Gamow-Teller transitions and neutrino-nucleus reactions based on new shell-model interactions

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Abstract. Gamow-Teller transitions in $p$-shell and $fp$-shell nuclei are investigated based on new shell model interactions. Neutrino-nucleus reactions induced by accelerator and supernova neutrinos are studied for $^{12}\text{C}$ as well as Fe and Ni isotopes by using the Gamow-Teller strengths obtained by the shell models. The charge exchange reaction cross section on $^{12}\text{C}$ is found to be enhanced compared with previous calculations both for decay-at-rest (DAR) neutrinos and supernova neutrinos. In the charge exchange reaction on $^{56}\text{Fe}$, the cross section is also found to be enhanced for a new shell model interaction in comparison with a previous shell model calculation. Neutrino-$^{37}\text{Cl}$ reaction is studied for solar neutrinos with the use of a recent experimental Gamow-Teller strength, and compared with shell model calculations. The USD shell model interaction with the universal quenching of the axial-vector coupling constant ($g_A$) is found to well reproduce the cross section obtained from the observed Gamow-Teller strength.

1. Introduction

Due to a recent development of shell model calculations which take into account important roles of spin-isospin interactions, significant improvements in magnetic and spin properties of nuclei as well as a proper shell evolution are obtained [1, 2]. A general important role of tensor interaction is pointed out for the realization of the shell evolution [3]. The Gamow-Teller (GT) transitions and magnetic moments of the $p$-shell nuclei are found to be described quite well by the modified Hamiltonian [1]. In the $fp$-shell, a recently invented shell model interaction is found to lead to a good description of nuclei with $N$ or $Z=28$ and $N$, $Z > 28$ in addition to the nuclei with $A = 47-52$ [4]. In particular, the distribution of the GT strength of $^{58}\text{Ni}$ is reproduced very well in contrary to previous interactions [5].

We here investigate neutrino-nucleus reactions using these modified shell model interactions. The reactions are induced mainly by GT transitions and spin-dipole transitions. We show calculated results of the neutrino-nucleus reactions on $^{12}\text{C}$, $^{56}\text{Fe}$ and Ni isotopes induced by decay-at-rest (DAR) neutrinos as well as supernova neutrinos. We study also the charge-exchange reaction on $^{37}\text{Cl}$ induced by solar neutrinos.
2. Neutrino-nucleus reactions on $^{12}$C

We first discuss effects of the tensor interaction on monopole terms of the shell model two-body matrix elements. It was pointed out that in general the monopole terms of the tensor force between $j_1 = \ell + \frac{1}{2}$ and $j_1 = \ell - \frac{1}{2}$ orbits are attractive while those between $j_1$ and $j_2$ (or $j_1$ and $j_2$) orbits are repulsive [3]. We will show that our modified interaction, SFO [1], actually has this nature. The monopole terms of the tensor components of the SFO interaction among the p-shell and p−sd shells are shown in Fig. 1. The zigzag structure as a function of a pair of orbits, $j_1 - j_2$, is clearly seen for the SFO interaction though their magnitude is small compared to that of the $\pi + \rho$ meson exchange potential model. This proper treatment of the tensor components of the interaction is important for the shell evolution, that is, the vanishing of the $N=8$ magic number toward the drip-line as well as for the improvements of the magnetic properties of the p-shell nuclei.

Now, we study neutrino-nucleus reactions on $^{12}$C as experimental data for the accelerator neutrinos from the muon decay are available [6]. The SFO Hamiltonian gives the $B(GT)$ value of the GT transition to the $1_{g.s.}^+$ state of $^{12}$N that is consistent with the experimental value within the (0+2) $\hbar \omega$ configuration space with the use of the bare axial-vector coupling constant, $g_A$ [1]. The use of an effective coupling, $g_A^{eff}/g_A = 0.95$, reproduces the observed $B(GT)$ [7].

The calculated reaction cross sections of the charge-exchange reaction $^{12}$C ($\nu, e^-$) $^{12}$N $^{1+}_{g.s.}$ induced by the DAR neutrinos are shown in Fig. 2(a) for various shell model Hamiltonians. The SFO Hamiltonian leads to larger cross sections than those obtained by the Millener-Kurath (PSDMK2 [8, 9]) or Warburton-Brown (WBT [10, 9]) interactions as well as in ref. [11]. The shell model values of the cross sections are consistent with the observed data [6].

