Physics Letters B 769 (2017) 549–553

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of key resonance states for the $^{30}P(p,\gamma)^{31}S$ reaction rate, and the production of intermediate-mass elements in nova explosions

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ARTICLE INFO

Article history:
Received 26 August 2016
Received in revised form 9 January 2017
Accepted 14 January 2017
Available online 16 February 2017
Editor: V. Metag

ABSTRACT

We report the first experimental constraints on spectroscopic factors and strengths of key resonances in the $^{30}P(p,\gamma)^{31}S$ reaction critical for determining the production of intermediate-mass elements up to Ca in nova ejecta. The $^{30}P(d,n)^{31}S$ reaction was studied in inverse kinematics using the GRETINA γ-ray array to measure the angle-integrated cross-sections of states above the proton threshold. In general, negative-parity states are found to be most strongly produced but the absolute values of spectroscopic factors are typically an order of magnitude lower than predicted by the shell-model calculations employing WBP Hamiltonian for the negative-parity states. The results clearly indicate the dominance of a single $3/2^-$ resonance state at 196 keV in the region of nova burning $T \approx 0.10$–0.17 GK, well within the region of interest for nova nucleosynthesis. Hydrodynamic simulations of nova explosions have been performed to demonstrate the effect on the composition of nova ejecta.

Lack of knowledge of the rate of proton capture on radioactive ^{30}P is the most prominent nuclear physics uncertainty in models of oxygen neon (ONe) nova explosions [1,2]. Such novae originate from stellar binary systems where hydrogen-rich material accretes from a less evolved partner star onto an ONe white dwarf. After typically 100,000s years of accretion, a thermonuclear runaway occurs that terminates with the ejection of material in the nova explosion [3–6]. Elements up to Ca are observed in the ejecta through spectroscopic observations with infrared and ultraviolet telescopes [7,8]. Theoretical models demonstrate that these elements are produced by a sequence of beta decays and proton captures, and that the rate of proton capture on unstable, neutron deficient ^{30}P plays a key role in determining the synthesis of ele-

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http://dx.doi.org/10.1016/j.physletb.2017.01.084
0370-2693/

ments in the Si–Ca range [2]. The production of these elements is particularly sensitive to the peak temperature achieved in the explosion, and with a well-defined ^{30}P$(p,\gamma)^{31}$S rate, their observed quantities could be used as a thermometer to guide astrophysical models [9]. This reaction rate is also critically important for understanding the large ^{30}Si/^{28}Si isotopic abundance ratios found in presolar grains from primitive meteorites, used to classify these grains as originating from a single nova event [10,11].

A direct measurement of the ^{30}P$(p,\gamma)^{31}$S reaction is not currently feasible owing to the low available intensities of radioactive ^{30}P ion beams at the energies of astrophysical interest. Most recent experimental work (see, *e.g.* Refs. [12–15]) has concentrated on characterizing the energies, spins and parities of states in the Gamow burning window of the compound nucleus ^{31}S that serve as resonances and determine the reaction rate. However, resonance strengths are essential to characterize the contribution of a resonance to the reaction rate. So far, these resonance strengths had to be taken from shell-model calculations. This introduces a large uncertainty in the reaction rate, especially as recent shell-model calculations have shown that negative-parity states, which are calculated with less reliable model spaces compared to the positive parity *sd*-shell states, contribute significantly to the astrophysical reaction rate [16]. We present here the first experimental constraints on the resonance strengths in the ^{30}P$(p,\gamma)^{31}$S reaction. We use a novel technique to extract constraints on proton spectroscopic factors from measurements of angle-integrated cross sections for the ^{30}P$(d,n)^{31}$S proton-transfer reaction in inverse kinematics using a radioactive ^{30}P beam. States were identified by their characteristic γ-decays and cross sections derived from their γ-ray intensities. A first study using this methodology applied to the ^{26}Al$(d,n)^{27}$Si reaction, has shown that spectroscopic factors and strengths of known states and resonances can be well reproduced [17]. The present ^{30}P$(d,n)^{31}$S study was performed using the same set-up at the National Superconducting Cyclotron Laboratory, Michigan State University.

