Thermonuclear reaction rates in rp process of sd-shell nuclei

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Abstract Using the newly constructed isospin non-conserving (INC) shell-model Hamiltonians, we derived a new set of resonant contributions to rapid-proton (*rp*) capture rates on sd-shell nuclei important for astrophysical modelling, namely, ^{23}Al(*p*,γ)^{24}Si, ^{35}Ar(*p*,γ)^{36}K, ^{31}Cl(*p*,γ)^{32}Ar and a few others. The INC Hamiltonian is a combination of an isospin-conserving Hamiltonian, Coulomb interaction and effective isospin-symmetry breaking forces of nuclear origin. The advantage is that Coulomb effects are taken into account with great care, thus the approach allows us to predict unknown nuclear level schemes and to describe decay modes more accurately than the standard shell model. We confirm that proton capture on excited states of some target nuclei may noticeably contribute to the total *rp*-process rates, e.g. ^{23}Al(*p*,γ)^{24}Si and ^{31}Cl(*p*,γ)^{32}Ar. We compare our results with previous shell-model calculations and with estimations provided by currently available statistical model.

Introduction

A radiative proton capture occurs in explosive hydrogen burning in stellar environment of extremely high temperature and density, e.g. X-ray bursts, novae explosions, etc. Masses, lifetimes and spectroscopic factors for nuclei along *N*=*Z* line and proton-rich nuclei up to *A*~100 are required for obtaining reaction rates used in astrophysical modelling. Nuclear shell model is extremely valuable in providing reliable estimations of relevant individual states and contributing resonances for *rp*-process rates.

Method/Formalism

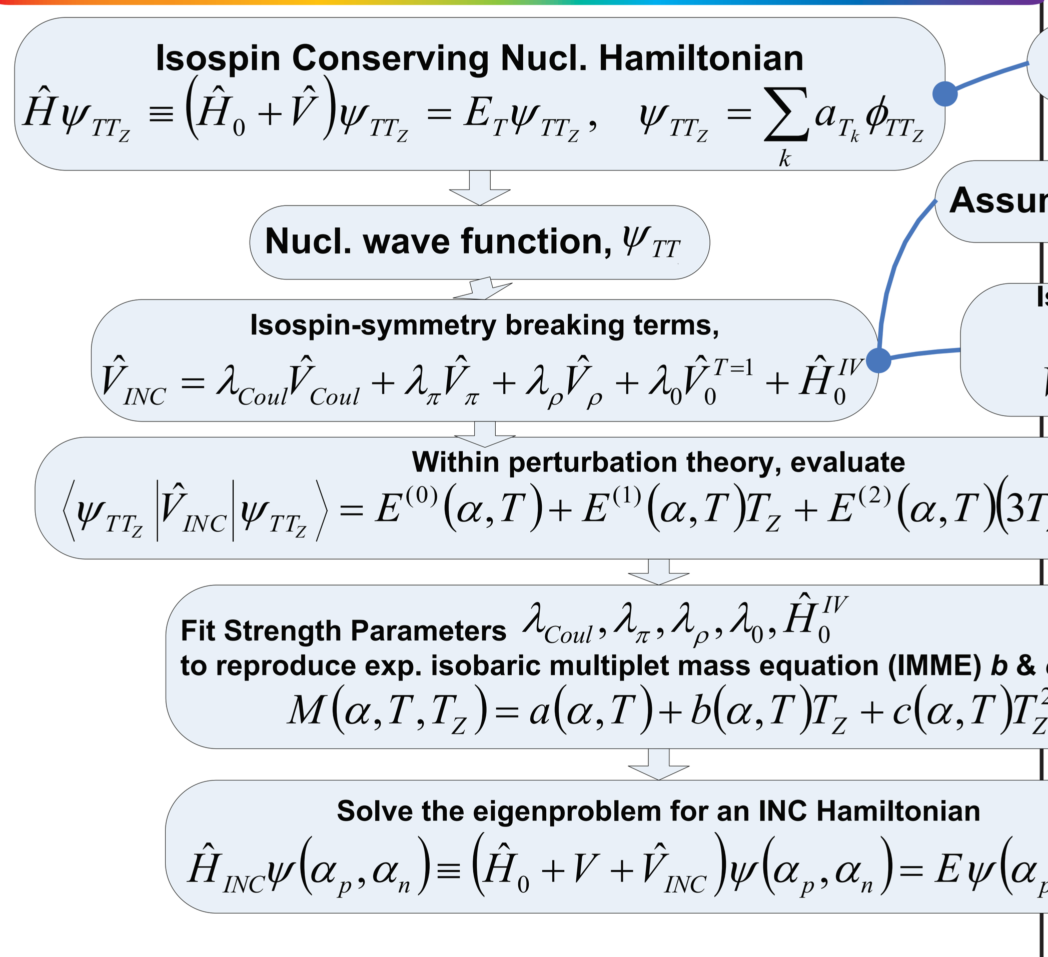
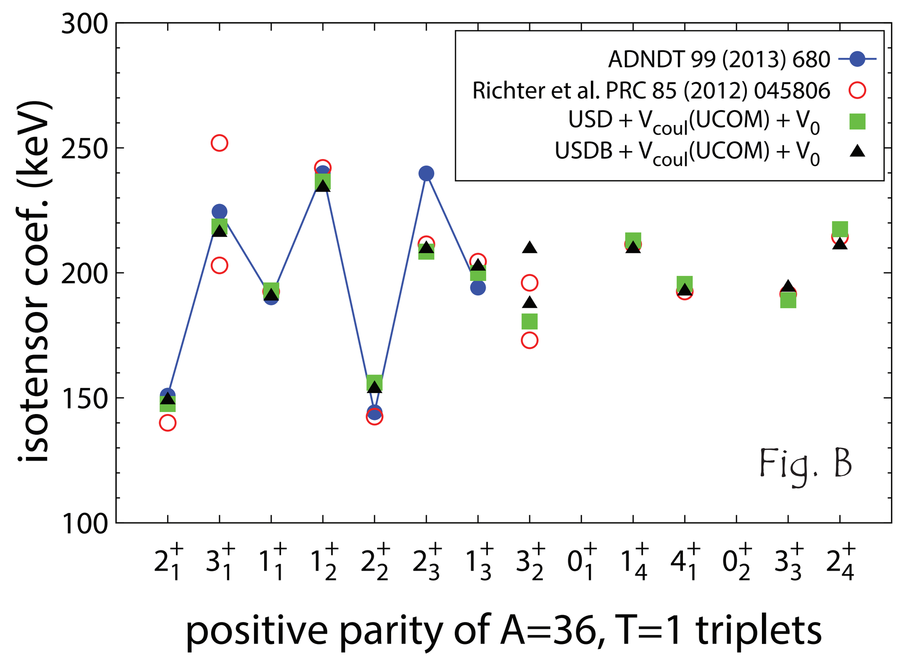


