Neutrino reactions in the nucleon resonance region

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Collaborators
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(KEK-theory center collaboration Y. Hayato, M. Hirai, W. Horiuchi, S. Kumano, K. Saito, M. Sakuda)


Contents

- introduction
- models of neutrino reaction in RES
- ANL-Osaka coupled channel model
  - brief description of the formalism
  - pion, photon, electron induced reaction
  - neutrino reaction
- Axial vector current
Neutrino oscillation parameters

- CP violation
- Mass ordering
- Improve accuracy of $\theta_{23}$

Experimentally allowed ranges for the oscillation parameters from a global fit to neutrino oscillation data. (Prog. Part. Nucl. Phys. 100(2018)1 Table 1)

Angle (degree), $\Delta m^2_{ij}$ (eV$^2$), normal ($m_1 < m_2 < m_3$), inverted ($m_3 < m_1 < m_2$)

<table>
<thead>
<tr>
<th></th>
<th>$\theta_{12}$</th>
<th>$\theta_{13}$</th>
<th>$\theta_{23}$</th>
<th>$\Delta m^2_{21}/10^{-5}$</th>
<th>$\Delta m^2_{3j}/10^{-3}$</th>
<th>$\delta_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>$33.56^{+0.77}_{-0.75}$</td>
<td>$8.46^{+0.15}_{-0.15}$</td>
<td>$41.6^{+1.5}_{-1.2}$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
<td>$2.524^{+0.039}_{-0.040}$</td>
<td>$261^{+51}_{-59}$</td>
</tr>
<tr>
<td>Inverted</td>
<td>$33.56^{+0.77}_{-0.75}$</td>
<td>$8.49^{+0.15}_{-0.15}$</td>
<td>$50.0^{+1.1}_{-1.4}$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
<td>$-2.514^{+0.038}_{-0.041}$</td>
<td>$277^{+40}_{-46}$</td>
</tr>
</tbody>
</table>
Oscillation probability $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, expanding in small quantities

$$P_{\mu e} = s_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{31}}{B_{\mp}} \right)^2 \sin^2 \left( \frac{\tilde{B}_{\mp} L}{2} \right) + c_{23}^2 \sin^2 2\theta_{12} \left( \frac{\Delta_{21}}{A} \right)^2 \sin^2 \left( \frac{A L}{2} \right) \\
+ \tilde{J} \frac{\Delta_{21}}{A} \frac{\Delta_{31}}{B_{\mp}} \sin \left( \frac{A L}{2} \right) \sin \left( \frac{\tilde{B}_{\mp} L}{2} \right) \cos \left( \mp \delta_{CP} - \frac{\Delta_{31} L}{2} \right),$$

$\Delta_{ij} = \Delta m_{ij}^2 L / 2E$, $A = \sqrt{2} G_F N_e$, $s_{ij} = \sin \theta_{ij}$, $\tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{12} \sin^2 2\theta_{23}$, $B_{\mp} = |A \mp \Delta_{31}|$

- surpression factor $\theta_{31}$, $\Delta_{21}$ → challenging measurement
- matter effects violate CP → hindering singnal of $\delta_{CP}$
- necessary to identify neutrino flavour and reconstruct neutrino energy → needs a solid knowledge of neutrino interaction
T2HK and CP

HK Atmospheric neutrino and MH

Importance of SIS/DIS in the atmospheric neutrino studies

- Statistically separate $\nu_e$ and $\overline{\nu}_e$
- Dominant interaction ($\sim$ 10 GeV)
  - Deep inelastic scattering

Differential cross-sections are different

<table>
<thead>
<tr>
<th>Observables</th>
<th>$\nu_e$ CC</th>
<th>$\overline{\nu}_e$ CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rings</td>
<td>More</td>
<td>Fewer</td>
</tr>
<tr>
<td>Transverse momentum</td>
<td>Larger</td>
<td>Smaller</td>
</tr>
<tr>
<td># of decay electrons</td>
<td>More</td>
<td>Fewer</td>
</tr>
<tr>
<td>Signal efficiency</td>
<td>52.9%</td>
<td>71%</td>
</tr>
<tr>
<td>Purity</td>
<td>58.4%</td>
<td>27.5%</td>
</tr>
</tbody>
</table>

ArXiv:1805.04163 HK Design Report

$$P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$$

$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)} \sim -0.27 \sin \delta_{CP} + 0.09$$

