Experimental studies of neutrino nuclear responses and nuclear structures for neutrino nuclear physics

Hiroyasu Ejiri
Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, Japan
E-mail: ejiri@rcnp.osaka-u.ac.jp

Abstract. Neutrino nuclear responses associated with astro neutrinos and double beta decays are crucial to extract neutrino properties of astro particle physics interests. The present report reviews briefly recent experimental studies of the neutrino nuclear responses. Single beta decays and electron captures, charge exchange nuclear reactions, muon and photon nuclear reactions, neutrino nuclear reactions and nucleon transfer reactions are used to study neutrino nuclear responses. Discussions are made on nucleonic and nonnucleonic spin isospin correlations and renormalization (quenching) effects on axial weak responses.

1. Introduction
Neutrino is a key particle for astro nuclear physics, particle physics and cosmology. It is the elementally particle that has only the weak charge, and has no electric and color charges. Neutrino interactions with nuclei are so weak that experimental studies of the neutrino and the weak interaction are very hard.

Several basic questions on the neutrino remain yet unsolved. Some of them are i the nature of the neutrino if it is the Majorara or the Dirac particle, ii the absolute mass scale and the mass hierarchy (spectrum), iii the lepton sector CP phases, iv solar neutrino sources and the fluxes, and iv supernova neutrino fluxes, spectra and nucleosyntheses.

These questions are studied well also by investigating neutrino weak processes in nuclei such as neutrino nuclear interactions, single beta decays (SBD) and electro captures (EC), inverse beta decays (IBD) induced by neutrinos and neutrino-less double beta decays (DBDs). The neutrino nuclear responses are crucial for the SBD/EC, IBD and DBD neutrino studies in nuclei. Historical reviews and previous works on the neutrino nuclear responses are given in reviews [1, 2] and references therein.

The present report reviews briefly recent experimental studies of the neutrino nuclear responses. The details of the review on neutrino nuclear responses for astro neutrino interactions and double beta decays will be given elsewhere [3]. The astro neutrino, DBD, SBD/EC and IBD processes are schematically shown in Figure 1. Astro neutrino interactions are studied by measuring astro neutrino interactions in nuclei. The interaction (IBD) rate \( R(\alpha) \) with \( \alpha \) being the interaction mode is expressed as

\[
R(\nu)(\alpha) = g^2 G_\nu B(\nu) I(\nu) = (2J_i + 1)^{-1} |M_\nu|^2,
\]

where \( g \) is the weak coupling constant, \( G_\nu \) is the phase space (kinematic) factor, and \( I(\nu) \) is
the astro neutrino flux. The nuclear response \( B(\nu) \) is given by the square of the nuclear matrix element \( (\text{NME} \; M^\nu) \) with \( 2J_i+1 \) being the initial state spin factor.

\[ \text{Figure 1.} \quad \text{Schematic neutrino CC interactions and transition processes in nuclear femto laboratories for IBD, SBD and DBD.} \quad p: \text{proton}, \; n: \text{neutron}, \; e: \text{electron}, \; \nu \text{ and } \bar{\nu}: \text{neutrino and anti neutrino}, \; E: \text{excitation energy}, \; B_i(\alpha): \text{nuclear response.} \]

The neutrino-less DBD rate for the neutrino mass mechanism is expressed as

\[ R(0\nu) = g_4^4 G^{0\nu} B(0\nu)(m^{eff})^2 \quad B(0\nu) = (2J_i + 1)^{-1}|M^{0\nu}|^2, \tag{2} \]

where \( G^{0\nu} \) is the phase space (kinematic) factor and \( m^{eff} \) is the effective mass. The nuclear response \( B(0\nu) \) is given by the square of the DBD NME \( M^{0\nu} \) with \( 2J_i + 1 \) being the initial state spin factor. The energy sum of the DBD electrons is given by the DBD Q value.

