 keV [28]. Based on the known structure of its mirror ^{36}Cl there are likely to be undiscovered levels in ^{36}K below an excitation energy of 3 MeV [5,23,24], close enough to the proton-emission threshold of 1658 keV [22,29] that they might contribute to the thermonuclear rate of the $^{35}\mathrm{Ar}(p,\gamma)^{36}\mathrm{K}$ reaction.

A more accurate knowledge of the reaction Q values and excitation energies E_x in the corresponding product nuclides could improve indirect estimates of these thermonuclear radiative proton-capture reaction rates and facilitate future direct measurements with radioactive ion beams by providing resonance energies $E_r = E_x - Q$. To date, a windowless hydrogen-gas target [30,31] filled with thicknesses on the order of 10 keV/nucleon has been used for several direct measurements in inverse kinematics. Radioactive ion beam time has been spent searching for resonances in cases where the expected resonance energies were sufficiently precise, but not sufficiently accurate, to immediately optimize the beam energy and target pressure [8,32,33]. In the present work, we report measurements of the excitation energies of bound and unbound levels in ^{32}Cl and ^{36}K via the $(^3\mathrm{He},t)$ reaction and compare the results to previous work. In addition, we compile new Q values (Table I) for the (p,γ) reactions leading to ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl based on our related mass measurements [34] of these nuclides. We use these results for E_x and Q together to calculate new (p,γ) resonance energies and explore the effects of these energies on the corresponding thermonuclear reaction rates.

TABLE I. Q values (keV) for selected radiative proton-capture reactions that occur during explosive hydrogen burning.

Reaction	Q value [22]	Q value (present)	Ref.[a]
$^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$	2193(7)	2190.1(11)	[39]
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$	1872(3)	1863.0(14)	[40]
$^{27}\mathrm{Si}(p,\gamma)^{28}\mathrm{P}$	2063(3)	2051.7(12)	[40]
$^{31}\mathrm{S}(p,\gamma)^{32}\mathrm{Cl}$	1574(7)	1578.2(19)[b]	[22][b]
$^{35}\mathrm{Ar}(p,\gamma)^{36}\mathrm{K}$	1668(8)	1658.4(8)[c]	[22]

[a]For the mass excesses of ^{19}Ne, ^{23}Mg, ^{27}Si, ^{31}S, and ^{35}Ar, respectively. The mass excess of ^{1}H is adopted from Ref. [22].
[b]However, the value for the mass excess of ^{31}S in Ref. [22] may be inaccurate [34,41]. Therefore, the value $Q = 1581.3(6)$ keV from Ref. [42] is adopted in the present work instead.
[c]The mass excess of ^{36}K is adopted from Ref. [29].

II. EXPERIMENT AND ANALYSIS

The mass measurements are described in detail in Ref. [34]. Briefly, an $\approx$400-enA, 32-MeV $^3\mathrm{He}^{2+}$ beam [35] was used to bombard thin ion-implanted carbon-foil targets of ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, and ^{36}Ar [36]. Tritons from the $(^3\mathrm{He},t)$ reactions on these targets were momentum analyzed using the Munich Q3D magnetic spectrograph and detected at the focal plane of the spectrograph [37,38]. Separate measurements were made with the spectrograph positioned at 10° and 20°. Peaks in the focal-plane position spectra corresponding to well-known levels in the product nuclei ^{20}Na, ^{24}Al, ^{28}P, and ^{36}K were used for momentum calibration of the focal plane at each angle. The masses of ^{20}Na, ^{24}Al, and ^{28}P were allowed to vary in the fits and the measured masses were determined by minimizing χ^2, with the $^{36}\mathrm{Ar}(^3\mathrm{He},t)^{36}\mathrm{K}$ reaction providing a calibration standard. A single ^{32}Cl peak was then used together with the fits to determine the mass of ^{32}Cl. This procedure led to mass measurements of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl with precisions of 1.1 or 1.2 keV.

