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Toward concordance of E_x and J^π values for proton unbound ^{31}S states

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Abstract. Nucleosynthesis in classical novae on oxygen-neon white dwarfs is sensitive to the poorly constrained thermonuclear rate of the ^{30}P(p,γ)^{31}S reaction. In order to improve this situation, a variety of experiments have been performed over the past decade to determine the properties of proton unbound ^{31}S levels up to an excitation energy of $\approx$ 6.7 MeV. Inconsistencies in the energies and J^π values for these levels have made it difficult to produce a useful ^{30}P(p,γ)^{31}S reaction rate based on experimental information. In the present work, we revisit a subset of published data on the structure of ^{31}S in order to shed light on these problems. First, we present an alternative calibration of ^{31}P(^{3}He,t)^{31}S spectra using newly available high precision data in order to address discrepant ^{31}S excitation energies. Second, we apply a similar method to a recently acquired ^{32}S(d,t)^{31}S spectrum. Third, for a different ^{31}P(^{3}He,t)^{31}S experiment in which angular distributions were acquired, we present alternative fits to the experimental data in order to address discrepant ^{31}S J^π values. Finally, we compare the J^π values from ^{31}P(^{3}He,t)^{31}S to those reported from in beam γ ray spectroscopy experiments in order to search for potential resolutions to the inconsistencies. Overall, viable new solutions to some of the problems emerge, but other problems persist.

PACS. 26.50.+x Nuclear physics aspects of novae, supernovae, and other explosive environments – 27.30.+t Properties of nuclei listed by mass ranges: $20 \leq A \leq 38$

1 Introduction

A classical nova explosion arises from a thermonuclear runaway in a shell of hydrogen-rich material accreted onto the surface of a white dwarf star in a close binary star system (for a review see, e.g., ref. [1]). Several hundred Galactic novae have been discovered to date, with roughly five events discovered per year. A typical nova explosion ejects $\approx 10^{-4} - 10^{-5}$ solar masses of material into the interstellar medium. Through spectroscopic analysis the chemical composition of this ejected material can be compared to nova model predictions, however these predictions depend upon various factors, including the assumed accretion rate, the composition of the accreted material, the mass and composition of the underlying white dwarf, mixing between the accreted material and the white dwarf, and the nuclear reaction rates adopted.

The ^{30}P$(p,\gamma)^{31}$S reaction rate has significant and demonstrated impact on the predicted composition of ejecta from novae occurring on massive white dwarfs. Models performed at varying levels of sophistication have revealed that ^{30}P$(p,\gamma)^{31}$S rates differing by factors of $\approx 10 - 100$ at the relevant temperatures affect the final calculated abundances of nuclei between $A \approx 30 - 40$ by factors of $\approx 2 - 10$ [2–7]. (See ref. [8] for a recent review of the impact of nuclear physics uncertainties on predicted yields from nova models.) Direct measurement of the ^{30}P$(p,\gamma)^{31}$S reaction ($Q = 6130.9(4)$ keV [9]) at the relevant energies in nova explosions ($T_{peak} = 0.2 - 0.4$ GK) is not yet possible due to the lack of sufficiently intense radioactive ^{30}P beams. Indirect methods must therefore be exploited: nuclear structure information is required for states within $\approx$ 600 keV of the ^{30}P+p threshold in ^{31}S. In particular, excitation energies E_x, J^π values, proton and γ-ray partial widths, proton-transfer spectroscopic factors, and total widths of these levels are needed to estimate the ^{30}P$(p,\gamma)^{31}$S rate.

There has been significant recent activity concentrated on determining the structure of proton unbound states in ^{31}S [4,5,10,12–18]. Unfortunately, discrepancies exist for both E_x and J^π values of states in the energy region of interest. No experimental information is available on the widths of states below $E_x = 6.7$ MeV. As such, estimates

Table 1. Excitation energies of ^{31}S (keV). The first and second columns show the values from refs. [11,13] originally used to calibrate and/or interpret the ^{31}P(^{3}He,t)^{31}S spectra in refs. [14,15]. The third column shows the values from refs. [17,23] used for the present, alternative calibration of the same ^{31}P(^{3}He,t)^{31}S spectra and the present calibration of a ^{32}S(d,t)^{31}S spectrum. Output E_x(^{31}S) values from these calibrations are presented in the fourth, fifth, and sixth columns. The seventh column shows values from a ^{31}Cl($\beta^+\gamma$)^{31}S experiment [16]. See text of sect. 2 for details.