2. Experimental probes for neutrino nuclear responses

Neutrino nuclear responses are neutral current (NC) and charged current (CC) weak responses for nucleons (neutron and proton) in the nucleus. The \( Z \) and \( W^\pm \) weak bosons are involved in the NC and CC interactions, respectively. The weak responses with weak couplings of \( g_A \) and \( g_V \) for astro neutrinos and DBD neutrinos are very sensitive to nucleonic and non-nucleonic correlations. Therefore they have been studied experimentally by using various kinds of weak, electro magnetic and nuclear probes to help theoretical evaluations for the responses and the NMEs. They are schematically shown in Figure 2.

The weak processes with astro \( \nu \) and \( \bar{\nu} \) are \( \frac{3}{2}X + \nu \rightarrow \frac{1}{2}X' + \nu \), \( \frac{3}{2}X + \bar{\nu} \rightarrow \frac{1}{2}X' + \bar{\nu} \) for NC process, and \( \frac{3}{2}X + \nu \rightarrow \frac{3}{2+1}X' + \beta^- \) and \( \frac{3}{2+1}X + \bar{\nu} \rightarrow \frac{3}{2}X' + \beta^+ \) for CC process. NC process is a nucleon excitation process of \( N \rightarrow N' \) with \( N \) and \( N' \) being nucleons in the nucleus, while CC is a charge exchange process of \( p \leftrightarrow n \) with \( p \) and \( n \) being proton and neutron in the nucleus.

The neutrino-less DBD process is \( \frac{1}{2}X \rightarrow \frac{3}{2}X + 2\beta^\pm \) with the two nucleon double charge exchange of \( (n_1, n_2) \leftrightarrow (p_1, p_2) \) in the nucleus. The nuclear response is given by the product of the initial spin factor \( 1/(2J_i + 1) \) and the square of the NME for \( (n_1, n_2) \leftrightarrow (p_1, p_2) \). Here the DBD NME is associated indirectly with the \( p_1 \leftrightarrow n_1 \) and the \( p_2 \leftrightarrow n_2 \) via the neutrino potential in case of the neutrino-less DBD \( (0\nu\beta\beta) \) and directly with them in case of the two neutrino DBD \( (2\nu\beta\beta) \).

The weak NMEs involved in the neutrino nuclear responses are essentially the NMEs for \( \frac{3}{2}X(N) \leftrightarrow \frac{3}{2}X'(N) \) and \( \frac{3}{2}X(n) \leftrightarrow \frac{3}{2+1}X(p) \) transitions via the NC and CC weak interaction.
operators. They are studied by using weak interaction probes and also by using electro magnetic (EM) probes with the interaction operators similar to the weak interaction ones as discussed in [4, 5, 6].

![Figure 2. Experimental probes for neutrino nuclear responses. A: leptons with weak interaction. B: photons with EM interaction. C: nuclei with strong/nuclear interaction. p: proton, n: neutron, e: electron, W: weak boson, γ: gamma ray, and πρ: mesons.](image)

Weak interaction probes of $\nu$ and $\bar{\nu}$ beams are used to study directly the weak (neutrino) responses. The neutrino cross section, however, is extremely small because of the weak interaction. It is of the order of $10^{-40-44}$ cm$^2$. Then one needs high flux neutrinos of the order of $10^{13-15}$/sec and multi-ton scale detectors for the $\nu$ beam experiment in order to get adequate event rates. Medium energy neutrinos obtained from stopped $\pi$ decays are used to study the neutrino reactions. The intense GeV protons from SNS and J-PARC may be used to produce the intense pions [4, 7, 8].

SBDs ($\beta^\pm$) and ECs are used to get CC neutrino $n\leftrightarrow p$ responses. They are limited mostly to allowed and first forbidden transitions from the ground and isomeric states. SBD responses are given in review articles [1, 2]. Recently, K-forbidden SBD NMEs of astro nucleosynthesis interests are studied [9].

Negative muons trapped in atomic orbits are captured mostly into nucleus by the weak interaction in case of medium heavy nuclei with the atomic number $Z \geq 20$. Then the ordinary muon capture reaction of $^{2}_{Z}X + \mu \rightarrow ^{2}_{Z-1}X + \nu_{\mu}$ is used to study the anti neutrino $p\rightarrow n$ response in the medium energy (10-70 MeV) and momentum (10-70 MeV/c) regions. Recently the anti neutrino response on $^{100}$Mo was studied by measuring RIs from muon captures [10]. The response shows for the first time a $\mu$-capture giant resonance (GR) around 10-15 MeV [10].

