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New neutrino-nucleus reaction cross sections at solar, reactor and supernova neutrino energies

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Abstract. Remarkable improvements in the evaluation of neutrino-nucleus reaction cross sections are obtained based on new shell-model Hamiltonians with proper tensor components. New ν-induced reaction cross sections on ^{12}C, ^{13}C, ^{56}Fe, ^{56}Ni and ^{40}Ar are presented, and predictions for nucleosynthesis in supernova explosions, ν-oscillation effects and low-energy reactor and solar neutrino detection are discussed based on these new cross sections.

1 Introduction

Considerable improvements in the evaluations of neutrino-nucleus reaction cross sections have been achieved based on new shell-model Hamiltonians at solar, reactor and supernova neutrino energies. New shell-model Hamiltonians can successfully describe spin responses in nuclei and explain shell evolutions toward drip-lines. A common feature of the new intearctions is that they have proper tensor components.

A new shell-model Hamiltonian for p-shell nuclei, SFO[1], is used to evaluate ν-^{12}C and ν-^{13}C cross sections[2–4]. The reaction cross sections on ^{12}C at DAR (decay-at-rest pion) energies are shown to be well reproduced by shell-model calculations. Implications on light element synthesis such as ^{11}B and ^{7}Li in supernova explosions and effects of neutrino oscillations are discussed. A possible determination of the oscillation parameters, in particular, the mass hierarchy from the abundance ratio of ^{7}Li/^{11}B is proposed[3, 5]. ^{13}C is shown to be an attractive target for detecting very low-energy neutrinos below 13 MeV with scintillator based experiments[4].

A new shell-model Hamiltonian for pf-shell nuclei, GXPF1J[6], is shown to reproduce ν-^{56}Fe cross section for DAR neutrinos[7]. It describes also well the Gamow-Teller (GT) strengths in Ni isotopes, in particular ^{56}Ni[8, 9]. Neutral-current reactions on ^{56}Ni are evaluated, and the enhancement of proton-emission cross sections and production of ^{55}Mn element in supernova explosions are discussed[8].

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A liquid argon detector is a powerful tool to measure solar and supernova neutrinos. GT strength in ^{40}Ar is studied by shell-model calculations with a monopole-based universal interaction[10], which has tensor components of $\pi + \rho$ meson exchanges. GT strength in ^{40}Ar and the charged-current reaction, ^{40}Ar (ν_e, e$^-$) ^{40}K, are evaluated [11] and compared with previous calculations. New cross section for solar neutrinos from ^{8}B will be also presented.

Carbon isotopes are treated in Sect. 2. Results for ^{56}Fe and ^{56}Ni are shown in Sect. 3. ^{40}Ar is discussed in Sect. 4. A summary is given in Sect. 5.

2 ν-induced reactions on ^{12}C and ^{13}C

2.1 ν-induced reactions on ^{12}C and synthesis of light elements

We constructed a new shell-model Hamiltonian, SFO[1], starting from Cohen-Kurath (CK) and Millener-Kurath (MK) interactions by enhancing monopole terms of matrix elements for $p_{1/2}$-$p_{3/2}$ orbits with isospin T=0. Systematic improvements in the description of magnetic moments of p-shell nuclei, reproduction of GT transitions in ^{12}C and ^{14}C are obtained with configuration space including up to $2\hbar\omega$ excitations and with the use of a small quenching of the axial-vector coupling constant and spin g-factor; $g_A^{eff}/g_A = g_s^{eff}/g_s$ =0.95. The SFO is found to have proper tensor components consistent with the general sign rule for the tensor-monopole terms[12], and can explain the change of the magic number from 8 to 6 toward the neutron-drip line.

The SFO is applied to evaluate ν-induced reaction cross sections at DAR energies. The cross sections for the exclusive charged-current reaction, ^{12}C (ν_e, e$^-$) ^{12}N ($1^+_{g.s.}$), obtained by SFO and CK-MK (PSDMK2[13]) are shown in figure 1 and compared with the experimental data[14]. The SFO reproduces well the experimental data. It can reproduce well both the exclusive charged-current and neutral-current reaction cross sections folded over the DAR neutrinos[2, 5]. The inclusive charged-current reaction cross section for the DAR neutrinos is also well reproduced by SFO.

