Evidence for the existence of the astrophysically important 6.40-MeV state of ^{31}S

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Proton-unbound excited states of ^{31}S have been populated with the ^{32}S$(d,t)^{31}$S reaction at a beam energy of 24 MeV. Tritons corresponding to ^{31}S states with $E_x(^{31}S) \approx 6.3$–7.1 MeV were momentum analyzed with a high resolution quadrupole-dipole-dipole-dipole (Q3D) magnetic spectrograph at six angles ranging from $\theta_{\rm lab} = 15^\circ$ to 58.5°. We report a statistically significant detection of an astrophysically important state at $E_x(^{31}S) =$ 6402 (2) keV, whose existence as a third state in this region has been under debate. Using updated $A = 31$ nuclear structure information, we present a new set of proposed ^{31}S-^{31}P mirror assignments for ^{31}S, in which this state is tentatively assigned a spin of 7/2. This level, corresponding to a ^{30}P + p resonance at 271 keV, is likely to have a significant influence on the ^{30}P$(p,\gamma)^{31}$S reaction rate in explosive hydrogen burning in classical novae.

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I. INTRODUCTION

A. Classical novae and the thermonuclear ^{30}P$(p,\gamma)^{31}$S reaction rate

Classical novae are stellar explosions occurring in close binary systems, through the ignition of unstable hydrogen burning in the envelope accreted onto a white dwarf (WD), from a main-sequence star. H-rich shells accumulate slowly on the white dwarf's surface and mix with the surface material until a critical pressure is reached at the base of the envelope. A thermonuclear runaway is thus triggered, followed by an increased shell-burning luminosity and the eventual ejection into the interstellar medium of material processed in the explosive hydrogen burning.

Elemental abundances extracted from spectroscopic observations can provide clues to the peak temperatures and characteristic timescales in the explosion [1], to properties of the white dwarf [2], and to the nucleosynthesis. In connection to the last, classical novae are expected to be important contributors to the galactic chemical evolution of some elements (i.e., ^{13}C, ^{15}N, ^{17}O) [3]; to serve as targets for γ-ray astronomy through ongoing searches for nuclear beta-delayed γ rays [4] [although note recent observations in the high-energy (>100 MeV) γ-ray range by the Fermi Large Area Telescope (LAT) [5]]; and to be identified potentially as the origin of presolar meteoritic grains with distinctive isotopic abundance ratios (e.g., ^{29}Si/^{28}Si and ^{30}Si/^{28}Si) [6].

Among classical novae, the oxygen-neon (ONe) subclass is of special importance. With ejecta containing large overabundances of neon, along with enrichments in intermediate-mass elements up to argon [7], ONe novae are thought to happen on the most massive white dwarfs, thereby reaching the highest peak temperatures in the explosion ($0.1 \leqslant T_{\rm peak} \leqslant 0.4$ GK) and releasing the most energy. These massive white dwarfs also form the basis for recent nova models under conditions of relatively low WD temperature and accretion rates, revealing breakout from the hot-CNO cycles, and nucleosynthesis up to the iron group [8].

In the context of thermonuclear reaction rates, ^{30}P$(p,\gamma)^{31}$S is one of the main reactions for which experiments are urgently required in order to reduce the contribution of its uncertainty to abundance predictions of ONe nova models [9,10]. Studies exploring the sensitivity of nova nucleosynthesis to rate uncertainties have shown that the ^{30}P$(p,\gamma)^{31}$S reaction rate has a substantial impact on the production of elements in the $A =$ 30–38 mass region [11,12]; in particular, the rate strongly influences the ^{30}Si/^{28}Si isotopic ratio, which, as mentioned earlier, is an important signature of presolar grains that may have condensed from ONe novae ejecta. Furthermore, a recent analysis of the use of specific elemental abundances in the nova ejecta, to constrain physical properties (i.e., temperature and mass) of

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the underlying white dwarf, discovered a strong dependence of some of the key abundances on the uncertainty in the ^{30}P$(p,\gamma)^{31}$S reaction rate, with abundance variations of up to a factor of six [2]. In light of the above, a significant amount of experimental work has been recently performed to better determine the ^{30}P$(p,\gamma)^{31}$S reaction rate, all by complementary indirect methods such as charged-particle spectroscopy with magnetic spectrographs and high-resolution γ-ray spectroscopy [12–18]. The most recent rate evaluations are provided in Refs. [12,18,19]. Since proton capture on ^{30}P becomes faster than ^{30}P β^+ decay at peak nova temperatures (0.1–0.4 GK), the Gamow window of the ^{30}P$(p,\gamma)^{31}$S reaction [$Q = 6130.9\,(4)$ keV [20]] covers the range $E_{\mathrm{c.m.}} \approx 100$–500 keV. Therefore, the important ^{30}P + p resonances correspond to ^{31}S excited states in the energy range of $6.2 \lesssim E_x \lesssim 6.7$ MeV.

