Spin Modes in Nuclei and Astrophysical Processes based on New Shell-Model Hamiltonians

Toshio Suzuki
Department of Physics, College of Humanities and Sciences, Nihon University
Sakurajosui 3-25-40, Setagaya-ku, Tokyo 156-8550, Japan
Center for Nuclear Study, University of Tokyo, Hirosawa, Wako-shi, Saitama 351-0198, Japan
National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
E-mail: suzuki@chs.nihon-u.ac.jp

Abstract. Neutrino-nucleus reactions on $^{12}$C and $^{16}$O are investigated by shell model calculations with the use of new shell model Hamiltonians for $p$-shell and $p-sd$-shell. The new Hamiltonians can describe spin modes in nuclei quite successfully, for example, the Gamow-Teller (GT) transitions in $^{12}$C and $^{14}$C. New reaction cross sections are compared with previous calculations. Possible implications on nucleosynthesis in supernova explosions are discussed. Electron capture reaction rates are evaluated by using new shell model Hamiltonians in $fp$-shell, which can describe magnetic dipole transitions and GT transitions quite nicely. Capture rates for Ni and Co isotopes in stellar environments are evaluated. The calculated rates in $^{58}$Ni and $^{60}$Ni are found to reproduce well the rates obtained by using experimental GT strengths.

1. Introduction
We study neutrino-nucleus reactions and electron capture reactions, which are dominantly induced by excitations of spin modes in nuclei. Recently, successful descriptions of spin responses in nuclei have been obtained by shell model investigations with the use of new shell model Hamiltonians in $p$-shell, SFO [1] and SFO-tls [2], and $fp$-shell, GXPF1 [3]. Neutrino induced reaction cross sections and electron capture rates are evaluated by shell model calculations with the new Hamiltonians, and applied to astrophysical processes in stars.

Neutrino nucleus reactions on $^{12}$C and $^{16}$O are studied in Sect. 2. Electron capture reactions on Ni and Co isotopes in stellar environments are discussed in Sect. 3.

2. Neutrino-Nucleus Reactions
2.1. Neutrino-Induced Reaction on $^{12}$C
We first explain some important points of the recent advances in the shell model calculations. Important roles of spin dependent interactions, especially, the tensor force are properly taken into account in the new Hamiltonians. The robust sign rule for the monopole terms of the tensor interaction is essential to explain shell evolutions and change of magic numbers toward drip-lines [4]. Magnetic moments of $p$-shell nuclei and Gamow-Teller (GT) transitions in $^{12}$C and $^{14}$C are well reproduced by SFO [1]. The model space including up to 2-3 $h\omega$ excitations is used with a small quenching for the axial-vector coupling constant, $g_{A}^{eff}/g_{A} = 0.95$.

Cross sections for the exclusive charge-exchange $\nu$-induced reaction, $^{12}$C ($\nu$, $e^{-}$) $^{12}$N, are shown in Fig. 1(a). The reaction is induced by the GT transition. The experimental values
of the cross section [5] are well reproduced by shell model calculations with the use of SFO. The calculated cross sections are enhanced compared to those of conventional ones obtained by PSDMK2 [6, 7]. Neutral current reaction cross sections induced by supernova neutrinos with temperature \( T \) (MeV) are also shown in Fig. 1(b). The enhancement of the neutrino-nucleus reaction cross sections in \(^{12}\text{C}\) as well as in \(^{4}\text{He}\) is found to lead to the enhancement of the production yields of light elements, \(^{11}\text{B}\) and \(^{7}\text{Li}\), in supernova explosions [8, 9].

Figure 1. (a) Neutrino-induced reaction cross sections for \(^{12}\text{C} \left( \nu, e^- \right) ^{12}\text{N}_{\text{g.s.}}\) obtained by shell model calculations with the use of SFO and PSDMK2 as well as the experimental data [5]. (b) Cross sections for the neutral current reaction, \(^{12}\text{C} \left( \nu, \nu' \right) ^{12}\text{C}\), induced by supernova neutrinos with temperature \( T \).

2.2. Spin-Dipole Strength in \(^{16}\text{O}\) and \(\nu\)-induced Reactions

Next, we discuss spin-dipole strengths in \(^{16}\text{O}\) and \(\nu\)-induced reactions on \(^{16}\text{O}\). The \(^{16}\text{O}\) nucleus is contained in water, which is an important target for the detection of neutrinos.

The SFO is modified to take full account of the important roles of the tensor force in the \(p-sd\) cross shell part. The tensor and the two-body spin-orbit components of the Millener-Kurath interaction [6] are replaced by those of \(\pi + \rho\) meson exchanges and \(\sigma + \omega + \rho\) meson exchanges, respectively [2].

