Neutrino-Nucleus Reactions based on Recent Structure Studies

Toshio Suzuki
Nihon University

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New shell-model Hamiltonians and successful description of Gamow-Teller (GT) and spin-dipole (SD) strengths

SFO (p-shell): GT in $^{12}$C, $^{14}$C
GXPF1J (fp-shell): GT in Ni isotopes
  Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)
  Suzuki, Honma et al., PR C79, (2009)
VMU (monopole-based universal interaction)

* important roles of tensor force

- $\nu^{12}$C and $\nu^{13}$C with SFO
- $\nu^{56}$Ni and e-captures on Ni isotopes with GXPF1J
- $^{40}$Ar ($\nu$, e$^-$) $^{40}$K with VMU
Shell-model interactions

- Phenomenological interaction
  single particle energies + fitted two-body matrix elements
  e.g. p-shell: Cohen-Kurath (1965), sd: USD (1988)
  p-sd: Millener-Kurath (1975)

- Microscopic interaction derived from NN interaction
  1. Renormalization of repulsive core part of NN interaction

  G-matrix:

  \[
  \begin{array}{c}
  \text{sum of ladders} \\
  \end{array}
  \]

  \( V_{\text{low-k}} \): integrating out high momentum components of two-nucleon interaction

  2. Effective interaction of truncated model space

  core-polarization effects

  \(+ 3^{\text{rd}} \text{order} \)
Good energy levels except for a few cases:
e.g. closed-shell structure of $^{48}$Ca can not be obtained
(3N forces can solve the problem)
Problems in saturation (binding energies)

• Improvements of G-matrix by monopole corrections

**Monopole terms**

$$V_M^T (j_1j_2) = \frac{\sum_J (2J + 1) < j_1j_2; JT | V | j_1j_2; JT >}{\sum_J (2J + 1)}$$

Effective single-particle energy:

$$E_{eff} (vj) = \varepsilon(vj) + \sum_j n(vj')V_{M}^{T=1} (j, j') + \sum_j n(\pi j')V_{M}^{np} (j, j')$$

$$\varepsilon(vj) = \text{s.p.e for the core}$$

* New phenom. interactions with monopole corrections

sd-pf: SDPF-M (1999)* → successful descriptions of
pf: KB3 (2001)*, GXPF1 (2004)* energies and transitions
Monopoles: G-matrix vs phenom. interactions

tensor force: $\pi + \rho$ -exchange

more repulsion than G in $T=1$

Three-body force

more attraction than G in $T=0$
Important roles of tensor force

- SFO: p-shell p-sd space up to 2-3 hw excitations

→ Enhancement of spin-isospin channel of monopole terms

Monopole terms p1/2-p3/2 (T=0) is enhanced

\[
V_M^T (j_1, j_2) = \frac{\sum_j (2J + 1) < j_1 j_2; JT | V | j_1 j_2; JT >}{\sum_j (2J + 1)}
\]

Shell evolution in N=8 isotones
GT strengths in $^{12}\text{C}$: reproduced with $g_A^{\text{eff}}/g_A = 0.95$

Nearly vanishing GT strength in $^{14}\text{C}$

**Nucleosynthesis processes of light elements**

$^{12}\text{C}(\nu, \nu'p)^{11}\text{B}$

$^{12}\text{C}(\nu, \nu'n)^{11}\text{C}$

Enhancement of $^{11}\text{B}$ and $^7\text{Li}$ abundances in supernova explosions
$^{13}\text{C}$: attractive target for very low energy $\nu$: $E_\nu < 15$ MeV

$\nu-^{12}\text{C}$: $E_\nu > 15$ MeV

$\nu$-induced reactions on $^{13}\text{C}$

$^{13}\text{C}(\nu_e, e^-)^{13}\text{N}$

$^{13}\text{C}(\nu_e, \nu_e')^{13}\text{C}$

GT transitions

Fukugita et al., PR C41 (1990)

$p$-shell: Cohen-Kurath

$g_A^{\text{eff}}/g_A = 0.69$

Detector for solar $\nu$
p-sd shell: SFO

Solar $\nu$ cross sections folded over $^8$B $\nu$ spectrum

$^1_3$C ($\nu$, $e^-$) $^{13}$N

$(\nu_e, e^-) \left[ \frac{1}{2} (\text{g.s.}) + \frac{3}{2} (3.50\text{MeV}) \right]$ 

CK: $1.07 \times 10^{-42}\text{cm}^2$

SFO: $1.34 \times 10^{-42}\text{cm}^2$

$(\nu, \nu') \frac{3}{2} (3.69\text{MeV})$

CK: $1.16 \times 10^{-43}\text{cm}^2$

SFO: $2.23 \times 10^{-43}\text{cm}^2$

Suzuki, Balantekin, Kajino, PR C (2012), in press.
New shell-model Hamiltonians in fp-shell:


KB3: Caurier et al, Rev. Mod. Phys. 77, 427 (2005)

- KB3G $A = 47$-$52$ KB + monopole corrections
- GXPF1 $A = 47$-$66$

Spin properties of fp-shell nuclei are well described

$B(GT^-)$ for $^{58}\text{Ni}$ $g_A^{\text{eff}}/g_A^{\text{free}} = 0.74$

M1 strength (GXPF1J)

$g_S^{\text{eff}}/g_S = 0.75 \pm 0.2$
$^{56}$Fe($\nu_e,e^-$) $^{56}$Co

RQRPA vs Shell-model

$\langle \sigma \rangle_{\text{th}} = (258 \pm 57) \times 10^{-42} \text{ cm}^2$

$\langle \sigma \rangle_{\text{exp}} = (256 \pm 108 \pm 43) \times 10^{-42} \text{ cm}^2$

N. Paar, T. Suzuki, M. Honma, T. Marketin, and D. Vretenar

PHYSICAL REVIEW C 84, 047305 (2011)
$f_7/2 \rightarrow f_7/2$

$e$-capture rates in stellar environments

$56\text{Ni}(e^-, \nu)56\text{Co}$

$\rho Y_e = 10^7 - 10^{10} \text{ g/cm}^3$

$T = T_9 \times 10^9 \text{K}$
$^{58}\text{Ni} \rightarrow ^{58}\text{Co}$


$^{60}\text{Ni} \rightarrow ^{60}\text{Co}$

Exp: Anantaraman et al., PR C78 (2008)
Type-Ia supernova explosion

Accretion of matter to white-dwarf from binary star → supernova explosion when white-dwarf mass is over Chandrasekhar limit
→ $^{56}\text{Ni}$ (N=Z)
→ $^{56}\text{Ni} (e^-, \nu) ^{56}\text{Co} \quad Y_e = 0.5 \rightarrow Y_e < 0.5$ (neutron-rich)
→ production of neutron-rich isotopes; more $^{58}\text{Ni}$

Decrease of e-capture rate on $^{56}\text{Ni} \rightarrow$ less production of $^{58}\text{Ni}$.

Problem of large $^{58}\text{Ni}/^{56}\text{Ni}$ ratio in previous calculations can be solved

Famiano
Neutral current reaction on $^{56}\text{Ni}$

- $B(\text{GT})=6.2$ (GXPF1J)
- $B(\text{GT})=5.4$ (KB3G)

**Figure (a):**
- $^{56}\text{Ni}$
- $GT_0$
- $B(\text{GT})$ comparison between GXPF1J and KB3G

**Figure (b):**
- $^{56}\text{Ni}$ ($\nu$, $\nu'$) $^{56}\text{Ni}$
- $\sigma$ vs. $T_\nu (\text{MeV})$ for various reactions:
  - $p$ (gamma, black square)
  - $n$ (yellow diamond)
- Models:
  - GXPF1J+SGII
  - GXPF1J(GT)
  - Kolbe-Langanke
  - Woosley et al.

**Figure (c):**
- Energy vs. $T_\nu (\text{MeV})$ for various reactions:
- Reactions include:
  - $p^{55}\text{Co}$
  - $n^{55}\text{Ni}$
  - $\alpha^{52}\text{Fe}$
  - $\alpha^{48}\text{Cr}$
  - $\alpha^{51}\text{Fe}$
  - $nn^{54}\text{Ni}$
  - $\nu^{56}\text{Ni}$

**Notes:**
- HW02
- $1^+ s$
- $1^+ f$
- $3/2^-$
- $7/2^-$
- $0^+$
Synthesis of Mn in Population III Star

$^{56}\text{Ni}(\nu, \nu'p)^{55}\text{Co}, \quad ^{55}\text{Co}(e^-, \nu)^{55}\text{Fe}(e^-, \nu)^{55}\text{Mn}$

$^{54}\text{Fe}(p, \gamma)^{55}\text{Co}$

Yoshida, Umeda, Nomoto

Suzuki et al.,
PR C79 (2009)

OBS: Cayrel et al.,

$^{59}\text{Co}, \quad ^{58}\text{Ni}(p, \gamma)^{59}\text{Cu}(e^-, \nu)^{59}\text{Ni}(e^-, \nu)^{59}\text{Co}$
VMU = Monopole based Universal Interaction

Monopole terms in $V_{nn}$

$$V_{MU} = \text{Monopole based Universal Interaction}$$

$$V_M^T (j_1 j_2) = \sum_J \frac{(2J+1) < j_1 j_2 ; JT | V | j_1 j_2 ; JT >}{\sum_J (2J+1)}$$

- Important roles of tensor force

Otsuka, Suzuki, Honma, Utsuno, Tsunoda, Tsukiyama, Hjorth-Jensen
PRL 104 (2010) 012501
Tensor: bare $\approx$ renormalized

