Reevaluation of the ^{30}P(p,γ)^{31}S astrophysical reaction rate from a study of the $T = 1/2$ mirror nuclei, ^{31}S and ^{31}P

D. G. Jenkins and A. Meadowcroft
Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom

C. J. Lister, M. P. Carpenter, P. Chowdhury, N. J. Hammond, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, and D. Seweryniak
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

T. Davinson and P. J. Woods
School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

A. Jokinen and H. Penttila
Department of Physics, University of Jyväskylä, Jyväskylä FIN-40014, Finland

G. Martínez-Pinedo
ICREA and Institut d'Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain

J. José
Institut d'Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain and
Dept. Fisica i Enginyeria Nuclear (UPC), E-08800 Vilanova i la Geltru, Spain
(Received 14 December 2005; published 30 June 2006)

The ^{30}P(p, γ)^{31}S reaction rate is expected to be the principal determinant for the endpoint of nucleosynthesis in classical novae. To date, the reaction rate has only been estimated through Hauser-Feschbach calculations and is unmeasured experimentally. This paper aims to remedy this situation. Excited states in ^{31}S and ^{31}P were populated in the ^{12}C(^{20}Ne,n) and ^{12}C(^{20}Ne,p) reactions, respectively, at a beam energy of 32 MeV, and their resulting γ decay was detected with the Gammasphere array. Around half the relevant proton unbound states in ^{31}S corresponding to the Gamow window for the ^{30}P(p, γ)^{31}S reaction were identified. The properties of the unobserved states were inferred from mirror symmetry using our extended data on ^{31}P. The implications of this new spectroscopic information for the ^{30}P(p, γ)^{31}S reaction rate are considered and recommendations for future work with radioactive beams are discussed.

DOI: 10.1103/PhysRevC.73.065802 PACS number(s): 26.30.+k, 21.10.Hw, 27.30.+t

I. INTRODUCTION

Astrophysical interest in the ^{30}P(p, γ) reaction rate involves several explosive scenarios, principally classical nova outbursts and X-ray bursts. For the former scenario, hydrodynamic models of the explosion with white dwarf masses near the Chandrasekhar limit ($M_{\text{Chan}} \simeq 1.4M_{\odot}$) show that the main nuclear path leading to the Si-Ca mass region is governed by ^{30}P(p, γ)^{31}S [1]. It is unfortunate, therefore, that the ^{30}P(p, γ) reaction rate is presently unmeasured experimentally. This state of affairs is unlikely to change in the near future because the production of an intense ^{30}P beam, needed to measure the reaction rate directly in inverse kinematics, is technically very difficult using the isotope separation on-line (ISOL) technique. The ^{30}P(p, γ) reaction rate has to be, therefore, estimated using Hauser-Feschbach calculations, for example, those presented by Rauscher and Thielemann [2] and discussed in the later compilation by Iliadis *et al.* [3]. For such calculations to make a good estimation of the reaction rate, a sufficiently high level density must occur in the Gamow window. This condition depends both on the mass region and reaction Q value. Rauscher and Thielemann recommend that the appropriate conditions pertain for temperatures $T_9 > 0.24$, although they suggest that this is a rather conservative lower limit and that the Hauser-Feschbach approach may still be appropriate at slightly lower temperatures [2], whereas Iliadis *et al.* only tabulate this reaction rate for $T_9 > 0.3$ [3].