The cross sections for $^{12}$C ($\nu, e^-$) $^{12}$N obtained by the shell models are also shown in Fig. 2 (b). The spin-dipole transitions are the dominant contributions to the cross section for the excited states of $^{12}$N. Calculated values of the cross section are larger than the observed value [6] except for the case in ref. [11], where Woods-Saxon wave functions are used instead of
Figure 2. Calculated cross sections for $^{12}$C ($\nu, e^-$) $^{12}$N induced by DAR neutrinos obtained by the shell models: (a) exclusive ($1^+_g.s.$) reaction and (b) reaction leading to excited states of $^{12}$N. The symbol * denotes that $g^A_{e,f}$ is used (see text). Experimental values [6] are within the range of two horizontal lines.

Figure 3. Calculated reaction cross sections for (a) $^{12}$C ($\nu, e^-$) $^{12}$N and (b) $^{12}$C ($\nu, \nu'$) $^{12}$C induced by supernova neutrinos with temperature $T$.

harmonic oscillator wave functions. The experimental value of the cross section is reproduced when $g^A_{e,f} = 0.70$ (0.75) is adopted for the SFO (PSDMK2) Hamiltonian.

Next, we investigate neutrino induced reactions on $^{12}$C for the supernova neutrinos. Energy spectra of the supernova neutrinos are taken to be Fermi distributions. The charge-exchange and neutral current reaction cross sections are shown in Fig. 3 for the neutrinos with the temperature $T = 2 \sim 12$ MeV. We find that the cross sections obtained by the SFO Hamiltonian are enhanced compared with those by the PSDMK2 Hamiltonian as well as the previous calculation [12].

Cross sections for the neutron and proton knock-out processes, ($\nu, \nu' n$) and ($\nu, \nu' p$), can
be obtained once the branching ratios for the channels are calculated by the Hauser-Feshbach theory. More on the subject will be given elsewhere [13].

Neutrino induced reactions on $^{12}$C as well as on $^4$He are important for the nucleosynthesis of light elements such as $^{11}$B and $^7$Li during the supernova explosion [14]. Effects of the enhancement of the cross sections discussed here for $^{12}$C by the modified Hamiltonian (SFO) on the abundances of $^{11}$B and $^7$Li will be discussed in ref. [13] together with the cross sections on $^4$He.

3. Neutrino-nucleus reaction on Fe and Ni isotopes
We now move on to the study of charge-exchange ($\nu, e^-$) reactions on Fe and Ni isotopes. Recently, an improved $fp$-shell model interaction, GXPF1 [4], is obtained by reducing $r.m.s$ deviations of the calculated energy levels from the observed values for $Z$ or $N =28$ and $Z,N >28$ nuclei compared with the KB3G interaction [15]. In the KB3G interaction, monopole corrections are taken into account starting from the Kuo-Brown G-matrix, and a remarkable improvement in the description of the $fp$-shell nuclei with $A=47-52$ was obtained [15]. In the GXPF1 interaction, a better systematic description of the $2^+_1$ energies in Ni, Ca, Ti, Cr and Fe isotopes is further obtained, and a successful treatment of the $fp$-shell nuclei with $A=47-66$ is realized.

For the Gamow-Teller strength in $^{56}$Fe obtained by the GXPF1 interaction, the summed $B(GT)$ value is found to be 9.47, which is close to the experimental value, $B(GT) = 9.9\pm2.4$ [16], while the KB3 interaction gives a smaller value of $B(GT) =8.85$ [17]. The peak found in the strength at $E_x (^{56}$Co) $\sim$ 2 MeV for the KB3 interaction is suppressed, and the strength is a little bit more fragmented for the GXPF1 interaction.

The reaction cross section for $^{56}$Fe ($\nu, e^-$) $^{56}$Co induced by the DAR neutrons is shown in Fig. 4(a) for the GT transitions as well as the transition to the IAS state. The calculated cross section for the GT transition is $\sigma = 1.99\times10^{-40}$ cm$^2$, which is larger than the previous calculated value of $\sigma =1.13\times10^{-40}$ cm$^2$ obtained by the KB3 interaction [18]. Note that our calculation includes both M1 and axial E1 contributions. The experimental value of the cross section obtained by the KARMEN collaborations, $\sigma =2.56\pm1.08\pm0.43\times10^{-40}$ cm$^2$ [18], includes also the contributions from the spin-dipole transitions and the Fermi transition.