Photons with EM interactions are used to study neutrino nuclear responses because EM interactions have similar spin isospin and multipole transition operators as the weak ones. The electric and magnetic transitions correspond to the vector and axial-vector weak transitions, respectively. In particular, photo nuclear reactions via IASs (Isobaric Analogue States) provide EM NMEs corresponding to the analogous $\beta^+ (\bar{\nu})$ NMEs [11].

Nuclear reactions with nuclear/strong interactions are very useful for studying neutrino nuclear responses because of the large reaction/interaction cross section. The nuclear (strong) interaction itself is quite different from the weak interaction, but the strong interaction includes the spin, isospin and multipole operators as the weak interaction. The spin-flip and spin non-flip inelastic scatterings of p,n,d, and light ions are used to study vector and axial vector NC responses, respectively. Charge exchange reactions (CERs) are used for the CC response study, (p,n), ($^{3}$He,t) and other CERs for (n$\rightarrow$p) responses and (n,p), (d,$^{2}$He), (t,$^{3}$He), (7Li,$^{7}$Be) and other CERs for p$\rightarrow$ n ones. They are discussed in review articles [2, 3].

High energy-resolution ($^{3}$He,t) CERs with the medium energy 0.42-0.45 GeV are used to study the n$\rightarrow$p axial vector responses because the spin isospin interaction gets predominant at this energy. Since both the projectile of $^{3}$He and the out-going particle of t are charged
particles, high precision energy-analyses of them are possible to perform high energy-resolution measurements required to separate individual states. The high energy-resolution system with the energy resolution of \(\Delta E / E \approx 10^{-5}\) at RCNP Osaka University has extensively been used to study neutrino nuclear responses [4, 5].

The \(^{\text{3}}\text{He},t\) CER on \(^{71}\text{Ga}\) was measured to study the solar neutrino responses. The measured responses for the low-lying states in \(^{71}\text{Ge}\) are found to be consistent with the calculated ones. This shows that the deviations of the measured neutrino capture rates from the estimations based on the calculated responses are not due to the responses, but something new (sterile neutrino)/unknown effects [12].

Spin dipole (SD 2\(^{-}\)) NMEs play major roles for neutrino-less DBD NMEs. They are for the first time studied by using the \(^{3}\text{He},t\) CERs on DBD nuclei [13]. The observed SD cross sections are shown to be consistent with the Fermi surface quasi particle model (FSQP) NMEs [14]. Thus it is shown that the SD NMEs are well studied by means of the \(^{3}\text{He},t\) CERs as GT NMEs.

Double charge exchange reactions (DCERs) are used to get strength distributions for DCER responses relevant to DBDs. The \(^{11}\text{B},^{11}\text{Li}\) DCER at \(E/A=80\) MeV shows that most double spin-isospin strengths are pushed up to the high excitation region, leaving little strengths at the low-lying states [15]. Heavy ion (HI) double CERs for low-lying states were studied [16, 17]. The NUMEN project there aims at extensive studies of DCERs for DBD neutrino nuclear responses.

Nucleon transfer reactions provide experimentally single quasi-particle properties of nucleons in the nucleus, which are used to help evaluate the neutrino nuclear responses [18]. The single particle and hole probabilities are smaller by a factor \(\approx 0.55\) than the shell model expectation [19], suggesting uniform reduction of the single nucleon nature in the nuclear medium.