The importance of nuclear uncertainties affecting some reaction rates of astrophysical interest has sometimes been overestimated. In the past, the identification of important reaction-rate uncertainties was frequently based on intuitive guesses (often unreliable because of the complicated interplay among the many nuclear reactions involved, as well as the influence of convection and hydrodynamical processes [4]). For this reason, substantial efforts have been recently made in identifying important reaction-rate uncertainties by performing numerical simulations. An extensive example is the work of Iliadis *et al.* [5], which clearly demonstrated (through a series of 7350 simulations in which reaction rates were individually varied by factors of 0.01, 0.1, 0.5, 2, 10, and 100) that for the vast majority of nuclear processes included in network calculations, reaction-rate variations have a negligible effect on final isotopic abundances in current nova models. As shown in Table 12 of Ref. [5], the nuclear reaction in the Si-Ca mass region that has the largest impact on the final yields is ^{30}P(p,γ), which dramatically affects the abundances of ^{30}Si, ^{32,33,34}S, ^{35,37}Cl, and ^{36,37,38}Ar in the nova ejecta. It is worth noting that the uncertainty assigned in that work to ^{30}P(p,γ) appears to be a factor of 100/0.01 (see Table 3 of Ref. [5]). Moreover, when other reactions in the Si-Ca region are varied up and down by the same factors, the impact on the final yields is much more moderate. As an example, ^{34}S(p,γ) affects only the final abundances of three species (^{34}S, ^{35}Cl, and ^{36}Ar), whereas uncertainties in the ^{33}Cl(p,γ) reaction rate affects only ^{33}S. These results lead us to conclude that (i) uncertainties associated with the ^{30}P(p,γ) reaction rate play an important role in the synthesis of nuclei in the S-Ca mass region during nova explosions and (ii) this justifies the need for a dedicated experiment aimed to reduce such uncertainties. It is important to stress that network calculations are very helpful for extensive tests (such as those performed in Iliadis *et al.* [5]), which become prohibitive with detailed hydrodynamic models; but they tend to overemphasize the impact of individual reactions on the overall nucleosynthesis, since they do not account for the smoothing role of convection between adjacent stellar shells. Therefore, it is very important to confirm the predictions obtained with network calculations with state-of-the-art hydrodynamic codes. José *et al.* [1] have made an extensive analysis of the role of the ^{30}P(p,γ) reaction through hydrodynamic calculations which has shown that for (massive) ONe novae, close to the Chandrasekhar mass, ^{30}P is a mandatory passing point to sulfur (and beyond). This proceeds either through the pathway ^{30}P$(p,\gamma)^{31}$S$(p,\gamma)^{32}$Cl$(\beta^+)^{32}$S or through ^{30}P$(p,\gamma)^{31}$S$(\beta^+)^{31}$P$(p,\gamma)^{32}$S because of other possible nuclear channels being strongly inhibited. This is the case for the ^{30}P$(\beta^+)^{30}$Si$(p,\gamma)^{31}$P$(p,\gamma)^{32}$S reaction that, because of the slow ^{30}P β^+ decay ($\tau = 2.5$ min), is bypassed by the ^{30}P(p,γ) reaction at temperatures typical for nova processing of material in the Si-Ca region (i.e., $T_9 > 0.1$). Other slow channels include ^{29}P$(p,\gamma)^{30}$S, which rapidly decays into ^{30}P ($\tau = 4$), since ^{30}S$(p,\gamma)^{31}$Cl faces a strong inverse photodisintegration reaction, ^{31}Cl$(\gamma,p)^{30}$S. In addition, the relatively small initial amount of ^{31}P in the envelope prevents significant synthesis of ^{32}S through ^{31}P$(p,\gamma)^{32}$S. Therefore, additional production of ^{31}P, which is tuned by the ^{30}P$(p,\gamma)^{31}$S rate, is required to favor the synthesis of ^{32}S and heavier nuclei. Energetically speaking, ^{30}P(p,γ) is irrelevant for nova outbursts since the major sources of energy production are reactions of the CNOF cycles (with a minor contribution of NeNa and MgAl pseudocycles). Since the energy released by nuclear reactions is critical to the dynamics of the explosion, we can conclude that ^{30}P(p,γ) plays with relevant role with respect to the time scale of the explosion, peak temperatures achieved, or characteristics of the nova ejection stage (amount of mass ejected, kinetic energy, etc.). Indeed, the role of the ^{30}P(p,γ) reaction is purely nucleosynthetic. It is crucial in our uncerstanding of the synthesis of nuclear species in the S-Ca mass region, often observed in the spectra of (ONe) novae. Moreover, ^{30}P(p,γ) plays a role in the field of presolar grains extracted from meteorites. The recent presolar grains isolated from the Murchison meteorite [6], which strongly point toward a likely nova origin, are characterized by close to solar values for the ^{29}Si/^{28}Si abundance ratio and excesses on ^{30}Si/^{28}Si with respect to solar values. Whereas conclusions regarding ^{29}Si/^{28}Si remain unaffected by the uncertainty on ^{30}P(p,γ), we find either ^{30}Si excesses for nominal or low ^{30}P(p,γ) rates, or ^{30}Si deficits when upper limits are adopted [1]. Through a better knowledge of the ^{30}P(p,γ) rate, we will be able to provide more realistic isotopic ratios that are expected to represent the composition of the ejecta from classical novae and thereby provide better arguments for the proper identification of the origin of future presolar grains.

II. EXPERIMENTAL DETAILS

In an earlier publication [7], we discussed the structural aspects of the mirror nuclei, ^{31}S and ^{31}P. In particular, we addressed the effect of the electromagnetic spin-orbit interaction which leads to large mirror energy differences (MEDs) for specific negative parity states with particularly pure single-particle configurations. In the present work, we set out additional information on proton-unbound levels in ^{31}S and consider their implications for the ^{30}P(p,γ) reaction rate. We conclude by providing suggestions for future measurements which could further constrain the uncertainties in the ^{30}P(p,γ) reaction rate.

The experimental technique is described in detail in our previous publication [7]. Briefly, excited states in ^{31}P and ^{31}S were produced at the same time through the ^{12}C(^{20}Ne,p) and ^{12}C(^{20}Ne, n) reactions using a 32 MeV beam from the ATLAS accelerator at Argonne National Laboratory. The resulting γ decays were detected by Gammasphere [8], an array of 100 large, Compton-suppressed germanium detectors. Transitions in ^{31}S were rigorously identified by selecting ^{31}S recoils using the fragment mass analyzer (FMA) [9] and an ion chamber. This information was used in conjunction with a γ-γ matrix and a γ-γ-γ cube to develop level schemes for the two nuclei. An angular correlation analysis was performed for the strongest γ rays observed. The ratio R_{DCO} was defined as the intensity of a γ ray observed at forward (32° and 37°) or backward (143° and 148°) angles to that measured at 90°. Under this geometry, a stretched quadrupole transition was expected to have a ratio of 1.6(1), while a stretched dipole transition was found to have a ratio of 0.90(5). Lifetimes for some of the states were extracted using the fractional Doppler shift technique.

We were able to very cleanly identify the strongest transitions in ^{31}S when we demanded that the separated recoils had $A = 31$ and $Z = 16$. The statistics did not allow, however, the identification of weak or high-energy γ rays which might be feeding the ground state, given the very low coincident efficiency. To develop the level scheme, we exploited the γ-ray coincidence data, which did not have a condition on the detection of ^{31}S residues. The analysis was therefore complicated by the presence of transitions with nearly identical energy in other nuclei which were more strongly populated in the experiment. For example, the first 5/2$^+$ state in ^{31}S decays by a 2236 keV γ ray, which is nearly degenerate with strong transitions in both ^{31}P and ^{30}Si and so is useless for a γ-γ analysis. However, we were able to find clean gating conditions

TABLE I. Properties of states in ^{31}S relevant to the ^{30}P(p,γ) reaction. Proton energies are calculated from the Q value of 6133.0(15) keV [11]. Spins and parities are from the present work, unless otherwise stated.