(^{20}Ne,$n\gamma$) [13]	(^{16}O,2$\alpha n\gamma$) [11]	(^{4}He,$n\gamma\gamma$) [17,23]	Present WNSL (^{3}He,t), 1.0°	Present WNSL (^{3}He,t), 1.5°	Present MLL (d,t)	($\beta^+\gamma$) [16]
5978.2(7)		5977.2(7)[a]				
		6138.3(21)	6132.9(7)	6132.1(6)		
6160.2(7)		6158.5(5)[a,b]	6158.6(4)	6157.6(4)		
			6258.4(8)	6259.4(7)	6261.3(11)[c]	6255.3(5)
			6283.7(5)	6283.7(4)	6284.8(15)[c]	6280.2(3)
		6327.0(5)[a,b]	6327.3(4)	6327.3(4)	6327.0(3)	
		6357.3(2)[a,b]	6357.5(7)	6356.9(7)	6356.3(4)	
6376.9(5)		6376.9(4)[b]	6380.1(20)	6378.8(19)	6377.9(4)	
6393.7(5)	6391.1(12)	6392.5(2)/6394.2(2)	6397.1(6)[d]	6396.7(5)[d]	6395.2(2)[d]	
		6541.9(4)[a,b]	6540.6(9)	6543.6(8)	6542.0(4)	
		6583.1(20)[a]	6583.6(6)	6583.4(6)	6583.4(9)	
6636.3(15)		6636.1(7)[a,b]	6636.6(6)	6634.8(5)	6636.1(4)	
7302.8(8)						

[a] Used for calibration of the ^{31}P(^{3}He,t)^{31}S spectra.
[b] Used for calibration of the ^{32}S(d,t)^{31}S spectra.
[c] Statistical and systematic uncertainties added in quadrature (systematics discussed in sect. 3).
[d] Based on centroid of potential doublet or triplet.

of rates based upon the available experimental information [4,5,13,15,17,19] suffer from uncertainties that are difficult to quantify. In the present work we use published data from measurements of the ^{31}P(^{3}He,t)^{31}S [5,14,15] and ^{32}S(d,t)^{31}S [20] reactions to address discrepancies in E_x (see sects. 2 and 3, respectively) and J^π values (see sect. 4) of states in ^{31}S between the proton threshold and $E_x = 6.7$ MeV. In this context we also discuss relevant published results from γ-ray spectroscopy experiments [13,16,17] and shell model calculations [21] to search for concordance, identify persistent discrepancies, and guide future measurements to improve estimates of the ^{30}P$(p,\gamma)^{31}$S rate. We consider data available up to June, 2015.

2 Excitation energies of ^{31}S levels from the ^{31}P(^{3}He,t)^{31}S reaction at WNSL

The ^{31}P(^{3}He,t)^{31}S spectra discussed in this section were acquired at the Wright Nuclear Structure Laboratory (WNSL) roughly a decade ago. These measurements employed a 20 MeV ^{3}He beam from an ESTU tandem Van de Graaf accelerator impinging upon a ^{31}P transmission target, which was prepared by vacuum evaporation onto a thin, natural C backing. Light reaction products emitted at forward angles were momentum analyzed using an Enge magnetic spectrograph and detected at the focal plane using a gas-filled counter backed by a scintillator, providing particle identification and a spectrum of triton position. More details on the experimental methods can be found in refs. [14, 15].

Using conservation of energy and momentum allows one to determine the excitation energy of the residual ^{31}S nucleus based on a momentum calibration of the focal-plane position. The original internal calibration was based on 4 isolated triton peaks that were identified with ^{31}S levels observed via in beam γ ray spectroscopy and reported [11,13] with precise excitation energies (table 1). This led to ^{31}S excitation energies from the (^{3}He,t) data that were assigned uncertainties of ≈ 2 keV. Additional excitation-energy constraints from the γ-ray experiment revealed the need for an unresolved, previously unknown, ^{31}S state at an excitation energy of 6401(3) keV in order to obtain a sufficiently good fit to the (^{3}He,t) data, which had an energy resolution of $\Delta E \approx 25$ keV. Further evidence for the existence of this state has since been reported in independent magnetic spectroscopy experiments [5,18] with improved energy resolution. However, the detection of nearby levels at 6393 and 6394 keV in a recent in-beam γ ray spectroscopy experiment [17, 23] has raised questions about whether or not there are really 3 levels within 10 keV, when the average density of known states in the region is only ≈ 0.02/keV [17,22].

The purpose of this section is to report an alternative calibration of the ^{31}P(^{3}He,t)^{31}S WNSL spectra using the excitation energies from a more recent in-beam γ-ray spectroscopy experiment [17,23]. The ^{28}Si(^{4}He,$n\gamma\gamma$)^{31}S reaction employed in the new measurements was much less selective in the ^{31}S states populated compared to the

^{12}C(^{20}Ne,$n\gamma$)^{31}S and ^{24}Mg(^{16}O,2$\alpha n\gamma$)^{31}S reactions used in the earlier experiments [11,13], which favored the population of high-spin states. Therefore, many more levels were observed in the region of interest, providing a higher density of precise calibration points and enabling a potential reduction in the interpolation uncertainties associated with the calibration of the ^{31}P(^{3}He,t)^{31}S spectra.

In the present work, we focus on two particular ^{31}P(^{3}He,t)^{31}S spectra because the statistics in these spectra were roughly an order of magnitude higher than the statistics available in any of the other individual spectra. These two spectra were acquired during different experimental runs several months apart using different targets. The first spectrum was acquired at 1.5 degrees and is shown in figs. 1 and 3a of refs. [14,15], respectively. The second spectrum was acquired at 1.0 degrees. When none of the peak positions are constrained, a good fit of both spectra is obtained using only 6 peaks in the densely-populated excitation energy range from 6200 to 6450 keV, including only one peak in the range of 6390 to 6405 keV. We have adopted this fit for the alternative calibration in the present work because it is the simplest possible fit that is independent of constraints from external data.

