Shell-model studies of the astrophysical mirror rp-reactions ^{34}S(p,γ)^{35}Cl and ^{34g,m}Cl(p,γ)^{35}Ar

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Abstract

The two mirror rp-reactions ^{34}S(p,γ)^{35}Cl and ^{34g,m}Cl(p,γ)^{35}Ar were studied via a shell-model approach. At energies in the resonance region near the proton-emission threshold many negative-parity states appear. We present results of calculations in a full (0+1)$\hbar\omega$ model space which addresses this problem. Energies, spectroscopic factors and proton-decay widths are calculated for input into the reaction rates. Comparisons are also made with a recent experimental determination of the reaction rate for the first reaction. The thermonuclear ^{34g,m}Cl(p,γ)^{35}Ar reaction rates are unknown because of a lack of experimental data. The rates for transitions from the ground state of ^{34}Cl as well as from the isomeric first excited state of ^{34}Cl are explicitly calculated taking into account the relative populations of the two states.

1 Introduction

Our analysis is confined to typical novae temperatures, going up to 1 GK. In a recent experiment [1], [2] the ^{34}S(^{3}He,d)^{35}Cl reaction was studied and proton-transfer spectroscopic factors measured for 21 states in an energy region of about 1 MeV above the threshold energy ($S_p = 6.371$ MeV). As a result a new ^{34}S(p,γ)^{35}Cl reaction rate could be determined directly from the experimental data. The product $(2J + 1)C^2S$ was measured so that it was not necessary to determine the J values of the resonances explicitly. We have done a theoretical calculation of the rate which takes into account contributions from positive and negative parity states in a full (0+1)$\hbar\omega$ model space based on the interaction sdpfmu [3]. The motivation is to correlate theory and experiment, to determine where differences exist and the reasons for these.

The thermonuclear ^{34g,m}Cl(p,γ)^{35}Ar reaction rates are unknown at nova temperature due to a lack of experimental nuclear physics data for the resonances up to about 800 keV above the ^{35}Ar proton separation energy [4]. Current nova models treat the ^{33}S(p,γ)^{34}Cl and ^{34}Cl(p,γ)^{35}Ar rates as single, total rates, without separately considering the ground state ^{34g}Cl and the isomeric first excited state ^{34m}Cl (Ex = 146.36(3) keV, $T_{1/2} = 2.5$ min). However, similar to the case of ^{26}Al, the ^{34}Cl ground state and its long-lived isomer are not necessarily in thermal equilibrium at nova temperatures and it is therefore necessary to calculate the reaction rates on both initial states, in order to represent their influence accurately in a nucleosynthesis calculation [5], [6]. In some cases capture on an excited state can dominate a thermonuclear reaction rate even when it is in thermal equilibrium with the ground state [7].

Estimates based on shell-model calculations are complicated by high level density and the presence of negative-parity states in the resonance region near the proton-emission threshold. We present results of calculations in a full (0+1)$\hbar\omega$ model space which addresses this problem using the interaction sdpfmu [3] and NuShellX [8]. The basis consists of a complete (0+1)$\hbar\omega$ basis made from all possible excitations of one nucleon from 1s-0d to 0p-1f. Such calculations were carried out recently for the first time for the ^{30}P(p,γ)^{31}S reaction [9]. We explicitly calculate the rates for transitions from the ground state of ^{34}Cl as well as from the isomeric first excited state of ^{34}Cl.

In a study by Fry et al. seventeen [4] new ^{35}Ar levels have been found in the energy region $E_x = 5.9 - 6.7$ MeV and their excitation energies= have been determined, but not spins and parities. Because of the paucity of such information we are obliged to rely on shell-model calculations. We have calculated energies, spectroscopic factors and proton-decay widths for input into the reaction rate.

Uncertainty limits for the total calculated reaction rates have been included based on Monte Carlo techniques of estimating statistically meaningful reaction rates and their associated uncertainties [10] via Starlib (starlib.physics.unc.edu).

2 The ^{34}S(p,γ)^{35}Cl reaction

2.1 Results for the reaction rate

In Fig. 1 in the top panel we show the total *rp* reaction rate versus temperature T9 (GigaK) as well as the contributions from positive and negative parity states. In the lower panel the contributions of the various dominant resonances are shown. The details of these resonances are shown in Table 1.