The 30-MeV/u ^{30}P^{15+} beam was produced in-flight via fragmentation reactions using a primary beam of 150-MeV/u 112-pnA ^{36}Ar^{18+} ions to bombard a 1857-mg/cm^2-thick Be target. The A1900 high-resolution fragment separator [18] selected the ions of interest based on their momentum/charge-state ratio after they had passed through a 450-mg/cm^2-thick Al wedge. The typical ^{30}P beam intensity on target was 1.04(8) $\times$ 10^6 pps with a beam purity of 97(2)%. The ^{30}P beam impinged onto a 10.7(8)-mg/cm^2-thick deuterated polyethylene target, $(CD_2)_n$, with the GRETINA (Gamma-Ray Energy Tracking In-beam Nuclear Array) [19] detectors positioned at laboratory angles of 58° and 90°. The projectile-like reaction products were identified with the S800 spectrograph [20] downstream of the GRETINA setup. The S800 was run in focused mode in order to allow a large momentum acceptance. ^{31}S^{15+} ions were clearly separated from other reaction products, and a nearly 100 % acceptance at the S800 focal plane was determined. The data acquisition was triggered either by coincidences between GRETINA and the first scintillator at the focal plane of the S800, or by scaled down projectile-like singles events. The GRETINA efficiency was calibrated with ^{56}Co, ^{152}Eu, and ^{226}Ra sources, and it was around 4.3% at 1.33 MeV for the used seven-module array in singles mode. The in-beam efficiency, assuming isotropic emission in the rest frame of ^{31}S ions, was Lorentz-boosted ($v/c = 0.237$) by a factor 1.06 compared to a stationary source (based on simulations using the UCGretina GEANT4 simulation package [21]). To account for ^{31}S γ-ray transitions produced by ^{30}P(d,n) reactions on carbon in the target, measurements were also performed for an approximately equal duration with a 8.8(15)-mg/cm^2-thick polyethylene target $(CH_2)_n$. Fig. 1 shows Doppler reconstructed γ-ray spectra in coincidence with ^{31}S ions

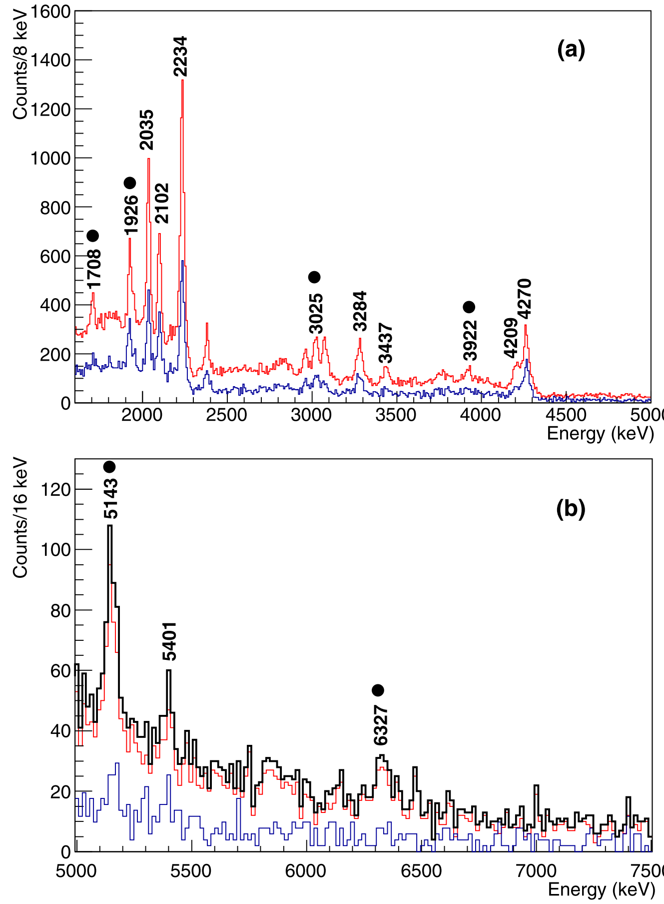

Fig. 1. (Color online.) Doppler-reconstructed γ-ray spectrum in coincidence with ^{31}S reaction products (in red) and a background spectrum scaled to similar conditions (in blue). The black circles highlight the transitions observed from states above the proton threshold. The thick black line in (b) shows the sum spectrum obtained with CD_2 and CH_2 targets. The energies labeled for the peaks in the spectrum are taken from the most precisely known values quoted in the literature [12,13,22].

obtained using the CD_2 and CH_2 targets, with the latter scaled to match the thickness and integrated beam on the CD_2 target. Cross sections were obtained by subtracting the scaled background from the data on $(CD_2)_n$ target (the radiative capture cross section on protons is negligible at these energies).