For each spectrum, we calibrated the focal plane internally in the range of $E_x(^{31}\mathrm{S}) = 5.98$ to 6.64 MeV (encompassing the bulk of the energy region of interest for novae) using peaks that were isolated by at least the energy resolution ΔE and clearly correspond to levels observed by Doherty *et al.* [17,23]. The excitation energies adopted in the calibration are listed in table 1. At 1.0° and 1.5°, the focal plane calibration yielded χ^2/ν values of 0.68/4 and 2.0/4, respectively, corresponding to p values of 0.98 and 0.85, respectively. Using the new calibrations, excitation energies were extracted from the ^{31}P(^{3}He,t)^{31}S data. The results from the two different angles display sub-keV uncertainties for most levels and they are consistent with each other, as shown in table 1. The excitation energy differences extracted from the ^{31}P(^{3}He,t)^{31}S spectra are also consistent with those reported from the γ-ray measurements to a high level of precision (with the exception, perhaps, of differences involving the level reported at 6138.3(21) keV in Refs. [17, 23]). However, there are two interesting anomalies.

First, a peak appears in the 1.0 and 1.5 degree data at 6397.1(6) and 6396.7(5) keV, respectively. This peak could, in principle, consist of non-negligible contributions from 3 different unresolved levels claimed to exist in the range of $E_x \approx 6390$ to 6405 keV [14,17,22], including the $5/2^+$ 6392.5 keV state observed by Doherty *et al.* [17,23], the $11/2^+$ ≈ 6394 keV state (observed by Jenkins *et al.* [13], Doherty *et al.*, and Della Vedova [11]), and a third state of unknown spin/parity in the vicinity of 6400 keV [5,14,15,18]. The fact that the ^{31}P(^{3}He,t)^{31}S peak position is not consistent with either of the excitation energies 6392.5(2) keV or 6394.2(2) keV reported in Doherty *et al.* appears to be further evidence for the population of the ≈ 6400 keV level, which is needed to shift the centroid of the single ^{31}P(^{3}He,t)^{31}S peak assumed here to positions corresponding to significantly higher excitation energies.

Second, the energies of the two levels populated in the range of 6200 to 6300 keV reveal some tension. These two levels have been observed at excitation energies of 6255.3(5) and 6280.2(3) keV (statistical uncertainties only) in a recent ^{31}Cl β-delayed γ decay experiment [16,24]. When the data from Doherty *et al.* [17,23] are used for calibration of the ^{31}P(^{3}He,t)^{31}S spectra, significantly different values of 6258.4(8), 6283.7(5) keV and 6259.4(7), 6283.7(4) keV are obtained at 1.0 and 1.5 degrees, respectively. Under the reasonable assumption that the same two levels are being populated in the two experiments, this leads to the conclusion that there is a ≈ 4 keV systematic discrepancy between the ^{31}Cl β-decay energies and the energies from the in-beam γ-ray spectroscopy experiment used to calibrate the (^{3}He,t) spectra. Unfortunately, it is not possible to compare the excitation energies from these two experiments directly (without the link through ^{31}P(^{3}He,t)^{31}S) because there are no states above $E_x = 6$ MeV observed in both experiments (table 1). Shifting the resonance energies by 4 keV will not have an enormous effect on the ^{30}P(p,γ)^{31}S reaction rate, but higher accuracy than 4 keV is essential for an accurate interpretation of ^{31}S levels in the excitation energy region between 6390 and 6405 keV and would also be valuable for the planning of direct measurements with radioactive ion beams.

Future work is needed to resolve the two anomalies presented. If possible, extremely high resolution ($\Delta E < 5$ keV) transfer reaction measurements with sufficient statistics complemented by detection of several γ-ray de-excitation cascades would likely help to clarify how many ^{31}S levels exist between $E_x = 6390$ and 6405 keV. With regard to the possible 4 keV discrepancy between energies from the ^{31}Cl β decay experiment and the ^{28}Si(^{4}He,$n\gamma\gamma$)^{31}S one [17,23], it would be useful to run a carefully calibrated independent γ ray spectroscopy experiment that populates a sample of proton unbound levels observed in each experiment.

3 Excitation energies of ^{31}S levels from the ^{32}S(d,t)^{31}S reaction at MLL

Using a similar method as the one described in sect. 2, ^{32}S$(d,t)^{31}$S spectra were acquired using a 22 MeV deuteron beam from an MP tandem van de Graaf accelerator at Maier-Leibnitz Laboratorium (MLL). The beam impinged upon a target of ^{32}S implanted in a ^{12}C foil. Light reaction products were momentum analyzed using a quadrupole-dipole-dipole-dipole (Q3D) magnetic spectrograph and detected at the focal plane with a gas-filled counter backed by a scintillator. These spectra were acquired for calibration of measurements using the ^{36}Ar$(d,t)^{35}$Ar reaction and further experimental details can be found in ref. [20].

A spectrum acquired at 15° and presented in fig. 1 shows essentially the entire energy region of interest for novae in ^{31}S with a resolution of 9 keV, which is slightly better than the resolution presented in the earlier 24-MeV (d,t) measurements of Irvine *et al.* [18]. We have re-investigated this spectrum in the context of the present work. The focal plane was calibrated internally using peaks corresponding to levels with $E_x = 6.1 - 6.7$ MeV observed by Doherty *et al.* [17,23] (table 1). This focal plane calibration yielded a χ^2/ν value of 1.6/3, corresponding to a p value of 0.80.