B. Previous results on excited states of ^{31}S near 6.40 MeV

Although a relatively consistent ^{31}S level scheme in the $6.2 \lesssim E_x \lesssim 6.7$ MeV energy region has emerged from previous experiments, one critical issue remains and forms the subject of this article. A level at 6402 keV [12] had been determined in the recent work of Ref. [12] to be potentially the most dominant resonance in the ^{30}P$(p,\gamma)^{31}$S reaction rate at nova temperatures, in light of all available experimental information at the time. Specifically, their recommended ^{30}P$(p,\gamma)^{31}$S rate had a variation of up to a factor of 20 between its high and low limits, with corresponding variations by up to a factor of four in Si-Ar isotopic-yield predictions from nova simulations; most of this variation was attributed to the unknown spin-parity assignment of this 6402-keV level. Since then, however, the work of Ref. [18] has claimed that a level at 6402 keV in ^{31}S does not exist, resulting in significant revisions to the ^{30}P$(p,\gamma)^{31}$S rate adopted in Ref. [12]—and in potentially large revisions to the impact of the ^{30}P$(p,\gamma)^{31}$S reaction in nova nucleosynthesis predictions.

Experimental evidence for this state was first found in the work of Refs. [16,17], in which ^{31}S states were populated with the ^{31}P(^{3}He, t)^{31}S and ^{32}S$(d,t)^{31}$S reactions and studied with a magnetic spectrograph. In the (^{3}He, t) experiment, a state at 6401 (3) keV, unresolved from the neighboring 6393.3 (5) keV [11/2$^+$] level, was required to fit the spectra at two spectrograph angles. In the (d,t) measurement, which was only exploratory and hence suffered from a low signal-to-background ratio, a state at 6398 (6) keV was nevertheless detected and was suggested to correspond to the 6401 (3)-keV level from the (^{3}He, t) study. This state, corresponding to a ^{30}P + p resonance at 270 keV, was then determined to be one of two levels that dominate the ^{30}P$(p,\gamma)^{31}$S reaction rate up to $T \sim 0.25$ GK [16]. In the work of Ref. [12], mentioned earlier, the ^{31}P(^{3}He, t)^{31}S reaction was studied with improved resolution over that of Ref. [16], also with a magnetic spectrograph. A state at 6402 keV was again required to fit the triton energy spectra at three spectrograph angles. From mirror-nucleus considerations, the spin and parity assignments of this 6402-keV state were suggested to be either $7/2^+$ or $5/2^-$, leading to a confirmation of the importance of this state to the ^{30}P$(p,\gamma)^{31}$S reaction and to the rate variation mentioned above. The recommended energy of this level was 6402.2 (16) keV [12].

Subsequently, in a recent γ-ray spectroscopy study in which ^{31}S states were populated and studied with the ^{28}Si$(\alpha,n\gamma)^{31}$S reaction [18], a new state was observed with $E_x = 6392.5\,(2)$ keV and $J^\pi = 5/2^+$. Importantly, on the basis of its J^π assignment, this state was regarded as distinct from the aforementioned 6394.2 (2)-keV [11/2$^+$] level discovered earlier in Ref. [13], with a similar technique at the same laboratory, but with a different fusion-evaporation reaction. Reference [18] then proceeds seemingly to suggest that, while the 6402.2 (16)-keV level measured in the (^{3}He, t) spectrograph experiments provided evidence for the existence of a second state in this region besides the 6394.2 (2)-keV [11/2$^+$] level, this second state in fact corresponds to their new state at 6392.5 (2) keV—a claim followed by the observation [18] that it consequently results in the pairing of all known ^{31}S levels in the $E_x \approx 6.1$–6.7 MeV region to states in the mirror nucleus ^{31}P. Interestingly, this new state, corresponding to a ^{31}P + p resonance at 262 keV, was found to be relatively unimportant astrophysically, contributing only marginally to the ^{30}P$(p,\gamma)^{31}$S rate (in contrast to the conclusions of Refs. [12,16] on the rate impact of their 6402-keV level, as discussed above).