The new cross sections evaluated by SFO are used for the study of light-element nucleosynthesis in supernova explosions[2, 3]. Neutral-current reactions on ^{12}C and ^{4}He are important for the production of ^{11}B and ^{7}Li. The production yields of ^{11}B and ^{7}Li are re-evaluated with the use of the new reaction cross sections of ^{12}C and those of ^{4}He obtained by WBP[15]. Calculated results are compared with previous calculations[16]. The abundances of ^{11}B and ^{7}Li evaluated by using a GCE (galactic chemical evolution) model are found to be enhanced by 13∼14% compared with those by HW92[16].

2.2 Effects of ν-oscillation and ν-mass hierarchy

The effects of matter ν-oscillations on the production of ^{11}B and ^{7}Li in supernova explosions are discussed. Matter oscillations in neutrinos by the MSW mechanism can occur near the O/C layer for the normal mass hierarchy case, while for anti-neutrinos the high-density resonance can occur for the inverted mass hierachy. When there is ν-oscillation and heavy-flavor neutrinos change into electron neutrinos with higher energies, charged-current reactions on ^{12}C and ^{4}He become important, and ^{11}B and ^{7}Li are produced more but the abundance ratio for ^{7}Li/^{11}B is modified dependent on the mixing angle θ_{13}. The dependence of the abundance ratio on θ_{13} is shown in figure 1 for both the normal and inveted mass hierarchies. In case of normal mass hierarchy, the ratio is found to be enhanced at $sin^2(2\theta_{13}) > 0.002$, where the transition is adiabatic. As the value of $sin^2(2\theta_{13})$ is recently determined to be around 0.1[17], we can determine the mass hierarchy from the abundance ratio of ^{7}Li/^{11}B. Recently, ^{11}B and ^{7}Li are found in pre-solar supernova grains[18]. Using Bayesian analysis, the inverted mass hierarchy is found to be statistically more favored with a probability of 74%[19].

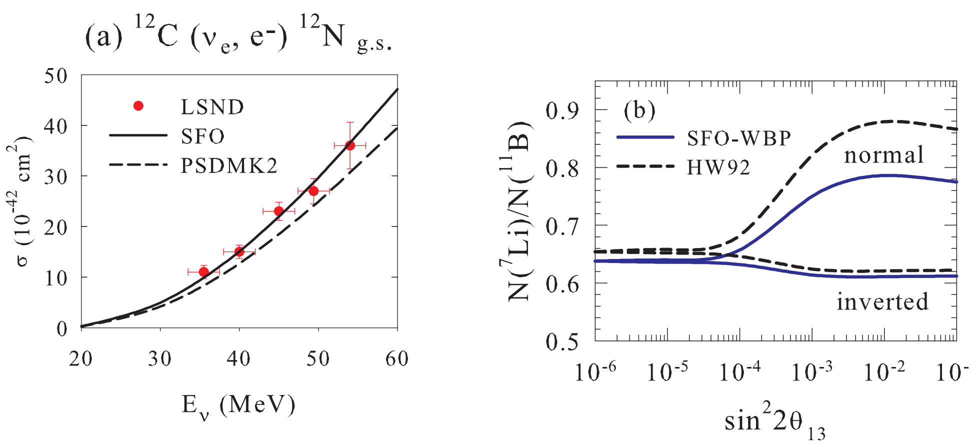

Figure 1. (a) Exclusive charged-current reaction cross sections on ^{12}C induced by DAR neutrinos obtained for SFO and PSDMK2. Experimental values (LSND) are taken from Ref. [14]. (b) Dependence of the abundance ratio ^{7}Li/^{11}B on the mixing angle θ_{13} for normal and inverted ν mass hierarchies obtained with SFO-WBP Hamiltonian set and HW92 cases[5].