Using this calibration in the region of 6200-6300 keV leads to excitation energies of 6284.8±1.1(stat)±1.1(sys) and 6261.3±0.3(stat)±1.1(sys) keV, including a small correction and an associated systematic uncertainty to account for the fact that the calibration peak corresponding to the 6.16-MeV state is not fully on the focal plane. This further supports the conclusion that there is a systematic discrepancy between the excitation energies from the ^{31}Cl β-delayed γ-decay experiment [16] and the in-beam γ-ray spectroscopy experiment [17,23]. Indeed, this is the reason for the ±2 keV systematic uncertainty assigned to the ^{35}Ar excitation energies reported in ref. [20].

4 J^π values of ^{31}S levels from the ^{31}P(^{3}He,t)^{31}S reaction at MLL

To investigate the discrepancies between experimental J^π constraints for five proton-threshold levels in ^{31}S ($E_x = 6.1 - 6.6$ MeV [5,17,22], see table 2) we have revisited the analysis of the ^{31}P(^{3}He,t)^{31}S experiment performed at MLL and presented in ref. [5]. Distorted wave Born approximation (DWBA) calculations were performed (see details in ref. [5]) assuming the J^π assignments of ref. [17] and compared with the ^{31}P(^{3}He,t) data and best-fit theoretical curves of ref. [5] – see fig. 2. A persistent lack of concordance is noted for the 6329, 6356, and 6543 keV levels, constrained to be $\{1/2^+,\ 3/2^+,\ (7/2,\ 9/2)\}$ in ref. [5] and $\{3/2^-,\ 5/2^-,\ 3/2^-\}$ in ref. [17], respectively. For the 6329 keV level, the $3/2^-$ theoretical curve is in poor agreement with the measured (^{3}He,t) cross section at the lowest measured angle; for the 6356 and 6543 keV levels, the $3/2^+$ and $9/2^-$ curves are clearly preferred over the alternatives. On the other hand, the discrepancies for the 6136 and 6160 keV levels, constrained to be $\{9/2,\ 5/2\}$ in ref. [5] and $\{(3/2,\ 7/2)^+,\ 7/2^+\}$ in ref. [17], respectively, may be resolved. For the 6136 keV level, although the $3/2^+$ curve is in poor agreement with the data, the $7/2^+$ curve does provide a fair fit, and constitutes the next-best-fit to the data after the $J = 9/2$ curves. Similar considerations apply to the 6160 keV level: the $7/2^+$ curve is the next-best-fit to the data [5] after the $J = 5/2$ curves.

A second reason to explore the viability of other J^π assignments to the ^{31}P(^{3}He,t) data of ref. [5] was to test for the existence of any $1/2^-$ levels near the ^{31}S proton threshold. These have been predicted through recent shell model calculations [21] but, based upon the available experimental J^π constraints [5,17], have not yet been observed. Among the levels with measured angular distributions in ref. [5], the best candidates for $1/2^-$ assignments are the 6260 and 6329 keV levels, both assigned as $1/2^+$. Fig. 2 shows that for the 6329 keV level the $1/2^-$ curve does provide a fair fit, and is the next-best-fit to the data after the $1/2^+$ curve. This is not the case for the 6260 keV level, for which a $1/2^-$ curve not only is a worse fit than $1/2^+$ between $\theta_{c.m.} = 25°$ and 35° (as with the 6329 keV level) but is also a worse fit to the data at angles below 20°. At temperatures encountered in classical novae, the 6329 keV level could have a significant impact on the ^{30}P(p,γ) thermonuclear rate: an assignment of $1/2^+$ would correspond to an important s-wave resonance. Even if it is a p-wave resonance with $1/2^-$ or $3/2^-$ [17], the large spectroscopic factors predicted for negative parity states [21] may compensate for the higher l value.

Finally, the number of levels between $E_x = 6.39 - 6.41$ MeV in ^{31}S is currently unclear, as mentioned in sect. 2 and displayed in table 1. Refs. [14,5,18] all observed two levels at about 6394 and 6402 keV; ref. [17] also observed two levels in this energy region, but at 6393 and 6394 keV. The reported excitation-energy uncertainties indicate that three levels seem required. A partial attempt at addressing this issue is shown in fig. 3, where the measured (^{3}He,t) angular distribution of the peak labeled "6395/6403" in fig. 1 of ref. [5] is plotted. Although the $5/2^+$ theoretical curve is in fair agreement with the data, the best fit (assuming two contributing levels) arises from a combination of $5/2^+$ and $11/2^+$ theoretical curves. This is mostly due to the influence of the measured cross sections between $\theta_{c.m.} = 30°$ and 40°. It is interesting that these are the J^π values assigned to the 6393 and 6394 levels by ref. [17]. We caution that other combinations of theoretical curves to fit the data in fig. 3 are certainly possible due in part to the lack of absolute normalization of the individual DWBA calculations and the similar shapes of curves with $J^\pi = J^{+,-}$ for large J. Moreover, we have assumed here that only two levels contribute to the cross section data in fig. 3, while three levels seem required as discussed above. Of course, all three levels may not be populated substantially in the ^{31}P(^{3}He,t) reaction. Nevertheless, these results suggest that if a level around 6394 keV has $J^\pi = 11/2^+$ [11,13,17,23] then the 6403-keV level may have $J = 5/2$. As the number of levels around 6.4 MeV and their resonance strengths have a direct and significant impact on nucleosynthesis predictions in models of classical nova explosions [5], further experimental studies are required to settle this issue. As well, additional theoretical study of the (^{3}He,t) reaction at these energies would be very valuable.

