Neutrino-Nucleus Reactions based on Recent Structure Studies

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Abstract. Neutrino-nucleus reactions are studied with the use of new shell model Hamiltonians, which have proper tensor components in the interactions and prove to be successful in the description of Gamow-Teller (GT) strengths in nuclei. The new Hamiltonians are applied to obtain new neutrino-nucleus reaction cross sections in ^{12}C, ^{13}C, ^{56}Fe and ^{56}Ni induced by solar and supernova neutrinos. The element synthesis by neutrino processes in supernova explosions is discussed with the new cross sections. The enhancement of the production yields of ^{7}Li, ^{11}B and ^{55}Mn is obtained while fragmented GT strength in ^{56}Ni with two-peak structure is found to result in smaller e-capture rates at stellar environments. The monopole-based universal interaction with tensor force of π+ρ meson exchanges is used to evaluate GT strength in ^{40}Ar and ν-induced reactions on ^{40}Ar. It is found to reproduce well the experimental GT strength in ^{40}Ar.

Keywords: shell model, neutrino induced processes, nucleosynthesis
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INTRODUCTION

New shell-model Hamiltonians have been constructed based on recent advances in the studies of exotic nuclei. A new Hamiltonian in p-shell, SFO[1], can describe spin responses in p-shell very well. Magnetic moments of p-shell nuclei and Gamow-Teller (GT) transition strengths in ^{12}C and ^{14}C are found to be well reproduced by SFO. A new one in pf-shell, GXPF1[2], is found to describe well the GT strengths in Ni isotopes and M1 strengths in pf-shell nuclei. An important point that these Hamiltonians have in common is that they have proper tensor components. The tensor force plays an important role in shell evolutions toward drip-lines and spin responses in nuclei[3, 4]. The monopole-based universal interaction is proposed as a simple generalization to take into account the important roles of the tensor force[4]. Here, we discuss ν-induced reactions on carbon isotopes, iron and nickel isotopes as well as argon based on the new Hamiltonians.

NEUTRINO-CARBON REACTIONS AND LIGHT ELEMENT NUCLEOSYNTHESIS

The new shell model Hamiltonian, SFO[1], is applied to obtain neutrino-nucleus reaction cross sections on ^{12}C. The Hamiltonian describes well the GT transition strength in ^{12}C and the exclusive reaction, ^{12}C (ν, e^-) ^{12}N ($1^+_{g.s.}$), at DAR energies[5]. The cross sections obtained by SFO are enhanced compared to those by conventional Hamiltonians such as PSDMK2[6, 7].

The new cross sections are applied to light element nucleosynthesis net-work calculations, and new production yields of ^{11}B and ^{7}Li are obtained[5]. The eaction cross sections for ^{12}C (ν, $\nu' p$) ^{11}B and ^{4}He (ν, $\nu' p$) ^{3}H followed by (α, γ) ^{7}Li (α, γ) ^{11}B are important to produce ^{11}B. New reaction cross sections for ν-^{4}He are also used to evaluate the yields of ^{7}Li and ^{11}B in supernova explosions. The production yields are found to be enhanced compared with previous calculations with the use of HW92[8]. The abundances of ^{7}Li and ^{11}B are obtained by using the new yields and a galactic chemical evolution model. Both of the abundances are enhanced while the ratio ^{7}Li/^{11}B remains rather stable. The latter point is important for the investigation of the neutrino oscillation effects on the ratio[9, 10].

The SFO is applied to study low-energy ν-^{13}C reactions. Both the charged and neutral current reactions leading to low-lying states in ^{13}N and ^{13}C, dominantly induced by GT and isobaric analog (IA) transitions, are investigated[11]. The enhancement of the cross sections compared to previous Cohen-Kurath (CK) case is found as presented in Table 1 for the cross sections folded over solar neutrinos from ^{8}B[12].

TABLE 1. Charged-current and neutral-current neutrino capture cross sections on ^{13}C folded over ^{8}B solar ν spectrum[12]. Cross sections for CK and SFO Hamiltonians are given in units of 10^{-43} cm^2.

