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# Nuclear Weak Rates for Astrophysical Processes in Stars

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We have updated nuclear weak rates relevant to the study of astrophysical processes in stars. Neutrino-induced reaction cross sections, electron-capture and β-decay rates at stellar environments are obtained with new shell-model Hamiltonians that prove to be successful in describing spin responses - Gamow-Teller and spin-dipole transitions - in nuclei. The cross sections and rates are applied to nucleosynthesis in supernovae, detection of $\nu$ and nuclear URCA processes.

**KEYWORDS:** e-capture, $\beta$-decay, $\nu$-nucleus reaction, Shell-model, Nucleosynthesis, URCA process, Gamow-Teller transition, spin-dipole transition

## 1. Introduction

We have updated nuclear weak rates which are important to the study of astrophysical processes in stars. ν-nucleus reaction cross sections on $^{12}$C [1], $^{13}$C [2], $^{16}$O [3], $^{40}$Ar [4], $^{56}$Fe, and $^{56}$Ni [5] have been updated and applied to nucleosynthesis in supernovae [1,3,5], ν detection [2-4] and study of ν properties such as mass hierarchies [6]. The total and partial cross sections for various channels are tabulated for $^{12}$C, $^{13}$C and $^{16}$O.

Electron-capture and β-decay rates in pf-shell and sd-shell nuclei at stellar environments have been updated with GXPF1J [7] and USDB, respectively. They have been used to study synthesis of iron-group nuclei in type Ia supernovae [8], and nuclear URCA processes in degenerate O-Ne-Mg cores in stars with 8-10 solar masses [9,10]. Nuclear pairs, $^{23}$Na-$^{23}$Ne and $^{25}$Mg-$^{25}$Na, are found to be important for the cooling of the core, and the final fate of the stars is sensitive to the nuclear weak rates as well as their mass. The rates for sd- and pf-shell nuclei are tabulated.

Extension of the study to e-capture and $\beta$-decay rates for neutron-rich nuclei along and near N=50 is in progress, where evaluations of forbidden transitions in pf-gds shells become crucial. The rates are important for stellar core-collapse processes. The rates for nuclei in the island of inversion with sd-pf shells are important for nuclear URCA processes in the neutron star crusts.

$\nu$-induced reaction cross sections on light nuclei are discussed in Sect. 2. We discuss e-capture and β-decay rates in sd-shell and pf-shell nuclei in Sect. 3. The rates for neutron-rich nuclei, where two-major shells are involved, will be discussed in Sect. 4. Summary is given in Sect. 5.

## 2. Neutrino-nucleus Reaction Cross Sections on Light Nuclei

### *2.1 ν- $^{12}$C and ν-$^{13}$C*

Neutrino-induced reactions on $^{12}$C and $^{13}$C at reactor and supernova ν energies are investigated by shell-model calculations with the SFO Hamiltonian, which can well reproduce the Gamow-Teller (GT) strength in $^{12}$C. Nucleosynthesis of light nuclei in supernovae is studied with the updated cross sections, and enhancement of the production yield of $^{11}$B and $^{7}$Li compared to previous studies is found [1]. ν-$^{13}$C cross sections are also updated for solar and reactor ν [2] as well as for supernova ν [11]. Coherent elastic scattering cross sections are also evaluated for $^{12}$C and $^{13}$C and sensitivity to neutron distributions are investigated [11].

### *2.2 ν-$^{16}$O*

ν-$^{16}$O reactions, induced dominantly by spin-dipole transitions, are studied by shell-model calculations with the SFO-tls Hamiltonian [12], in which p-sd cross-shell matrix elements are improved with proper inclusion of the tensor forces. Charged- and neutral-current reaction cross sections in various channels are obtained, and applied to nucleosynthesis of $^{11}$B and $^{11}$C in supernovae through sizable αp emission channels [3]. Neutrino mass hierarchy dependence of the charged-current cross sections are studied for future detection of supernovae [6].

## 3. Electron-capture and β-decay Rates of Nuclei within One-major Shells

### *3.1 sd-shell*

Electron-capture and β-decay rates for nuclear pairs in the sd-shell are evaluated at high densities and high temperatures relevant to the final evolution of electron-degenerate O–Ne–Mg cores of stars with initial masses of 8–10 $M_{\odot}$. The rates are important to determine the final fate of the stars, whether they end up with electron-capture supernovae or Fe core-collapse supernovae. The rates obtained by shell-model calculations with the USDB Hamiltonian are provided in tables with fine enough meshes at various densities and temperatures [10]. Effects of Coulomb corrections on the rates are taken into account. The rates for pairs with A = 23 and 25 are important for nuclear URCA processes that determine the cooling rate of the O–Ne–Mg core, while those for pairs with A = 20 and 24 are important for the core-contraction and heat generation rates in the core.

*3.2 pf-shell*

Electron-capture and β-decay rates in pf-shell nuclei have been updated with the use of the GXPF1J Hamiltonian, which can describe the GT strengths of Ni and Fe isotopes quite well [7]. The rates are applied to study nucleosynthesis of iron-group elements in type Ia supernovae. An over-production problem of the elements for the previous single-particle rates disappears for the updated shell-model rates, in particular, for the supernova model of delayed detonation after deflagration [8]. The updated rates are provided in the REACLIB database.

