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Electron Capture Reactions and β-Decays in Astrophysical Processes

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Gamow-Teller (GT) strengths in Ni and Co isotopes are studied by shell model calculations with the use of a new Hamiltonian in fp-shell, GXPF1J. The GT strengths obtained are used to evaluate electron capture reaction rates at stellar environments. The calculated capture rates in ^{56}Ni, ^{58}Ni and ^{60}Ni as well as ^{55}Ni are found to reproduce well the rates obtained by using the experimental GT strengths. The evaluation of the capture rates has been considerably improved compared with previous calculations.

β-decay half-lives for waiting-point nuclei at N=126 are studied by shell-model calculations including both the GT and first-forbidden (FF) transitions. The FF transitions reduce the half-lives obtained with the GT contributions by nearly twice to several times. The half-lives obtained here are short compared to standard values of FRDM. Possible implications of the short half-lives on the r-process nucleosynthesis are investigated. Quenching of axial-vector (g_A) and vector (g_V) coupling constants at and near the waiting-point nuclei is discussed.

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1. Gamow-Teller Strengths in Ni and Co Isotopes and Electron Capture Rates

Electron capture reactions play the most essential roles in the core-collapse processes at the last stage of the life-cycle of stars. Accurate evaluations of the electron capture rates at high densities and temperatures are quite important to determine the initial conditions for the nucleosynthesis in supernova explosions.

Gamow-Teller (GT) transition strengths in Ni and Co isotopes are studied by shell model calculations with the use of a new Hamiltonian in fp-shell, GXPF1J[1],which can successfully describe spin-dependent transitions in fp-shell, for example, GT strength in ^{58}Ni and M1 strengths in fp-shell nuclei. The GT strengths for GXPF1J are generally more fragmented compared to those of conventional Hamiltonians such as KB3G[2] as shown in Fig. 1(a) for ^{56}Ni. The GT strength by GXPF1J shows a two-peak structure while KB3G gives only a single peak. Recently, the two-peak structure of the GT strength was confirmed by (p, n) experiment[3]. One of the reasons of the different structure of the GT strength can be attributed to a wider single-particle shell gap between $0f_{7/2}$ and $0f_{5/2}$ orbits for GXPF1J. The GT strength in ^{55}Co recently measured by (p, n) reaction is also found to be reproduced well by GXPF1J[4], which is more fragmented compared to the case of KB3G as shown in Fig. 2(a).

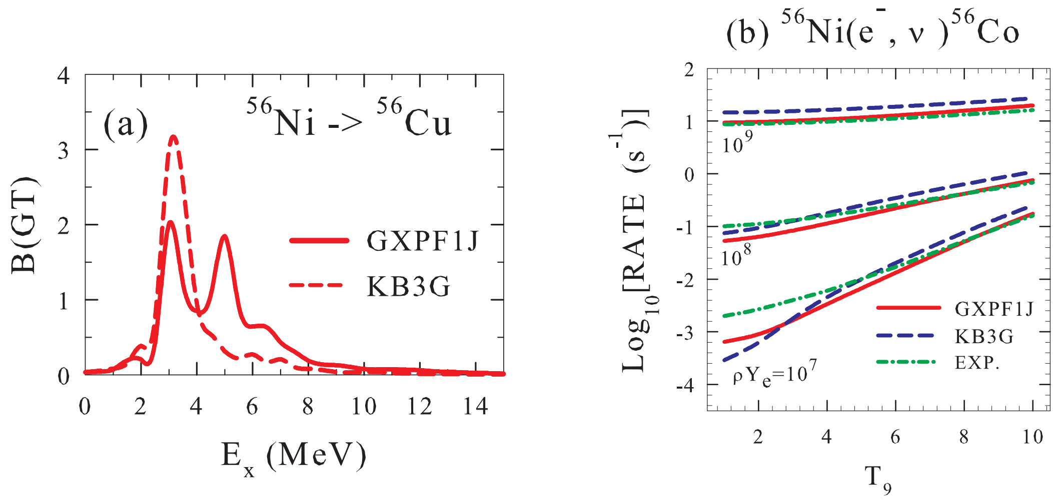

Figure 1: (a) The GT strength in ^{56}Ni obtained by GXPF1J and KB3G. (b) Electron capture rates on ^{56}Ni evaluated by GXPF1J, KB3G and experimental GT strength.

The GT strengths obtained are used to evaluate electron capture rates at stellar environments[5]. The capture rates at high densities $\rho Y = 10^{7-9}$ g/cm^3 and high temperatures $T = T_9 \times 10^9$ K are shown in Fig. 1(b) for ^{56}Ni.