E_x(keV)		E_p (c.m.) (keV)	I_i^{π}	I_f^{π}	E_γ (keV)	R_{DCO}
Endt [12,13]	Present					
6155(10)	6160.2(7)	27.2(16)	$5/2^-$	$7/2^-$	1709.2(6)	0.90(9)
					2875.3(8)	
6257(5)[a]	unobs.	124(5)	$1/2^+$			
6280(2)[b]	unobs.	147(2)	$3/2^{+c}$			
6350(11)	unobs.	217(11)	$(5/2^+)$			
	6376.9(5)	243.9(16)	$9/2^-$	$7/2^-$	1926.0(3)	0.44(6)
6393(5)[a]	6393.7(5)	260.7(16)	$11/2^+$	$7/2^+$	3042.4(4)	1.58(13)
				$9/2^+$	1090.7(10)	
6543(11)	unobs.	410(11)	$(3/2,5/2)^-$			
(6593(15))		460(15)	$(3/2/5/2)^-$			
6628(13)	6636.3(15)	503.3(21)	$9/2^-$	$7/2^+$	2049.2(6)	
				$7/2^+$	3285.1(5)	0.57(19)
				$7/2^-$	2187.2(5)	
6712(11)	unobs.	579(11)	(3/2,7/2)			
6748(10)	unobs.	615(10)	(3/2,7/2)			
6796(25)	unobs.	663(25)	(3/2,7/2)			
6835(9)	6833.4(3)	700.4(15)	$11/2^-$	$7/2^-$	2382.8(3)	1.68(6)
				$9/2^+$	1532.2(2)	0.94(7)
6870(10)	unobs.	737(10)	(3/2,5/2)			

[a]From more recent transfer measurement by Vernotte *et al.* [14].
[b]From more recent β-decay measurement by Kankainen *et al.* [15].
[c]$T = 3/2$.

to observe transitions feeding the $3/2_1^+$, $5/2_2^+$, $7/2_1^+$, and $7/2_1^-$ levels in ^{31}S. It should be noted that two γ-decaying levels in the Gamow window have also recently been reported by Della Vedova *et al.* [10].

III. RESULTS

The present work has allowed us to identify many of the states in the Gamow window in ^{31}S (see Table I) as well as states at lower energies (see Table 1 of [7]). Prior to our work, little was known about ^{31}S at high excitation energies. In the present work, ^{31}P was copiously produced and the decay scheme was considerably extended.

The mirror pair ^{31}S and ^{31}P exhibit good mirror symmetry (Figs. 1 and 2 of [7]), with mirror energy differences of <100 keV and similar decay patterns, with rather few exceptions. The exceptional states are those with rather pure single amplitude wave functions, usually involving promotion of a particle into the $f_{7/2}$ shell, and were caused by a combination of electromagnetic and binding energy effects, both of which could be estimated. In these cases, shifts in excess of $\sim$250 keV were observed [7]. We used our ^{31}P decay scheme, which extends well above 6 MeV in excitation, together with our findings on mirror energy differences [7] in making the assignments for states in the Gamow window of ^{31}S that we did not populate in the current study. We also employed information from earlier transfer reaction studies [12–14,16] populating relevant levels in ^{31}S. In the following section, we summarize the information on the resonances in the ^{30}P$(p,\gamma)^{31}$S reaction above the proton threshold at 6133.0(15) keV (calculated from the 2003 Atomic Mass Evaluation [11]). As a guide, we list the relevant proton-unbound levels in ^{31}S alongside their possible mirror counterparts in ^{31}P in Table II; arguments for these assignments are given in detail below.

TABLE II. Comparison of ^{31}S proton-unbound levels with their likely mirror states, their excitation energy, spin/parity, and lifetime [12,13]. Levels marked with an asterisk cannot be definitively fixed to their mirror partner; arguments for such mirror assignments are discussed in detail in the text.

$E_x(^{31}$S) (keV)	$E_x(^{31}$P) (keV)	J^{π}	τ (fs)
6155(10)	6398.6(7)	$5/2^-$	43(14)
6257(5)	6336.6(15)	$1/2^+$	
6280(2)	6380.8(17)	$3/2^+, T = 3/2$	<10
6350(11)	6460.8(16)	$5/2^+$	
6376.9(5)	6500.6(9)	$9/2^-$	55(17)
6393.7(5)	6453.7(11)	$11/2^+$	33(13)
6543(11)*	6594.2(14)	$5/2^-$	
6593(15)*	6610.3(10)	$3/2^-$	
6636.3(15)	6782.9(9)	$9/2^-$	
6712(11)*	6842.3(12)	$(5/2,7/2)^-$	
6748(10)*	6909.2(14)	$3/2^-$	4(1)
6796(25)*	6931.7(14)	$5/2^+$	<45
6833.4(3)	6825.1(9)	$11/2^-$	125(50)
6870(10)*	7079.9(14)	$(3/2^-,5/2^+)$	