Thus, given the importance of the issues above, additional evidence for or against the existence of an astrophysically important level at 6.4 MeV—as well as of potentially other states yet undiscovered—will be helpful to clarify both the structures of ^{31}S near threshold and the detailed impact of the ^{30}P$(p,\gamma)^{31}$S reaction rate in nova nucleosynthesis. To this end, we present results from a study of ^{31}S states with the ^{32}S$(d,t)^{31}$S transfer reaction, using charged-particle spectroscopy with a high-resolution magnetic spectrograph. The focus of our discussion will be on results near $E_x(^{31}\mathrm{S}) \sim 6.4$ MeV.

II. EXPERIMENT PROCEDURE AND DATA ANALYSIS

The ^{32}S$(d,t)^{31}$S reaction [$Q = -8786.2\,(4)$ keV [20]] was studied over a period of four days at the Maier-Leibnitz-Laboratorium (MLL) in Garching, Germany. A 0.5–1 eμA ^{2}H^{1+} beam of 24 MeV was delivered with the MP tandem Van de Graaff accelerator to the target location from an electron cyclotron resonance ion source [21]. The beam was first focused through a removable 1 mm $\times$ 3 mm collimator at the target position and then allowed to impinge upon the reaction target.

Targets of ^{32}S were prepared at the Tandetron Accelerator Laboratory (TAL) at Western University by implanting ^{32}S ions into a 40-μg/cm^2-thick foil of 99.9% isotopically enriched ^{12}C, using the procedure described in Ref. [22]. The target production through implantation was chosen in order to minimize contamination from (d,t) reactions on other stable isotopes of sulfur and carbon. Rutherford backscattering measurements performed at TAL determined target thicknesses of up to 11.7 ± 0.5 μg/cm^2. During the experiment, the background from reactions on carbon isotopes was characterized with a 20-μg/cm^2-thick target of natural carbon.

The reaction products were momentum analyzed with a Q3D magnetic spectrograph with an angular acceptance of 13.9 msr. The spectrograph was tuned to focus tritons corresponding to ^{31}S excited states from the ^{32}S$(d,t)^{31}$S reaction onto the focal plane. The focal plane detector was a multiwire gas-filled proportional counter backed by a scintillator [21,23], which measured the energy loss, residual energy, and position of the tritons for particle identification and momentum (and hence energy) determination. Applying a series of two-dimensional gates on the aforementioned parameters produced triton position spectra for measurements taken at each spectrograph angle. The resolution at 53.75° is worse due to kinematic broadening which becomes larger at higher angles.

States between $E_x \approx 6.3$–7.1 MeV were observed at spectrograph angles of $\theta_{\rm lab} = 15°, 20°, 25°, 49°, 53.75°$, and $58.5°$. These angles were chosen in order to minimize the presence of ^{11}C and ^{15}O contaminant states (from target oxidation) on the focal plane. Triton spectra for three sample angles (53.75°, 20°, and 25°) are shown in Fig. 1 to illustrate the consistent detection of prominent ^{31}S states on the focal plane as the angle is changed.

Triton peaks in each spectrum were fit with exponentially modified Gaussian functions to determine the channel position