Table 1. Calculated cross sections for ^{13}C induced by solar ^{8}B neutrinos. Cross sections obtained for SFO are given in units of 10^{-43} cm^2

Reaction	CK	SFO
^{13}C (ν_e, e$^-$) ^{13}N ($1/2^-_{g.s}$ + $3/2^-$ (3.50 MeV))	10.7	13.4
^{13}C (ν, ν') ^{13}C ($3/2^-$, 3.69 MeV)	1.16	2.23

We are very much interested in the results of accelerator experiments on the determination of mass hierarchy in near future.

2.3 ν-induced reactions on ^{13}C

^{13}C is an attractive target for very low energy neutrinos below E_ν =13 MeV as ^{12}C can be excited only above E_ν =13 MeV and there is no sufferering from the contamination of ^{12}C. A knowledge of cross sections leading to various states in ^{13}N and ^{13}C would help scintillator-based searches for low-energy electron neutrinos in environments dominated by the electron antineutrinos, such as nuclear reactors.

Neutral-current and charged-current cross sections leading to low-lying states in ^{13}C and ^{13}N are evaluated with SFO[4]. The cross sections to excite $3/2^-_1$ states in ^{13}C and ^{13}N induced by GT transitions are found to be enhanced compared to those obtained by the Cohen-Kurath interaction as shwon in figure 2[20]. Calculated cross sections for solar ^{8}B neutrinos are compared in table 1.

Partial cross sections for γ and particle emission channels are evaluated by statistical Hauser-Feshbach method to estimate the count rate for the measurement of γ-rays from the daughter states of the reactions. The partial cross sections for the neutral-current reaction are shown in figure 2. The detection of reactor antineutrinos would be accessible by the measurement of γ's in the neutral-current reaction.

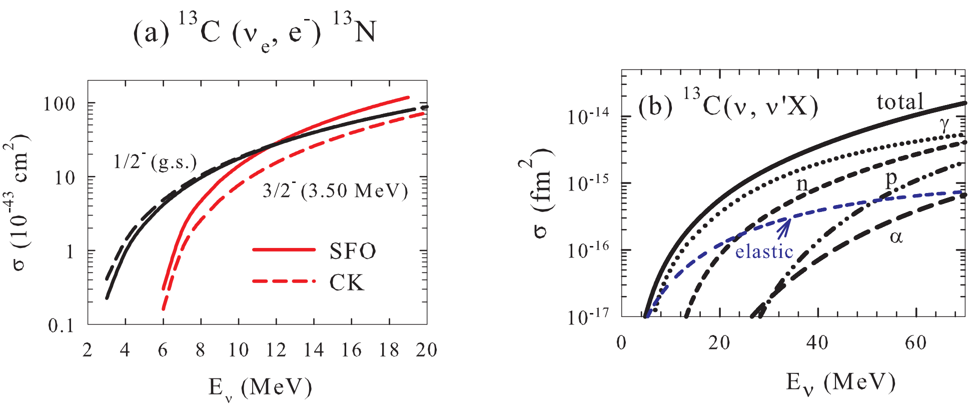

Figure 2. (a) Reaction cross sections for ^{13}C (ν_e, e$^-$) ^{13}N leading to $1/2^-_{g.s.}$ and $3/2^-$ (3.50 MeV) states. Results for SFO and CK are compared. (b) Partial cross sections for ^{13}C (ν, ν'X) for particle and γ emission channels as well as the elastic scattering obtained with SFO.

3 ν-induced reactions on ^{56}Fe and ^{56}Ni

3.1 Charged-current reaction on ^{56}Fe

A new shell-model Hamiltonian in pf-shell, GXPF1J[6], can describe well the spin responses in pf-shell nuclei. GT strengths in Fe and Ni isotopes and magnetic dipole transition strengths in ^{48}Ca, ^{50}Ti, ^{52}Cr and ^{54}Fe are well reproduced with GXPF1J with a universal quenching factor of g_A^{eff}/g_A =0.74 and g_s^{eff}/g_s =0.75.