3. Axial vector responses and quenching of the axial vector coupling

Experimental GT and SD NMEs \(M_{EX}(\alpha)\) derived from SBD/EC and CER data are uniformly reduced with respect to the single quasi-particle NMEs \(M_{QP}(\alpha)\) and pnQRPA NMEs \(M_{QR}(\alpha)\), where the transition modes are given by \(\alpha=\text{GT and SD}\) [1, 2, 20, 21]. They are expressed as

\[
M_{EX}(\alpha) = k(\alpha)M_{QP}(\alpha) = k_{NM}(\alpha)M_{QR}(\alpha), \quad M_{QR}(\alpha) = k_{r\sigma}(\alpha)M_{QP}(\alpha).
\]

Here the reduction coefficient \(k(\alpha)\approx 0.25\) is expressed as \(k(\alpha) = k_{r\sigma}(\alpha) \times k_{NM}(\alpha)\) with \(k_{r\sigma}(\alpha) \approx 0.4\) and \(k_{NM}(\alpha) \approx 0.6\) standing for the reduction coefficients due to the nucleonic \(\sigma\tau\) correlation and non-nucleonic (nuclear medium) effect, respectively [20, 21]. The nucleonic correlation is taken into accounts by the pnQRPA, while the \(\Delta\) isobar and other non-nucleonic correlation may be incorporated with the effective axial vector coupling \(g_A^{eff}/g_A \approx 0.6\).

Neutrino nuclear responses associated with medium energy supernova neutrinos and neutrino-less DBDs involve medium momentum and angular momentum transfers of \(q=20-200\) MeV/c and \(\hbar=1-5\hbar\). Nuclear and muon CERs provide opportunities to study neutrino nuclear responses in the wide momentum-transfer region. The \(^{3}\text{He},t\) CERs on DBD nuclei were measured for F(IAS \(0^+\)), GT(\(1^+\)) and SD(\(2^-\)) states in the wide angular range of \(\theta=0-4\) deg., corresponding to the momentum-transfer range of \(q=5-100\) MeV/c in order to study the momentum dependence of the neutrino nuclear responses. The \(q\) dependent cross section is expressed as

\[
\frac{d\sigma_q}{d\Omega} = K_q(\alpha)F_q(\alpha, q)J_q(\alpha)^2k^{eff}(q)^2B_q(\alpha),
\]

where \(K_q(\alpha)\) and \(J_q(\alpha)\) with \(\alpha=\text{F,G,T, SD}\) are the kinematic factor and the volume integral of the interaction, respectively, and \(B_q(\alpha)\) is the nuclear response at \(q=0\). The kinematic \(q\)-dependence is given by \(F_q(\alpha, q) \approx |J_q(qR)|^2\) and the \(q\) dependence of the nuclear response is by \(k^{eff}(q)^2\). The kinematic \(q\) dependence \(F_q(\alpha, q)\) is given by the DWBA (Distorted Wave Born Approximation) calculation, and the \(q\) dependent coupling \(k^{eff}(q)\) manifests as deviation
of the observed q (angular) distribution from the DWBA calculation. Actually, the observed q-dependence (angular distribution) is well reproduced by the constant $k_{eff}(q)^2$ as shown in Figure 3.

Figure 3. Momentum dependence of the $^{76}$Ge($^3$He,t) CER cross sections [22]. The ratio of $k_{eff}(q)/k_{eff}(q=0)$ for $\alpha$ = F (IAS), GT (1st GT), and SD (ground) states in $^{76}$Ge. The red point is the normalization point at $q=0$.

The ($^3$H,t) CER spectra for medium heavy nuclei show that i. the Fermi strength is concentrated in the sharp IAS (Fermi GR) and no other Fermi strengths are in the low excitation region, ii. the GT and SD strengths are mainly concentrated, respectively, in the broad GT and SD GRs, and thus some strengths are in the low excitation region. In other words, the IAS is a good eigen state because of the good isospin symmetry, while GT and SD GRs are kinds of quasi-eigen states because of the quasi (incomplete) spin-isospin (super-multiplet) symmetry.

Figure 4. Left hand side. Fermi (IAS), GT and SD GR energies in units of MeV for DBD nuclei as a function of $2T_z = N - Z$. Right hand side: Summed GT strengths, $\sum_L GT$ for the low-lying states (L) and the $\sum GT$ for all GT states (A) in units of the sum rule limit $B_S$ as a function of $2T_z = N - Z$. The GT GR tail at $E=3-4$ MeV in the $^{76}$Ge is corrected for. Ref. [3].