The excitation-energy measurements were mostly derived from the same spectra that were used for the mass measurements (Fig. 1). Excitation energies in ^{32}Cl were determined by fitting each triton peak with a Gaussian function, extracting the centroid, and employing the same focal-plane momentum calibrations that were used for the mass measurements. These calibrations were used to determine the differences in momentum between tritons detected in the peaks of interest and tritons detected in the $E_x = 1168.5(2)$-keV ^{32}Cl peak at each angle. Excitation energies in ^{36}K below 2.5 MeV were extracted in a similar manner with respect to the

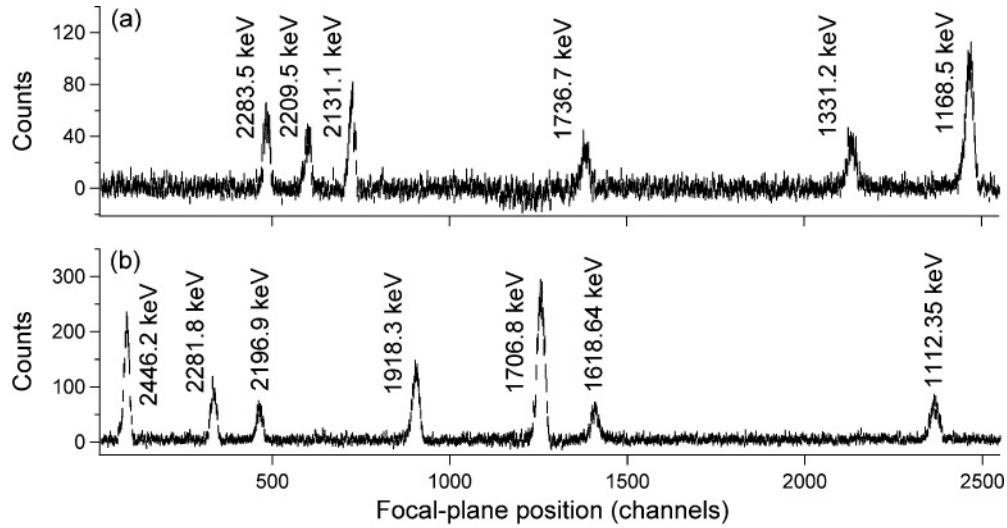

FIG. 1. Q3D focal-plane position spectra of tritons from the (^{3}He,t) reactions leading to (a) ^{32}Cl and (b) ^{36}K, acquired using a beam energy of 32 MeV at $\theta_{\rm lab} = 10^\circ$. The data are sorted into bins comprised of two channels. For each bin, the datum is plotted as a vertical line with a length that spans the standard deviation. Increases in fluctuations between channels 1100 and 1300 are due to the subtraction of background from the ^{13}C(^{3}He,t)^{13}N reaction. Peaks are labeled by the corresponding excitation energies. Identical spectra are shown in Fig. 1 of Ref. [34].

$E_x = 1112.35(45)$-keV and $E_x = 1618.64(75)$-keV ^{36}K peaks [34,43–45]. Uncertainties arose from counting statistics in the determinations of the peak centroids, the adopted excitation energies for the reference peaks, the focal-plane fit, and angular-distribution effects. These uncertainties are discussed in more detail in our previous publication [34]. Several of the uncertainties considered in Ref. [34] do not apply when determining relative momenta from peaks in a single spectrum because they are generated from the problems associated with comparing different spectra. For example, differences in the beam energy and position, differences between the targets, and uncertainties in the absolute momentum did not generate significant uncertainties in the relative momenta. As a result, we were able to determine the excitation energies with higher precision than the ground-state masses. The measurements at the two angles produced consistent excitation energies and a weighted average was taken to produce ^{32}Cl and ^{36}K excitation energies that are summarized in Tables II and III, respectively.

Additional spectra of the ^{36}Ar(^{3}He,t)^{36}K (Fig. 2), ^{24}Mg(^{3}He,t)^{24}Al, ^{28}Si(^{3}He,t)^{28}P, and ^{13}C(^{3}He,t)^{13}N reactions were acquired with the spectrograph positioned at 10° using reduced magnetic fields to investigate ^{36}K at excitation energies above 2.5 MeV. The ^{13}C(^{3}He,t)^{13}N spectrum was featureless, indicating that this reaction did not introduce background peaks to the other spectra acquired with these experimental settings. Therefore, it was not necessary to subtract the ^{13}C(^{3}He,t)^{13}N background. Six peaks from the ^{24}Mg(^{3}He,t)^{24}Al, ^{28}Si(^{3}He,t)^{28}P, and ^{36}Ar(^{3}He,t)^{36}K reactions were used for momentum calibration of the focal plane. The calibration employed the new ^{24}Al and ^{28}P masses from Ref. [34] and adopted excitation energies in ^{24}Al [21], ^{28}P [23,49–51], and ^{36}K (Table IV). A second-degree polynomial fit relating focal-plane position to momentum was used and yielded a good χ^2/ν of 0.33/3. Excitation energies in ^{36}K were determined with respect to the $E_x = 2446.2(6)$-keV ^{36}K peak, whose excitation energy had already been determined using the low-E_x spectra. The measurements at these settings had relatively large uncertainties because the counting statistics were relatively poor and the calibration was not free from significant uncertainties in the ground-state masses and excitation energies of ^{24}Al and ^{28}P (Table IV). To account for these uncertainties in calibration data and angular-distribution effects, combined systematic uncertainties of 1.6 to 1.9 keV