Y. Hayato, NuInt2018 (Gran Sasso)
List of currently operating and future long-baseline neutrino experiments
(Prog. Part. Nucl. Phys. 100(2018)1 Table 2)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Baseline</th>
<th>Peak energy</th>
<th>Energy range</th>
<th>Target</th>
<th>Detector</th>
<th>Fiducial Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2K</td>
<td>295 km</td>
<td>0.6 GeV</td>
<td>0.3–0.8 GeV</td>
<td>H$_2$O</td>
<td>WC</td>
<td>22.5 kton</td>
</tr>
<tr>
<td>NOvA</td>
<td>810 km</td>
<td>2 GeV</td>
<td>1.5–2.7 GeV</td>
<td>CH$_2$</td>
<td>Tracking+Calorimetry</td>
<td>13 kton</td>
</tr>
<tr>
<td>Future:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2HK</td>
<td>295 km</td>
<td>0.6 GeV</td>
<td>0.3–0.8 GeV</td>
<td>H$_2$O</td>
<td>WC</td>
<td>520 kton</td>
</tr>
<tr>
<td>DUNE</td>
<td>1300 km</td>
<td>2 GeV</td>
<td>0.6–3.3 GeV</td>
<td>Ar</td>
<td>Tracking+Calorimetry</td>
<td>40 kton</td>
</tr>
</tbody>
</table>

- Importance of knowledge on neutrino reaction in $N^*$, $\Delta$ resonance and DIS region

\[
N_{FD}^{\alpha \rightarrow \beta}(p_{\text{reco}}) = \sum_i \phi_\alpha(E_{\text{true}}) \times P_{\alpha \beta}(E_{\text{true}}) \times \sigma_i^\beta(p_{\text{true}}) \times \epsilon_\beta(p_{\text{true}}) \times R_i(p_{\text{true}}; p_{\text{reco}}) ,
\]

NuSTEC(Neutrino Scattering Theory Experiment Collaboration https://nustec.fnal.gov/)

Shallow and Deep Inelastic Scattering(Gran Sasso 2018)
Neutrino-Nucleus Pion Production in the Resonance Region(Pittsburgh 2019)
GeV neutrino reaction

\[ E_\nu \sim 0.6 \pm 0.2 \text{(GeV)} \]
\[ \text{Dune} \quad 2 \pm 2 \]
\[ \text{atmospheric (MH)} \quad \text{a few} \quad \sim 10 \]

\[ W = \sqrt{(p + q)^2}, \quad Q^2 = -q^2 = -(p_\nu - p_l)^2 \]
Feature of meson production reactions $m_N + m_\pi < W < 2GeV$

- **$\Delta(1232)$ region:**
  - single pion production, $\Delta(1232)$ dominant mechanism ($\nu p \rightarrow \mu^- \pi^+ p$)

- **Beyond delta resonance:**
  - Multi-pion (mainly $2\pi$) production including $\eta N, K\Lambda, K\Sigma, \ldots$
  - $N^*$ and $\Delta$ resonances $M_R < 2GeV$

- Neutrino event generator (NEUT, GENIE)
  - Mix Single-pion production (Resonance isobar model) + multi-pion(DIS)
Pion production in the resonance region

Abrupt change of model

“Resonance region” — DIS region

Pion production threshold

2 GeV/c²

W

Resonances
(1π, 1K, 1η)
+DIS background
(“Multi-pi” mode)

DIS mode (PYTHIA 5.72 based)

Resonant models
Single pion production only
Resonant + non-resonant contribution

Multi-particle model
Multi-pion only (nπ≥2)
Custom DIS model

No 2π/3π resonances
No DIS contribution to single pion production below W<2 GeV

C. Bronner, NuSTEC workshop pion production 2019, Pittsburgh)
**Isobar model**

- Neutrino:
  - RS: D. Rein, L. M. Sehgal AP133(81)
  - R. Gonzales-Jimenes et al. PRD95,113007(2017) + Regge

- Pion, Photon: Bonn-Gatchina, VPI/GWU, MAID, Jlab/Yerevan .. : amplitudes analysis

**Dynamical coupled channel model**

- Neutrino, Pion, Photon, Electron: SL, ANL-Osaka
- Pion, Photon: Jeulich-Bonn, Dubuna-Mainz-Taipei
**Isobar model:** single pion production

- **Rein-Sehgal model (in generators):**
  - Resonance parameter from PDG + phen. non-resonant mechanism

- **Valencia model (E. Hernandez, J. Nieves, M. Valverde):**
  - $\Delta(1232)$ + non-resonant from chiral L, unitarity correction

- **Amplitudes (resonance, non-resonance) of isobar-model have to be tested against data of pion, photon, electron induced meson production reactions**
Need to describe well resonant/non-resonant mechanism and unitarity