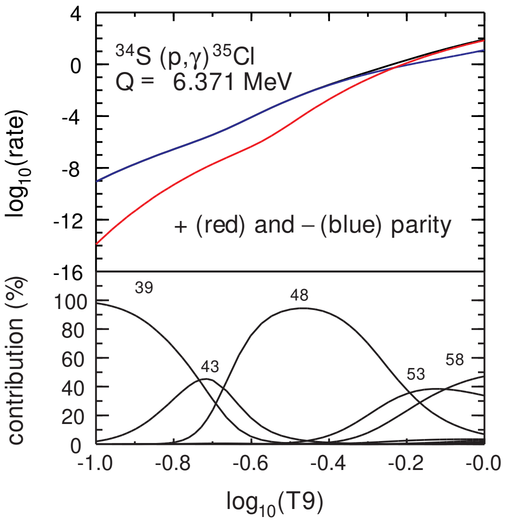

Fig. 1: The total *rp* reaction rate versus temperature T9 (GigaK) for positive and negative parity states for transitions from the ground state of ^{34}S(top panel) (solid line), and the contribution of each of the final states (lower panel) obtained with the data from Table 1.

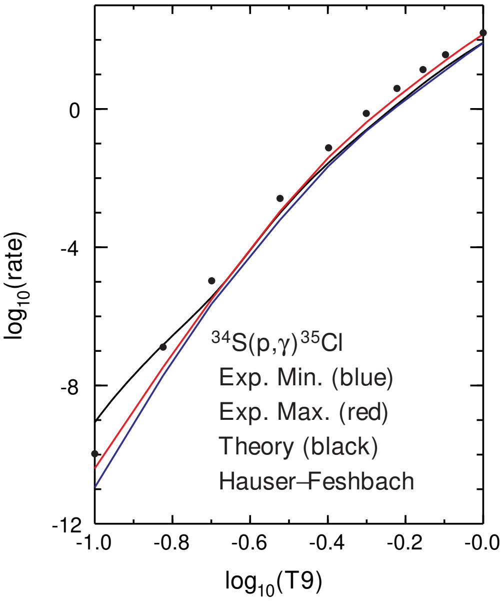

Fig. 2: The total *rp* reaction rate versus temperature T9 (GigaK) for transitions from the ground state of ^{34}S (dotted line), and the minimum and maximum rates from Ref. [2], as well as a Hauser-Feshbach rate [11].

In Fig. 2 we show a graph of the minimum and maximum rates from Ref. [2], Table 4.5 and our result. A statistical Hauser-Feshbach plot is also shown [11]. Evidently our result is larger in the low temperature region, otherwise the agreement is quite good. The three dominant contributions in the lower temperature region according to our calculations are from the negative parity states 1/2$^-$(2) (6.513 MeV), 3/2$^-$(4) (6.587 MeV) and 3/2$^-$(5) (6.762 MeV). The corresponding energies for Refs. [1], [2] are 6.545 MeV, 6.643 MeV and 6.671 MeV. The $\omega\gamma$ values for the three states correspond reasonably well with the maximum values of Gillespie et al., which correspond to $l = 1$ transfer and thus negative parity as in our calculation. In Ref. [1] it has been assumed that the contribution from Γ_γ is dominant, so that

Table 1: Properties of the rp-resonance states for transitions from the ground state of ^{34}S

n	J^π	k	E_x(th)	E_{res}	C^2S+	C^2S+	Γ_γ	Γ_p	$\omega\gamma$
			(MeV)	(MeV)	$\ell = 0(1)$	$\ell = 2(3)$	(eV)	(eV)	(eV)
39	1/2$^-$	2	6.513	0.142	3.6×10^{-1}		2.4	2.4×10^{-9}	2.4×10^{-9}
43	3/2$^-$	4	6.587	0.216	1.5×10^{-2}		3.7×10^{-2}	1.2×10^{-7}	2.5×10^{-7}
48	3/2$^-$	5	6.761	0.390	4.1×10^{-2}		4.1×10^{-2}	1.7×10^{-3}	3.3×10^{-3}
53	1/2$^+$	4	7.006	0.635	6.3×10^{-3}		1.6	3.3×10^{-1}	2.8×10^{-1}
58	1/2$^+$	5	7.116	0.745	1.4×10^{-2}		2.5	3.1	1.4