Charged-current reaction on ^{56}Fe, ^{56}Fe (ν_e, e$^-$) ^{56}Co, induced by DAR neutrinos is investigated. The iron target is one of few examples where experimental data are available. Calculated cross section obtained by shell-model with GXPF1J for the GT and IA transitionis and RPA for other multipoles is $\sigma = 259\times10^{-42}$ cm^2, which is close to the experimental value; $\sigma = 256\pm108\pm43\times10^{-42}$ cm^2 [21]. We can now evaluate neutrino-nucleus reaction cross sections on ^{56}Fe accurately with the use of the new shell-model Hamiltonian. Calculated cross sections by various methods, SM+RPA, RPA and QRPA, result in an averaged value of $\sigma = 258\pm57\times10^{-42}$ cm^2[7].

3.2 GT strength in ^{56}Ni and nuclear weak processes in stars

We discuss GT strength in ^{56}Ni and possible implications on nucleosynthesis of medium-mass elements. The GT strengths in Ni and Fe isotopes obtained by GXPF1J are generally more fragmented compared with those given by KB3G Hamiltonian[22]. In particular, the GT strength in ^{56}Ni has two-peak structure for GXPF1J while it has a single peak for KB3G as shwon in figure 3. Larger fragmentation of the GT strength in ^{56}Ni for GXPF1J comes from a larger single-particle energy gap between $0f_{5/2}$ and $0f_{7/2}$ orbits and a larger T=0 pairing strength for GXPF1J. Recent (p, n) experiment confirmed the two-peak structure of the GT strength in ^{56}Ni[9].

This feature leads to smaller e-capture rates due to a smaller amount of the strength in the lower excited energy region. The e-capture rates obtained with GXPF1J, KB3G and experimental GT strength are shown in figure 3 at stellar environments[23]. The rates are smaller for GXPF1J at high densities (ρY_e = 10^7-10^9 with Y_e the lepton to baryon ratio) and high temperatures (T =T_9 $\times 10^9$ K) as shown in figure 3. The GXPF1J reproduces fairly well the rates for the experimental strength. Smaller e-capture rates on ^{56}Ni leads to less neutron fraction in hadrons, which might help to solve the over-production problem of neutron-rich isotopes such as ^{58}Ni[24].

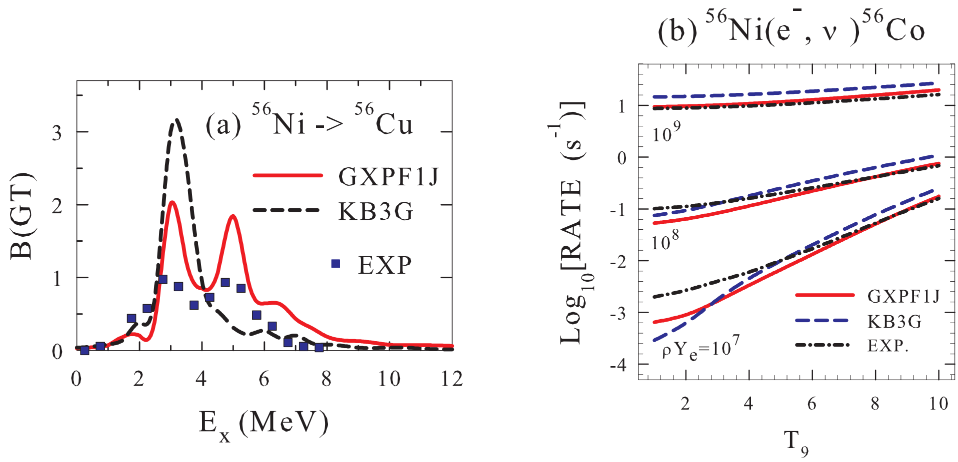

Figure 3. (a) GT strength in ^{56}Ni for GXPF1J and KB3G. Experimental data are taken from Ref. [9]. (b) Electron capture rates on ^{56}Ni obtained by GXPF1J and KB3G as well as with experimental GT strength[23].

A larger amount of the GT strength at higher excitation energy, on the other hand, leads to an enhancement of the proton-emission cross section, ^{56}Ni (ν, ν' p) ^{55}Co. This enhancement results in an enhancement of the production yield of ^{55}Mn through two successive e-capture reactions on ^{55}Co in population III stars (see Ref. [8] for the details).