Example: $\pi N$ amplitude $F = \frac{S - 1}{2i} \sim \frac{R}{W - M + i\Gamma/2} + F_{\text{non-res}}$

$F = (S-1)/(2i)$

$W [\text{GeV}]$

$W$ [GeV]

$P_{33}$: $M - i\Gamma/2 = 1211 - i50$

$(3/2^+,3/2)$

$(1/2^+,1/2)$

$(Re(F), Im(F))$

$P_{11}$: $1374 - 76i$
Combined analysis of available single pion, eta, kaon production incorporating two pion final state with Coupled-Channels approach

Extraction of resonance parameters (Mass, transition form factor) from the partial wave amplitudes

Dynamical Coupled channel approach: ANL-Osaka, Julich
Model developed for $N^*$ physics: spectrum of nucleon excited states, transition form factors

- Fock-Space: isobar($N^*, \Delta$), Meson-Baryon ($\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N(\pi\Delta, \rho N, \sigma N)$)
- Interaction: isobar excitation and non-resonant meson-baryon interaction
- Coupled-channel (Lippmann-Schwinger) equation is solved numerically.

\[ T = V + VG_0T \]

Physics included inside $V$
Resonance energy, coupling constants are obtained from the pole of S-matrix:

$$\mathcal{F}(W)$$

Partial wave amplitude

Resonance parameter

Analytic continuation

$$|\beta\rangle \langle \alpha| \mathcal{F}(W) \sim -\frac{R_{\beta,\alpha}}{W - M_{N^*}}$$

mass and width

$$M_{N^*} = M - i\Gamma/2$$

coupling constant

$$R_{\beta,\alpha} = g_{\beta,N^*} g_{\alpha,N^*}$$

residue

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Neutrino reaction in RES

Oct. 24 2019 RCNP
channel coupling: unitarity $\rightarrow$ amplitudes of MB channels are related
signal of resonances might be enhanced at some channel (inelastic reaction)

near threshold of opening channel $\rightarrow$ a few partial wave, enhanced sensitivity

complex analytic structure of amplitudes

SL: T. Sato, T.-S. H. Lee: PRC54(96), PRC63(01)
Model for neutrino reaction

\[ < MB | J^\mu_\alpha | N > \]

\[ J_{em}^{\mu} = V_3^{\mu} + V_{IS}^{\mu} \]

\[ J_{CC}^{\mu} = V_{1+i2}^{\mu} - A_{1+i2}^{\mu} \quad (\Delta S = 0 \text{ current without CKM}) \]

\[ J_{NC}^{\mu} = V_3^{\mu} - A_3^{\mu} - 2 \sin^2 \theta_W J_{em}^{\mu} - \frac{1}{2} \bar{s} \gamma^\mu (1 - \gamma_5) s \]

- The model is constructed by fitting available data on pion, photon, electron induced meson production reaction (two-body final state). (Recent model: H. Kamano, S. X. Nakamura, T. -S. H. Lee, TS PRC88, 035209 (2013))

\[ \pi p \rightarrow \pi N, \eta N, K\Lambda, K\Sigma \]

\[ \gamma p \rightarrow \pi N, \eta N, K\Lambda, K\Sigma \]

\[ ep \rightarrow e' \pi N \]

- The model is extended for \( \gamma - n \) (H. Kamano, S. X. Nakamura, T. -S. H. Lee, TS PRC94 015291 (2016))

- Axial vector current: \( g_A^{NN^*} \) from \( g_\pi^{NN^*} \) assuming PCAC and dipole form factor. (Neutrino: S. X. Nakamura, H. Kamano, TS, PRD92 07402 (2015))
Pion, photon and Electron induced reaction (DCCmodel)
Total cross section of pion induced reaction

**π N → π π N reaction**

Parameters used in the calculation are from πN → πN analysis.


(Right: H. Kamano Baryon2010)
Total cross section of $\gamma p$

Total cross section of $p(e, e')$

Angular distribution of pion

\[
\frac{d\sigma}{dE_e, d\Omega_e d\Omega_\pi} = \Gamma \left[ \frac{d\sigma_T}{d\Omega_\pi} + \epsilon \frac{d\sigma_L}{d\Omega_\pi} + \epsilon \frac{d\sigma_{TT}}{d\Omega_\pi} \cos 2\phi_\pi + \sqrt{2\epsilon(\epsilon + 1)} \frac{d\sigma_{LT}}{d\Omega_\pi} \cos \phi_\pi \right]
\]

\(d\sigma_T\) and \(d\sigma_L\) are determined from the angular distribution of pion.