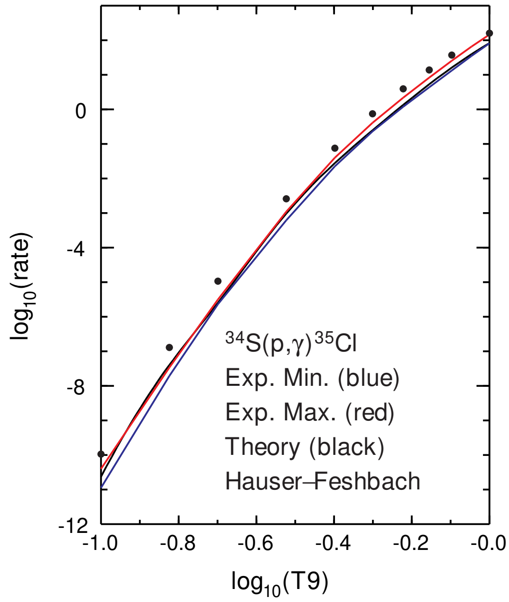

Fig. 3: The same as the previous figure but with the spectroscopic factor for the 1/2$^-$(2) state of Ref. [1] substituted (dotted line).

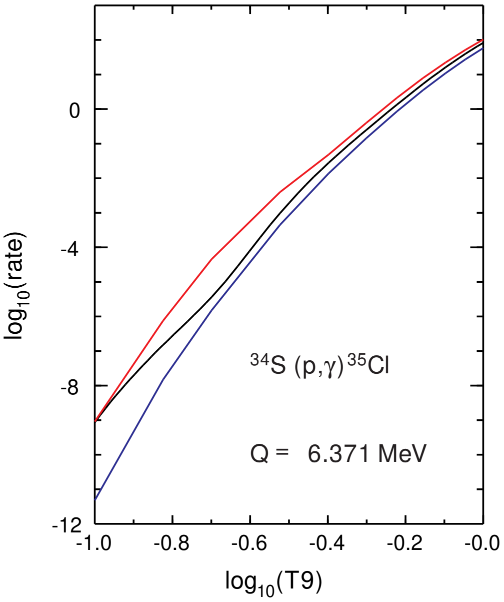

Fig. 4: The total rp reaction rate versus temperature T9 (GigaK) for transitions from the ground state of ^{34}S, and the high and low rates according to the Monte Carlo estimates indicated in red and blue respectively.

$\omega\gamma$ depends only on Γ_p. The main difference between experiment and theory resides in the contribution of the 1/2$^-$(2) state through the spectroscopic factor. The theory value $(2J+1)C^2S$ is 0.36 while the experimental value is 0.0028. When we substitute the spectroscopic factor of Gillespie et al. in our calculation the discrepancy at lower temperature is removed. (Fig. 3).

In Fig. 4 the total reaction rate is shown as well as a low rate and a high rate for each temperature, corresponding to the 0.16 and 0.84 quantiles of the cumulative reaction rate distribution [10].

3 The ^{34g,m}Cl(p,γ)^{35}Ar reaction

3.1 Results for the reaction rate

Fig. 5 shows the total rp reaction rate versus temperature T9 (GigaK) for positive and negative parity states for transitions from the ground state of ^{34}Cl(top panel) and the contribution of each of the final states(lower panel) obtained with the data from Table 2. It is evident that the negative parity states dominate the reaction rate by up to three orders of magnitude at the lower temperatures. The rate is