Reaction	Final states	CK	SFO
(ν_e, e^-)	$1/2^-_{g.s.}$ + $3/2^-$ (3.50 MeV)	10.7	13.4
(ν, ν')	$3/2^-$ (3.69 MeV)	1.16	2.23

NEUTRINO-INDUCED REACTIONS ON ^{56}FE AND ^{56}NI

Neutrino-induced reactions on iron and nickel isotopes as well as electron capture reactions on nickel isotopes are investigated by using a new shell-model Hamiltonian, GXPF1J[13]. Reaction cross sections for ^{56}Fe (ν, e^-) ^{56}Co induced by DAR neutrinos are obtained by GXPF1J for the GT and IA transitions (other multipolarities are evaluated by RPA) with the universal quenching factor for g_A^{eff}/g_A =0.74. Calculated cross section, σ = 259$\times$10^{-42} cm^2[14], reproduces the experimental value, σ_{exp} = (256$\pm$108$\pm$43) $\times$10^{-42} cm^2[15].

GT strengths for GXPF1J are more spread compared with those for KB3G[16]. In particular, the GT strength in ^{56}Ni for GXPF1J has two-peak structure [14], which has been confirmed by recent (p, n) reactions[17] (see Fig. 1(a)). As there is smaller amount of the strength in low energy region for GXPF1J, electron capture rates in stellar environments are found to be also small compared to those for KB3G[18] as shown in Fig. 1(b). Calculated capture rates obtained with GXPF1J reproduce the rates obtained from the experimental GT strength fairly well. As a possible consequence of small e-capture rates on ^{56}Ni, the lepton-to-baryon (or proton fraction) Y_e remains larger in statistical equilibrium conditions, which results in less abundances of ^{58}Ni and neuron-rich Ni isotopes.

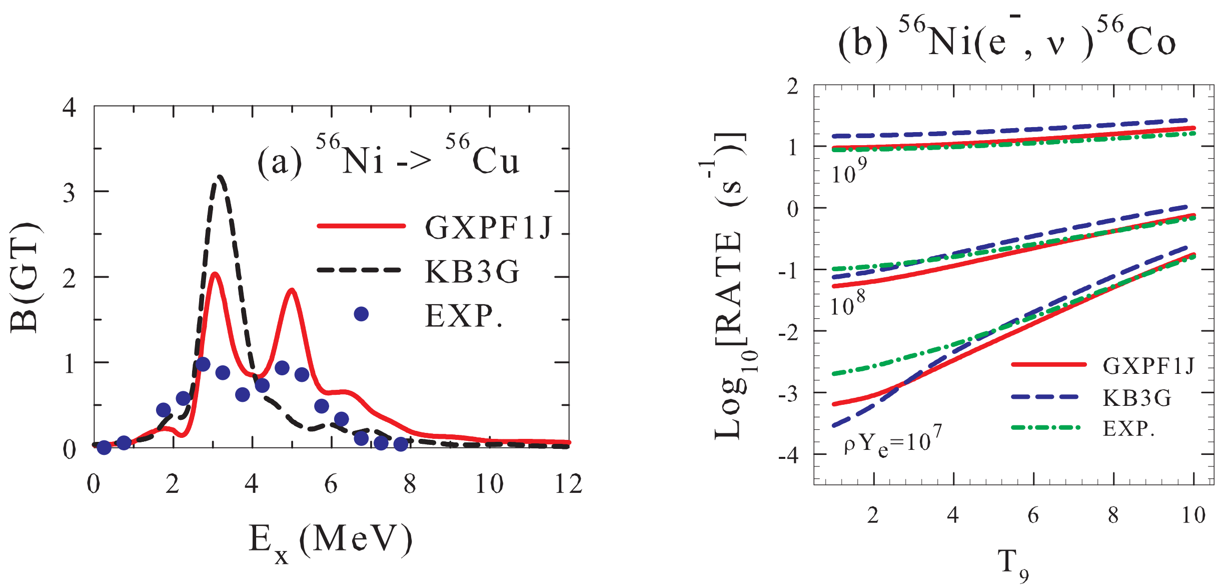

FIGURE 1. (a) GT strength in ^{56}Ni obtained for GXPF1J and KB3G. Experimental data[17] are also shown. (b) Electron capture rates obtained for GXPF1J and KB3G as well as for experimental GT data.