**Figure 4.** Calculated reaction cross sections for (a) $^{56}$Fe ($\nu, e^-$) $^{56}$Co induced by (a) DAR and (b) supernova neutrinos.
We also investigate $^{56}\text{Fe (}\nu, e^-\text{) }^{56}\text{Co}$ reaction induced by the supernova neutrinos. Fermi distributions are used for the supernova neutrino spectra. Calculated results of the GT transitions for the GXPF1 interaction are shown in Fig. 4(b) for the neutrino temperature of $T = 2\sim12$ MeV. Previous results of the calculations in refs. [12] and [19], where contributions other than the GT transitions are taken into account, are also shown in Fig. 4(b). When the contributions from all the multipoles are included, the present results would get larger than those of ref. [19] for $T \leq 8$ MeV while they are still smaller than those of ref. [12]. This is also true for the calculated results for the $^{56}\text{Ni (}\nu, e^-\text{) }^{56}\text{Cu}$ reaction cross sections.

The observed GT strength distribution for $^{58}\text{Ni}$ is well explained by the GXPF1 interaction, in particular, around $E_x\left(^{58}\text{Cu}\right) = 3\sim4$ MeV [5], whereas the KB3G interaction fails to reproduce the strength in this energy region though it explains well the observed strength in other energy regions. Calculated cross sections for $^{58}\text{Ni (}\nu, e^-\text{) }^{58}\text{Cu}$ induced by the supernova neutrinos are

$$\sigma = 3.67, 9.80 \text{ and } 18.6 \times 10^{-41} \text{ cm}^2 \text{ for } T = 6, 8 \text{ and } 10 \text{ MeV, respectively, for the GXPF1 interaction.}$$

It would be interesting to compare calculated reaction cross sections for the two cases.

Cross sections for particle emission channels such as neutron, proton and $\alpha$-particle knock-out can be obtained by calculating the branching ratios for the channels by the Hauser-Feshbach theory. This subject for Ni and Fe isotopes will be discussed elsewhere [20] as well as the role of the knocked-out neutrons. More neutrons are emitted as the nucleus becomes more neutron rich.

4. $^{37}\text{Cl (}\nu, e^-\text{) }^{37}\text{Ar induced by solar neutrinos}$

Finally, we discuss $^{37}\text{Cl (}\nu, e^-\text{) }^{37}\text{Ar}$ reaction induced by solar neutrinos. In case of the solar neutrinos, it is enough to consider the GT transitions only. Here, we use experimental GT strength for the evaluation of the cross section, and compare with the shell model calculations. Calculated cross sections are shown in Fig. 5 for the solar neutrinos from $^8\text{B}$. A recent experimental GT strength measured at RCNP [21] is used to evaluate the cross section. Shell
model calculations are done with the USD interaction [22] within the sd-shell configurations. The calculated cross sections are similar below $E_x = 9\ \text{MeV}$, while above $E_x = 10\ \text{MeV}$ shell model calculations fail to reproduce the cross section obtained by using the observed GT strength because of the limitations of the present shell model space. The total cross section calculated is $\sigma = 4.55 \times 10^{-43}\ \text{cm}^2$ for the case with the experimental GT strength. This value is well reproduced by the shell model calculation with the universal quenching factor $q=0.77$ for $g_A$ [22], that is, $\sigma_{SM} = 4.58 \times 10^{-43}\ \text{cm}^2$. When another quenching factor $q=0.87$ is adopted so that the summed strength up to $E_x = 8.65\ \text{MeV}$ is equal to the experimental one, the calculated cross section becomes larger, $\sigma_{SM} = 5.83 \times 10^{-43}\ \text{cm}^2$. Thus, the USD shell model interaction can describe quite well the GT transitions in $^{37}\text{Cl}$ with an appropriate quenching factor.

5. Summary
Due to the recent progress in shell model calculations and the development of experimental measurements of the GT strength, we can evaluate neutrino induced reaction cross sections on more sound grounds than before. We find some enhancement of the cross sections on $^{12}\text{C}$ as well as on $^{56}\text{Fe}$ using new modified shell model interactions, SFO and GXPF1, in comparison to previous calculations. This may lead to possible interesting consequences, for example, such as an enhancement of light element abundances in supernova explosion [13]. Owing to the recent accurate measurement of the GT strength in $^{37}\text{Cl}$ [21], we can calculate neutrino-$^{37}\text{Cl}$ reaction cross sections induced by the solar neutrinos quite accurately. We find that the USD shell model interaction with the universal quenching of $g_A$ can describe the reaction process very well up to $E_x = 9\ \text{MeV}$. It would be quite important to make a progress both on theoretical and experimental sides for further development of the subject in future.

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