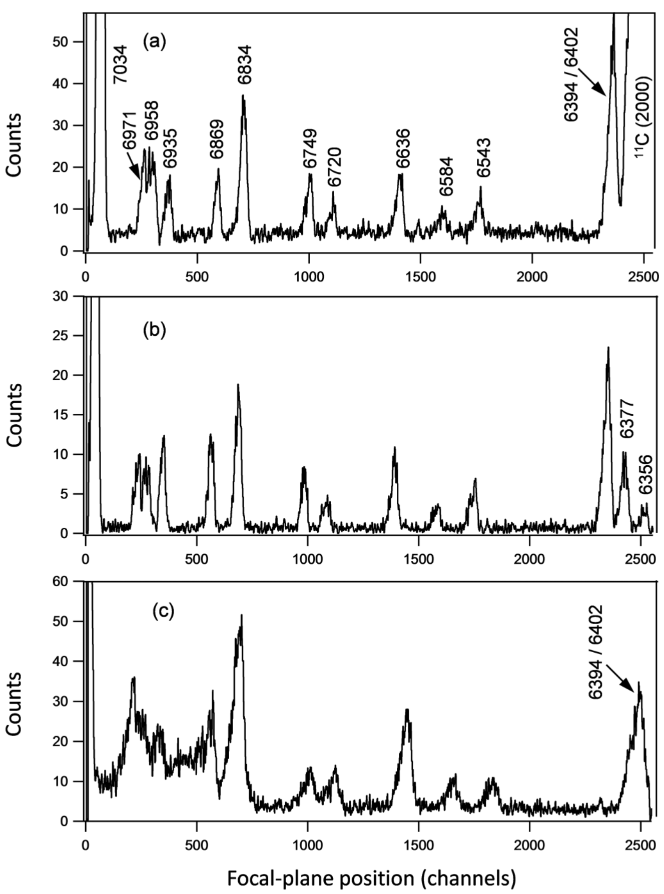

FIG. 1. Triton position spectra for the ^{32}S$(d,t)^{31}$S reaction with $E_{\rm beam}(d) = 24$ MeV for selected spectrograph angles: (a) $\theta_{\rm lab} = 25°$, (b) 20°, and (c) 53.75°. The ^{31}S excitation energies are in keV and are adopted from the present work. For 53.75°, roughly between channels 50 and 800, the ^{31}S states are superimposed on a broad background contaminant peak from the ^{16}O$(d,t)^{15}$O reaction. The spectra have been scaled horizontally to approximately align identical states for clarity. The energy for the contaminant ^{11}C state in panel (a) is adopted from Ref. [24].

of each peak centroid. The asymmetric Gaussian shapes are required to fit properly the typical peak shape resulting from the known response of our Q3D focal plane detector. The background was characterized with a constant, linear or smooth cubic polynomial function, depending on the spectrograph angle.

Each spectrum was internally calibrated using isolated ^{31}S single peaks with polynomial least-squares fits of momentum vs centroid channel ($0.95 \leqslant \chi^2_\nu \leqslant 1.4$). The calibration energies were determined from weighted averages over all previous measurements for a given state. A different combination of calibration states was used for each angle, depending on which states were detected on the focal plane. An iterative procedure was then used in order to self-consistently determine ^{31}S excitation energies at each spectrograph angle. The states at 6327, 6377, 6636, 6834, and 7034 keV were used in the calibration for every angle in which they were present on the focal plane, and thus their energies were not determined in our experiment. For the remaining states, after ascertaining that their measured energies were consistent from angle to angle, the adopted energies were then calculated by averaging over at least three angles, with the exception of the 6356-keV state, which was only observed at two angles. An overall uncertainty of ±1–2 keV was determined, due to statistics and reproducibility of energies at different angles.

III. RESULTS AND DISCUSSION

A. Excited states near $E_x(^{31}S) = 6.40$ MeV

The ^{31}S energies extracted from the present work are listed in Table I, together with a summary of the work to date on ^{31}S excitation energies in the region $E_x \approx 6.3$–7.1 MeV. From the widths of the fits to known singlet states, the energy resolution was determined to be approximately 10 keV full width at half maximum (FWHM). This represents an improvement on the resolution in the recent (^{3}He, t) studies by Parikh *et al.* ($\Delta E \approx 12$ keV) and Wrede *et al.* ($\Delta E \approx 25$ keV) [12,17], which also used magnetic spectrographs.

We observe a broad peak near 6.4 MeV at all angles, whose width is larger than those of neighboring known singlet states, such as the levels at 6377 and 6543 keV, by up to a factor of two. At all measured angles, the best fit quality for this peak was consistently achieved with two states ($1.0 \leqslant \chi^2_\nu \leqslant 1.4$, $0.04 \leqslant p \leqslant 0.27$) rather than a single state ($1.8 \leqslant \chi^2_\nu \leqslant 2.0$, $p < 0.001$), each with fit parameters (i.e., the width and decay parameter of asymmetric Gaussian function) similar to those of the neighboring single peaks. By also looking at the effect of treating the width and decay parameter of the asymmetric Gaussian function as free parameters, we found that the peak centroids changed by less than a channel, corresponding to a change in energy much less than a keV. The resulting energies of these two states were consistent from angle to angle. By averaging over the values obtained from all angles, we determine energies of 6394 (1) and 6402 (2) keV.

The angles at which the 6402-keV state was observed with the highest statistical significance were $\theta_{\rm lab} = 25°$ and $53.75°$, with detections at the 4.5σ and 4.3σ levels, respectively, for a combined detection of well over 5σ above background. Figure 2 shows partial focal plane spectra for these two angles,

TABLE I. Energies of ^{31}S excited states (in keV) from the present study compared to previous measurements. States marked with an asterisk were used for the energy calibration at every angle in which they were present on the focal plane. In the present work, a state at 6402 keV was observed (see text for discussion).