Fig. A - The procedure of constructing INC Hamiltonian.

First, we construct a set of reliable INC Hamiltonians as schematically shown in Fig. A (see Ref. [1] for details). Since experimental data on the states above the proton separation threshold is very scarce, we obtain missing information either from a diagonalization of an INC shell-model Hamiltonian, or find resonance energies in a proton-rich member of an isobaric multiplet from experimental binding energies of the other multiplet members [2] and theoretical coefficients of the isobaric-multiplet-mass equation (IMME). Such isotensor coefficients are shown in Fig. B for *A*=36 case.



Using shell-model spectroscopic factors (C^2S), γ widths (Γ_γ), proton widths (Γ_p) of relevant (*p*,γ) resonances, and then we get resonant strengths (ωγ) and finally contribution of those resonances to the theormonuclear reaction rates ($N_A\langle\sigma v\rangle$), see Fig. C.

Proton width (Woods-Saxon pot. or Coul. tunneling method),

$$\Gamma_p = \sum_{nlj} C^2S(nlj)\Gamma_{sp}(nlj) \quad \text{or} \quad \Gamma_p = \frac{3\hbar^2}{\mu R^2}P_l(E)C^2S$$

Resonance strength

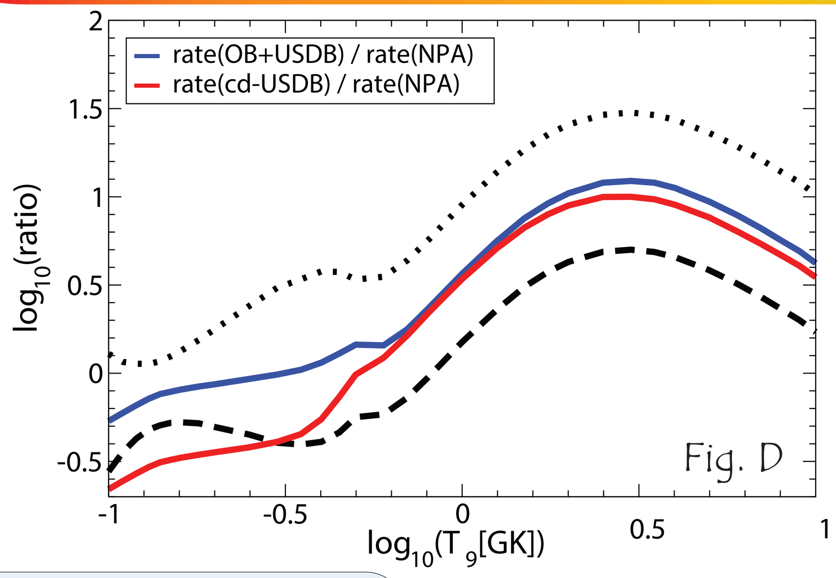
$$\omega\gamma = \frac{2J+1}{2(2J_T+1)}\frac{\Gamma_p\times\Gamma_\gamma}{\Gamma_{\text{total}}}$$

Resonant term of the reaction rate [3]

$$N_A\langle\sigma v\rangle_r = 1.54\times10^{11}(\mu T_9)^{-3/2}\omega\gamma\exp\left(-\frac{11.605E_r}{T_9}\right)$$

Fig. C - Procedure of obtaining resonant term of the *rp*-reaction rate.