TABLE II. Excitation energies in ^{32}Cl and corresponding ^{31}S(p,γ)^{32}Cl resonance energies (keV). The Q value of 1581.3(6) keV from Ref. [42] has been employed in the final column (see footnote in Table I).

E_x							E_r	
(βp) [46]	(^{3}He,t) [25]	(βp) [47]	(^{3}He,t) [26]	(^{3}He,$t\gamma$) [48]	Endt [24]	(^{3}He,t) present	[5]	Present
	1326(5)		1329(3)		1331(3)	1331.2(5)		
	1719(4)		1735(3)	1736(2)	1733(2)	1736.7(6)	158(7)	155.4(8)
	2122(5)		2129(3)	2130(2)	2130(3)	2131.1(4)	555(8)	549.8(7)
2201(20)	2193(7)	2196(10)	2213(3)		2212(3)	2209.5(5)	637(8)	628.2(8)
	2270(5)		2281(3)		2281(3)	2283.5(5)	706(8)	702.2(7)

TABLE III. Excitation energies in ^{36}K and corresponding ^{35}Ar$(p,\gamma)^{36}$K resonance energies (keV). The mass excesses of ^{35}Ar and ^{1}H from Ref. [22] and the mass excess of ^{36}K from Ref. [29] have been employed in the final column.

E_x			E_r	
(^{3}He,t) [28]	[5,24]	Present	[5]	Present
1670(20)	1670(20)	1706.8(6)	4(21)	48.4(8)
1890(20)	1890(20)	1918.3(7)	224(21)	259.9(9)
		2196.9(7)		538.5(9)
2270(30)	2270(30)	2281.8(7)	604(31)	623.4(9)
2410(30)	2410(30)	2446.2(6)	744(31)	787.8(8)
2560(30)	2560(30)	2578.7(17)[a]		920.3(19)
		2628.4(30)[a,c]		970(3)
2850(30)	2850(30)	2869.4(20)[a]		1211.0(22)
3350(40)[b]	3360(25)	3383.0(31)[a]		1725(3)
		3627(6)[a,c]		1969(6)
		3653.2(21)[a]		1994.9(22)

[a]Tentative detection (not kinematically verified).
[b]Also detected at $E_x = 3370(29)$ keV via ^{36}Ca(βp) [43].
[c]Tentative detection (low statistics).

were assigned that increased with excitation energy. Statistical uncertainties were added in quadrature. The ^{36}K excitation energies are summarized in Table III.

III. RESULTS AND DISCUSSION

A. Q values for (p,γ) reactions

In Table I we compile the new recommended Q values for the (p,γ) reactions under consideration, which employ these recent mass-excess measurements together with adopted values for the mass excesses of the reactants from Refs. [22,39,40]. Table I includes a comparison between our new (p,γ) Q values and the Q values obtained using the 2003 Atomic Mass Evaluation (AME03). The ^{19}Ne$(p,\gamma)^{20}$Na and ^{31}S$(p,\gamma)^{32}$Cl Q values are consistent with the corresponding AME03 values and are more precise by factors of 6 and 4, respectively. The ^{23}Mg$(p,\gamma)^{24}$Al and ^{27}Si$(p,\gamma)^{28}$P Q values are lower than the corresponding AME03 values by 9.0 and 11.3 keV, respectively, and are more precise by over a factor of 2.