The GT strength at higher excitation energy region, on the other hand, is found to enhance the proton knock-out cross sections, ^{56}Ni $(\nu, \nu' \mathrm{p})$ ^{55}Co. The enhancement of the proton emission cross section leads to the enhancement of the production yield of ^{55}Mn by two successive e-capture processes[14]. This scenario of nucleosynthesis by the neutrino process now becomes more solid due to the recent experimental confirmation of the GT strength in ^{56}Ni.

NEUTRINO-INDUCED REACTIONS ON ^{40}AR

A liquid Argon detector is quite important and excellent for the detection of core-collapse supernova neutrinos. A liquid Argon TPC (time projection chamber), proposed by the ICARUS Collaborations [19], can provide three-dimensional imaging of ionizing events. Here, neutrino-induced reaction on ^{40}Ar, ^{40}Ar (ν, e^-) ^{40}K, is studied with the use of the monopole-based universal interaction (V_{MU})[4]. V_{MU} is used to make the *sd*-*pf* cross shell matrix elements while the *sd*-shell and *pf*-shell interactions are taken to be SDPF-M[20] and GXPF1J, respectively. Contributions from two-body spin-orbit interaction is also added to the cross shell matrix elements. The V_{MU} with the tensor components of π+ρ meson exchanges can reproduce well the monopole terms of SDPF-M and GXPF1. The use of V_{MU} in the *p*-*sd* cross shell part of the interaction is also found to be successful in the description of Gamow-Teller transitions and magnetic moments in *p*-*sd* shell nuclei [21].

The experimental GT strength in ^{40}Ar obtained from p, n) reactions[22] is found to be rather well reproduced as shown in Fig. 2. The cross sections induced by the GT transitions are larger than the previous work[23]. Calculated cross sections folded over ^{8}B solar ν[12] are compared in Table 2. Calculated total cross sections are shown in Fig. 3, where multipoles other than 0^+ and 1^+ are obtained by RPA. The present result is rather close to that in Ref. [24] except that the GT contributions are enhanced in our case. The direct measurement of ν-induced reactions on ^{40}Ar is accessible with the use of a liquid Ar TPC and a spallation neutron source for neutrinos[26]. It is highly desirable to carry out the measurement for future detection of supernova neutrinos and studies of neutrino oscillations.

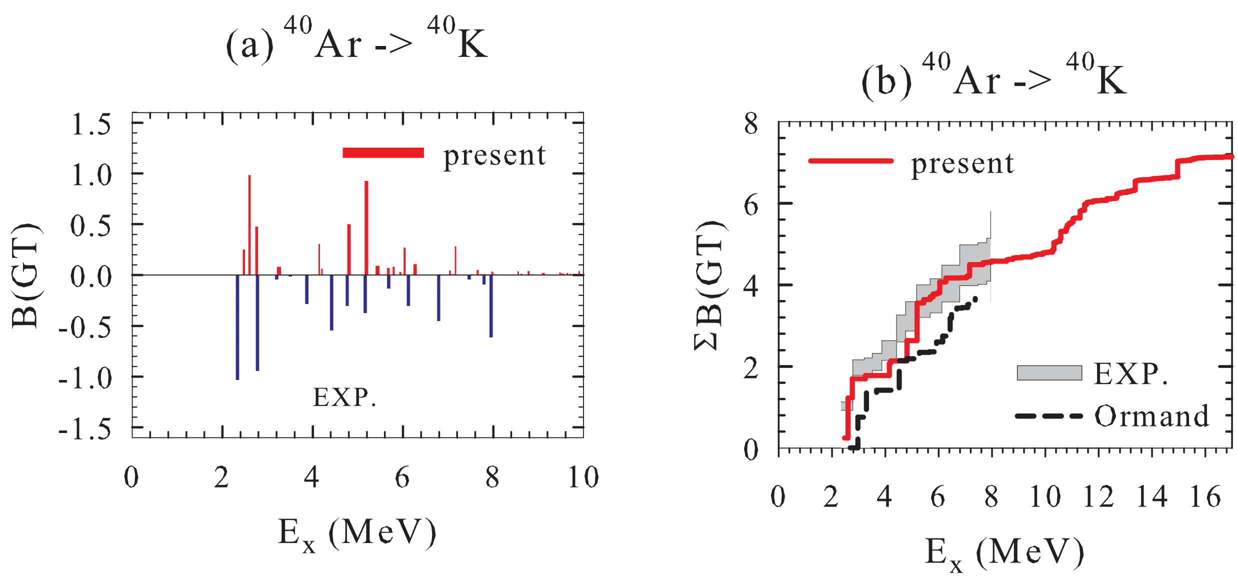

FIGURE 2. (a) GT strength in ^{40}Ar obtained by the present calculation as well as the experimental data[22]. (b) Cumulative sum of the GT strength in ^{40}Ar up to excitation energies of ^{40}K, E_x, obtained by the present shell model calculation. The experimental data[22] are shown by shaded area. Calculated values in Ref. [23] are also shown by dashed line.