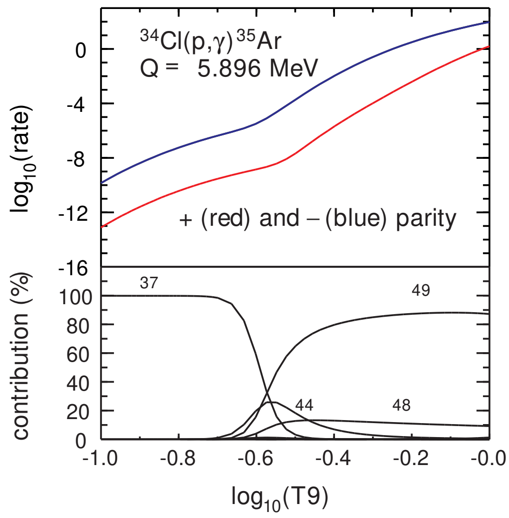

Fig. 5: The total rp reaction rate versus temperature T9 (GigaK) for positive and negative parity states for transitions from the ground state of ^{34}Cl(top panel) (solid line), and the contribution of each of the final states (lower panel) obtained with the data from Table 2.

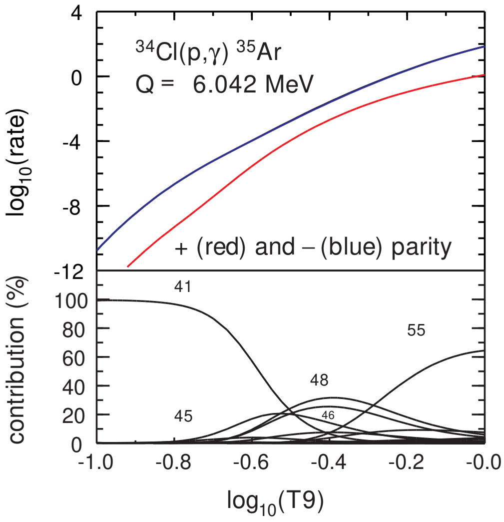

Fig. 6: The total rp reaction rate versus temperature T9 (GigaK) for positive and negative parity states for transitions from the first excited state of ^{34}Cl(top panel) (solid line), and the contribution of each of the final states (lower panel) obtained with the data from Table 3.

Table 2: Properties of the rp-resonance states for transitions from the ground state of ^{34}Cl

n	J^{π}	k	$E_{\mathrm{x}}(\mathrm{th})$	E_{res}	C^2S	C^2S	Γ_{γ}	Γ_p	$\omega\gamma$
			(MeV)	(MeV)	$\ell = 0(1)$	$\ell = 2(3)$	(eV)	(eV)	(eV)
37	3/2$^-$	3	6.052	0.156	3.7×10^{-1}		1.9×10^{-1}	1.0×10^{-9}	2.0×10^{-9}
44	3/2$^-$	4	6.345	0.449	3.5×10^{-3}		7.8×10^{-2}	2.7×10^{-4}	5.4×10^{-4}
46	5/2$^-$	6	6.469	0.573		1.6×10^{-2}	3.5×10^{-1}	2.6×10^{-5}	7.7×10^{-5}
48	3/2$^-$	5	6.476	0.580	2.6×10^{-2}		6.0×10^{-2}	3.7×10^{-2}	4.6×10^{-2}
49	1/2$^-$	2	6.501	0.605	2.2×10^{-1}		1.4	9.8×10^{-1}	5.8×10^{-1}

Table 3: Properties of the rp-resonance states for transitions from the first excited state of ^{34}Cl

n	J^{π}	k	$E_{\mathrm{x}}(\mathrm{th})$	E_{res}	C^2S	C^2S	Γ_{γ}	Γ_p	$\omega\gamma$
			(MeV)	(MeV)	$\ell = 0(1)$	$\ell = 2(3)$	(eV)	(eV)	(eV)
41	5/2$^-$	5	6.278	0.236	1.9×10^{-1}	6.0×10^{-2}	8.5×10^{-2}	6.1×10^{-6}	2.6×10^{-6}
45	7/2$^-$	7	6.395	0.353	2.6×10^{-2}	3.0×10^{-2}	7.8×10^{-2}	3.0×10^{-4}	1.7×10^{-4}
46	5/2$^-$	6	6.469	0.427	3.3×10^{-2}	1.0×10^{-3}	3.5×10^{-1}	6.4×10^{-3}	2.7×10^{-3}
48	3/2$^-$	5	6.476	0.434	5.3×10^{-2}	4.4×10^{-2}	6.0×10^{-2}	1.9×10^{-2}	4.1×10^{-3}
55	5/2$^-$	7	6.695	0.653	1.9×10^{-1}	7.1×10^{-2}	1.9	4.4	5.6×10^{-1}