B. ^{23}Mg$(p,\gamma)^{24}$Al resonance energies and strengths

Combining the new ^{23}Mg$(p,\gamma)^{24}$Al Q value from Table I with the ^{24}Al excitation energy from the (^{16}O,2$n\gamma$) measurement of Ref. [21] yields an indirectly determined center of mass energy of 482.1(20) keV for the lowest-energy resonance. Similarly, the new ^{28}P mass [34] may be used to recalibrate the (^{3}He,t) work of Ref. [18], yielding an indirectly determined energy of 485(5) keV. These values are consistent with the direct value of $485.7^{+1.3}_{-1.8}$ keV from Ref. [8]. This resolves an ≈10-keV discrepancy between the directly [8] and indirectly [18,21] determined values by confirming the assertion in Ref. [8] that the AME03 [22] values for the mass excesses of ^{24}Al and ^{28}P were likely at fault.

In Fig. 15 of Ref. [8] the correlation between the energy and the strength of this resonance was described by a two-dimensional probability density function (PDF) in $(E_r, \omega\gamma)$ space that is reproduced in Fig. 3(a) of the present work. Folding our new indirectly determined value of $E_r =$ 482.1(20) keV (based on the most precise excitation energy from Ref. [21]) with the PDF from Ref. [8] yields the new PDF shown in Fig. 3(b). Our new constraint has nearly eliminated one mode of the bimodal distribution, which corresponded to a higher resonance strength. A new value of $\omega\gamma = 26.6^{+15.4}_{-7.0}$ meV has been determined from the median of the new PDF, with upper and lower limits determined by the 14% and 84% quantiles. This value may be compared with the previous value $\omega\gamma = 37.8^{+20.5}_{-15.4}$ meV [8]. The new PDF may also be used to generate a new resonance energy that is a combination of the indirectly determined and direct [8] results, $484.3^{+1.3}_{-1.7}$ keV.

Our value of 26.6 meV for $\omega\gamma$ is very close to the values of 27 and 25 meV from the estimates of Refs. [17] and [4], respectively, which were dependent primarily on the γ-ray partial width Γ_γ of the resonance because $\Gamma_\gamma \ll \Gamma_p$. In Ref. [17], Γ_γ was estimated by adopting the lifetime of the analog state in ^{24}Na, whereas Γ_γ was calculated using the shell model in Ref. [4]. The agreement between these three different methods of determining $\omega\gamma$ highlights the efficacy of the indirect methods to determine resonance strengths in cases where $\Gamma_\gamma \ll \Gamma_p$ and a clear identification of the level can be made.

Excitation energies for higher-energy ^{24}Al levels were determined in Ref. [18] based on measurements of the

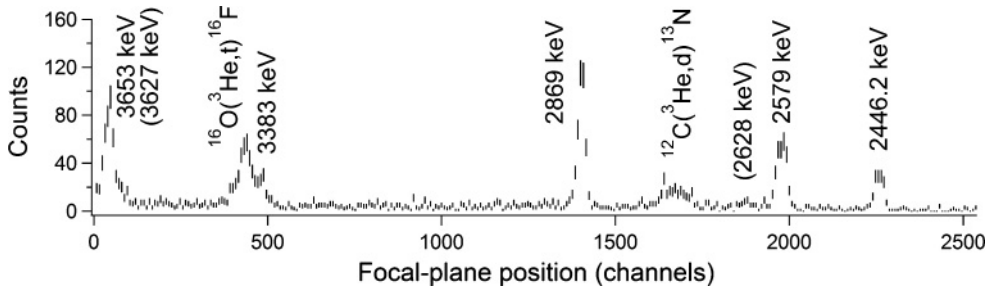

FIG. 2. Q3D focal-plane position spectra of tritons from the (^{3}He,t) reaction leading to ^{36}K, acquired using a beam energy of 32 MeV at $\theta_{lab} = 10^\circ$. The data are sorted into bins composed of eight channels. For each bin, the datum is plotted as a vertical line with a length that simply spans $2\sqrt{N}$ because ^{13}C(^{3}He,t)^{13}N background subtraction was not necessary at these settings. Peaks are labeled by the corresponding excitation energy in ^{36}K, with energies based on statistically tentative detections in parentheses. Background peaks are labeled by the reaction that produced them.

TABLE IV. Adopted excitation energies for peaks used in the focal-plane calibration for the spectrum shown in Fig. 2.

Nuclide	E_x (keV)	References
^{24}Al	1261.2(3)	[21]
^{24}Al	1617.0(8)	[21]
^{24}Al	2345.1(14)	[21]
^{28}P	1516(2)	[23,49–51]
^{28}P	1568(3)	[23,49–51]
^{36}K	2446.2(6)	Present work[a]

[a]See Table III.