Measured angle-integrated (d,n) cross-section values for states in ^{31}S above the proton threshold are shown in Table 1. These are compared with theoretical cross-sections for single l-transfers computed within the finite-range adiabatic approximation model [23], as described in Ref. [17]. Based on a previous study [24], we estimate a theoretical uncertainty of about 30% in the cross-section calculations. This is typically the largest source of uncertainty in the derived experimental spectroscopic factors, C^2S. Shell-model calculations of C^2S values discussed in the text are based on the USDA Hamiltonian within the *sd* shell-model space [25] for positive-parity states, and on the WBP Hamiltonian, which includes a *sd*–*pf* Hamiltonian, for negative-parity states [26].

For the important 6327(2)-keV, $3/2^-$ level, at a resonance energy of 196 keV [12,13], we observe for the first time the direct to ground-state branch (see Fig. 1(b)). Such a single transition would not have been observed in the study of Doherty et al. [12,13], which required $\gamma-\gamma$ coincidences, and demonstrates the power of GRETINA for detecting high-energy γ-ray lines. In the work by Doherty et al., a 5078-keV transition was observed to the $3/2^+$ first excited state. This transition is not observed in the present study, and we can set an upper limit on the branch of 46%. For the ana-

Table 1
Experimental cross sections (σ_{exp}) and spectroscopic factors $C^2S(d,n)$ determined in this work for relevant states above the proton separation energy ($S_p = 6130.64(24)$ keV [27]) in ^{31}S. The excitation energies have been adopted from Refs. [13,22], and for the 6279.0(6) keV and 6390.2(7) keV states from Ref. [15]. The 6330(5) keV transition was observed for the first time. An uncertainty of 30% for the theoretical cross sections has been taken into account for $C^2S(d,n)$. The relative γ-ray intensities are given in curly brackets for states with more than one transition observed. Observed transition energies E_γ are from this work. The resonance strengths $\omega\gamma$ used for the astrophysical reaction rate calculations are given in the last column (see text for details).

E_x (keV)	E_{res} (keV)	$J_i^\pi \to J_f^\pi$	E_γ (keV)	σ_{exp} (mb)	C^2S	l	$\omega\gamma$ (eV)
6138.6(6)	8.0(6)	$(3/2^+, 7/2^+) \to 7/2^+$		≤0.030	≤0.16(7)	0	
6158.5(5)	27.9(6)	$7/2^{(-)} \to 7/2^-$	1706.5(13) {100}	0.177(33)	0.036(13)	3	
		$7/2^{(-)} \to 5/2^+$	3922(4) {98}				
6255.3(5)	124.7(6)	$1/2^+ \to 1/2^+$		≤ 0.019	≤ 0.19	0	9.5×10^{-12} [16]
6279.0(6)	148.4(6)	$3/2^+, T = 3/2$	–	≤ 0.029	≤ 0.16	0	
6327.0(5)	196.4(6)	$3/2^- \to 1/2^+$	6330(5)	0.025(10)	0.023(12)	1	$3.5(19) \times 10^{-7}$
6357.3(2)	226.7(3)	$5/2^{(-)}$	–	≤ 0.017	≤ 0.011	1	$\leq 1.4 \times 10^{-6}$
6376.9(4)	246.3(5)	$9/2^- \to 7/2^-$	1926.4(9) {100}	0.32(5)	0.051(17)	3	
		$9/2^- \to 7/2^+$	3022.3(15) {69}				
6390.2(7)	259.6(7)	$3/2^+$	–	≤ 0.042	≤ 0.22	0	2.4×10^{-5} [15]
6392.5(2)	261.9(3)	$5/2^{(+)} \to 3/2^+$	5145(3)	0.034(9)	0.007(3)	2	$4.8(21) \times 10^{-7}$
6394.2(2)	263.6(3)	$11/2^+$	–	≤ 0.018	≤ 0.002	4	
6402(2)	271.4(20)	unknown	–				
6541.9(4)	411.3(5)	$7/2^+$	–	≤ 0.037	$\leq 5.9 \times 10^{-3}$	2	$\leq 1.7 \times 10^{-4}$
6583.1(20)	452.5(20)	(7/2)	–	≤ 0.027	≤ 0.007	3	

log level at 6496 keV in ^{31}P, the ground-state branch is found to be dominant with a branch of 68(9)% with the remaining intensity to the $3/2^+$ first excited state [22]. For estimating the cross section quoted in Table 1, we use this branch value for the ground-state branch, consistent with the upper limit of our non-observation of the branch to the first excited state. The shell model predicts this state to have the second highest spectroscopic factor $C^2S(l = 1) = 0.29$ [16]. However, the value of $C^2S(l = 1) = 0.023(12)$ deduced from our data is again lower than the shell-model calculation predicts. This value implies a resonance strength $\omega\gamma = 0.35(19)$ µeV, obtained by scaling theoretical values from Ref. [16] with the measured C^2S value.

