Stellar weak interaction rates for pf-shell nuclei using shell-model

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Introduction

In the stellar environments, the evaluation of weak interaction rates and the corresponding energy produced is very important. There are various theoretical models that can be used for weak interaction rates evaluations but here, we are using shell model since shell model has proven best for the nuclear structure study near the shell closures. Sometimes, in stellar environment the temperature and densities are so high such that this leads to the URCA processes. In URCA processes the electron capture and the beta decay occur concurrently. Thus, URCA process is responsible for the cooling of the star as neutrinos leave the star and also this process leads to decrease in the leptonic pressure.

The study of weak interaction rates requires the correct evaluation of Gamow-Teller (GT) strengths. There are two types of GT strengths, i.e., GT^+ and GT^-, based on the type of weak interaction process. The interacting nuclear shell model with appropriate effective interaction is considered the most efficient model for the calculation of these GT strengths [1]. The GXPF1A effective interaction has demonstrated its efficacy in describing the nuclear structure properties of pf-shell nuclei. We have used this effective interaction for the evaluation of weak interaction rates of (^{55}Ti, ^{55}Sc) nuclear pair [2].

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Formalism

The weak interaction rates are given as

$$\lambda = \frac{ln2}{K}\sum_i W_i \sum_j (B_{ij}(F) + B_{ij}(GT))\phi_{ij}^{\alpha}, \tag{1}$$

where $K = 6146 \pm 6$ s is the constant value and W_i denotes the statistical weight function. The quantities $B_{ij}(F)$ and $B_{ij}(GT)$ are the Fermi and GT reduced transition probabilities, respectively. The term ϕ_{ij}^{α} denotes the phase space factor for the weak process where $\alpha = ec$ for electron capture and $\alpha = \beta^-$ for β^- decay. Now, the phase space factors for weak interactions are given as

$$\phi_{ij}^{ec} = \int_{w_{min}}^{\infty} wp(Q_{ij} + w)^2 F(Z, w) S_e(w) dw, \tag{2}$$

$$\phi_{ij}^{\beta^-} = \int_{1}^{Q_{ij}} wp(Q_{ij} - w)^2 F(Z+1, w)(1 - S_e(w)) dw, \tag{3}$$

where Q_{ij} is the Q-values for the transition and the terms w and $p = \sqrt{w^2 - 1}$ denotes electron energy and momentum, respectively. The term $F(Z, w)$ denotes the Fermi function and $S_e(w)$ denotes the Fermi-Dirac distribution for electrons. The lower limit of the integration is given by: $w_{min} = 1$ if $Q_{ij} > -1$ and $w_{min} = |Q_{ij}|$ if $Q_{ij} < -1$. Now, the average energy of the emitted neutrino is given by $< E_\nu >= \frac{\xi}{\lambda}$, where

$$\xi = \frac{ln2(m_e c^2)}{6146(s)} \sum_i W_i \sum_j (B_{ij}(GT) + B_{ij}(F))\psi_{ij}. \tag{4}$$

Further, in the case of electron capture, the average energy production is given by

$$< E_{prod} >= \mu_e - Q_{nucl} - < E_\nu >, \tag{5}$$

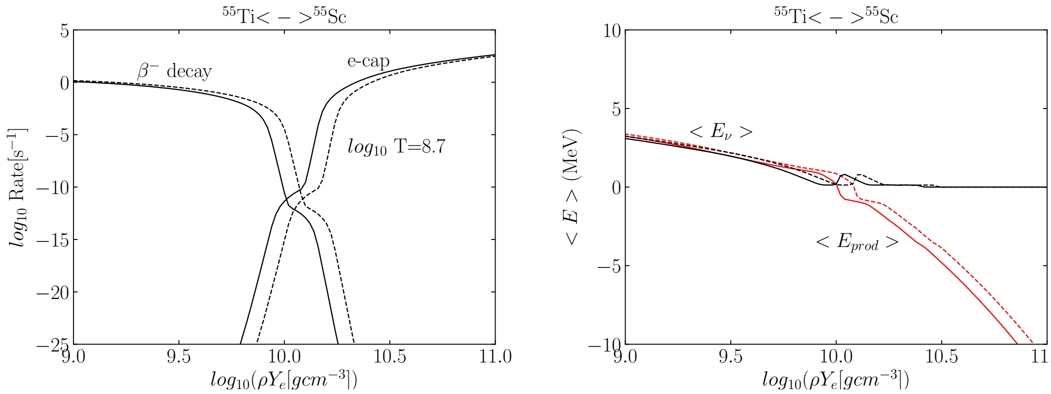

FIG. 1: (Left) The electron capture and β^--decay rates of (^{55}Ti,^{55}Sc) pair with (dashed-line) and without (solid-line) screening effects calculated via GXPF1A interaction at $\log_{10} T = 8.7$. (Right) The average neutrino energy (black) and average energy production (red) of (^{55}Ti,^{55}Sc) pair with (dashed-line) and without (solid-line) screening effects calculated via GXPF1A interaction at $\log_{10} T = 8.7$.

while, for β^- decay, it is given by

$$< E_{prod} >= Q_{nucl} - \mu_e - < E_\nu > . \qquad (6)$$

Results and Discussions

In this work, we have evaluated weak interaction rates for pf-shell nuclei, i.e., $A = 55$ (^{55}Ti, ^{55}Sc) pair. We have already studied beta decay properties in the ^{208}Pb and ^{132}Sn regions [3–5]. Thus, we are extending our work towards the evaluation of weak interaction rates in the stellar environment. In this work, we have used GXPF1A effective interaction for the evaluation of Gamow-Teller (GT) strengths with the help of NushellX [6]. The parent states are populated up to the excitation energy of 2 MeV and accordingly the $B(GT)$ values have been calculated from the ($1/2^-_1$,$5/2^-_1$,$3/2^-_1$,$5/2^-_2$,$3/2^-_2$,$7/2^-_1$) states of ^{55}Ti to ^{55}Sc(J_f) for electron capture rates evaluation, and ($7/2^-_1$,$3/2^-_1$,$1/2^-_1$) states of ^{55}Sc to ^{55}Ti(J_f) are calculated for the evaluation of β^- decay rates. The quenching factor ($q = 0.74$) [7] in the axial vector coupling constant is used such that $g_A^{eff} = 0.94$.

Further, the weak interaction rates are evaluated for $A = 55$ (^{55}Ti, ^{55}Sc) pair using $B(GT)$ values calculated with GXPF1A interaction. These weak interaction rates are evaluated at high temperatures $10^{8.7}$ K, and the density is varied as $\rho Y_e = 10^9$-10^{11} in fine grids. The variation of weak interaction rates with the density is shown in Fig. 1 (left), and the variation of average neutrino energy and average energy produced for β^- decay with density is shown in Fig. 1 (right). According to this plot the URCA density comes out to be $log_{10}(\rho Y_e) = 10.01$ without screening and it comes out to be $log_{10}(\rho Y_e) = 10.09$ with screening.

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