## 4. Electron-capture and β-decay Rates of Nuclei with Two-major Shells

*4.1 sd-pf shell in the island of inversion*

Electron-capture and β-decay rates are evaluated for nuclei in the island of inversion, where excitations of nucleons from sd-shell to pf-shell play important roles. Neutron-rich Ne and Mg isotopes are studied with an interaction obtained with the extended Kuo-Krenciglowa (EKK) method [13] from chiral $N^3LO$ interaction and Fujita-Miyazawa three-body forces. Large admixtures of pf-shell components with both 2p-2h and 4p-4h excitations are found in $^{32}$Mg, and energy spectra in $^{31}$Mg are well reproduced; the ground state is $1/2^+$ consistent with the observation. The weak rates for the $^{31}$Mg-$^{31}$Al pair, which are important for the URCA process in neutron star crusts [14], are evaluated, and the URCA density is assigned to be at $\log_{10}(\rho Y_e)$ =10.14 [15].

*4.2 pf-gds shell for $^{78}$Ni*

Electron-captures in neutron-rich nuclei near the N=50 closed neutron shell are pointed out to be important for core-collapse process in stars [16]. The e-capture rates for $^{78}$Ni are evaluated by shell-model with pf-gds shell. The shell-model calculation is an extension of that for pf-$g_{9/2}d_{5/2}$ configuration with the use of the modified A3DA interaction [17]. Here, up to 5p-5h excitations outside filling configurations of $^{78}$Ni are taken into account with full pf-gds shells. Dominant contributions come from the spin-dipole transitions. The spin-dipole strengths in $^{78}$Ni are shown in Fig. 1. Sum of the strengths for $J^\pi$ = $0^-$, $1^-$ and $2^-$ are 11.60, 19.89 and 12.57 fm$^2$, respectively, which exhaust 95%, 96% and 79% of the sum-values, respectively.

Electron-capture rates on $^{78}$Ni obtained by the shell-model calculations with pf-gds configuration space at densities $\rho Y_e \sim 10^9$ -$10^{12}$ g cm$^{-3}$ ($Y_e$ = proton fraction) and temperatures T = (1-5)×$10^{10}$ K are shown in Fig. 2. Calculated results are compared with those of an RPA calculation with the SG2 interaction [19]. The same Q value for the shell-model is used for the RPA calculation. Similar rates are obtained for the two methods.

## 5. Summary

Neutrino-nucleus reaction cross sections, e-capture and β-decay rates in stellar environments have been updated with the use of new shell-model Hamiltonians. The new rates are applied to nucleosynthesis in supernovae, nuclear URCA processes, evolution of stars, and ν detection. We have provided these updated cross sections and rates in tables so that they can be used for studies of astrophysical processes sensitive to the weak rates.

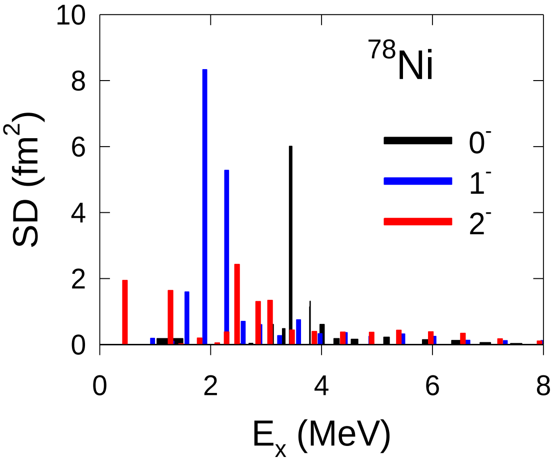


**Fig. 1**. Spin-dipole strengths in $^{78}$Ni obtained with the modified A3DA interaction with pf-gds shells.

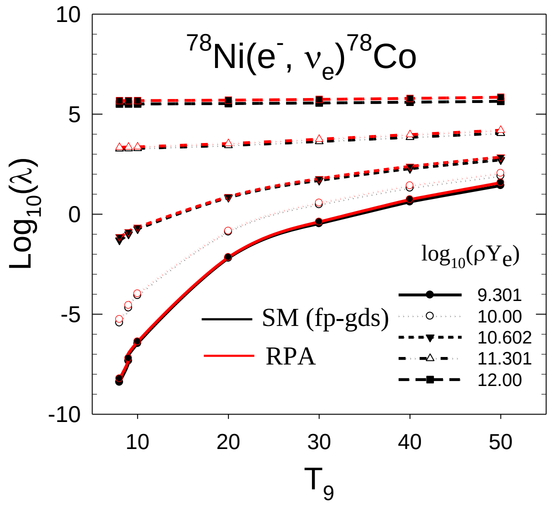


**Fig. 2.** Electron capture rates on 78Ni obtained with shell-model (pf-gds) and RPA calculations.

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