Results and Discussion

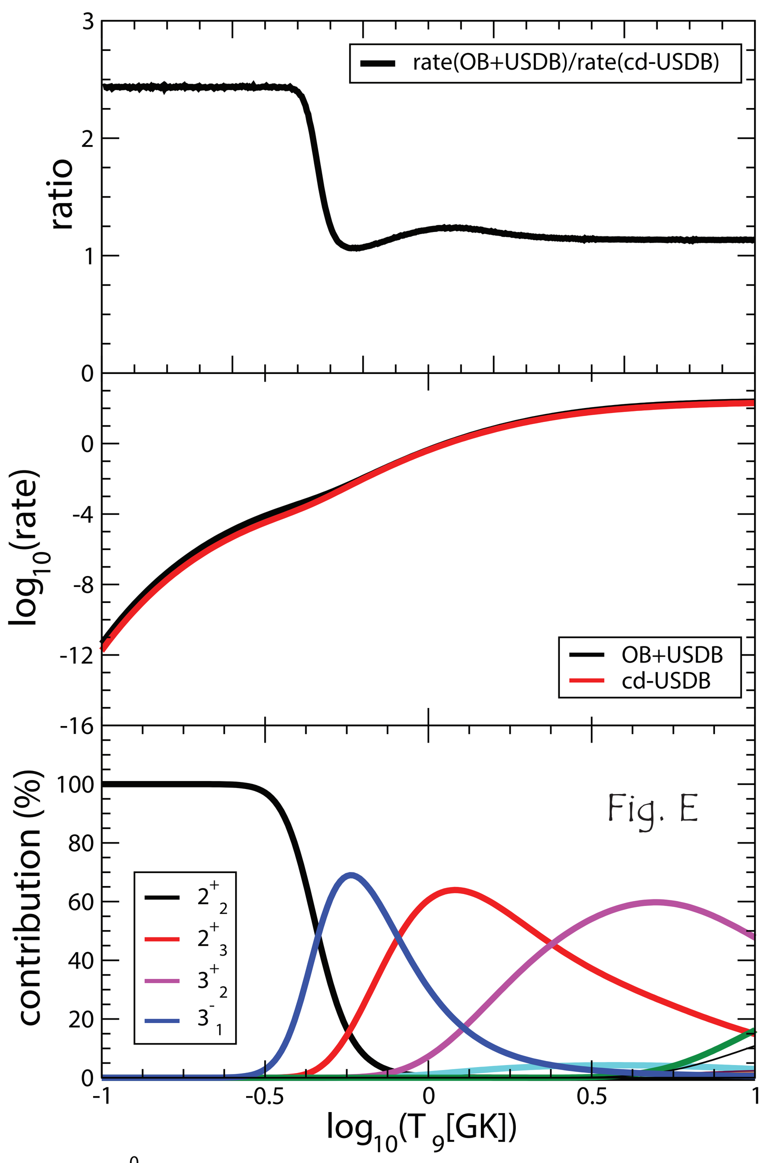


(1) ^{35}Ar(*p*,γ)^{36}K

The comparison of resonant term of *rp* reaction rates of ^{35}Ar(*p*,γ)^{36}K in a ratio form shows the differences of rates from: cd-USDB (present work) and OB+USDB (Ref.[4]) with NPA (Ref.[5], upper {dotted line} and lower {dashed line} bounds), c.f. Figs. D.

The contribution from various resonances are shown in Fig. E. Using an optimized INC Hamiltonian, the present rate is not in the bounded range of NPA, and is different from OB+USDB at temperature 0.1≤T[GK]≤0.9, due to the main contribution from 2^+_2 resonance in ^{36}K.

Level schemes produced from cd-USDB is closer to exp. data than OB-USDB.