The Fermi, GT and SD GRs are expressed as coherent (in-phase) $\tau^-, \tau^-\sigma$ and $\tau^-\sigma rY_1$ excitations of the all neutron-hole proton-particle states, respectively. Their excitation energies are pushed up to the high excitation region due to the repulsive $\tau, \tau\sigma$ and $\tau\sigma rY_1$ interactions. The GR energies are shown as a function of $N - Z = 2T_z$ with $T_z$ being the isospin z component. The IAS, GT GR, and SD GR energies are expressed in units of MeV as

$$E(IAS) = 5 + 0.6T_z, \quad E(GT) = 9.0 + 0.4T_z, \quad E(SD) = 16.5 + 0.4T_z. \quad (5)$$

Note that the GT GR and SD GR energies increase as $T_z$ increases, and the SD GR is higher in energy than the GT GR by $\hbar\omega \approx 8$ MeV, reflecting the transition operator $r$ involved in the
SD. The energies of IAS with the upper T increase more with $T_z$ than the GT and SD GRs with the lower T.

The sum $\sum B_i(GT)$ for all GT states including the GT GR is derived from the measured $^3$He(t) CERs by assuming the Lorentzian shape of the GR and the quasi-free scattering shape at the higher excitation region beyond $E=30$ MeV. The sum is around 0.50-0.55 of the sum rule limit, indicating the large reduction of the GT strengths, as seen in other CERs.

The reduction of the GT strengths suggests some nuclear medium and non-nucleonic NΔ isobar effects [23]. The isobar effect is discussed for the first forbidden $\beta$ transitions [24]. The reduction (quenching) of the B(GT) sum is very interesting in views of the reduced effective $g_A$ suggested for low-lying GT and SD states [1, 20, 21, 23, 24].

The author thank Prof. D. Frekers and Prof. J. Suhonen for valuable discussions.

References
[1] Ejiri H and Fujita J.I 1978 Phys. Rep. C 38 85
[2] Ejiri H 2000 Phys. Rep. C 338 265
[3] Ejiri H, Suhonen J and Zuber K 2018 Phys. Rep. C submitted
[4] Ejiri H 2005 J. Phys. Soc. Jpn. 74 2101
[5] Vergados J, Ejiri H and Simkovic F 2012 Rep. Prog. Phys. 75 106301
[6] Vergados J, Ejiri H and Simkovic F 2016 Int. J. Mod. Phys. E 25 1630007
[7] Avignone III F, ORLaND Collaboration 1999 ORLaND proposal
[8] Ejiri H 2003 Nucl. Instr. Methods Phys. Research A 503 276
[9] Ejiri H and Shima T 2017 J. Phys. G: Nucl. Part. Phys. 44 065101
[10] Hashim I and Ejiri H et al. 2018 Phys. Rev. C 97 014617
[11] Ejiri H, Titov A, Boswell M and Young A 2013 Phys. Rev. C 88 054610
[12] Frekers D, Ejiri H, et al. 2011 Physics Letters B 706 134
[13] Ejiri H and Frekers D 2016 J. Phys. G: Nucl. Part. Phys. 43 11LT01
[14] Ejiri H 2017 J. Phys. G: Nucl. Part. Phys. 44 115201
[15] Takahisa K, Ejiri H, et al. 2017 arXiv 1703.08264 nucl-ex
[16] Cappuzzello F et al. 2015 Eur. Phys. J. A 51 145
[17] Cappuzzello F et al. 2018 Eur. Phys. J. A 54 72
[18] Freeman S J and Schiffer J, P 2012 J. Phys. G: Nucl. Part. Phys. 39 124004
[19] Kay B.P, Schiffer J.P and Freeman S.J 2013 Phys. Rev. Lett. 111 042502
[20] Ejiri H, Soukouti N and Suhonen J 2015 J. Phys. G: Nucl. Part. Phys. 42 055201
[21] Ejiri H and Suhonen J 2014 Phys. Letters B 729 27
[22] Thies J H, et al. 2012 Phys. Rev. C 86 014304
[23] Bohr A and Mottelson B.R 1975 Nuclear Structure II (Benjamin, New York)
[24] Ejiri H 1982 Phys. Rev. C 26 2618