The capture rates are calculated by

$$\lambda = \frac{\ln 2}{6146(s)} \sum_i W_i \sum_f B(GT; i \to f) \int_{\omega_{min}}^{\infty} \omega p (Q_{if} + \omega)^2 F(Z,\omega) S_e(\omega) d\omega, \tag{1.1}$$

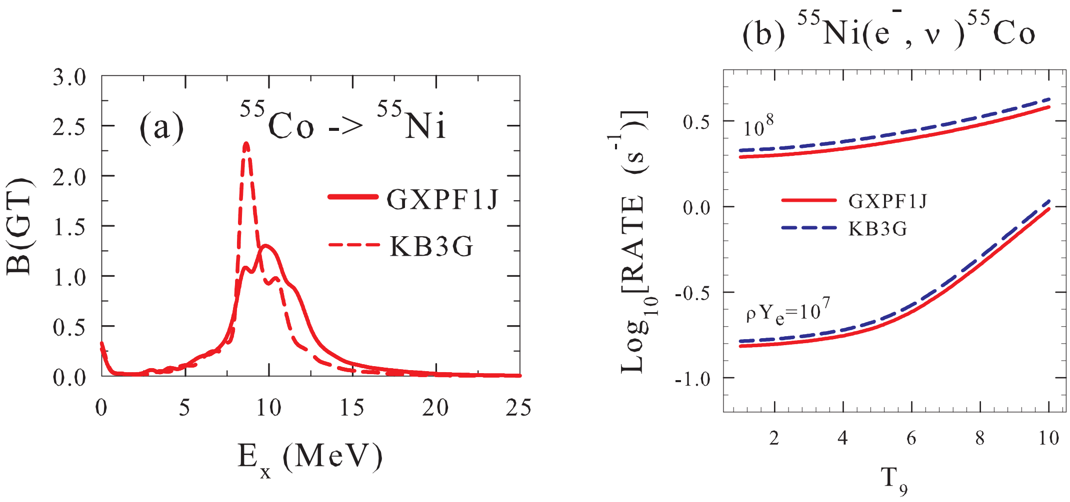

Figure 2: (a) The GT strength in ^{55}CO obtained by GXPF1J and KB3G. (b) Electron capture rates on ^{55}Ni evaluated by GXPF1Jand KB3G.

where ω and p are electron energy and momentum in units of $m_e c^2$ and M_p, respectively. Q_{if} is the Q-value for the reaction, and W_i is the statistical weight facor for the initial state. $F(Z,\omega)$ is the Fermi function, and $S_e(\omega)$ is the Fermi-Dirac distribution for electrons where the chemical potential, μ_e, is determined from the density, ρY_e, by

$$\rho Y_e = \frac{1}{\pi^2 N_A}(\frac{m_e c}{\hbar})^3 \int_0^\infty (S_e - S_p) p^2 dp \tag{1.2}$$

where N_A is the Avogadro constant and S_p is the Fermi-Dirac distribution for positrons with the chemical potential $\mu_p = -\mu_e$. It can become as large as 5∼10 MeV at high densities $\rho Y_e = 10^9 \sim 10^{10}$ g/cm^3. The reaction rates become larger at higher densities because of the large chemical potential of electrons.

We find that GXPF1J reproduces well the capture rates in ^{56}Ni obtained by the experimental GT strength at higher densities and temperatures. The difference of the capture rates in ^{55}Ni between GXPF1J and KB3G is shown in Fig. 2(b). The capture rates for GXPF1J are smaller than those for KB3G due to larger spreading of the strength.

The calculated capture rates in ^{58}Ni and ^{60}Ni are also found to reproduce well the rates obtained by using the experimental GT strengths[6, 7]. Accurate evaluation of the electron capture rates in Ni and Co isotopes has been achieved by using GXPF1J compared with previous calculations[8].

2. β-Decay Half-Lives at and near N=126 Waiting Point Nuclei and R-Process Nucleosynthesis

β-decay half-lives at the waiting point nuclei with N=126 are evaluated by shell-model calculations including contributions from both the GT and FF transitions[9]. A modified G-matrix, which describes well the energy spectra of the isotones with Z =77∼80[10], is used for the shell-model interaction. The quenching of g_A, g_A/g_A^{free} =0.70, is adopted for both the GT and FF transitions except for 0^-, where an enhancement of the $\vec{\sigma}\cdot\vec{p}$ term due to the meson-exchange current effects are taken into account.