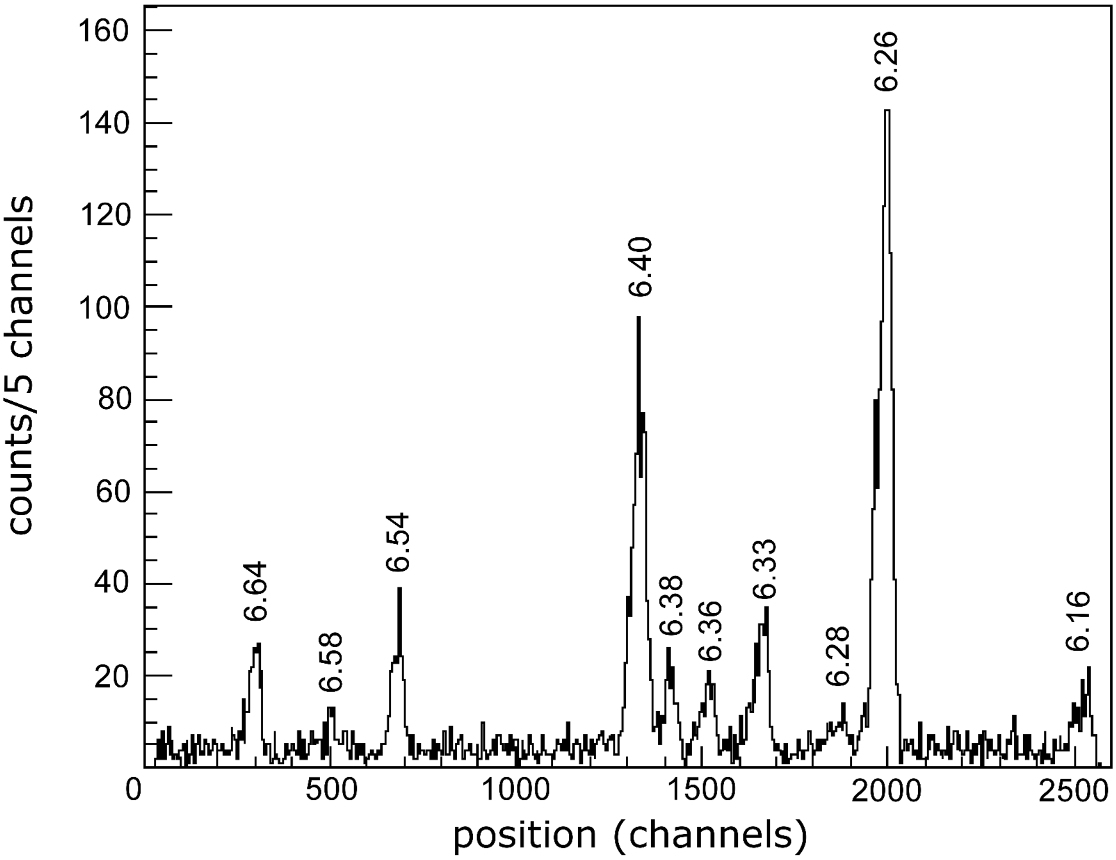

Fig. 1. Triton position spectrum with E_{beam}=22 MeV for the ^{32}S$(d,t)^{31}$S reaction for a spectrograph angle of $\theta_{lab} = 15°$. Peaks are labeled with E_x in MeV.