mainly due to two resonances, the 3/2$^-$(3) and 1/2$^-$(2) states. Fig. 6 shows the same for positive and negative parity states for transitions from the first excited state of ^{34}Cl (top panel) using the data from Table 3. Again the negative parity states dominate the rate by up to two orders of magnitude, and the rate is mainy due to two resonances, the 5/2$^-$(5) and 5/2$^-$(7) states. Fig. 7 shows the total rate including positive and negative parity and transitions from both the ground and first excited state of ^{34}Cl. The

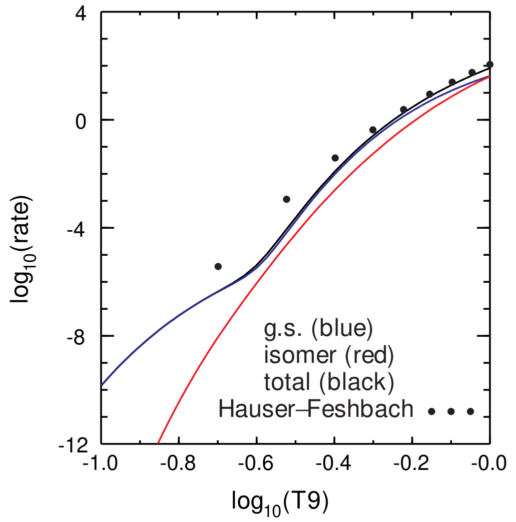

Fig. 7: The total rp reaction rate (which includes positive and negative parity with the relative populations of the ground and first excited isomeric states of ^{34}Cl taken into account) versus temperature T9 (GigaK). The contributions from the ground state and the isomeric state are also shown.

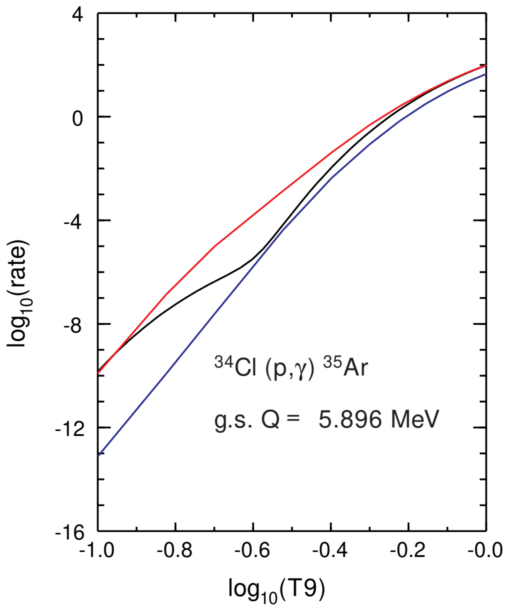

Fig. 8: The total rp reaction rate versus temperature T9 (GigaK) for transitions from the ground state of ^{34}Cl, and the high and low rates according to the Monte Carlo estimates indicated in red and blue respectively.

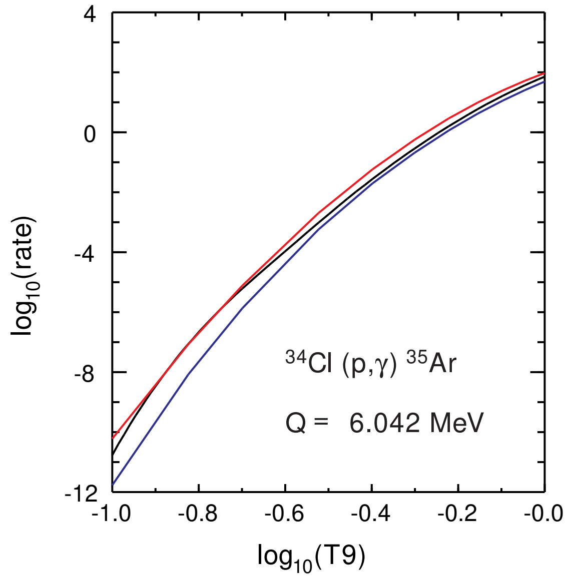

Fig. 9: The total rp reaction rate versus temperature T9 (GigaK) for transitions from the isomeric first excited state of ^{34}Cl, and the low and high rates according to the Monte Carlo estimates indicated in red and blue respectively.