Two previously observed γ-ray transitions [12,13] from the $9/2^-$ state at 6377 keV were observed in the present experiment. This was the most intensely produced state above the proton threshold. Shell-model calculations predicted the largest spectroscopic factor for this state $C^2S(l = 3) = 0.39$ [16]. The value obtained here of 0.051(17), is lower than this calculation but nonetheless represents a relatively high value for high excitation energy states. Negative-parity states can have a relatively high single-particle strength compared to positive-parity states around the same excitation energy in *sd*-shell nuclei [16] (a recent similar example was found for a strong resonance in the ^{26}Al$(p,\gamma)^{27}$Si reaction [28]). In this case, the $9/2^-$ state will not strongly influence the ^{30}P$(p,\gamma)^{31}$S reaction rate due to the high l-value.

The second largest cross section in Table 1 is associated with the state at 6159 keV with two γ-decay branches. The strongest branch is to the lowest-lying $7/2^-$ state (this branch was also seen by Doherty et al. [12,13]). In the mirror nucleus ^{31}P, such a strong transition to the $7/2^-$ state is only observed from the $7/2^{(-)}$ state at 6399 keV [22], which has subsidiary transitions to the $5/2_1^+$ (observed in the present study of ^{31}S) and $5/2_2^+$ (observed in the study of Doherty et al. [12,13]) states. This strongly supports the assignment of the 6159-keV state as the analog of the 6399-keV level in ^{31}P. Shell-model calculations predict a $7/2^-$ state that has a strong $C^2S(l = 3) = 0.26$ consistent with its relatively strong production here, but again with the measured strength about a factor ≈ 10 lower in absolute terms compared to theory. For comparison, shell-model calculations assuming a $7/2^+$ state predict $C^2S(l = 2)$ values of 4.4×10^{-4} (USDA calculation) and 2.6×10^{-8} (USDB), which are incompatible with the measured strength. This state has too low a resonance energy (28 keV) to affect the astrophysical reaction rate.

The 6392-keV state [12,13] corresponds to a resonance energy of 262 keV. The cross-section in Table 1 is based on the 5143-keV transition to the $3/2^+$ first excited state previously observed by Doherty et al. [12,13]. The 5143-keV transition is strongly present in the spectrum of Fig. 1(b), and no other transitions are found from the 6392-keV level, indicating it is the dominant decay branch. The angular distribution and R_{DCO} data from Doherty et al. [12,13], and analysis of light-ion transfer-reaction studies [29], indicate a $5/2^+$ assignment for this state. The spectroscopic factor obtained in this work, $C^2S(l = 2) = 7(3) \times 10^{-3}$, is in a reasonable agreement with the shell-model value, $C^2S(l = 2) = 3.2 \times 10^{-3}$ [16].

It is important to note the existence of a neighboring $3/2^+$ state at 6390 keV observed following the β-decay of ^{31}Cl [15]. The dominant γ-decay transition from the 6390-keV state to the $5/2^+$ state at 2234 keV [15] is not observed in the present data, and we can only set an upper limit for its production cross section. The relatively high upper limit on $C^2S(l = 0)$ is consistent with the theoretical prediction of $C^2S(l = 0) = 0.007$ [15]. The resonance strength used to calculate the reaction rate contribution in Fig. 2 is taken from this theoretical calculation, $\omega\gamma = 24$ µeV [15]. From the measured γ-decay branches reported in Ref. [15], we can deduce that the unresolved 5141.7-keV transition from the 6390-keV state has a negligible contribution to the 5143-keV transition from the 6392 keV state.

No γ-transitions from a state at 6357 keV, assigned as $5/2^-$ based on γ-ray angular distribution and R_{DCO} data [12,13], were observed. This state was not populated via β-decay [15] which is consistent with negative parity. Shell-model calculations predict the existence of $5/2^-$ states in this energy region with comparable $l = 1$ and $l = 3$ contributions, but with weaker absolute values than predicted for the other negative-parity states discussed above, consistent with non-observation in this work. Therefore, the $C^2S(l = 1)$ value in Table 1 should be treated as an upper limit.