The decay rates, Λ, as well as the partial half-lives, $t_{1/2}$, of the transitions are obtained by the following formulae[11, 12, 13];

$$
\begin{aligned}
\Lambda(s^{-1}) &= \ln 2/t_{1/2} = f/8896(s) \\
f &= \int_1^{w_0} C(w)F(Z,w)pw(w_0-w)^2 dw \\
C(w) &= K_0 + K_1 w + K_{-1}/w + K_2 w^2,
\end{aligned}
\tag{2.1}
$$

where w the electron energy, $F(Z,w)$ is the Fermi function, and K_n's depend on nuclear transition matrix elements. Here, relativistic corrections from the expansion of electron radial wave functions in powers of electron mass and nuclear charge parameters are included; matrix elements of one-body operators, $[\vec{r}\times\vec{\sigma}]^{\lambda}$ with λ =0, 1, 2 and $\vec{r}$, as well as those from weak hadronic currents, γ_5, $\vec{\alpha}$, are taken into account for the FF transitions. The effects of finite nuclear charge distribution are taken into account[11, 12]. The so-called ξ-approximation was not made.

Calculated half-lives are shown in Fig. 3 (left) for GT and GT+FF cases as well as those of FRDM[14] and CQRPA[15]. The FF transitions reduce the half-lives by about 1.5 to several times compared to the case of GT only. The net half-lives are found to be short compared with those of FRDM model[14], which are often used as standard values for astrophysical calculations. They are, on the other hand, longer than those of CQRPA[15]. We also note that the odd-even staggering seen in FRDM is not found in the present shell-model results.

Effects of the short half-lives obtained here on r-process nucleosynthesis are investigated. The dependence of the abundances of the elements around mass number A ∼195 on the half-lives of the isotones is studied for various astrophysical conditions. An analytic model of neutrino-driven winds[16] is used for the time evolution of thermal profiles (see Ref. [9] for more details). The neutrino energy spectra are assumed to obey Fermi distributions with zero chemical potentials. The temperatures of of ν_e, $\bar{\nu}_e$ and ν_x = $\nu_{\mu,\tau}$, $\bar{\nu}_{\mu,\tau}$ are set to be (T_{ν_e} , $T_{\bar{\nu}_e}$, T_{ν_x}) = (3.2 MeV, 5 MeV, 6 MeV)[17] . The abundances of elements in the r-process nucleosynthesis obtained by using the present β-decay half-lives for N=126 isotones are compared with those of the standard FRDM half-lives in Fig. 3 (right). The third peak of the element abundances is found to be slightly shifted toward higher mass region. This shift is a robust effect independent of the present astrophysical condition for the r-process.

We now discuss the dependence of the β-decay half-lives on the quenching factors of g_A and g_V. A large quenching of both g_A and g_V for 1^- spin-dipole transitions was suggested by FF β-decays in the lead region; (g_A/g_A^{free}, g_V/g_V^{free}) =(0.47, 0.64)[18]. Two sets of quenching factors, (0.34, 0.67) and (0.51, 0.30), are obtained from the analysis of ^{205}Tl ($1/2^+$) → ^{205}Pb ($1/2^-$)[10]. A large quenching of g_A is suggested from the studies of FF β-decays of the isotones with Z =78∼80, while a large quenching for g_V is unlikely (see Ref. [9]).

Dependence of the calculated half-lives on the quenching of g_A and g_V is studied for the N=126 isotones. Half-lives obtained with the set (0.34, 0.67) for the 1^- transitions are shown by