^{24}Mg(^{3}He,t)^{24}Al and ^{28}Si(^{3}He,t)^{28}P reactions. The calibration in Ref. [18] was refined in Ref. [20] using the data of Ref. [21]. The new mass values for ^{24}Al and ^{28}P [34] affect the initial calibration of Ref. [18]. Recalibrating the work of Ref. [18] using these new mass values leads to excitation energies that are consistent with those of Ref. [20], but less precise. Therefore, we recommend adopting the excitation energies of Ref. [20]. However, the new ^{23}Mg(p,γ)^{24}Al Q value leads to new resonance energies. For example, we obtain a new value of $E_r = 659.7(34)$ keV for the second-lowest proton resonance, based on the excitation energy from Ref. [20], to be compared with $E_r = 651(4)$ keV obtained with the old Q value [20]. This resonance is expected to make a significant contribution to the thermonuclear ^{23}Mg(p,γ)^{24}Al reaction rate for $T \gtrsim 0.5$ GK and has not yet been measured directly. A similar treatment may be applied to deduce improved resonance energies for the other potential resonances in this reaction identified in Refs. [18,20].

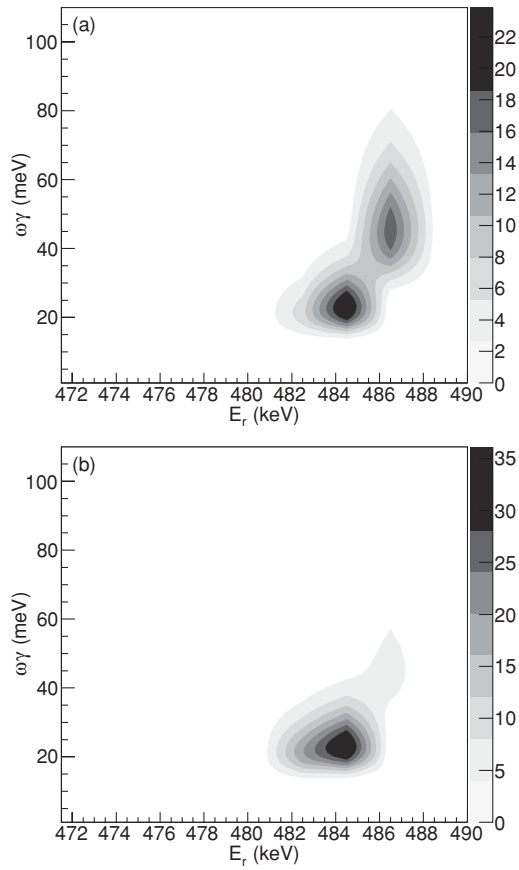

FIG. 3. Two-dimensional probability density functions (PDFs) for the strength and c.m. energy of the lowest energy resonance in the ^{23}Mg(p,γ)^{24}Al reaction. Panel (a) is the result from Ref. [8]. Panel (b) is a new PDF derived by combining the PDF from panel (a) with the present constraint on resonance energy, $E_r = 482.1(20)$ keV.

TABLE V. The first column shows the ^{28}P excitation energies from Refs. [23,50,51]. The second and third columns show the ^{27}Si(p,γ)^{28}P resonance energies ($E_r < 600$ keV) determined in Ref. [5] and the present work, respectively, by adopting the excitation energies from Refs. [23,50,51]. The difference is due to the adopted Q value, which was 2065.6(37) keV in Ref. [5] based on Ref. [52] and is 2052.2(11) keV in the present work (Table I). All values are in units of keV.

E_x	E_r	
[23,50,51]	[5]	Present
2104(1)	38(4)	51.8(15)
2143(5)	77(6)	91(5)
2216(5)	150(6)	164(5)
2406(5)	340(6)	354(5)
2483(5)	417(6)	431(5)
2628(5)	562(6)	576(5)

C. ^{27}Si(p,γ)^{28}P resonance energies

Resonance energies for the ^{27}Si(p,γ)^{28}P reaction have been calculated in previous work [5] using the excitation energies of the corresponding levels in ^{28}P [23,50,51] and the Q value of 2065.6(37) keV from Ref. [52]. We have determined new resonance energies for this reaction, based on our new Q value of 2052.2(12) keV, and the same excitation energies [23,50,51] that were used before (Table V). The resonance energies have changed by 13.4 keV: a large enough change to affect the planning and execution of future direct measurements significantly. The uncertainties are now limited in almost every case by the uncertainties in the excitation energies of Ref. [51].