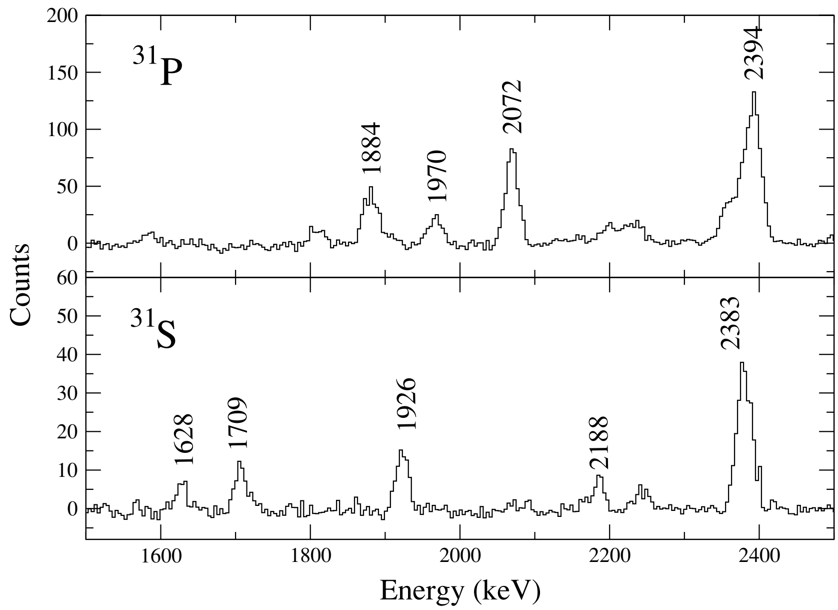

FIG. 1. Top spectrum shows transitions above the 7/2$^-$ level in ^{31}P and is double-gated by the 1136 and 2029 keV transitions in the γ-γ-γ cube. Bottom spectrum contains transitions above the 7/2$^-$ level in ^{31}S and is double-gated by the 1166 and 2036 keV transitions in the γ-γ-γ cube. Mirror transitions of interest are labeled with their energies in keV.

A. E_{ex} = 6155 keV

This level appears to be a good candidate for the mirror partner of the 5/2$^-$ level at 6398 keV in ^{31}P on the basis of its very similar decay branches. The ^{31}P level decays predominantly to the 7/2$^-$ level. The dominant decay from the ^{31}S state is also to the 7/2$^-$ level via a 1709 keV γ ray, which has an angular distribution consistent with a dipole transition (see Fig. 1). The implied mirror energy difference (MED) between the the 5/2$^-$ states in ^{31}S and ^{31}P is -243 keV. Note that this is very similar to the MED for the first 13/2$^-$ levels (-247 keV) [7]. The very low energy of this resonance means that its contribution to the total reaction rate is negligible for temperatures associated with nova explosions.

B. E_{ex} = 6257 keV

This state is well known from transfer studies and has been confidently assigned spin and parity quantum numbers of 1/2$^+$ [12,13]. It was most recently observed by Vernotte *et al.* [14] who were able to reduce the uncertainty in its excitation energy. We would not expect to observe this state in the present work since the mirror level at 6336 keV in ^{31}P has a single γ branch to the ground state. We adopt the excitation energy of this state from the most recent work of Vernotte *et al.*, i.e., 6257(5) keV [14]. Shell model calculations in the *sd*-configuration space using the USD interaction [17] predict that this state should lie at 6531 keV and give a spectroscopic factor of 2.93×10^{-3} for the $s_{1/2}$ component and 1.46×10^{-2} for the $d_{3/2}$ component. These values were employed in estimating a resonant strength associated with this state.

C. E_{ex} = 6268 keV, $T = 3/2$

This state, which has isospin $T = 3/2$, is known from a ^{33}S(p, t) study [16]. Kankainen *et al.* very recently observed the strong population of this state following the β decay of ^{31}Cl and detected its decay via a 4045 keV γ ray to the first 5/2$^+$ state in ^{31}S [15]. This work has allowed a more precise excitation energy of 6280(2) keV to be deduced for this state. We would not expect to populate this particular level in our reaction given that both beam and target nuclei have $T = 0$ ground states. Despite the fact that this state would correspond to $l = 0$ proton capture, we cannot reliably estimate its contribution, because the shell model calculations treat isospin as a good quantum number, meaning that we cannot reach a $T = 3/2$ state by proton capture on a ^{30}P, $T = 0$ ground state. In fact, the capture probability will depend on the level of isospin mixing of $T = 1/2$ components in the predominantly $T = 3/2$ state. This is not easily calculable, but a typical isospin suppression factor might be 2.5×10^{-3}.

D. E_{ex} = 6350 keV

We do not observe this state in the present work. However, once we exclude the high spin states in this energy region which we can assign, and take into account that all states observed so far have MEDs that are negative, or very small, then several candidate mirror states in ^{31}P emerge as possible analogs for this state in ^{31}S. First, the analog state could be one of the low-spin negative parity states known in ^{31}P which lie around 6.5–6.6 MeV. An alternative for the analog state is the 5/2$^+$ level at 6453 keV in ^{31}P. The implied MED would then be -110 keV, which is large, but not much larger than that for the 1/2$^+$ and 3/2$^+$ states discussed above. In their ^{29}Si(^{3}He, n) study, Davidson *et al.* found that the 6350 keV state is well populated [18]. While they do not make a definitive assignment to this level, they note that the angular distribution of neutrons from this state is characteristic of $l = 2$ transfer. Indeed, the relevant angular distribution has a nearly identical shape to that of other states in ^{31}S, which are known, independently, to correspond to $l = 2$ transfer in the ^{29}Si(^{3}He, n) reaction, such as the 6268 keV state. This would allow $J^\pi = 3/2, 5/2^+$ for the 6350 keV level. Given that there is a $J^\pi = 5/2^+$ of similar energy in ^{31}P, we prefer this assignment for the ^{31}S level. The *sd* shell model predicts such a level should lie at 6546 keV, and the spectroscopic factors attributable to the $d_{3/2}$ and $d_{5/2}$ components are 4.08×10^{-2} and 2.89×10^{-3}, respectively.

E. New level: $E_{\rm ex}$ = 6377 keV

This level has not previously been observed. On the basis of angular distributions and from comparison with mirror states, we assign $J^\pi = 9/2^-$ to this level (see Fig. 1). The corresponding mirror energy difference is -125 keV; the origin of this shift in terms of the electromagnetic spin-orbit interaction has been discussed in detail in our earlier publication [7]. In relation to the nearby 6350 keV resonance, the contribution of this resonance which corresponds to $l = 3$, will be negligible.