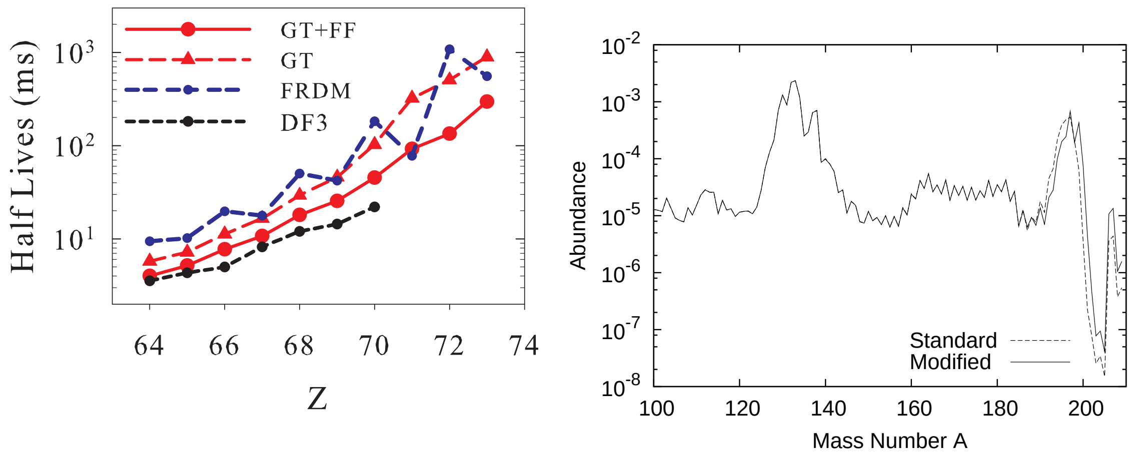

Figure 3: Calculated β-decay half-lives for isotones with N=126 obtained with GT and GT+FF transitions. Half-lives for FRDM[14] and CQRPA[15] (denoted as DF3) are also shown (left). Element abundances of r-process nucleosynthesis obtained with the present shell-model half-lives (denoted as "Modified") as well as those of the FRDM model (denoted as "Standard") (right).

long-dashed line in Fig. 4(a). The half-lives get longer but still remain shorter than those of Ref. [14] except for Z =71. The dependence of the half-lives on the Q-values of the transitions are also studied. The present shell-model calculations give smaller Q-values compared to the experimental ones for Z =78∼80, while there is no experimental information on the Q-values for Z =64∼73. When calculated Q-values are increased by 1MeV for Z =64∼73, the half-lives become small as shown by short-dashed line in Fig. 4(a). The effects are found to be rather large.

Dependence of the FF β-decay half-lives on the quenching factors is also studied in ^{204}Pt and some nuclei near the waiting points, ^{203}Pt, ^{202}Ir and ^{201}Ir. Recently, experimental information on the half-lives of these nuclei become available. The half-lives of FRDM[14] are far off the experimental values[19, 20]. A set of the quenching (g_A/g_A^{free}, g_V/g_V^{free}) =(0.70, 1.0) is rather consistent with the experimental values except for ^{201}Ir as shown in Fig. 4(b). A large quenching of g_V is not favored for the Pt isotopes similar to the case of the N=126 isotones with Z =78∼80. Quenching of g_V is not taken for the case of DF3-QRPA[15] also. Further study is necessary to understand the quenching of g_A and g_V in nuclei around this region.

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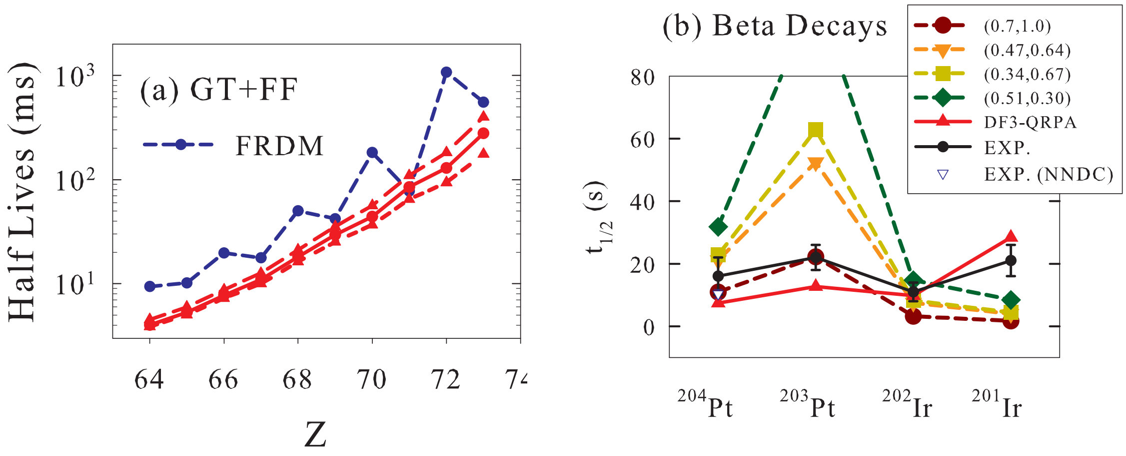

Figure 4: (a) The same as for Fig. 3 (left). Half-lives with larger quenchings in g_A and g_V are shown by long-dashed line. Q-value is enhanced by 1 MeV for short-dashed line. (b) Dependence of β half-lives of Pt and Ir isotopes on the quenching factors of g_A and g_V. Experimental values are taken from Refs. [19] and [20].

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