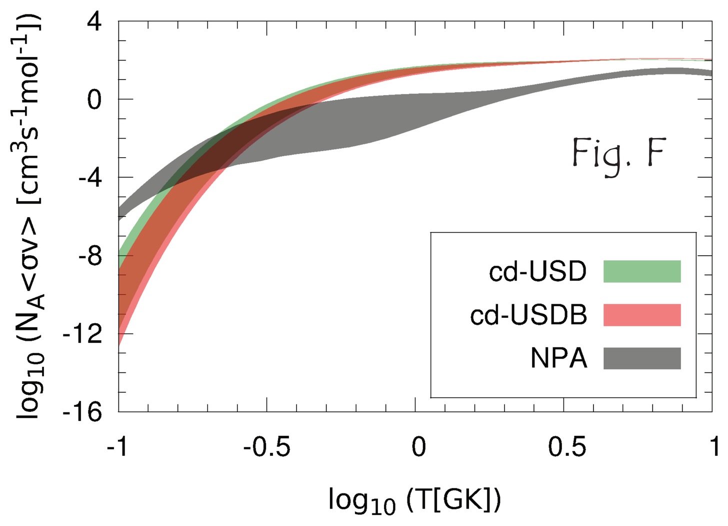


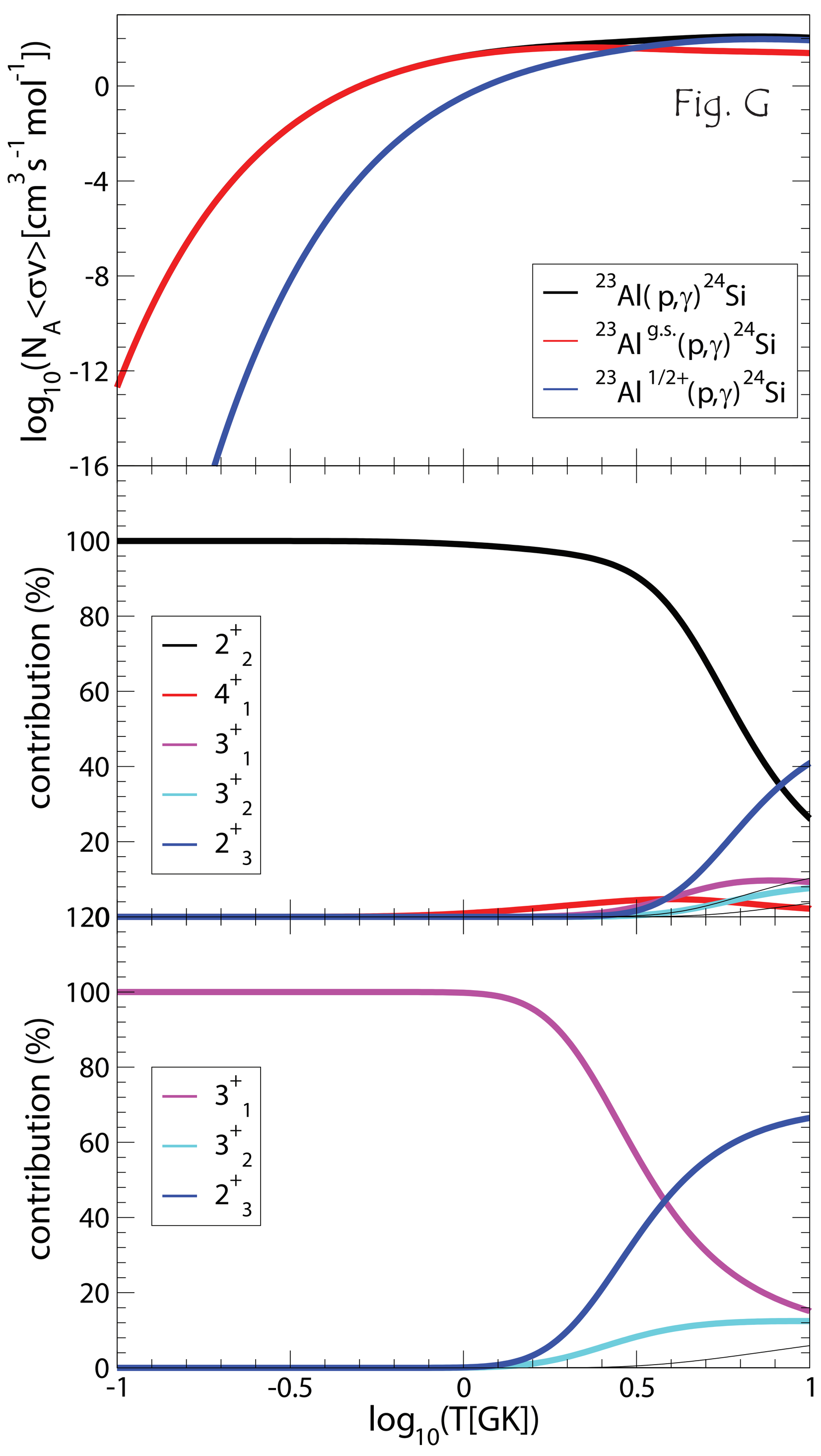
(2) ^{23}Al(*p*,γ)^{24}Si

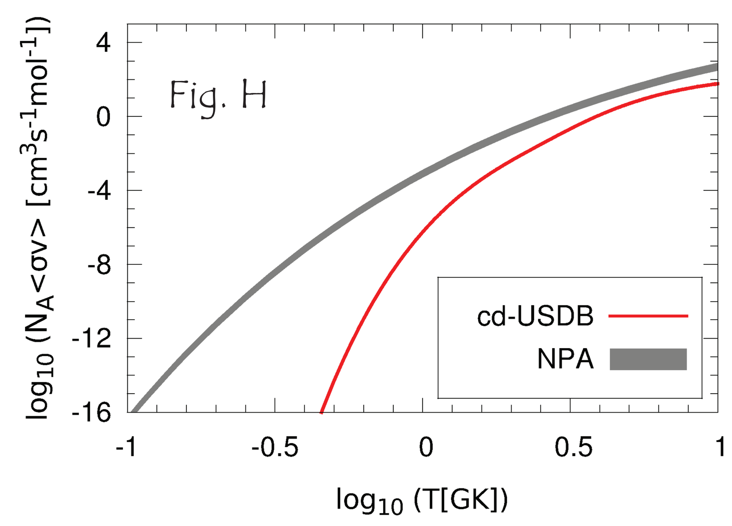
Experimental level scheme of ^{24}Si is very limited. We calculate contribution to the *rp*-reaction rate from fifteen resonances above the proton separation threshold (3.293 MeV), as in NNDC [6].

Charge-dependent interactions propose a different profile of resonant contribution to *rp*-reaction rate compared to Monte-Carlo statistical model (NPA), c.f. Fig. F.

Contribution of the proton capture on the 1st excited state of ^{23}Al is non-negligible, c.f. Fig. G.