Endt [25,26]	(^{3}He, α) [27]	($\beta^+\nu_e$) [28]	(^{20}Ne, $n\gamma$) [13,14]	(p, d) [15]	(^{3}He, t) [16,17]	(^{3}He, t) [12]	($\alpha, n\gamma$) [18]	(d, t) Present Work
					6327 (2)	6329 (3)	6327.0 (5)	6327*
6350 (11)					6357 (2)	6356 (3)	6357.3 (2)	6356 (2)
			6376.9 (5)			6378 (3)	6376.9 (4)	6377*
	6393 (5)						6392.5 (2)	6394 (1)
			6393.7 (5)		6393.3 (5)[b]	6395 (4)	6394.2 (2)	
6396 (10)				6411 (9)	6401 (3)	6403 (4)		6402 (2)
6543 (11)				6546 (15)	6543 (2)	6543 (3)	6541.9 (4)	6543 (2)
[6593 (15)]					6585 (2)	6586 (3)	6583.1 (20)	6584 (1)
6628 (13)			6636.3 (15)		6639 (3)	6637 (3)	6636.1 (7)	6636*
6712 (11)					6720 (2)	6720 (3)		6720 (1)
6748 (10)					6749 (2)	6749 (3)		6749 (2)
6796 (25)[a]								
6835 (9)			6833.4 (3)	6848 (9)	6836 (2)	6835 (3)		6834*
6870 (10)					6872 (2)	6870 (3)		6869 (2)
6921 (25)		6921 (15)			6939 (3)	6936 (4)		6935 (2)
					6961 (3)	6958 (4)		6958 (2)
6990 (19)	6966 (5)				[6975 (3)]	6971 (4)		6971 (2)
7006 (25)		7012 (16)			7036 (2)	7030 (4)		7034*

[a]We note that this state has not been observed in any subsequent experiment and therefore likely corresponds to either the 6749- or the 6834-keV level.

[b]Adopted energy.

illustrating the best fits achieved for the two states near 6.40 MeV (for $\theta_{\mathrm{lab}} = 25^\circ$, the high-energy tail of the fit to the ^{11}C background peak is also shown). Our energy of 6402 (2) keV is in good agreement with energies of states observed in Refs. [12,16], and we therefore associate these three states with one another in Table I.

The lower 6394 (1)-keV state observed in the present work is in turn essentially consistent within uncertainties with either the 6394.2 (2)-keV [$11/2^+$] or 6392.5 (2)-keV [$5/2^+$] states from the γ-ray-spectroscopy studies of Refs. [13,18], respectively. We associate our state with the $5/2^+$ level of Ref. [18], since the (d, t) transfer reaction [as well as (^{3}He, α)] might not be expected to populate states with high spin such as 11/2, due to the large angular momentum transfer required. In Table I, we also associate, admittedly somewhat arbitrarily given the relatively large uncertainty and limited additional information, the state at 6395 (4) keV detected in the (^{3}He, t) experiment of Ref. [12] with the $11/2^+$ level of Ref. [13]. A similar argument can be made for the 6393 (5)-keV state observed with the (^{3}He, α) reaction in Ref. [27]. This ambiguity notwithstanding, the upshot of our results is that they support a scenario in which *three* states, instead of two, exist in ^{31}S near 6.39–6.40 MeV, in contrast to the conclusions of Ref. [18].

B. Mirror assignments between ^{31}S and ^{31}P levels

In the following, one must keep in mind that the extraction of resonance parameters for astrophysically important states from their mirror assignments is often tenuous and rarely free of ambiguities—which are present (e.g., in spectroscopic factors) even when such assignments are firm. Nevertheless, with this caveat, this approach is often the only way to obtain experiment-based constraints on these level parameters. In this spirit, Ref. [18] in particular concluded that two ^{31}S states exist near 6.39–6.40 MeV, largely on the basis of their proposed scheme of ^{31}S -^{31}P mirror assignments for proton unbound ^{31}S states up to about 6.7 MeV.