SUMMARY

In summary, we have shown that we are now able to evaluate ν-induced reaction cross sections accurately with the use of new shell-model Hamiltonians as presented for ^{12}C and ^{56}Fe. The present evaluations of the neutrino-nucleus reaction cross sections for ^{13}C and ^{40}Ar as well as e-capture rates on ^{56}Ni can be considered to be quite reliable. It

TABLE 2. Calculated cross sections for ^{40}Ar (ν_e, e^-) ^{40}K induced by solar ^{8}B neutrinos for the present interaction. Cross sections folded over the ^{8}B neutrino spectrum [12] are given in unit of 10^{-43} cm^2. Cross sections in Ref. [23] are also given.

Hamiltonian	GT	IA	GT+IA
present	11.95	2.10	14.05
Ref. [23]	7.70	3.80	11.50

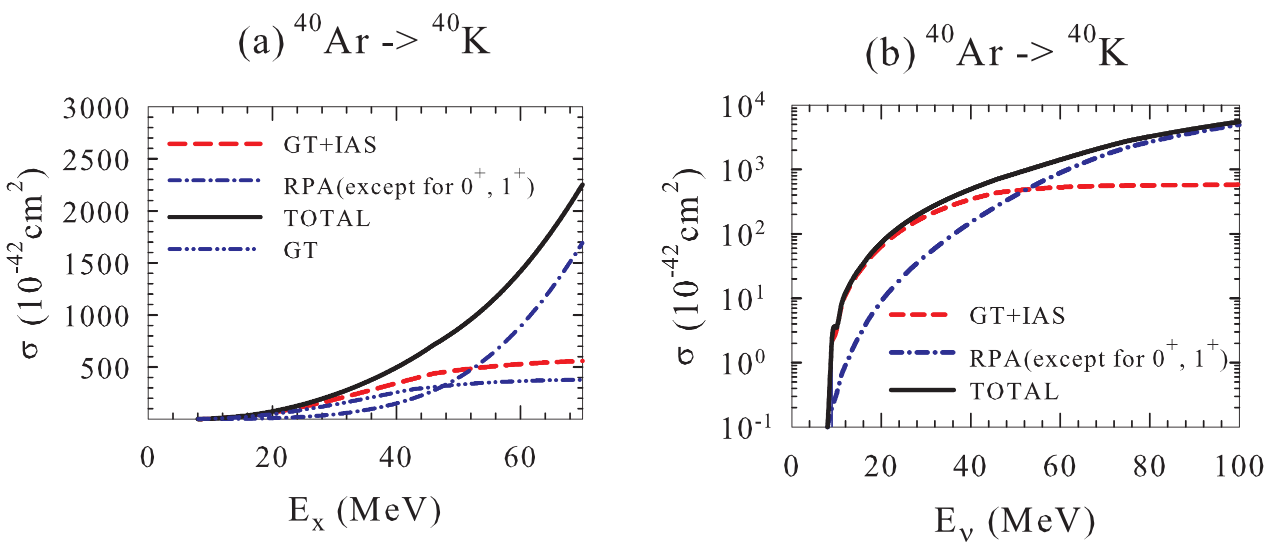

FIGURE 3. Calculated reaction cross sections for ^{40}Ar (ν_e, e^-) ^{40}K in (a) linear and (b) logarithmic scales. Total cross section, cross sections for GT+IA, GT and other multipolarities are shown by solid, dashed, dash-two-dotted and dash-dotted curves, respectively[25].

is important to carry out accurate measurement of neutrino-induced reaction cross sections in various nuclear targets including argon[26], iron and lead[27] for future detection of supernova neutrinos as well as for studies of neutrino oscillations and element synthesis.

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