An important result is that the three states with the strongest single-particle strengths are all negative-parity states, and correspond to those predicted by shell-model calculations to have the largest C^2S values. However, the absolute values are systematically an order of magnitude lower than predicted. The shell-model Hamiltonian for the negative-parity states has been constrained to reproduce the energies of the well known $3/2^-$ states in ^{29}Si and ^{29}P. These are observed with a spectroscopic strength of $C^2S \approx 0.6$ in agreement with the calculated value of 0.7. The total strength to all $3/2^-$ states is 1.0 since the $1p_{3/2}$ orbit is empty in the model

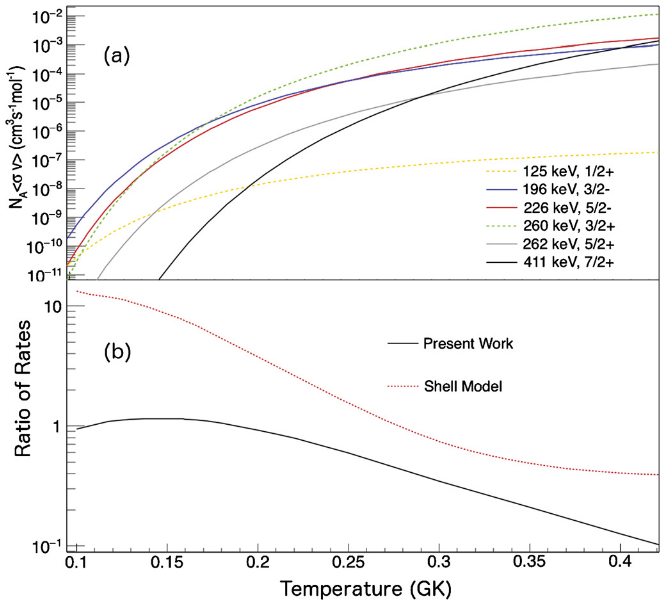

Fig. 2. (Color online.) (a) The resonant proton-capture rates for the $^{30}P(p,\gamma)^{31}S$ reaction over the temperature region relevant for explosive hydrogen burning in novae. The dashed lines indicate the resonances based on theoretical calculations. The solid lines are based on spectroscopic factors from this work. (b) The present estimated reaction rate (black solid line) and the rate based on shell-model spectroscopic factors (red dotted line) shown as a ratio to the statistical model rate used in nova models [30,31].

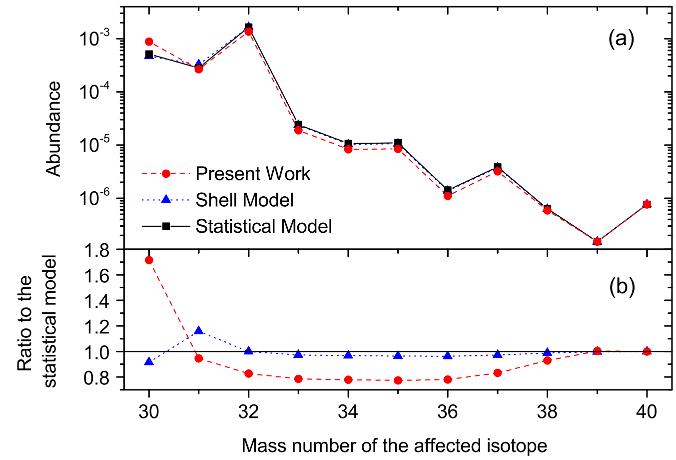

Fig. 3. (Color online.) (a) Abundances in nova ejecta calculated using the reaction rate from this work, the shell-model rate from Ref. [16] and the statistical model rate [31] as a function of the mass number of the affected isotope (^{30}Si, ^{31}P, $^{32-34}S$, ^{35}Cl, ^{36}Ar, ^{37}Cl, ^{38}Ar, ^{39}K, and ^{40}Ca). (b) The abundances based on the reaction rates from the present work and from the shell model shown as a ratio to the abundances obtained with the statistical model rate.

ground state of ^{28}Si. The same total strength of 1.0 is expected for ^{31}S, but the strength is fragmented due to the couplings to the low-lying states in the odd-odd nuclei of ^{30}P (5 states below 2 MeV). A fraction (0.25) of the strength is predicted for the $3/2^-$ state associated with the one observed in this experiment. The experimental strength observed is only 0.023. This means that most of the $0p_{3/2}$ strength must be located above about 6.7 MeV where the proton decays start to dominate over the gamma decays observed in this experiment. This is the first test of this Hamiltonian for the $0p_{3/2}$ strength distribution in this complex situation.