We have recalculated the thermonuclear resonant ^{27}Si(p,γ)^{28}P reaction rate using our new resonance energies, accounting for the energy dependence of the penetration factor [53]. All other parameters have been adopted from Ref. [5] and are based on the properties of mirror levels in ^{28}Al. In the temperature region of interest for explosive hydrogen burning, we find that the central values of the rates from Ref. [5] change by <60% due to the new resonance energies. The new rate is within the uncertainty bounds prescribed in Ref. [5].

D. Excitation energies in ^{32}Cl

We find the ^{32}Cl excitation energies to be in good agreement with the (^{3}He,t) measurements of Ref. [26] and the (^{3}He,$t\gamma$) measurements of Ref. [48] (Table II). Our values are

TABLE VI. The sixth column shows predictions of excitation energies in ^{36}K using information on $T = 1$ analog levels [23,24] from the first five columns as input to the relation defined in the text of Sec. III F. A comparison is made with the measured values in the final column. All energies are in units of keV.

E_x (^{36}Cl) [23]	J^π (^{36}Cl) [23]	E_x (^{36}Ar) [24]	E_x* (^{36}Ar) [24]	$J^\pi; T$ (^{36}Ar) [24]	Predicted E_x (^{36}K) present	Measured E_x (^{36}K) present
1951	2^-	8448	1837		1723	1707
1959	2^+	8556	1944	$2^+; 1$	1931	1918
2468	3^-	8938	2327	$(2^+, 3)$;	2186	2197
2492	2^+	9024	2414	2;	2288	2282

systematically higher than the (^{3}He,t) measurements of Ref. [25] by ≈10 keV, confirming the assertion in Ref. [24] that an adjustment should be made to the values from Ref. [25]. Our result also eliminates uncertainties in ^{31}S$(p,\gamma)^{32}$Cl resonance energies that would otherwise be significant to the planning and execution of direct measurements.

The most recent indirect evaluation of the thermonuclear ^{31}S$(p,\gamma)^{32}$Cl reaction rate [5] employed the accurate excitation energies from Ref. [24], and therefore our new results do not change the central values of the rate significantly.

E. Excitation energies in ^{36}K

We have reduced the uncertainties in the excitation energies of known ^{36}K levels by at least an order of magnitude and find the excitation energies to be higher than the values from the (^{3}He,t) measurements of Ref. [28] by 12 to 37 keV (Table III).

We find a new level in ^{36}K at $E_x = 2196.9(7)$ keV that was kinematically verified by measurements at both angles, with a statistical significance $\gg 5\sigma$ at each angle. We tentatively detect new levels at 2628.4(30), 3627(6), and 3653.2(21) keV that were not verified kinematically by measuring at another angle. Counting statistics are also too low to claim a definite detection for the first two of these three tentative levels.

F. $A = 36$, $T = 1$ triplets

The new level at $E_x = 2197$ keV prompted us to reexamine the analog assignments in Ref. [5] that were used to calculate the commonly adopted thermonuclear ^{35}Ar$(p,\gamma)^{36}$K reaction rate. It was shown in Ref. [5] that the excitation energy of the $T_z = -1$ member of a $T = 1$ isospin triplet can be predicted within an absolute average deviation $|E_x^{\rm calc} - E_x^{\rm meas}| = 50$ keV for bound states in this mass region using the relation $E_x(T_z = -1) = 2E_x^*(T_z = 0) - E_x(T_z = 1)$. Here, $E_x^*(T_z = 0)$ is defined as the difference between the excitation energy of the level of interest and that of the lowest $T = 1$ level. This relation was applied in Ref. [5] to match ^{36}K levels of unknown spin and parity with ^{36}Cl mirror levels of known spin and parity. We have applied the same relation and summarized the results in Table VI. The new level at 2197 keV matches much better with the $J^\pi = 3_1^-$ level in ^{36}Cl than the level measured at 2282 keV in the present work, which had been determined to be the $J^\pi = 3_1^-$ level in Ref. [5]. The 2282-keV level matches much better with the $J^\pi = 2_3^+$ level in ^{36}Cl than the level measured at 2446 keV in the present work, which had been determined to be the $J^\pi = 2_3^+$ level in Ref. [5]. Adopting these new assignments for the 3_1^- and 2_3^+ levels yields an average absolute deviation between these two predicted energies and the measured energies of only 9 keV, compared to 127 keV if the old assignments are used together with the present energies. Our analog assignments are the same as those in Ref. [5] for the other two levels considered.