Tensor force $\rightarrow$ proper shell evolutions toward drip-lines
p-sd shell: VMU for p-sd,
Yuan, Suzuki, Otsuka, Xu, Tsunoda, PR C85, 064324 (2012).

p: SFO
sd: SDPF-M (Utsuno)
p-sd: VMU tensor = $\pi+\rho$,
2-body LS = $\sigma+\rho+\omega$ (M3Y)
central = renormalized VMU
$^{40}$Ar ($\nu$, e$^-$) $^{40}$K

SDPF-VMU-LS

sd: SDPF-M  (Utsuno et al.)
fp: GXPF1   (Honma et al.)

sd-pf:  VMU + LS

$(sd)^{-2} (fp)^2 : 2hw$

B(GT)

$\nu$-$^{40}$Ar cross sections

Solar $\nu$ cross sections  folded over $^8B$ $\nu$ spectrum

$B(GT) = \Sigma |<f||f_q \sigma_t||i>|^2$  \(f_q = 0.775\) (Ormand et al.)
(p,n) Bhattacharyya et al., PR C80 (2009)
$^{40}\text{Ar} \rightarrow ^{40}\text{K}$

$^{40}\text{Ar} (\nu, e^-)^{40}\text{K}$

**GT+IAS**

$E_e > 5 \text{ MeV} : \text{ICARUS}$

Solar $\nu$ cross sections folded over $^8\text{B} \nu$ spectrum

- **GT:** $E_1^5 + \text{M1} + C_1^5 + L_1^5$
- **IAS:** $C_0 + L_0 \approx [(q^2 - \omega^2)/q^2]^2 \times C$
- $^+ C_0$ only
- $^+ E_1^5$ only


**(p,n)** Bhattacharya et al., PR C80, 055501 (2009)
$^{40}\text{Ar} \rightarrow ^{40}\text{K}$

<table>
<thead>
<tr>
<th>$\sigma$ ($10^{-42} \text{cm}^2$)</th>
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<tr>
<td>3000</td>
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<td>2000</td>
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<tr>
<td>1000</td>
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<td>0</td>
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$E_x$ (MeV)

- SDPF-VMU-LS (GT+IAS)
- RPA (except for $0^+$, $1^+$)
- TOTAL
- GT

Figure 4: $\nu_e$ CC cross section as a function of the neutrino energy. The dashed line corresponds to the Ormand [21] cross section calculation, dotted line assumes that the total cross section of the absorption interaction is 3 times the cross section of the Fermi transition [16] and the solid line is the cross section used in this analysis calculated from RPA including all the transitions [20].


Cheoun, Ha and Kajino, PR C83, 028801 (2011)
Neutral-current reactions

$^{40}\text{Ar} \rightarrow ^{40}\text{Ar}$

Cheoun, Ha and Kajino, PR C83, 028801 (2011)

Martinez-Pinedo, Kolbe, Langanke
$B(M1) = 0.148(59) \mu_N^2$

Li et al, PR C73, 054306 (2006)
Summary

New $\nu$ –induced cross sections based on new shell-model Hamiltonians with proper tensor forces

- New $\nu$ capture cross sections on $^{13}$C by SFO in p-sd shell
  Enhanced solar $\nu$ cross sections compared to Cohen-Kurath (p shell)

- New $\nu$-induced cross sections on $^{16}$O by SFO-tls
  Energies of spin-dipole states are well reproduced.
  Enhanced cross sections compared with SFO and CRPA
• A new shell model Hamiltonian GXPF1J well describes the spin responses in fp-shell nuclei → New GT strengths in Ni isotopes which reproduce recent experimental data, and more accurate evaluation of e-capture rates at stellar environments.

• New ν-nucleus reaction cross sections in $^{56}$Ni → Enhancement of p-emission channel in $^{56}$Ni and production rates of Mn and Co in supernova explosions

  Suzuki, Honma et al., PR C79, 061603(R) (2009)

• sd-pf-VMU: GT strength consistent with (p, n) reaction → New cross section for $^{40}$Ar (ν,e$^-$) $^{40}$K induced by solar ν
Collaborators

M. Honma\textsuperscript{a}, T. Yoshida\textsuperscript{b},
S. Chiba\textsuperscript{c}, K. Higashiyama\textsuperscript{d}
T. Kajino\textsuperscript{b,e}, B. Balantekin\textsuperscript{f}
T. Otsuka\textsuperscript{g}

\textsuperscript{a}University of Aizu
\textsuperscript{b}Department of Astronomy, University of Tokyo
\textsuperscript{c}Tokyo Institute of Technology
\textsuperscript{d}Chiba Institute of Technology
\textsuperscript{e}National Astronomical Observatory of Japan
\textsuperscript{f}Univ. of Wisconsin
\textsuperscript{g}Department of Physics and CNS, University of Tokyo