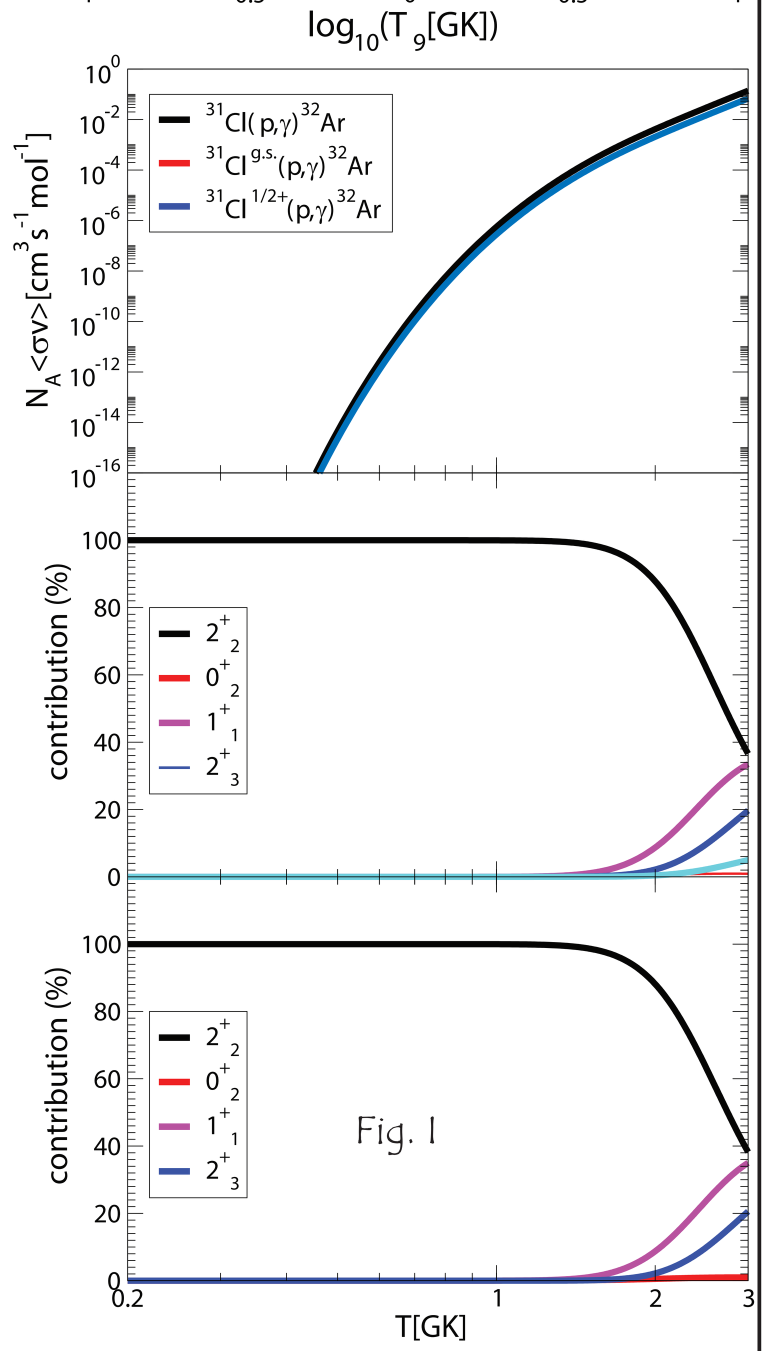


(3) ^{31}Cl(*p*,γ)^{32}Ar

There is only one experimental energy level of ^{32}Ar, i.e. 2^+ (1.867 MeV). We calculate contribution to the *rp*-reaction rate from seven resonances above the proton separation threshold (2.42 MeV), as in NNDC [6].

Charge-dependent interaction suggests a lower resonant comtribution to *rp*-reaction rate compared to Monte-Carlo statistical model (NPA), c.f. Fig. H.

Contribution of the proton capture on the 1st excited state of ^{31}Cl is significantly close to proton capture on the ground state, c.f. Fig. I.



Conclusions and Perspectives

A. We obtained some *rp*-process rates of *sd*-shell nuclei based on empirical INC Hamiltonians which provides an accurate description of structure of proton-rich nuclei.

B. Some of the resonant contributions to the *rp*-reaction rates are not in the range of and some may have different profile compared to Monte-Carlo statistical model. These preliminary results are under evaluation.

C. The resonant contributions to *rp*-reaction rates of ^{25}Al(*p*,γ)^{26}Si, ^{28}P(*p*,γ)^{29}S, ^{29}P(*p*,γ)^{30}S, ^{35}Ar(*p*,γ)^{36}K, and ^{32}Cl(*p*,γ)^{33}Ar, have also been calculated, and calculations of more (*p*,γ) reaction rates are in progress.

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