The excitation energies of ^{31}P used in their scheme were taken from Refs. [29–31], with the lowest proton-unbound ^{31}S state [6138 keV; $(3/2,7/2)^+$] paired with the ^{31}P level at 6233 keV [$(3/2,7/2)^+$]. Building on this pair, the mirror assignments were then deemed complete up to about 6.7 MeV in ^{31}S, assuming the existence of only two states near 6.4 MeV. Implicit in this conclusion is the assumption that the mirror assignments *below* the ^{31}S proton threshold are also complete. However, this assumption does not appear to be justified upon inspection of excitation energies recommended in the most recent evaluation of nuclear structure information for $A = 31$ nuclei [32] (including the experimental results from Refs. [13,14], in which several ^{31}S -^{31}P mirror assignments were determined from a comparison of γ-decay intensities of states in both nuclei).

To follow up on this observation, we note that a plausible alternative set of mirror assignments can be constructed (see Fig. 3), preserving most of the assignments proposed in Ref. [18] while also accommodating the existence of a third ^{31}S state near 6.4 MeV, as supported by the present work. We emphasize at the outset that our main goal is not to claim that this new set is necessarily better, but rather merely to put forward a different scenario to that of Ref. [18], while clearly stating our assumptions behind doing so. This in turn will bring to the fore the need for further studies of the structure of ^{31}S

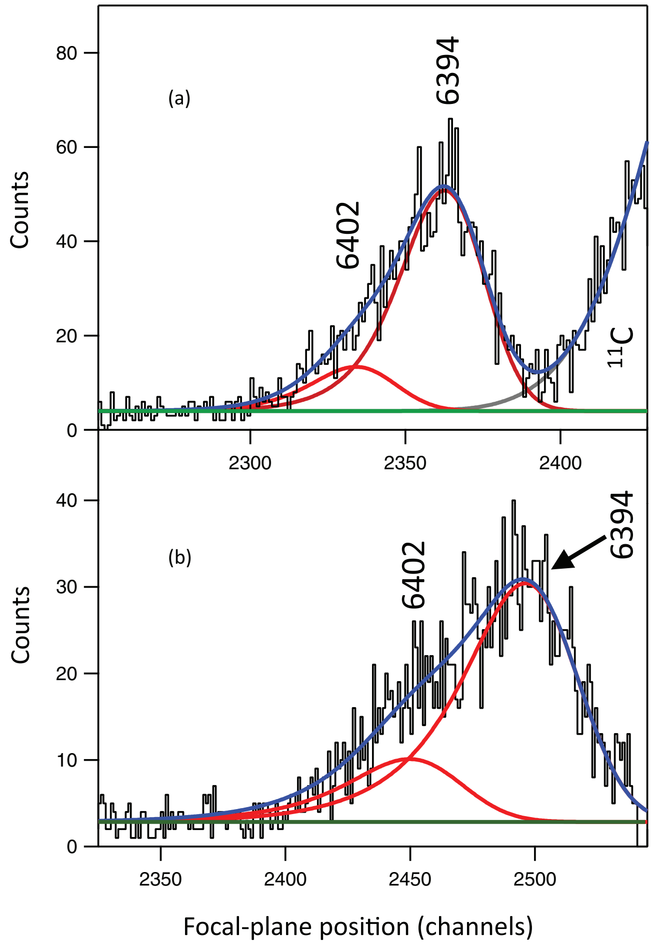

FIG. 2. (Color online) Partial triton position spectra for the ^{32}S$(d,t)^{31}$S reaction at (a) $\theta_{\rm lab} = 25^\circ$ and (b) 53.75°. Excitation energies are in keV. The best total fit (blue) along with the individual exponentially modified Gaussian fits (red) are shown, resulting in states at 6394 and 6402 keV observed with statistical significance of 4.5σ and 4.3σ, respectively. The fits to the two peaks have widths and decay parameters for the asymmetric Gaussian function similar to those of neighboring single-state peaks. In panel (a), the tail of the fit to the ^{11}C background peak (gray) is displayed. In panel (b), the spectrum terminates near the highest channel displayed. A constant background (green) was assumed. The 6402-keV peak was also required at the other spectrograph angles (see text for discussion).