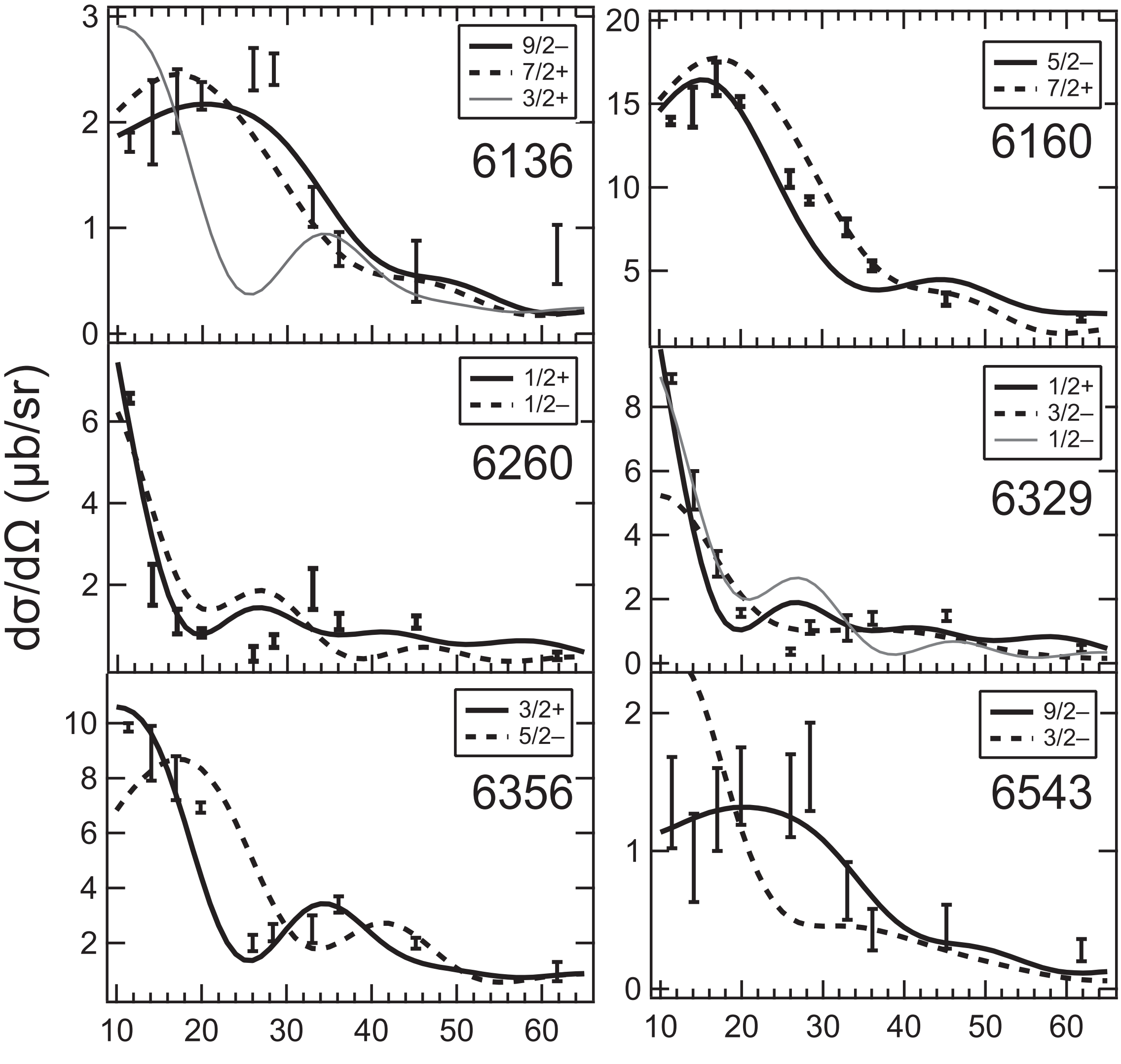

Fig. 2. Triton angular distributions measured with the ^{31}P(^{3}He,t) reaction at 25 MeV, for proton-threshold levels in ^{31}S [5]. Excitation energies are given in keV. Theoretical curves assuming different J^π for each ^{31}S level are indicated.

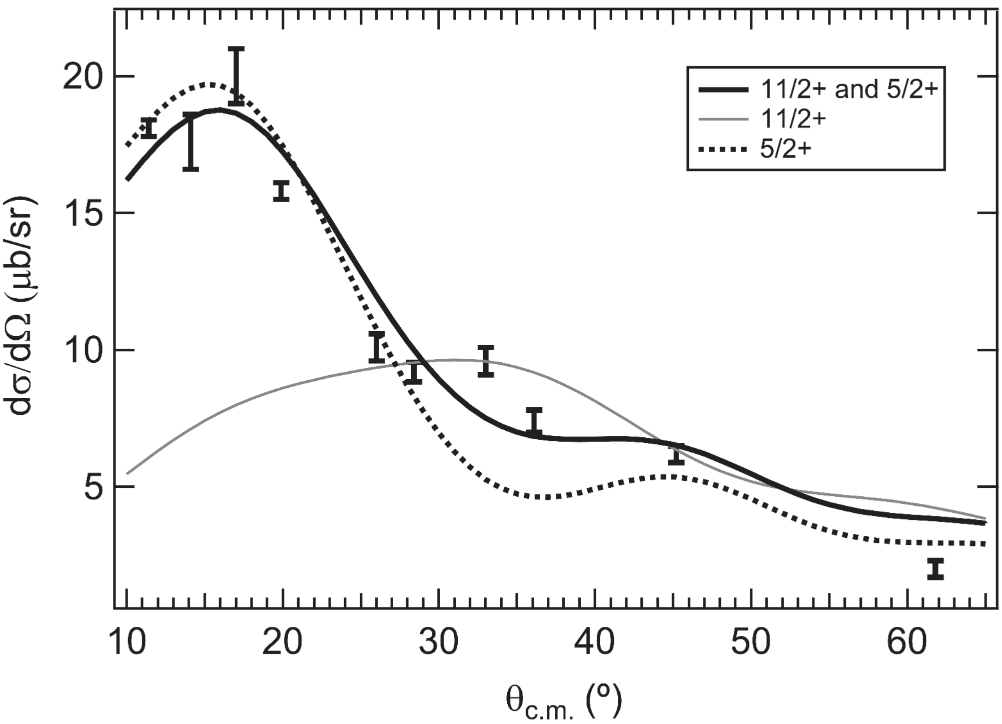

Fig. 3. As fig. 2, but for the summed cross sections of the two levels observed in ref. [5] at 6395 and 6403 keV.