4 ν-induced reactions on ^{40}Ar

4.1 Monopole-based universal interaction and GT strength in ^{40}Ar

A liquid argon detector is an excellent powerful tool to detect core-collapse supernova neutrinos. Here, we study charged-current ν-induced reactions on ^{40}Ar at solar and supernova neutrino energies. Direct measurement of the charged-current reaction cross sections are accessible by using a liquid argon time projection chamber (TPC) detector and a spallation neutron source for neutrinos.

We study GT transition strength in ^{40}Ar by shell-model calculations. The SDPF-M[25] and GXPF1J[6] interactions are used for *sd*-shell and *pf*-shell, respectively. The monopole-based universal interaction (VMU)[10], which has the tensor components of π+ρ meson exchanges, is adopted for the *sd*-*pf* cross-shell part. The bare tensor force due to π+ρ meson exchanges has been shown to be little modified by the renormalization procedures for both the short-range correlation and core-polarization corrections[10]. A proper inclusion of the tensor force is essential for successful description of spin-dependent modes in nuclei. The use of VMU in the *p*-*sd* cross shell part of the interaction proved to be successful in the spin modes in *p-sd* shell nuclei[26]. The two-body spin-orbit interaction due to σ, ω and ρ meson exchanges is also added to the cross-shell part of the interaction. The interaction thus made will be referred to "SDPF-VMU" hereafter.

Calculated cumulative sum of $B(GT)$ are shown in figure 4. Calculated values obtained by previous calculation[27] and WBT[15] as well as experimental data from (p, n) reaction[28] are also presented. Here a quenching factor of g_A^{eff}/g_A =0.775[27] is used with configurations within $2\hbar\omega$ excitations, $(sd)^{-2}$-$(pf)^2$. The experimental $B(GT)$ and the cumulative sum of $B(GT)$ are rather well described by SDPF-VMU while the strength in Ref. [27] is smaller than the observed strength. The GT strength by WBT also becomes smaller than the experimental values at larger excitation energies.

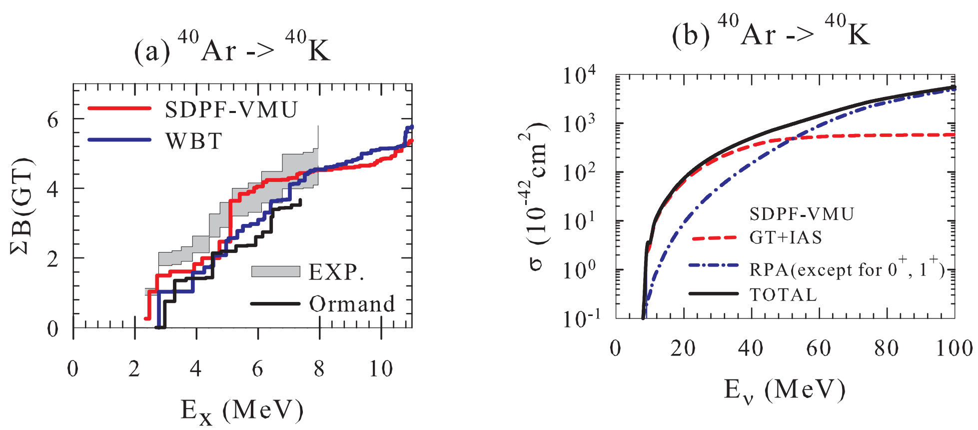

Figure 4. (a) Cumulative sum of $B(GT)$ for ^{40}Ar obtained with SDPF-VMU and WBT. Experimental data are taken from Ref. [28]. Results of Ref. [27] are also shown. (b) Reaction cross section for ^{40}Ar (ν_e, e^-) ^{40}K obtained with SDPF-VMU for the GT and IA transitions[11]. The other multipole contributions are obtained by RPA method.