F. $E_{\rm ex}$ = 6396 keV

We identify this state as the yrast $11/2^+$ on the basis of angular distributions and a comparison with the ^{31}P mirror. We would expect the resonance strength to be correspondingly small for such an $l = 4$ proton. This state and the high spin state at 6835 keV were also reported recently by Della Vedova *et al.* [10]. Their tentative spin/parity assignments agree with the present work.

G. $E_{\rm ex}$ = 6543 and 6593 keV

We have not observed either of these previously reported levels in the present work [12,13]. It is important to note that an apparent typing mistake has occurred in the most recent volume of *Table of Isotopes* [19], where the 6543(11) keV level is incorrectly presented as 6453(11) keV. Clearly, our assignment for the 6543 and 6593 keV levels is interrelated to that for the 6350 keV level. Because we prefer on the basis of transfer studies [18] that the 6350 keV level has $J^\pi = 5/2^+$, the 6543 and 6593 keV levels are then most likely the analogs of the $3/2^-$ state at 6496 keV, the $5/2^-$ state at 6593 keV, or the $3/2^-$ state at 6610 keV in ^{31}P. Given that the latter two states in ^{31}P lie close together, then if their mirror counterparts did not experience a significant mirror energy shift, the 6593 keV state in ^{31}S might, in fact, be a close-lying doublet of states. In practice, how we make these assignments is not very critical since they both correspond to $l = 1$ proton capture. It is not possible to calculate spectroscopic factors for these states as no reliable cross-shell *sd-pf* interaction exists for this mass region. If neutron spectroscopic factors had been measured for the mirror states in ^{31}P, then it would have been possible to assume these values, because they should be very similar to the proton spectroscopic factors of the ^{31}S states. Unfortunately, these are not known either, since both sets of spectroscopic factors could only be obtained from transfer reactions using an unstable ^{30}P beam or target. We have therefore taken the indirect approach of investigating typical proton spectroscopic factors for states at similar excitation energy in ^{31}P, which have been measured in a $^{30}\mathrm{Si}(^3\mathrm{He}, d)$ reaction by Vernotte *et al.* [20]. We have taken the average of these measurements for negative parity states in the excitation energy range 6 to 7 MeV in ^{31}P, which leads to a typical spectroscopic factor of 0.02. We adopt this value for the unknown spectroscopic factors for the negative parity states in the Gamow window in ^{31}S.

H. $E_{\rm ex}$ = 6628 keV

This state is found to decay to both the first and second $7/2^+$ states as well as the first $7/2^-$ state. We therefore propose that it is the analog of the $9/2^-$ state in ^{31}P at 6793 keV, implying a mirror energy difference of -165 keV, which is fairly similar to the mirror energy difference for the first $9/2^-$ states. Figure 2 supports this assignment where the 3285 keV transition in ^{31}S appears as the clear analog of the 3380 keV $9/2^- \to 7/2^+$ transition in ^{31}P. There is a small discrepancy, however, in

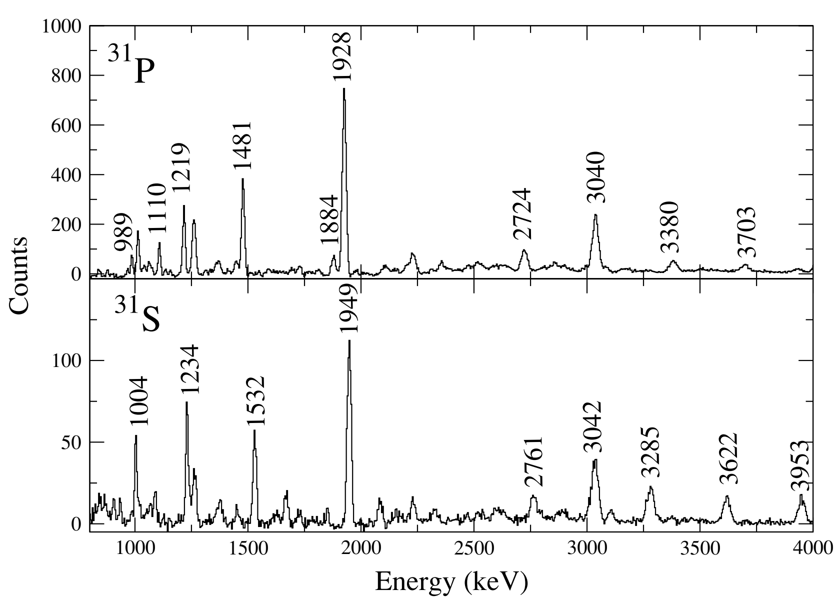

FIG. 2. Top spectrum shows transitions above the $7/2^+$ level in ^{31}P and is double-gated by the 1266 and 2148 keV transitions in the γ-γ-γ cube. Bottom spectrum contains transitions above the $7/2^+$ level in ^{31}S and is double-gated by the 1249 and 2102 keV transitions in the γ-γ-γ cube. Mirror transitions of interest are labeled with their energies in keV.