G. Thermonuclear ^{35}Ar$(p,\gamma)^{36}$K reaction rate

The new results on ^{36}K have an interesting overall effect on the ^{35}Ar$(p,\gamma)^{36}$K reaction rate. The reaction rate has already been shown [5] to be dominated by the lowest two s-wave resonances that correspond to the $J^\pi = 2_2^+$ and 2_3^+ levels in ^{36}K. As a result of the present work, the energies of these resonances have moved toward each other, such that both contributions to the ^{35}Ar$(p,\gamma)^{36}$K rate are amplified at the temperatures relevant to explosive hydrogen burning. The resonance energy for the $J^\pi = 2_2^+$ level has increased from 224(21) to 259.9(9) keV, and the reassignment of the $J^\pi = 2_3^+$ analog level has changed the corresponding resonance energy from 744(31) to 623.4(7) keV. To calculate the thermonuclear rate the proton partial widths from Ref. [5] were scaled according to the energy dependencies of the penetration factors [53], and the γ-ray partial widths were adopted from Ref. [5] (Table VII). The new central values for the reaction rate are higher than the previous estimates [5] by up to a factor of 7 in the temperature range of interest to explosive hydrogen burning (Fig. 4). The present reaction rate is higher by over a factor of 2 in the temperature range $0.2 < T < 1.8$ GK, over a factor of 3 in the temperature range $0.3 < T < 1.2$ GK, and over a factor of 5 in the temperature range $0.4 < T < 0.8$ GK. The new rate is above the upper uncertainty bounds prescribed in Ref. [5] over a wide range of temperatures.

We have also improved the uncertainties in the ^{35}Ar$(p,\gamma)^{36}$K reaction rate appreciably. Some of these uncertainties had been accounted for in previous work [5], and some had not. In Ref. [5], the uncertainties in the rate were assigned

TABLE VII. Recommended ^{35}Ar$(p,\gamma)^{36}$K resonance parameters (see text in Sec. III G for details).

(E_r (keV)	J^π	Γ_p (meV)	Γ_γ (meV) [5]	$\omega\gamma$ (meV)
48.4(8)	2^-	4.0×10^{-22}	0.27	2.5×10^{-22}
259.9(9)	2^+	8.0×10^{-3}	10	5.0×10^{-3}
538.5(9)	3^-	110	0.47	0.41
623.4(9)	2^+	400	11	6.7

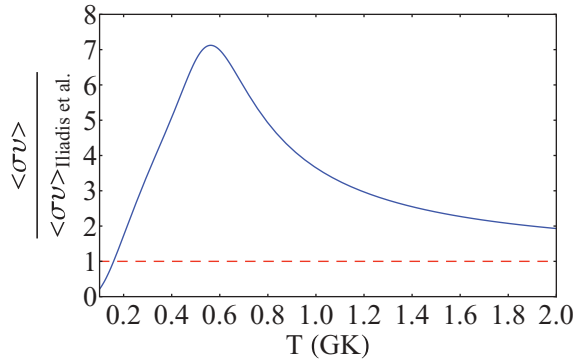

FIG. 4. (Color online) Ratios of the thermonuclear ^{35}Ar$(p,\gamma)^{36}$K reaction rates from the present work (solid line, blue online) and Ref. [5] (dashed line, red online) to the rates from Ref. [5]. Resonances other than those in Table VII have been omitted because their (presumably small) contributions are difficult to estimate reliably.

