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 $\nu$-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, $\nu$-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 interactions is that they have proper tensor components.

A new shell-model Hamiltonian for $p$-shell nuclei, SFO\textsuperscript{1}, is used to evaluate $\nu$-$^{12}$C and $\nu$-$^{13}$C cross sections\textsuperscript{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\textsuperscript{3, 5}. $^{13}$C is shown to be an attractive target for detecting very low-energy neutrinos below 13 MeV with scintillator based experiments\textsuperscript{4}.

A new shell-model Hamiltonian for $pf$-shell nuclei, GXPF1J\textsuperscript{6}, is shown to reproduce $\nu$-$^{56}$Fe cross section for DAR neutrinos\textsuperscript{7}. It describes also well the Gamow-Teller (GT) strengths in Ni isotopes, in particular $^{56}$Ni\textsuperscript{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\textsuperscript{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\cite{10}, which has tensor components of $\pi + \rho$ meson exchanges. GT strength in $^{40}$Ar and the charged-current reaction, $^{40}$Ar ($\nu_e, e^-$) $^{40}$K, are evaluated \cite{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 $\nu$-induced reactions on $^{12}$C and $^{13}$C

2.1 $\nu$-induced reactions on $^{12}$C and synthesis of light elements

We constructed a new shell-model Hamiltonian, SFO\cite{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\cite{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 $\nu$-induced reaction cross sections at DAR energies. The cross sections for the exclusive charged-current reaction, $^{12}$C ($\nu_e, e^-$) $^{12}$N ($^1g.s.$), obtained by SFO and CK-MK (PSDMK2\cite{13}) are shown in figure 1 and compared with the experimental data\cite{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\cite{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\cite{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\cite{15}. Calculated results are compared with previous calculations\cite{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\cite{16}.

2.2 Effects of $\nu$-oscillation and $\nu$-mass hierarchy

The effects of matter $\nu$-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 hierarchy. When there is $\nu$-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 $\theta_{13}$. The dependence of the abundance ratio on $\theta_{13}$ is shown in figure 1 for both the normal and inverted 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\cite{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\cite{18}. Using Bayesian analysis, the inverted mass hierarchy is found to be statistically more favored with a probability of 74%\cite{19}.
Figure 1. (a) Exclusive charged-current reaction cross sections on $^{12}\text{C}$ induced by DAR neutrinos obtained for SFO and PSDMK2. Experimental values (LSND) are taken from Ref. [14]. (b) Dependence of the abundance ratio $^{7}\text{Li}/^{11}\text{B}$ on the mixing angle $\theta_{13}$ for normal and inverted $\nu$ mass hierarchies obtained with SFO-WBP Hamiltonian set and HW92 cases[5].

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

| Reaction | CK   | SFO   |
|----------|------|-------|
| $^{13}\text{C}(\nu_e, e^-)^{13}\text{N}(1/2_g^+, 3/2^- (3.50\text{MeV}))$ | 10.7 | 13.4  |
| $^{13}\text{C}(\nu, \nu')^{13}\text{C}(3/2^-, 3.69\text{MeV})$       | 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 $\nu$-induced reactions on $^{13}\text{C}$

$^{13}\text{C}$ is an attractive target for very low energy neutrinos below $E_\nu=13\text{MeV}$ as $^{12}\text{C}$ can be excited only above $E_\nu=13\text{MeV}$ and there is no sufferering from the contamination of $^{12}\text{C}$. A knowledge of cross sections leading to various states in $^{13}\text{N}$ and $^{13}\text{C}$ 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 $^{13}\text{C}$ and $^{13}\text{N}$ are evaluated with SFO[4]. The cross sections to excite $3/2^-_1$ states in $^{13}\text{C}$ and $^{13}\text{N}$ 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 $^{8}\text{B}$ neutrinos are compared in table 1.

Partial cross sections for $\gamma$ and particle emission channels are evaluated by statistical Hauser-Feshbach method to estimate the count rate for the measurement of $\gamma$-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 $\gamma$’s in the neutral-current reaction.
Figure 2. (a) Reaction cross sections for $^{13}\text{C} (\nu_e, e^-) ^{13}\text{N}$ leading to $1/2^-$, and $3/2^-$ (3.50 MeV) states. Results for SFO and CK are compared. (b) Partial cross sections for $^{13}\text{C} (\nu, \nu'X)$ for particle and $\gamma$ emission channels as well as the elastic scattering obtained with SFO.

3 $\nu$-induced reactions on $^{56}\text{Fe}$ and $^{56}\text{Ni}$

3.1 Charged-current reaction on $^{56}\text{Fe}$

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 $^{48}\text{Ca}$, $^{50}\text{Ti}$, $^{52}\text{Cr}$ and $^{54}\text{Fe}$ 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 $^{56}\text{Fe}$, $^{56}\text{Fe} (\nu_e, e^-) ^{56}\text{Co}$, 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 $\sigma = 259 \times 10^{-42}$ cm$^2$, which is close to the experimental value; $\sigma = 256 \pm 108 \pm 43 \times 10^{-42}$ cm$^2$ [21]. We can now evaluate neutrino-nucleus reaction cross sections on $^{56}\text{Fe}$ 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 $\sigma = 258 \pm 57 \times 10^{-42}$ cm$^2$[7].

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

We discuss GT strength in $^{56}\text{Ni}$ 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 $^{56}\text{Ni}$ 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 $^{56}\text{Ni}$ 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 $^{56}\text{Ni}$[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 ($\rho Y_e = 10^7-10^9$ 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 ($\nu, \nu'$ 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 $\nu$-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 $\nu$-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 $\pi+\rho$ meson exchanges, is adopted for the $sd$-$pf$ cross-shell part. The bare tensor force due to $\pi+\rho$ 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

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proved to be successful in the spin modes in $p$-$sd$ shell nuclei[26]. The two-body spin-orbit interac-
tion due to $\sigma$, $\omega$ and $\rho$ 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 pre-
vious calculation[27] and WBT[15] as well as experimental data from (p, n) reaction[28] are also
presented. Here a quenching factor of $g_{eff} / g_A = 0.775$[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 ($\nu_e, e^-)$ $^{40}$K
obtained with SDPF-VMU for the GT and IA transitions[11]. The other multipole contributions are obtained by
RPA method.](image)

### 4.2 Charged-current reaction on $^{40}$Ar

Charged-current reaction cross sections for $^{40}$Ar ($\nu_e, e^-)$ $^{40}$K are evaluated by shell-model calcula-
tions 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 calcula-
tions 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 ($\nu_e, e^-)$ $^{40}$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 ($\nu_e$, 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 $p_f$-shell nuclei, respectively. A monopole-based universal interaction, VMU, is used to obtain the $sd$-$p_f$ cross-shell matrix elements. Experimental cross sections for $^{12}$C ($\nu$, e$^-$) $^{12}$N, $^{12}$C ($\nu$, $\nu'$) $^{12}$C and $^{56}$Fe ($\nu$, e$^-$) $^{56}$Co induced by DAR neutrinos are found to be well reproduced with the new Hamiltonians.

Nucleosynthesis of light elements in supernova explosions 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 $\nu$-oscillations on the abundance ratio of $^7$Li/$^{11}$B are investigated. The ratio is found to be sensitive to the oscillation angle $\theta_{13}$ and the $\nu$ mass hierarchy. A recent study on supernova grains suggests that the inverted mass hierarchy is statistically more favored.

New $\nu$ 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-$\nu$ by neutral-current reactions and neutrinos in reactor anti-$\nu$ 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 $\nu$-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, $\nu$-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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