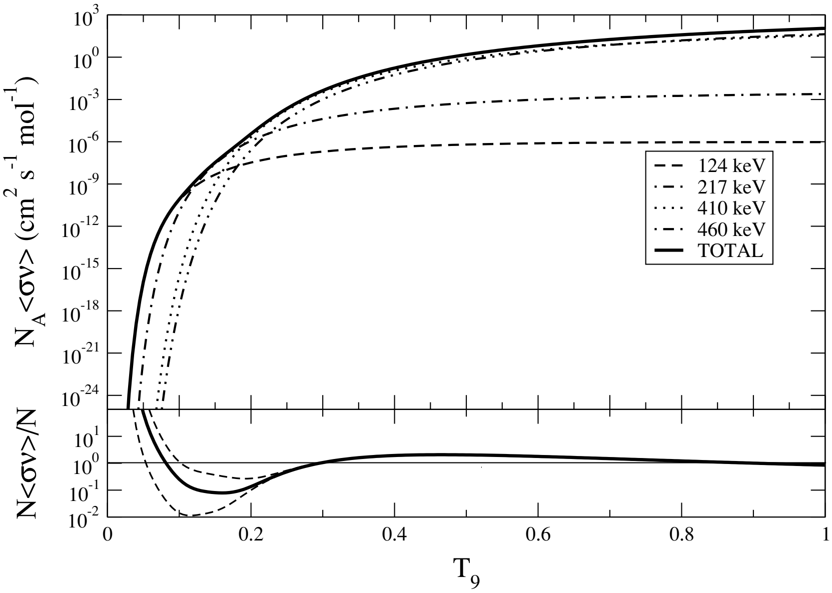

FIG. 3. Evaluation of the $^{30}P(p,\gamma)$ reaction rate. Top panel shows the individual contributions, labeled by E_p (c.m.) in keV, to the total reaction rate. Bottom panel shows the ratio of the reaction rate obtained in the present work to the reaction rate deduced from Hauser-Feschbach calculations taken from Ref. [2]. Dashed lines bound the uncertainties arising from variation of the resonance energies of the resonances at E_p (c.m.) = 124(5) and 217(11) keV.

the mirror symmetry, in that the ^{31}P state does not decay to the second $7/2^+$ state. This may very likely be explained in terms of isospin mixing causing constructive and destructive mixing in the $E1$ matrix element for this transition. Similar behavior is seen in the decay of the first $7/2^-$ state which, in ^{31}P, decays strongly to both the first and second $5/2^+$ states, while in the mirror nucleus, ^{31}S, the latter decay is essentially absent. This behavior is described in detail in our earlier publication [7].

There are also some interesting differences in the population of this level. In ^{31}S, this level is fed very strongly by a 1004 keV transition. There is no evidence for the feeding of the mirror level in ^{31}P by any discrete γ ray. This might also be evidence for isospin mixing.

TABLE III. Proton widths and resonance strengths deduced for resonances in the $^{30}P(p,\gamma)$ reaction. For resonance strengths that are more than two orders of magnitude less than that of neighboring resonances, we list the resonance strengths as negligible. The $T = 3/2$ resonance at E_p = 147(2) keV is omitted since we cannot reliably estimate its strength due to the strong isospin suppression. We have assumed a typical γ width of $\Gamma_\gamma = 1.5 \times 10^{-4}$ keV for cases where the lifetime of the state is unknown. This corresponds to a lifetime of 4 fs. Where there is more than one possible value for l, we present the proton width consistent with the lowest value of l.

E_p (c.m.) (keV)	l	$\Gamma_{\rm s.p.}$ (keV)	C^2S	Γ_p (keV)	Γ_γ (keV)	$\omega\gamma$ (keV)
27.2(16)	1	$2.10^{+26.6}_{-1.98} \times 10^{-32}$	0.02	$4.2^{+53.2}_{-4.0} \times 10^{-34}$	$1.5^{+0.5}_{-0.5} \times 10^{-5}$	$4.2^{+53.2}_{-4.0} \times 10^{-34}$
124(5)	0	$2.37^{+2.97}_{-2.20} \times 10^{-11}$	0.003	$7.11^{+8.91}_{-6.60} \times 10^{-14}$	[a]	$2.45^{+2.97}_{-2.25} \times 10^{-14}$ [b]
	2	$1.66^{+2.08}_{-0.97} \times 10^{-13}$	0.015	$2.49^{+3.12}_{-1.46} \times 10^{-15}$		
217(11)	2	$4.25^{+4.97}_{-2.41} \times 10^{-9}$	0.044	$1.87^{+2.18}_{-1.06} \times 10^{-10}$	[a]	$1.87^{+2.18}_{-1.06} \times 10^{-10}$
243.9(16)	3	$3.58^{+0.40}_{-0.37} \times 10^{-10}$	0.02	$7.16^{+0.80}_{-0.74} \times 10^{-12}$	$1.2^{+0.4}_{-0.4} \times 10^{-5}$	$1.19^{+0.14}_{-0.14} \times 10^{-11}$
260.7(16)	4	$6.21^{+0.64}_{-0.62} \times 10^{-12}$	0.02	$1.24^{+0.13}_{-0.12} \times 10^{-13}$	$2.0^{+0.8}_{-0.8} \times 10^{-5}$	$2.4^{+0.2}_{-0.2} \times 10^{-13}$
410(11)	1	$5.11^{+1.79}_{-1.31} \times 10^{-4}$	0.02	$1.02^{+0.36}_{-0.26} \times 10^{-5}$	1.5×10^{-4}	$6.4^{+2.3}_{-1.5} \times 10^{-6}$
460(15)	1	$1.80^{+0.75}_{-0.53} \times 10^{-3}$	0.02	$3.60^{+1.50}_{-1.06} \times 10^{-5}$	1.5×10^{-4}	$1.9^{+0.8}_{-0.6} \times 10^{-5}$
503.3(21)	3	$4.46^{+0.22}_{-0.22} \times 10^{-6}$	0.02	$8.92^{+0.44}_{-0.44} \times 10^{-8}$	$3.3^{+0.7}_{-0.7} \times 10^{-6}$	neg.
579(11)	(1,3)	$1.88^{+0.32}_{-0.32} \times 10^{-2}$	0.02	$3.76^{+0.64}_{-0.64} \times 10^{-4}$	1.5×10^{-4}	$7.1^{+1.2}_{-1.2} \times 10^{-5}$
615(10)	(1,3)	$3.31^{+0.52}_{-0.52} \times 10^{-2}$	0.02	$6.62^{+0.10}_{-0.10} \times 10^{-4}$	1.5×10^{-4}	$8.2^{+1.3}_{-1.3} \times 10^{-5}$
663(25)	(1,3)	$6.55^{+2.52}_{-1.92} \times 10^{-2}$	0.02	$1.31^{+0.50}_{-0.38} \times 10^{-3}$	1.5×10^{-4}	$9.0^{+3.6}_{-3.0} \times 10^{-5}$
700.4(15)	5	$\sim 10^{-9}$	0.02	$\sim 10^{-11}$	$5.4^{+2.2}_{-2.2} \times 10^{-6}$	neg.
737(10)	(1,2)	$1.60^{+0.23}_{-0.23} \times 10^{-2}$	0.02	$3.20^{+0.46}_{-0.46} \times 10^{-4}$	1.5×10^{-4}	$6.7^{+0.7}_{-0.7} \times 10^{-5}$