5 J^π values of ^{31}S levels from in beam γ-ray spectroscopy experiments

In this section, we attempt to disentangle the J^π assignments reported from the in beam γ ray spectroscopy experiments in order to search for allowed alternative values that were not tabulated explicitly in refs. [13,17,23]. For example, we attempt to isolate spin-parity constraints derived from measured data from those derived from subjective interpretations, such as attempts to match ^{31}S levels with ^{31}P mirror levels. The spectroscopy of ^{31}P is incomplete [24] and this increases the risk of obtaining erroneous constraints through mirror assignments [22]. We have chosen to use the angular distribution coefficients a_2 and a_4 reported by Doherty *et al.* because they are documented thoroughly in two papers [17,23]. We did not use the R_{DCO} ratios, which were only reported in Ref. [17], because they are are not independent of a_2 and a_4, being derived from the same angular distributions. Finally, we compare the newly derived J^π possibilities to those discussed in sect. 4 and attempt to reconcile them.

For the 6160-keV level, as discussed above, the ^{31}P(^{3}He,t)^{31}S angular distribution from ref. [5] favors a $J = 5/2$ assignment, with $J = 7/2$ being a possibility. The $J = 5/2, 7/2$ values are consistent with the $J^\pi = 5/2^-$ assignment from ref. [13] and the $J^\pi = 7/2^+$ assignment from refs. [17,23], respectively. However, the latter assignments are not consistent with each other and this warrants further investigation. The $J^\pi = 5/2^-$ assignment was based on the observation of a transition, consistent with dipole character, to the 4451-keV state, which has been tentatively assigned $J^\pi = (7/2)^-$ in the $A = 31$ data evaluation [24]; the parity was apparently deduced by comparison to the mirror nucleus. The $J^\pi = 7/2^-$ assignment was based on the observation of a $\Delta J = 0$ transition to the same state, based on the γ ray angular distribution. It is difficult to reconcile these assignments. We adopt an indefinite value of $J = (5/2, 7/2)$.

For the 6329-keV level, as discussed above, the ^{31}P(^{3}He,t)^{31}S angular distribution from ref. [5] favors a $J^\pi = 1/2^+$ assignment, with $J^\pi = 1/2^-$ being a possibility, and $J^\pi = 3/2^-$ disfavored. The $J = 1/2$ value is inconsistent with the $J^\pi = 3/2^-$ assignment from refs. [17,23] and this warrants further investigation. The $J = 3/2$ assignment is based on the $\Delta J = 0$ angular distribution of γ rays from a transition to the $J^\pi = 3/2^+$ first excited state. In this case, the angular distribution coefficients $a_2/a_4 = 0.14(7)/0.10(9)$ have relatively large uncertainties, which suggests that other ΔJ values might be possible. In particular, a $J = 1/2$ assignment and the assumption of a dipole transition would yield an isotropic angular distribution with $a_2 = a_4 = 0$ [17,23] and this possibility does not appear to be ruled out completely. Therefore, we conclude that $J = 1/2$ is a possibility for the 6329-keV level and it is, in fact, the only value which is consistent with the constraints from both experiments. Therefore, the 6329-keV level is a viable candidate to be one of the predicted $J^\pi = 1/2^-$ states. Since the parity assignment in refs. [17,23] seems to be based on comparisons to the mirror nucleus ^{31}P and shell model predictions, $J = 3/2^+$ should also be an allowed alternative in that work.

For the 6356-keV level, as discussed above, the ^{31}P(^{3}He,t)^{31}S angular distribution from ref. [5] favors a $J^\pi = 3/2^+$ assignment. In particular, the angular distribution appears to be incompatible with the $J^\pi = 5/2^-$ assignment reported in refs. [17,23] and this warrants further investigation. The $J = 5/2$ assignment is based on the angular distribution of a γ ray transition to the $J^\pi = 3/2^+$ first excited state, which was fit well by $\Delta J = 1$. In this case, the value of the coefficient $a_2 = -0.25(5)$ appears to clearly favor a negative value, which supports the $\Delta J = 1$ assignment. Moreover, a spin of $J = 1/2$ also appears to be disfavored because the corresponding angular distribution would be isotropic under the assumption of a dipole transition, with $a_2 = 0$. The choice of negative parity is based on a mirror assignment that may or may not be accurate. Therefore, it remains difficult to reconcile the J^π constraints, except to assume an indefinite value of $J = (3/2^+, 5/2)$.

For the 6543-keV level, the ^{31}P(^{3}He,t)^{31}S angular distribution from ref. [5] clearly indicates a high spin, with $J = 7/2, 9/2$ preferred [5]. These constraints are incompatible with the $J^\pi = 3/2^-$ assignment reported in refs. [17,23] based on ^{28}Si(^{4}He,$n\gamma\gamma$)^{31}S measurements and this warrants further investigation. The $J = 3/2$ assignment is based on the γ ray angular distribution of a transition to the $J^\pi = 3/2^+$ first-excited state, which yields a reported value of $\Delta J = 0$. It is noted in ref. [23] that $\Delta J = 0, 2$ transitions may have similar angular distributions. In these cases, the authors considered other information such as observed decay branches or the known level structure of the mirror nucleus in order to break the degeneracy. For this particular level, there are no other observed decay branches and the $\Delta J = 0$ assignment was influenced by the assumption that there must be a known ^{31}P mirror level to pair it with [17]. If one removes this assumption and considers the angular distribution alone, it would seem that a $\Delta J = 2$ assignment is a possibility. Based on these arguments, a $J = 7/2$ assignment seems to be a realistic possibility for the 6543-keV level.