\(G_M\) (main term) sensitive to \(\frac{d\sigma_T}{d\Omega_\pi} + \epsilon \frac{d\sigma_L}{d\Omega_\pi}\), \(G_E\) : \(\frac{d\sigma_{TT}}{d\Omega_\pi}\), \(G_C\) : \(\frac{d\sigma_{LT}}{d\Omega_\pi}\)

\(\gamma N\Delta\) transition form factors are determined from the angular distribution of pion.
Neutrino induced reaction
$d\sigma/dW\ E_\nu = 2\text{GeV}$

**CC $\nu_\mu p$**

**CC $\nu_\mu n$**

**CC a-$\nu_\mu p$**

**CC a-$\nu_\mu n$**

T. Sato (Osaka U.)

Neutrino reaction in RES

Oct. 24 2019 RCNP
\[ \frac{d\sigma}{dW_{\pi N}} \] of single pion production \( E_\nu = 40 GeV \)

- \( \Delta(1232) \) gives most important contribution for all channels.
- Qualitative test of model on \( W \) dependence.
Single pion production in $\Delta(1232)$ region

$\nu_{\mu}p \rightarrow \mu^- p\pi^+, W_{\pi N} < 1.4$ GeV

$\nu_{\mu}n \rightarrow \mu^- n\pi^+, W_{\pi N} < 1.4$ GeV

$\nu_{\mu}p \rightarrow \mu^- p\pi^+, W_{\pi N} < 2$ GeV

$\nu_{\mu}n \rightarrow \mu^- n\pi^+, W_{\pi N} < 2$ GeV

$\nu_{\mu}n \rightarrow \mu^- p\pi^0, W_{\pi N} < 2$ GeV


- Re-analyzed ANL/BNL data, C. Wilkinson et al. PRD90
- ANL-Osaka DCC, PRD92, Hernandez, Nieves, Valverde PRD76

Caution on $\sigma(\nu N)$ of ANL/BNL data extracted from $\sigma(\nu d)$.
About 10 $\sim$ 30% correction due to FSI effects should be corrected.
Angular distribution of pion

Angular distribution of pion is sensitive to the interference among partial waves

\[ < Y_{lm} > = \frac{\int d\Omega_{\pi} Y_{lm}^* \frac{d\sigma}{dW d\Omega_{\pi}}}{\int d\Omega_{\pi} Y_{00}^* \frac{d\sigma}{dW d\Omega_{\pi}}} \]

\[ < Y_{lm} > \text{ ANL-Osaka Model (preliminary) (} \bar{\nu} p \rightarrow \mu^+ p \pi^-, E_{\nu} = 20 GeV \text{)} \]

\[ \frac{d\sigma}{dW d\Omega_{\pi}} = \sigma_0 + \sigma_c \cos \phi_{\pi} + \sigma_s \sin \phi_{\pi} + \sigma_{2c} \cos 2\phi_{\pi} + \sigma_{2s} \sin 2\phi_{\pi} \]

Data: NPB343 (1990) D. Allasia et al.
total cross section \( \frac{\sigma_p + \sigma_n}{2E_\nu} \)

ANL-Osaka model\((W < 2.1 GeV, Q^2 < 3 GeV^2 \text{ (preliminary), nucleon})\)

Note: in this model, strangeness, charm production is not included.


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Axial Vector Current
How good our Axial vector current?

- $Q^2 = 0$: data of $\pi - N$ elastic, total cross section
- $Q^2 \sim 1 - 2 GeV^2$: Parton model
- Adler’s sum rule

$$1 = [g_A(Q^2)]^2 + \int_{\nu_{th}}^{\infty} [W_{2,n}^A(\nu, Q^2) - W_{2,p}^A(\nu, Q^2)] d\nu$$
Axial Vector current $F_{2}^{CC}$ (total cross section) at $Q^2 = 0$

DCC model: $1\pi$ dash, a Total solid

$\pi N$ cross section data: $1\pi$ green, a Total brown

$$F_{2}^{CC}(Q^2 = 0) = \frac{2f_{\pi}^2}{\pi} \sigma(\pi + N)$$

- Description of axial vector current at $Q^2 = 0$ is consistent with pion scattering data.
Parton picture vs DCC model

Parton Picture (Isospin-symmetry, neglect $s$)

\[
F_{2EM} = \frac{x}{2} \left[ \left( \frac{2}{3} \right)^2 u_p + \left( \frac{1}{3} \right)^2 d_p \right] + \left[ \left( \frac{2}{3} \right)^2 u_n + \left( \frac{1}{3} \right)^2 d_n \right] = \frac{x}{2} \left( \frac{5}{18} \right) (u + d)
\]

\[
F_{2CC} = \frac{x}{2} (d_p + d_n)(1 + 1) = x(u + d) = \frac{18}{5} F_{2EM}
\]

Hadron picture

\[
F_{2EM} \sim \sum_f | < f | V_3 + V_{IS} | N > |^2
\]

\[
F_{2CC} \sim \sum_f \left[ | < f | V_{1+i2} | N > |^2 + | < f | A_{1+i2} | N > |^2 \right]
\]
Does DCC model describe boundary between RES and DIS?