[a]Lifetime of the mirror state is unknown but $\Gamma_p \ll \Gamma_\gamma$.
[b]Sum of the two contributions from $l = 0$ and $l = 2$.

I. E_{ex} = 6712, 6748, 6796, and 6870 keV

We do not observe any of these states in the present work. They are most likely analogs of the (5/2,7/2)$^-$ state at 6842 keV, the 3/2$^-$ state at 6906 keV, the 5/2$^+$ state at 6932 keV, and the (3/2$^-$,5/2$^+$) state at 7080 keV in ^{31}P. The precise provenance of these levels is unimportant as their contribution is dominated by their γ width, since we are in the regime where $\Gamma_p > \Gamma_\gamma$.

J. E_{ex} = 6835 keV

On the basis of both its angular distribution and comparison with the mirror states in ^{31}P, we firmly assign this level as $J^\pi = 11/2^-$, which corresponds to an $l = 5$ proton. Hence, the contribution of this state may safely be neglected.

IV. REEVALUATION OF REACTION RATE

We reevaluated the reaction rate using the information on resonances discussed above. The resonance strength for a state with spin J is given by

$$\omega\gamma = \omega\frac{\Gamma_p\Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}, \tag{1}$$

where

$$\omega = \frac{2J+1}{2(2J_T+1)}. \tag{2}$$

In the case where $\Gamma_p \ll \Gamma_\gamma$, this reduces to

$$\omega\gamma = \omega\Gamma_p. \tag{3}$$

We follow the procedure of Fisker *et al.* [21] in calculating single-particle proton widths using a Woods-Saxon potential with $r = 1.25$ fm and diffuseness $a = 0.65$ fm. These are converted into proton widths using spectroscopic factors. For the 1/2$^+$ and 5/2$^+$ states, we employ spectroscopic factors obtained from an *sd* shell model calculation. For states where the spectroscopic factor is unmeasured, we assumed $S = 0.02$ for reasons discussed above. For the first six resonances above threshold, where $\Gamma_p \ll \Gamma_\gamma$, the γ width can safely be ignored. For the higher lying resonances, we extract a γ width from the lifetime of the mirror state where known, or for the higher lying low-spin, negative parity states, which would be expected to decay by high-energy $E1$ transitions, we adopt a typical γ width corresponding to the 4 fs lifetime of the 3/2$^-$ state at 6909 keV in ^{31}P. In the final rate evaluation, we explicitly exclude the 6160, 6628, and 6833 keV resonances, which have negligibly small contributions from their correspondingly small proton energy and high l values. We also neglect the 6280 keV, $T = 3/2$ state since it lies very close to the 1/2$^+$ state at 6257 keV. We would expect capture into the $T = 3/2$ state to be strongly suppressed relative to the latter state at the level of isospin mixing ($\sim 10^{-3}$). The resonance energies, proton and gamma widths, and resonance strengths employed in evaluating the reaction rates are presented in Table III. The individual resonance rates and total reaction rate are given in Fig. 3. The total reaction rate is presented separately in Table IV.

Clearly, the reaction rates presented in Fig. 3 have substantial uncertainties given some of the assumptions made such as the employment of a typical spectroscopic factor of $S = 0.02$ for the unmeasured spectroscopic factors. Nevertheless, this reaction rate is determined empirically from what we know about ^{31}S, so it is arrived at completely independently from previous Hauser-Feschbach theoretical estimates. This figure clearly shows which resonances make the most important contribution to the total reaction rate. At the lowest temperatures, the resonances with E_p (c.m.) = 124 and 217 keV are the most important. The E_p (c.m.) = 124 keV resonance has well-established spin and parity, and we can adopt a spectroscopic factor for this state using the *sd* shell model. Accordingly, the uncertainty in the reaction rate is dominated by the uncertainty in the excitation energy of this near-threshold resonance. We find that adopting the lower limit on the resonance energy leads to a 25-fold reduction in reaction rate for $T_9 = 0.1$, while the upper limit on the resonance energy leads to a fourfold increase for the same temperature. The total variation is, therefore, two orders of magnitude. Reducing the uncertainty in the excitation energies of the E_p (c.m.) = 124 and 217 keV resonances would therefore be the most important contribution to constraining the reaction rates below $T_9 = 0.20$. At temperatures above $T_9 = 0.20$, the reaction rate is dominated by the E_p (c.m.) = 410 and 460 keV resonances. The uncertainty in these resonance energies is less important and can at most lead to a factor

TABLE IV. Recommended total thermonuclear reaction rate for ^{30}P(p, γ)^{31}S from the present work.