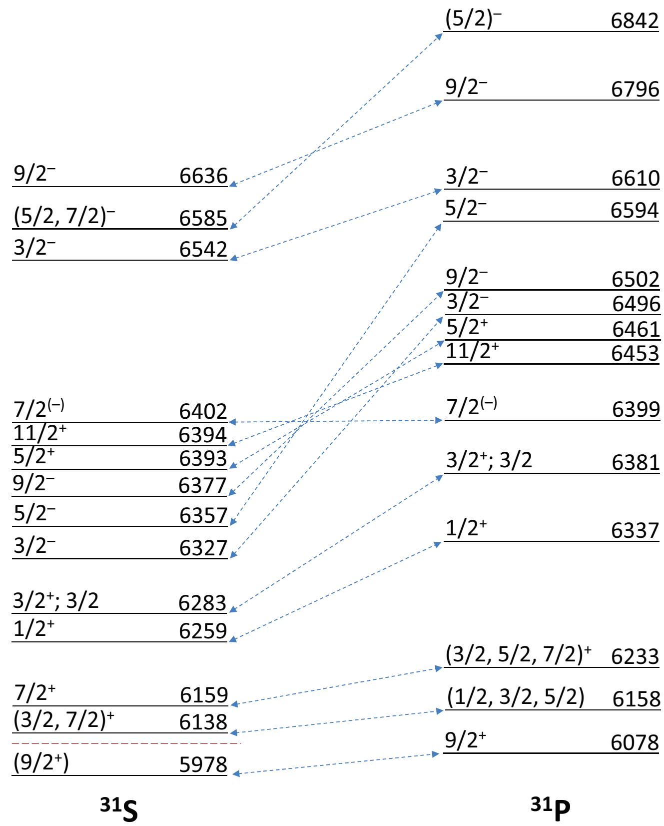

FIG. 3. (Color online) ^{31}S-^{31}P mirror diagram for levels below 500 keV of the ^{30}P + p threshold (at 6131 keV, shown as a red dashed line). Excitation energies and spin-parity assignments of ^{31}S states, with the exception of the 6402-keV level, are taken from Ref. [18] for ease of comparison. Level parameters in ^{31}P are adopted from the most recent nuclear structure evaluation for $A = 31$ isotopes [32].

(and ^{31}P) to clarify the situation. In the following discussion, we use ^{31}S excitation energies from Ref. [18] to facilitate comparison, and we adopt the properties of ^{31}P levels from the latest evaluation [32].

First, instead of pairing the $E_x(^{31}S) = 6138$ keV $[J^\pi = (3/2, 7/2)^+]$ with the $E_x(^{31}P) = 6233$ keV $[J^\pi = (3/2, 7/2)^+]$, as in Ref. [18], the former state can be paired with the $E_x(^{31}P) = 6158$ keV $[J^\pi = (1/2, 3/2, 5/2)]$. This is not implausible, since the mirror assignment proposed in Ref. [18] appears to have been based solely on the matching tentative J^π values (note that none of these three states had decay intensities reported in Refs. [13,14]). We note further that the state immediately below the $E_x(^{31}S) = 6138$-keV level, with $E_x(^{31}S) = 5978$ keV, has a tentatively assigned spin-parity of $9/2^+$, which would make it the probable mirror partner of the $E_x(^{31}P) = 6078$-keV $[9/2^+]$ state located immediately below the $E_x(^{31}P) = 6233$-keV level. Our new mirror assignment thus suggests that $J^\pi = 3/2^+$ is favored over $7/2^+$ for the $E_x(^{31}S) = 6138$-keV state.

Moving up in energy from these first two mirror assignments, the $E_x(^{31}S) = 6159$ keV $[J^\pi = 7/2^+]$ would then be a natural choice for the mirror partner of the $E_x(^{31}P) = 6233$-keV $[J^\pi = (3/2, 5/2, 7/2)^+]$ level. This differs from the assignment proposed in Ref. [18], where the $E_x(^{31}P) = 6399$-keV state was used instead. Incidentally, Ref. [18] adopts $J^\pi = 7/2^+$ for this ^{31}P state, whereas the recent evaluation work of Ref. [32] recommends $7/2^{(-)}$. We should also mention that in the γ-ray-spectroscopy study of Refs. [13,14], a spin-parity assignment of $5/2^-$ was adopted for the $E_x(^{31}S) = 6159$-keV state instead of $7/2^+$ [18]. Our proposed mirror assignment clearly favors the latter [although we also note that analysis of triton angular distributions from the (^{3}He, t) experiment of Ref. [12] favors $J = 5/2$].

For the next seven ^{31}S states $[E_x(^{31}S) = 6259$, 6283, 6327, 6357, 6377, 6393, and 6394 keV], our proposed mirror assignments agree with those of Ref. [18], on the basis of the same arguments used therein. However, as a consequence of our aforementioned new mirror assignment for the $E_x(^{31}S) =$ 6138-keV state, we now propose to pair the $E_x(^{31}S) = 6402$-keV state with the $E_x(^{31}P) = 6399$-keV $[7/2^{(-)}]$ level. If we assume that these states' parity assignments are indeed negative, then the relatively small mirror energy difference (MED) observed for this pair is comparable to the MED determined for the lowest $7/2^-$ mirror pair in Ref. [13], in which the MED systematics between ^{31}S and ^{31}P mirror states was studied.