A summary of the J^π values discussed in the present work is presented in table 2, which includes some alternative values that were already tabulated in ref. [21]. For the alternative values, we have attempted to decouple experimental information from interpretations based on mirror assignments and focus on the experimental values. We have also tabulated the J^π values reported in ref. [13] without attempting to extract alternatives because the discussion in that work intimately ties the assignments to data on the mirror nucleus.

Conclusions

We have applied an alternative calibration to two high statistics ^{31}P(^{3}He,t)^{31}S spectra acquired at the WNSL based on a new set of calibration data that was not available for the original analysis. As before, we find evidence for an unresolved ^{31}S state at an excitation energy slightly higher than that of the $5/2^+$, $11/2^+$ levels observed at 6393/6394 keV via in beam γ-ray spectroscopy. The alternative calibration also reveals evidence for a $\approx$ 4 keV systematic discrepancy between the ^{31}S excitation energies from the recent in beam γ-ray spectroscopy experiment [17,23] and those from the β delayed γ decay of ^{31}Cl [16]. A similar conclusion was reached by analyzing a ^{32}S(d,t)^{31}S spectrum acquired at MLL.

In addition, we have provided alternative J^π assignments for several ^{31}S proton threshold states using ^{31}P(^{3}He,t)^{31}S angular distributions measured at the MLL. We are able to reconcile discrepant J^π values for the 6136 keV level. Through consideration of the methodology used to assign J^π values in an in beam γ-ray spectroscopy measurement, we are also able to reconcile discrepant J^π values for the 6329 and 6543 keV levels. Outstanding issues in this context include (a) J^π of the 6160 keV level (for which two in beam γ-ray spectroscopy measurements give different J^π values, both of which are now consistent with constraints from the ^{31}P(^{3}He,t)^{31}S data) (b) J^π of the 6356 keV level, for which the available experimental constraints cannot be easily reconciled (c) the number and J^π of levels between 6.39 and 6.41 MeV. Concerning (c), we note that refs. [17,23] assign $5/2^+$, $11/2^+$ to two levels at 6392.5(2) and 6394.2(2) keV, while we tentatively assign (5/2,11/2) to two nearby levels, at least one of which has a significantly higher energy.

Table 2. J^π values for proton unbound ^{31}S levels reported explicitly in the cited publications and experimentally-allowed alternatives derived in the present work. The final "combined" column is an attempt to consolidate the possibilities into overall J^π constraints.

	MLL (^{3}He,t)		(α,$n\gamma\gamma$)		(^{20}Ne,$n\gamma$)	
E_x (keV)	ref. [5]	alternative (present)	ref. [17,23]	alternative (present)	ref. [13]	combined
6136	9/2	7/2	$3/2^+$,$7/2^+$	$3/2^-$,$7/2^-$		7/2
6160	5/2	7/2	$7/2^+$	$7/2^-$	$5/2^-$	5/2,7/2
6260	$1/2^+$					$1/2^+$
6282	$3/2^+$					$3/2^+$
6329	$1/2^+$	$1/2^-$	$3/2^-$	1/2,$3/2^+$		1/2
6356	$3/2^+$		$5/2^-$	$5/2^+$		$3/2^+$,5/2
6377	9/2		$9/2^-$	5/2,$9/2^+$	$9/2^-$	9/2
6393		5/2,11/2	$5/2^+$			$5/2^+$
6394		5/2,11/2	$11/2^+$	$11/2^-$	$11/2^+$	11/2
6402		5/2,11/2				
6543	7/2,9/2		$3/2^-$	$3/2^+$,7/2		7/2
6585	7/2		$5/2^-$,$7/2^-$	3/2,$5/2^+$,$7/2^+$		7/2
6636	9/2		$9/2^-$	5/2,$9/2^+$	$9/2^-$	9/2

We emphasize that the ^{31}P(^{3}He,t)^{31}S excitation energies and J^π values extracted in the present work from previously published data are not intended to supersede the previous values reported in refs. [5,14]. For example, the ^{31}P(^{3}He,t)^{31}S and ^{32}S(d,t)^{31}S excitation energies reported in columns 4, 5 and 6 of table 1 are completely dependent on the results of the in-beam γ-ray spectroscopy experiment [17,23] and will be $\approx$ 4 keV too high if the energies from the ^{31}Cl β decay experiment are accurate. The goal of this work has simply been to explore reasonable alternative interpretations of available data to provoke concordance of different experimental constraints for the structure of ^{31}S above the proton threshold.

Note added: After this work was submitted, a more sensitive measurement of ^{31}Cl β delayed γ decay was published [25]. The reported excitation energies are consistent with those from Ref. [16]. A new ^{31}S level was reported at 6390.2(7) keV with $J^\pi = 3/2^+$.

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