under the assumption that the analog assignments were solid. The uncertainties were then dominated by uncertainties (assumed to be randomly distributed) in the resonance energies and the possible contributions of undiscovered higher-lying resonances. Ultimately, the uncertainties were determined to be roughly factors of 2 to 3 up and down. Our rearrangement of the analog levels has shown that the previous analog-level assignments were likely incomplete, eliminating a probable inaccuracy. We have shown that the uncertainties in the old resonance energies were not randomly distributed. Rather, they had a substantial systematic component, which is not surprising considering that the adopted excitation energies were from a single measurement and that the mass of ^{36}K has changed. We have reduced the uncertainties in the resonance energies to a level where they no longer contribute significantly to the total uncertainty in the reaction rate. The uncertainties in the reaction rate are now dominated by uncertainties in the proton-decay partial width of the 260-keV resonance (for $T \lesssim 0.6$ GK), and the the γ-decay partial width of the 623 keV resonance (for $T \gtrsim 0.6$ GK). Both of these quantities are based on the estimates in Ref. [5], where they were assigned uncertainties of a factor of 1.7 up and down based on the accuracy of applying information from mirror levels. There remains the potential contribution of higher-lying resonances, which could only increase the reaction rate. We expect that contributions from higher-lying resonances are relatively small at the temperatures relevant to explosive hydrogen burning because of their relatively high resonance energies. We estimate the uncertainty in the new reaction rate to be roughly a factor of 2, up and down, over the range of explosive hydrogen burning temperatures based on the uncertainties in the partial widths [5]. Although this uncertainty is not much smaller than that assigned in Ref. [5], it appears that the uncertainty in Ref. [5] was underestimated. Based on our new reaction rate and the corresponding uncertainty, the reaction rate could be more than a factor of 10 higher than the previous estimate [5] over the range $0.4 < T < 0.8$ GK, which covers temperatures that are very relevant to the rp-process in type I x-ray bursts.

In the recent literature [2,5,54,55] contradictory conclusions are reached about the importance of the ^{35}Ar$(p,\gamma)^{36}$K reaction to explosive hydrogen burning. On one extreme, this reaction is argued to be crucial to explosive hydrogen burning and recommendations are made to measure it directly using radioactive ion beams [2,54,55]. On the other extreme, it is argued that varying the rate of this reaction by a factor of 10 from the 1999 rate has only minor effects on nuclear energy generation and final abundances in novae and type I x-ray bursts and that it was already sufficiently well understood at that time [5]. In the postprocessing approach of Ref. [5], reaction rates are decoupled from temperature and density evolution in a stellar explosion to reduce computing time. At the heart of the debate is the question of under what conditions the postprocessing approach is sufficiently detailed to rule out the importance of particular reactions. The limitations are obvious if, say, an enhancement to a rate significantly affects the temperature and density conditions in an explosion relative to another calculation with the standard rate. This limitation was demonstrated recently when it was shown that even relatively small (a factor of 3) variations in the ^{35}Ar$(p,\gamma)^{36}$K reaction rate could affect the overall energy generation type I x-ray bursts significantly [6]. For such cases (which must be examined on a case-by-case basis [6]), one must proceed very carefully in the interpretation of postprocessing results. More astrophysical modeling appears to be needed before a consensus is reached on the importance of this reaction to explosive hydrogen burning. Whether the ^{35}Ar$(p,\gamma)^{36}$K reaction turns out to be crucial or not, we have made substantial changes and improvements to its thermonuclear rate and set the stage for a direct measurement.

IV. SUMMARY

In summary, we have improved the experimental data on the ^{19}Ne$(p,\gamma)^{20}$Na, ^{23}Mg$(p,\gamma)^{24}$Al, ^{27}Si$(p,\gamma)^{28}$P, ^{31}S$(p,\gamma)^{32}$Cl, and ^{35}Ar$(p,\gamma)^{36}$K reactions. The Q values of the (p,γ) reactions leading to ^{20}Na, ^{24}Al, and ^{28}P have been improved substantially, yielding improved resonance energies. The experimental strength of the lowest-energy resonance in the ^{23}Mg$(p,\gamma)^{24}$Al reaction has been constrained by resolving a discrepancy in the resonance energy. The excitation energies of known levels in ^{32}Cl and ^{36}K have been improved, yielding improved resonance energies. New levels have been discovered in ^{36}K, one of which prompted a reassignment of analog levels in the $A = 36$, $T = 1$ triplets. A reevaluation of the thermonuclear ^{35}Ar$(p,\gamma)^{36}$K reaction rate indicates it is significantly higher than a previous estimate over a broad range of temperatures. In general, these new data may be used to calculate the rates of thermonuclear radiative proton-capture reactions that occur during explosive hydrogen burning and to facilitate direct measurements with radioactive ion beams.

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