Spin dipole strengths in \(^{16}\text{O}\) are studied by using the modified Hamiltonian, SFO-tls [2]. Calculated spin-dipole strengths with the rank \(\lambda\)

\[
SD(\lambda) = \frac{1}{2J_f + 1} |\langle J_f \| r[Y^1 \times \sigma]^{\lambda} t_- \| J_i \rangle|^2
\]

are shown in Fig. 2 for the transition; \(^{16}\text{O} \rightarrow ^{16}\text{F}\). The observed energy levels of the spin-dipole states, \(0^-, 1^-\) and \(2^-\), are rather well reproduced by SFO-tls. The strength is shifted toward lower energy region for SFO-tls compared to SFO as shown in Fig. 2(b).
Figure 2. (a) Spin-dipole strengths for $^{16}$O $\rightarrow$ $^{16}$F transition obtained by using SFO-tls. (b) Comparison of the spin-dipole strengths in $^{16}$O obtained for SFO-tls and SFO.

The $\nu$-induced reaction cross sections, whose main contributions come from the spin-dipole transitions, are therefore enhanced for SFO-tls as shown in Fig. 3(a) for $^{16}$O ($\nu$, $e^{-}$) $^{16}$F. The enhancement factors are 1.60, 1.30 and 1.15 - 1.06 at $E_\nu$ = 20, 30 and 40 - 60 MeV, respectively. They are also enhanced compared to CRPA results [10] at low neutrino energies, $30 \text{ MeV} \leq E_\nu \leq 80 \text{ MeV}$, by about 10%. Cross sections for supernova neutrinos with temperature $T$ (MeV) are shown in Fig. 3(b). The calculated cross sections are enhanced for SFO-tls compared to SFO by about 17 - 5% for $T = 4 - 10 \text{ MeV}$, and also compared to CRPA by about 41% and 17% for $T = 4$ and 8 MeV, respectively. Situations are similar for $(\bar{\nu}, e^{+})$ reaction as well as the neutral current reaction. It would be interesting to study effects of the enhancement of the cross sections for SFO-tls on nucleosynthesis and neutrino detections.

3. Electron Capture Reactions in $fp$-Shell Nuclei
Spin properties of $fp$-shell nuclei are well described by the new shell model Hamiltonian, GXPF1J [11]. Magnetic dipole strengths in $fp$-shell nuclei and GT $^{-}$ strength in $^{58}$Ni are well reproduced by GXPF1J with the universal quenching factors of $g_A^{dff}/g_A = 0.74$ and $g_s^{dff}/g_s = 0.75$. Experimental GT $^{+}$ strengths in the $\beta^{+}$ channel in $^{58}$Ni [12] and $^{60}$Ni [13] are also well reproduced by GXPF1J [14].

Electron capture reactions in Ni isotopes, which are dominantly induced by the GT $^{+}$ transitions, are studied in stellar environments, that is, at high temperatures, $T = T_9 \times 10^9 \text{ K}$ with $T_9 = 1 - 10$, and at high densities, $\rho Y_e = 10^7 - 10^{10} \text{ g/cm}^3$ with $Y_e$ the lepton-to-baryon ratio in stars. The capture rates obtained by shell model calculations with GXPF1J are found to reproduce well the rates in $^{58}$Ni and $^{60}$Ni evaluated by using the experimental GT $^{+}$ strengths [14]. The capture rates in $^{58}$Ni for GXPF1J are found to be smaller compared to those for a conventional Hamiltonian KB3G [15] except for the case of $\rho Y_e = 10^7$ at low $T_9$. The difference can be attributed to larger fragmentation of the GT strength for GXPF1J compared to KB3G [8]. See Ref. [14] for more details as for Ni isotopes.

The capture rates in Co isotopes are also studied. Capture rates in $^{56}$Co, $^{58}$Co and $^{60}$Co are obtained for GXPF1J and compared with previous calculations of FFN [16] and LSSM calculations of Ref. [17]. The present results are consistent with those of Ref. [17] obtained...
Figure 3. (a) Calculated reaction cross sections for $^{16}$O ($\nu$, $e^-$) $^{16}$F obtained by shell model calculations with the use of SFO-tls and SFO, as well as CRPA calculations. (b) The same as in (a) for supernova neutrinos with temperature $T$.

with KBF but much smaller than those of FFN. In $^{60}$Co, the present capture rates are enhanced compared to KBF at low $T_9$ for $\rho Y_e = 10^7$ g/cm$^3$ [18]. Use of the GXPF1J is quite promising in $fp$-shell nuclei including neutron-rich isotopes [14]. The extension of the present work to various isotopes will be reported in future publications.

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