4.2 Charged-current reaction on ^{40}Ar

Charged-current reaction cross sections for ^{40}Ar (ν_e, e^-) ^{40}K are evaluated by shell-model calculations with SDPF-VMU for the GT (1^+) and isobaric-analog (0^+) transitions. Cross sections for other multipoles are obtained by RPA method as they can not be evaluated accurately by shell-model calculations with the present restricted configuration space. The contributions from spin-dipole transitions and multipoles other than 0^+ and 1^+ are found to become dominant at $E_\nu > 50$ MeV. The calculated total cross section obtained here is found to be rather close to that in Ref. [29] obtained by RPA calculations for all the multipoles. The GT part of the present result is enhanced by about 20-40 % compared to that in Ref. [29].

Cross sections for ^{40}Ar (ν_e, e^-) ^{40}K folded over ^{8}B neutrino spectrum are shown in table 2. The cross section for the GT transition is enhanced for SDPF-VMU compared to that of Ref. [27] by about 55 %. Note that Ref. [27] include only dominant components (see Ref. [11] for the details).

Table 2. Calculated cross sections for ^{40}Ar (ν_e, e$^-$) ^{40}K induced by solar ^{8}B neutrinos for SDPF-VMU as well as for Ref. [27]. Values are given in units of 10^{-43} cm^2.

Hamiltonian	GT	IA	GT + IA
SDPF-VMU	11.95	2.10	14.05
Ref. [27]	7.70	3.80	11.50

5 Summary

New neutrino-nucleus cross sections are obtained based on new shell-model Hamiltonians with proper tensor interactions. New Hamiltonians, SFO and GXPF1J, are used for the shell-model calculations of p-shell and pf-shell nuclei, respectively. A monopole-based universal interaction, VMU, is used to obtain the sd-pf cross-shell matrix elements. Experimental cross sections for ^{12}C (ν, e$^-$) ^{12}N, ^{12}C (ν, ν') ^{12}C and ^{56}Fe (ν, e$^-$) ^{56}Co induced by DAR neutrinos are found to be well reproduced with the new Hamiltonians.

Nucleosynthesis of light elements in supernova exolosions is studied using new neutrino-nucleus cross sections on ^{12}C as well as ^{4}He. The enhancement of the abundances of ^{7}Li and ^{11}B is found compared with previous evaluations. The effects of MSW ν-oscillations on the abundance ratio of ^{7}Li/^{11}B are investigated. The ratio is found to be sensitive to the oscillation angle θ_{13} and the ν mass hierarchy. A recent study on supernova grains suggests that the inverted mass hierarchy is statistically more favored.

New ν capture cross sections on ^{13}C are obtained by shell-model calculations with SFO. Charged and neutral-current reaction cross sections leading to low-lying states in ^{13}N and ^{13}C are evaluated. The enhancement of the cross sections in GT transitions as well as for solar ^{8}B neutrinos are found compared with previous calculations with Cohen-Kurath. ^{13}C is pointed out to be an attractive target for the detection of very low energy neutrinos. It would help detection of low energy reactor anti-ν by neutral-current reactions and neutrinos in reactor anti-ν environment by charged-current reactions.

The GT strength in ^{56}Ni obtained by GXPF1J has two-peak structure, which has been confirmed by observation. Accurate evaluations of e-capture rates at stellar environments become possible, and hence it is expected to make more reliable estimations of element synthesis such as isotope abundance ratios in Ni isotopes. A larger GT strength ^{56}Ni at higher excitation energy region is found to lead to larger proton emission cross sections for ^{56}Ni and production of more ^{55}Mn in supernova explosions.

The VMU is used to evaluate GT strength in ^{40}Ar. The GT strength and the cumulative sum of $B(GT)$ in ^{40}Ar obtained with VMU are found to be consistent with the experimental data. New charged-current reaction cross sections on ^{40}Ar are obtained with VMU. The cross section induced by solar ^{8}B neutrinos is found to be enhanced compared with previous calculations.

We have shown that we can now evaluate ν-induced reaction cross sections such as on ^{12}C and ^{56}Fe accurately with the use of new shell-model Hamiltonians. We can, thus, discuss nucleosynthesis in stars, ν-oscillation parameters, and detection of solar, reactor and supernova neutrinos with more accuracies and reliabilities. We hope to have further progress in this direction in near future.

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