T (GK)	$N_A\langle\sigma v\rangle$ (cm^2 s^{-1} mol^{-1})
0.01	1.27×10^{-65}
0.02	7.92×10^{-35}
0.03	1.12×10^{-24}
0.04	1.18×10^{-19}
0.05	1.12×10^{-16}
0.06	1.03×10^{-14}
0.07	2.53×10^{-13}
0.08	2.73×10^{-12}
0.09	1.75×10^{-11}
0.1	8.18×10^{-11}
0.11	3.22×10^{-10}
0.12	1.16×10^{-9}
0.13	3.83×10^{-9}
0.14	1.16×10^{-8}
0.15	3.18×10^{-8}
0.16	7.94×10^{-8}
0.18	4.04×10^{-7}
0.2	1.83×10^{-6}
0.25	6.88×10^{-5}
0.3	1.23×10^{-3}
0.35	1.02×10^{-2}
0.4	5.11×10^{-2}
0.45	1.80×10^{-1}
0.5	4.98×10^{-1}
0.6	2.34×10^{0}
0.7	7.22×10^{0}
0.8	1.70×10^{1}
0.9	3.32×10^{1}
1.0	5.68×10^{1}

of 3 increase or decrease in the reaction rate. The uncertainty arising from the assumption of a spectroscopic factor, $S = 0.02$, for these states, is likely of similar order. Deducing a spectroscopic factor for these states should therefore be a key goal of future measurements. For the purposes of gaining an impression of these uncertainties, the total rate is compared with the tabulated values from Hauser-Feschbach calculations [3] in the bottom panel of Fig. 3. Clearly, the Hauser-Feschbach calculations appear to provide a good estimate of the reaction rate down to $T_9 = 0.24$, which was the claimed lower limit of applicability [2]. At lower temperatures, the Hauser-Feschbach calculations [2] appear to overestimate the reaction rate by around a factor of 10 for $T_9 = 0.2$. Taking these effects into account, it appears most likely that the scenario where the reaction rate significantly exceeds the Hauser-Feschbach estimate is physically unreasonable. Indeed, for a considerable portion of the temperature range, the reaction rate appears to be significantly below the Hauser-Feschbach estimate. The present experimental uncertainties discussed above, however, preclude the accurate quantification of the extent of this reduction.

V. OUTLOOK FOR FUTURE MEASUREMENTS

We have considerably improved the experimental information for unbound states in ^{31}S. As we have shown, from the present measurements and careful comparisons with mirror states, there are no ambiguities on spin/parity assignments for the near-threshold resonances whose proton widths principally determine the reaction rate at lower temperatures. We are therefore able to supply a reaction rate with meaningful error bars below $T_9 = 0.3$. It would be fundamentally difficult to improve on the present assessment. One approach would be to measure the ^{30}P(p, γ) reaction directly—in particular for the E_p (c.m.) = 410 and 460 keV resonances. This would be a challenging measurement given the difficulty in producing a beam of ^{30}P using the ISOL technique, though "in-flight" production via the ^{30}Si(p, n) reaction may be possible. Given a modest radioactive beam of $\sim 10^6$ s^{-1}, a (^{3}He,d) reaction could be performed to measure spectroscopic factors for these states. The inaccurate spectroscopic factors are not, however, the only source of error. Several key resonances are not yet well located in energy. The uncertainty in the resonance energies might, in principle, be reduced slightly given a very careful transfer measurement.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W-31-109-ENG38 and by the Nuffield Foundation.

[1] J. José, A. Coc, and M. Hernanz, Astrophys. J. **560**, 897 (2001).
[2] T. Rauscher and F.-K. Thielemann, At. Data Nucl. Data Tables **75**, 1 (2000).
[3] C. Iliadis, J. M. D'Auria, S. Starrfield, W. J. Thompson, and M. Wiescher, Astrophys. J. Suppl. Ser. **134**, 151 (2001).
[4] J. José, M. Hernanz, and C. Iliadis, Nucl. Phys. A (to be published).
[5] C. Iliadis, A. Champagne, J. José, S. Starrfield, and P. Tupper, Astrophys. J. Suppl. Ser. **142**, 105 (2002).
[6] S. Amari, X. Gao, L. R. Nittler, E. Zinner, J. José, M. Hernanz, and R. S. Lewis, Astrophys. J. **551**, 1065 (2001).
[7] D. G. Jenkins *et al.*, Phys. Rev. C **72**, 031303(R) (2005).
[8] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[9] C. N. Davids, Nucl. Instrum. Methods Phys. Res. B **70**, 358 (1992).
[10] F. Della Vedova *et al.*, in *Nuclei at the Limits*, AIP Conf. Proc. no. 764, edited by D. Seweryniak and T. L. Khoo (AIP, New York, 2005), p. 205.
[11] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A779**, 337 (2003).
[12] P. M. Endt, Nucl. Phys. **A521**, 1 (1990).
[13] P. M. Endt, Nucl. Phys. **A633**, 1 (1998).
[14] J. Vernotte *et al.*, Nucl. Phys. **A655**, 415 (1999).
[15] A. Kankainen *et al.*, Eur. Phys. J. A **27**, 67 (2006).
[16] H. Nann and B. H. Wildenthal, Phys. Rev. C **19**, 2146 (1979).
[17] E. Caurier *et al.*, Rev. Mod. Phys. **77**, 427 (2005).
[18] J. M. Davidson, D. A. Hutcheon, D. R. Gill, T. Taylor, D. M. Sheppard, and W. C. Olsen, Nucl. Phys. **A240**, 253 (1975); **A162**, 295 (1971).
[19] *Table of Isotopes*, Vol. 1, edited by R. B. Firestone and V. S. Shirley (Wiley, New York, 1996).
[20] J. Vernotte, A. Khendriche, G. Berrier-Ronsin, S. Grafeuille, J. Kalifa, G. Rotbard, R. Tamisier, and B. H. Wildenthal, Phys. Rev. C **41**, 1956 (1990).
[21] J. L. Fisker, V. Barnard, J. Görres, K. Langanke, G. Martínez-Pinedo, and M. C. Wiescher, At. Data Nucl. Data Tables **79**, 241 (2001).
[22] D. G. Jenkins *et al.*, Phys. Rev. Lett. **92**, 031101 (2004).