Lastly, our assignments are also identical to those of Ref. [18] for the remaining three states above $E_x(^{31}S) =$ 6402 keV (i.e., at 6542, 6585, and 6636 keV). We note, however, that in the evaluation of Ref. [32], the spin-parity assignment of the 6842-keV level of ^{31}P is now favored to be $5/2^-$ over $7/2^-$, and thus the same should be true of its corresponding mirror state at $E_x(^{31}S) = 6585$ keV.

C. Impact on the ^{30}P$(p,\gamma)^{31}$S reaction rate

We defer a full reevaluation of the thermonuclear ^{30}P$(p,\gamma)^{31}$S reaction rate until ongoing and planned experiments address the remaining uncertainties (see below). For the moment, we limit ourselves to some qualitative conclusions that follow from our results. On the one hand, the first two proton-unbound states of ^{31}S (6138 and 6159 keV), due to their low energies, lie outside the relevant Gamow window and thus contribute only negligibly to the thermonuclear ^{30}P$(p,\gamma)^{31}$S reaction rate at temperatures characteristic of nova explosions; our new mirror assignments for these two states do not affect this conclusion. On the other hand, the addition of the 6402-keV level—corresponding to a ^{30}P + p resonance at 271 keV—may have a significant impact on the rate, the size of which will depend on whether this level's parity is positive or negative. For example, if $J^\pi = 7/2^+$ is adopted for this state, then the capture of protons with $l_p = 2$ through this resonance will result in a substantial enhancement of the reaction rate. Similarly, since a $5/2^-$ assignment for the 6585-keV state (452-keV resonance) is now preferred over $7/2^-$, $l_p = 1$ proton capture populating this resonance will increase the ^{30}P$(p,\gamma)^{31}$S rate as well (by about a factor of two, as pointed out in Ref. [18]).

IV. SUMMARY AND OUTLOOK

In summary, our measurement of the ^{32}S$(d,t)^{31}$S reaction with a high-resolution magnetic spectrograph has resulted in a statistically significant detection of an astrophysically important state at $E_x(^{31}S) = 6402$ (2) keV, whose existence as a third state in this region has been debated in recent work [18]. Based on a new set of proposed mirror assignments, this state is tentatively assigned a spin of 7/2. More peripherally to the focus of this article, our results when combined with previous work also indicate that the existence of additional ^{31}S states in this energy region is unlikely.

Accelerated, radioactive ^{30}P beams of sufficient intensity for a direct measurement of ^{30}P + p resonance strengths remain prohibitive in the foreseeable future. Thus, further progress must rely on indirect techniques that can address some of the remaining issues related to the relevant structures of ^{31}S and ^{31}P. Among these issues, several involve clarifying the level parameters for lower-energy states, so that mirror assignments for the astrophysically important ones can be made with more confidence. In particular, we highlight the need to (i) determine the spin-parity assignment of the 6158-keV state of ^{31}P, upon which our new mirror assignments are built; (ii) determine the spin-parity assignment of the 6159-keV state of ^{31}S, on which experiments presently disagree [12,13,18]; (iii) confirm the spin-parity assignment of the 5978-keV level of ^{31}S, which is presently tentatively assigned $J^\pi = (9/2)^+$; (iv) determine the parity of the 6399-keV level of ^{31}P, which we tentatively propose to be the mirror of the 6402-keV level; and (v) last, but not least, to further strengthen the evidence for the existence of the 6402-keV state and determine its spin parity.

Among ongoing and future experiments to study further the structure of ^{31}S are a recent investigation of β-delayed γ- and proton-decays of ^{31}Cl that was performed at Texas A&M University [33], and an upcoming ^{31}Cl β-delayed γ-decay experiment at the National Superconducting Cyclotron Laboratory, which could indeed provide some of this much needed additional information [34]. Other approaches—such as measurements of the ^{29}Si$(^3$He$, n\gamma)^{31}$S and ^{32}S$(p,d)^{31}$S reactions—may also prove fruitful. Taken together, these experiments should help clarify our knowledge of the thermonuclear ^{30}P$(p,\gamma)^{31}$S reaction rate and its role in nova nucleosynthesis.

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