relative populations of the two states have been taken into account through the stellar enhancement factor (SEF), which is the ratio of the stellar rate (including the isomeric state) and the rate from the ground state. It is evident that the rate from the ground state is dominant. In Figs. 8 and 9 the high and low rates based on a Monte Carlo analysis are shown for the ground state and isomeric state respectively.

4 Conclusions

In the comparison of our calculations for ^{34}S(p,γ)^{35}Cl with the recent experiment of Gillespie et al. on ^{34}S(^{3}He,d)^{35}Cl there is good agreement between the calculated total rate and the experimental rate up to 1 GK, except in the low-temperature region where the theory is up to an order of magnitude larger. The difference is due to the spectroscopic factor of the $1/2^{-}(2)$ state. Adopting the experimental value resolves the problem. However, given the large energy uncertainty at low energy in particular, the discrepancy could be due to an energy shift within this uncertainty.

The contribution from negative parity dominates except for a region near 1 GK. Our theoretical analysis shows that the ^{34g,m}Cl(p,γ)^{35}Ar reaction rates both for transitions from the ground state of ^{34}Cl and the first excited state are dominated by negative parity states by between two and three orders of magnitude. The contributions to the total rate from the isomeric first excited state of ^{34}Cl become important and dominant above about half of the temperature range considered. The statistical Hauser-Feshbach rate differs from our ground-state rate at lower temperatures by up to about a order of magnitude, but is close to our result for higher temperatures. The calculations also identify the most prominent resonances in the reaction rates, and the analysis should serve as a guide for experiments as the spin-parity assignments of the most prominent resonances are given.

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References

[1] S. A. Gillespie, A. Parikh, C. J. Barton, T. Faestermann, J. Jose, R Hertenberger, H.-F. Wirth, N. de Sereville, J. E. Riley, and M. Williams Phys. Rev. C 96, 025801 (2017)

[2] S. A. Gillespie, Ph.D thesis, University of York (2016).

[3] Y. Utsuno, T. Otsuka, B. A. Brown, M. Honma, T. Mizusaki, and N. Shimizu, Phys. Rev. C 86, 051301 (2012)

[4] C. Fry, C. Wrede, S. Bishop, B. A. Brown, A. A. Chen, T. Faestermann, R. Hertenberger, A. Parikh, D. Pérez-Loureiro, H.-F. Wirth, A. García, and R. Ortez, Phys. Rev. C 91, 015803 (2015)

[5] M. Coc, M. Porquet and F. Nowacki, Phys. Rev. C 61, 015801 (1999)

[6] P. Banerjee, G. Wendell Misch, S. K. Ghorui and Yang Sun2, Phys. Rev. C 97, 065807 (2018)

[7] H. Schatz, C. A. Bertulani, B. A. Brown, R. R. C. Clement, A. A. Sakharuk, and B. M. Sherrill, Phys. Rev. C 72, 065804 (2005).

[8] B. A. Brown and W. D. M. Rae, Nuclear Data Sheets 120, 115 (2014).

[9] B. A. Brown, W. A. Richter, and C. Wrede, Phys. Rev. C 89, 062801(R) (2014)

[10] R. Longland, C. Iliadis, A. E. Champagne, J. R. Newton, C. Ugalde, A. Cocc, and R. Fitzgerald, Nucl. Phys. A 841, 1 (2010)

[11] C. Iliades, J. M. D'Auria, S. Starfield, W. J. Thompson, and M. Wiescher, Astrophys. J. Suppl.134,151 (2001).

[12] A. Graue, L. H. Herland, J. R. Lien, G. E. Sandvik, E. R. Cosman and W. H. Moore, Nucl. Phys. A 136, 577 (1969)