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 (p̄) capture rates on sd-shell nuclei important for astrophysical modelling, namely, 12Al(p̄,y)30Si, 27Al(p̄,y)35Cl, 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.

Introduction
A radioactive 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 Na-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
Isospin Conserving Nucl. Hamiltonian
\[ H_{ICN} = \sum_{jl} \left( E_j - E_{j-l} \right) \sigma_{jl} a_j^{\dagger} a_l \]

Isospin Non-conserving Nucl. Hamiltonian
\[ H_{INC} = H_{ICN} + \sum_{jl} \left( E_j - E_{j-l} \right) \sigma_{jl} a_j^{\dagger} a_l + \sum_{jk} \left( E_j - E_{j-k} \right) \sigma_{jk} a_j^{\dagger} a_k \]

Solve eigenvalue prob.
Assume
\[ \text{Evolution on Heavy, evaluate} \]

Nucl. wave function, \( \psi_{ICN} \)

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 resonances 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).

Results and Discussion
(1) 30Si(p̄,y)30Al
The comparison of resonant term of rp reaction rates of 30Si(p̄,y)30Al 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-F.

The contribution from various resonances are shown in Fig. 1. Using an optimized INC Hamiltonian, the present rate is not in the bounded range of NPA, and is different from OB-USDB at temperature 0.1c(T)\( < 0.9 \) due to the main contribution from \( \Sigma_1 \) resonance in INC.

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

(2) 32Si(p̄,y)32Al
Experimental level scheme of 32Si is very limited. We calculate contribution to the \( p̄ \)-reaction rate from fifteen resonances above the proton separation threshold (3.293 MeV), as in NNDC [6].

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

Contribution of the proton capture on the 1st excited state of 34Al is non-negligible, c.f. Fig. G.

(3) 36Cl(p̄,y)36Ar
There is only one experimental energy level of 36Cl, i.e. 2.1867 MeV. We calculate contribution to the \( p̄ \)-reaction rate from seven resonances above the proton separation threshold (2.42 MeV), as in NNDC [8].

Change-dependent interaction suggests a lower resonant contribution to \( p̄ \)-reaction rate compared to Monte-Carlo statistical model (NPA), c.f. Fig. H.

Contribution of the proton capture on the 1st excited state of 36Cl is significantly close to proton capture on the ground state, c.f. Fig. I.

Acknowledgments
We thank B. Brown for his stimulating discussions. The work was supported by the Embassy of the Republic of France in the People’s Republic of China (HNC Xu Guangxi 2015, no. 344574A), by the National Natural Science Foundation of China (Nos. U1223203, U1431215), by the Ministry of Science and Technology of China (Talent Young Scientist Program) and by the China Postdoctoral Science Foundation (2014MS62481), and by the funding of CFT (CNRS/IN2P3, France), AP’2014.

References

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 \( \Sigma_1 \), \( \Sigma_2 \), \( \Sigma_3 \), \( \Delta \), \( \Delta_3 \), \( \Delta'_3 \) and \( \Delta''_3 \) have also been calculated, and calculations of more \( p̄ \)-reaction rates are in progress.

Fig. B
positive parity of A=36, T=1 triplets

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

Fig. D
Comparison of the reaction rates of 30Si(p̄,y)30Al for different calculations, c.f. Fig. 1.

Fig. E
Comparison of resonant term of rp reaction rates of 32Si(p̄,y)32Al for different calculations, c.f. Figs. D-F.

Fig. F
Comparison of the resonant term for rp reaction rates of 34Al(p̄,y)34Si for different calculations, c.f. Fig. G.

Fig. G
Comparison of contribution of resonances on rp reaction rates of 34Al(p̄,y)34Si, c.f. Fig. I.

Fig. I
Comparison of the contribution of resonances on rp reaction rates of 36Cl(p̄,y)36Ar, c.f. Fig. H.