Fig. 2 shows the reaction rate for the novae burning temperature regime and a comparison with rates calculated with the shell model and statistical model [30,31]. The reaction rate for $T \approx$ 0.10–0.17 GK is predicted to be dominated by the $3/2^-$, 196-keV resonance determined in this work. The new recommended reaction rate is significantly smaller than the shell-model rate [16] at low temperatures due to the much weaker 196 keV resonance (see Fig. 2). In the higher temperature region, the 260-keV, $3/2^+$ resonance may dominate the reaction rate, however, its strength is currently relying on theoretical calculations. We note that a state has been reported at an excitation energy of 6402 keV corresponding to a resonance energy of 271 keV [32]. However, there is no definitive information on its spin/parity, nor are any γ-ray transitions known from this state, so we have not included this in the reaction rate plot. A recent re-analysis of light-ion transfer data [29] has conclusively shown the state at 6542 keV, corresponding to a resonance energy of 411 keV, has a minimum spin of 7/2, and thus will only have a modest influence on the reaction rate. We assume $7/2^+$ for the assignment here, consistent with the observation of a γ-decay branch to a $3/2^+$ state [12,13]. Finally, we note that the shell-model calculations [16,33] have predicted the existence of a $1/2^-$ state that may reside in the energy region relevant for nova burning. However, its location is uncertain and there is presently no firm experimental evidence for such a state.

To demonstrate the potential importance of our results for predictions of the composition of nova ejecta, we performed new hydrodynamic simulations of nova explosions with SHIVA [6,34] a 1D, implicit, Lagrangian code used extensively in the modeling of stellar explosions. A series of models of nova outbursts with an accreting 1.35-solar-mass ONe white dwarf have been computed from the early accretion stage through the explosion, expansion and ejection stages. These models were identical except for the $^{30}P(p,\gamma)$ rate adopted. Fig. 3 shows how the reaction rate determined in this work, which includes the first experimental resonance strength value for the 196 keV resonance, propagates into the predictions of the composition of the nova ejecta. For comparison, similar calculations performed with the shell-model [16] and statistical-model [31] reaction rates are included. With the reaction rate determined in this work, more ^{30}Si is produced in novae whereas the amount of heavier elements is reduced up to ^{39}K.

In summary, we report the first experimental information on key resonance strengths in the $^{30}P(p,\gamma)^{31}S$ reaction. Using a new experimental approach, we find that the spectroscopic factors are typically an order of magnitude lower than shell-model calculations predict for negative-parity states. This underlines the need for experimental data on resonance strengths for proton capture rates in this region. One resonance at 196 keV has been found to dominate the rate in the temperature region $T \approx 0.10$–0.17 GK for nova explosions, however, its importance at higher temperatures depends on the strength of the $3/2^+$ state which is currently based on shell-model calculations and should be experimentally constrained in the future. The nova explosion simulations show that the main effect of the present results on the composition of nova ejecta is an increase in the abundance of ^{30}Si critical for determining the $^{30}Si/^{28}Si$ ratio. The overall uncertainty on the $^{30}P(p,\gamma)^{31}S$ reaction rate has been reduced, thereby placing nova nucleosynthesis predictions on a firmer basis.

Acknowledgements

The Edinburgh group is grateful for the support from the STFC grants. A.K. acknowledges the support from the Academy of Finland under project No. 275389. J.J. acknowledges support from the Spanish MINECO grant AYA2014-59084-P, the E.U. FEDER funds, and from the AGAUR/Generalitat de Catalunya grant SGR0038/2014. This work was supported by the National Science Foundation under Grants No. PHY-1403906, PHY-1430152 (JINA Center for the Evolution of the Elements) and PHY-1404442, in part by the National Nuclear Security Administration under the Stewardship Science Academic Alliance program through the DOE cooperative agreement DE-FG52-08NA28552, and by the US DOE, Office of Science, Office of Nuclear Physics, under contract number DE-AC02-06CH11357 (ANL). GRETINA was funded by the US DOE Office of Science. Operation of the array at NSCL is supported by the NSF under Cooperative Agreement PHY-1102511(NSCL) and by the DOE under Grant No. DE-AC02-05CH11231(LBNL). We thank L. Riley for providing us the UCGretina GEANT4 code.

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