- Electromagnetic structure function of proton

![Graph showing electromagnetic structure function of proton with data points and models for LO Parton Model and Our RES Model, with CLAS data.](image-url)
Does DCC model describe boundary between RES and DIS?

- Charged Current \( \left[ F_{2p}^{CC} + F_{2n}^{CC} \right]/2 \)

![Diagram showing Charged Current with different curves for \( Q^2 = 0.5 \), 1, and 2.

- Missing Strength in higher \( W \) region
- around \( W \sim 2GeV, Q^2 = 1 \sim 2GeV^2, F_{2}^{CC} \sim |V|^2 \).
- Question on Quark-Hadron duality in neutrino reaction

PRC 75 015202(2007), Lalululich et al.
Δ(1232): Left Electron Scattering (EM), Right Neutrino reaction (CC)

Example of transition form factors $N^*(1/2, 1/2^+)$

- **Vector(EM):** Helicity amplitudes extracted from the residue of partial wave amplitude (DCC-model) at resonance pole (figure from H. Kamano)

- **Axial Vector (Quark model)**

Simple Exercise of DCC model

\[ A_A^\lambda(Q^2) = A_A^\lambda(0) \times \frac{A_V^\lambda(Q^2)}{A_V^\lambda(0)} \quad \text{except } P_{33} \]

Modify \(Q^2\) dependence of axial N-'bare' resonance form factor. (Meson cloud part is not modified)

preliminary
Parity Violating Asymmetries

Parity violating asymmetry of $d(\bar{e}, e')$ reaction

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{Q^2 G_F}{\sqrt{24\pi\alpha}} \frac{N}{D}$$

$$N = \cos^2 \frac{\theta}{2} W_2 \gamma Z + \sin^2 \frac{\theta}{2} [2W_1 \gamma Z + (1 - 4 \sin^2 \theta_W) \frac{E_e + E_e'}{M_N} W_3 \gamma Z]$$

$$D = \cos^2 \frac{\theta}{2} W_{2em} + \sin^2 \frac{\theta}{2} W_{1em}$$

The PVDIS Collaboration PRC91 045506 (2015) ($E_e = 4.867\, GeV$, $\theta = 12.9^\circ$)
ANL-Osaka DCC model

  - Resonance parameters (Pole position, residue, helicity amplitudes)
  - Partial wave amplitudes $\pi, \gamma, \gamma^* N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$
  - and $\pi N \rightarrow \sigma N, \rho N, \pi\Delta$
- Tables of Structure functions $W_i (W, Q^2)$ for EM, CC, NC

$$\frac{d\sigma}{d\Omega \, dE_l} = \frac{G_F^2 C_{\alpha}^2 |p_l| E_l}{2\pi^2} \bigg[ 2W_1 \sin^2 \frac{\chi}{2} + W_2 \cos^2 \frac{\chi}{2} \\
\pm \frac{W_3}{M_N} \left( (E_\nu + E_l) \sin^2 \frac{\chi}{2} - \frac{m_l^2}{2E_l} \right) + \frac{m_l^2}{M_N^2} W_4 \sin^2 \frac{\chi}{2} - \frac{m_l^2}{M_N E_l} W_5 \bigg]$$

$$C_{\alpha} = V_{ud}^2 \left( \frac{1}{1 + Q^2/m_W^2} \right) \left[ C_{\alpha} = \frac{1}{1 + Q^2/m_Z^2} \right] \text{ for CC [NC]. } \cos \chi = \frac{|p_l|}{E_l \cos \theta_l}$$
ANL-OSAKA DCC model is extended to describe weak meson production reaction up to $W < 2 GeV$.

Neutrino induced single pion production in $N^*, \Delta$ resonance region is studied using ANL-Osaka model. Comparison with Neutrino event generators (NEUT, GENIE, NuWro,..) and other models will be very useful.

Model of axial vector current is examined.
At $Q^2 = 0$, DCC model reproduce $\pi N$ data. Comparison with PDF at high $Q^2$, suggests need for more strength at high $W$ region. Improvement of axial transition form factors is important.
PV asymmetry, in principle, gives information of axial vector current.