Prospect of neutrino interaction and nuclear effect studies

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Introduction

T2K has collected $\sim 11 \times 10^{20}$ POT = 14% of T2K Goal

$\sim 7 \times 10^{20}$ POT (neutrino-mode)

$\sim 4 \times 10^{20}$ POT (anti-neutrino mode)

$\nu_\mu$ disappearance analysis

$\sin^2 \theta_{23} \quad [0.427, 0.596]$

$\Delta m_{32}^2 \quad [2.34, 2.68]$

($\times 10^{-3}$ eV$^2$/c$^4$)

$\#$ of candidates: 120 events

Systematic errors

( on $\#$ of events for $\nu_\mu$ disappearance)

Total 7.7%

Flux and ND280/SK Common cross-sections 2.7%

Independent cross-sections (non-cancelling) 5.0%

Necessary to reduce neutrino interaction systematic uncertainty
Neutrino-nucleon interactions from 100 MeV ~ a few GeV

Charged current quasi-elastic scattering (CCQE)

\[ \nu + n \rightarrow l + p \]

Neutral current elastic scattering

\[ \nu + N \rightarrow \nu + N \]

Single meson productions

\[ \nu + N \rightarrow l + N' + \pi (\eta, K) \]

Single photon productions

( radiative decay of resonance )

\[ \nu + N \rightarrow l + N' + \gamma \]

Deep ( / shallow ) inelastic scattering

\[ \nu + N \rightarrow l + N' + m\pi(\eta, K) \]

Charged current quasi-elastic scattering and single \( \pi \) production dominates in the T2K energy region.
Neutrino-nucleus interactions from 100 MeV ~ a few GeV

Most of the neutrino interaction targets are in nucleus. Different from the ‘free’ nucleon.

Target nucleon is in the nuclear medium (matter). Impulse approximation and Fermi-gas model works fairly well in this energy region.

Interacted nucleon or produced mesons interact with the other nucleons in nucleus, so-called final state interactions.

However, this simple models (treatments) are not precise enough for the recent experiments.
Charged current quasi-elastic scattering $\nu + n \rightarrow l + p$

Current (experimental) situation

- Low energy experiments (K2K-SciFi, MiniBooNE, $E_\nu < \text{a few GeV}$)
  1) small $q^2$ or very forward region
     seems to have larger suppression than naive model.
  2) interaction probability (cross-section)
     seems to be larger than expected.

- Medium energy experiment (MINERνA, $< E_\nu > \sim 3.5 \text{ GeV}$),
  discrepancies seem to be smaller.

- High energy experiment (NOMAD, $< E_\nu > \sim 24 \text{ GeV}$)
  Consistent with the simple Fermi-Gas model...

Several possible improvements have been proposed.

- Random phase approximation (RPA) correction
  The presence of strongly interacting nucleons in nucleus may change the weak interaction strength.

- Multi-nucleon effects
  Interactions with strongly coupled nucleons.
  Confirmed w/ electron scat. exp.

\[ \nu + n \rightarrow l^- + p \]
Charged current quasi-elastic scattering  \( \nu + n \rightarrow l^- + p \)

~ Fit existing data sets with new models ~

a) Relativistic Fermi Gas model with RPA correction (Nieves et al.)
   + Multi-Nucleon interactions (Nieves et al.)

b) Spectral function model (A. Ankowski, O. Benhar et al.)
   + Multi-Nucleon interactions (Nieves et al.)
Charged current quasi-elastic scattering \( \nu + n \rightarrow l^- + p \)

~ *Fit existing data sets with new models* ~

<table>
<thead>
<tr>
<th>Model</th>
<th>( M_A ) (GeV/c(^2))</th>
<th>( P_F ) (MeV/c)</th>
<th>MEC fraction</th>
<th>( \chi^2 ) / # of D.O.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFG with RPA + MEC</td>
<td>1.15 ± 0.03</td>
<td>223 ± 5</td>
<td>27% ± 12%</td>
<td>97.84/195</td>
</tr>
<tr>
<td>Spectral Function + MEC</td>
<td>1.33 ± 0.02</td>
<td>234 ± 5</td>
<td>0 ( at limit )</td>
<td>97.46/196</td>
</tr>
</tbody>
</table>

* Additional normalization factors are included for MiniBooNE data

Selection of the model based on the fit is difficult at this moment. Also, some tensions between data sets were observed.
Neutrino-nucleus interaction studies in T2K

For the oscillation analyses, we performed the fit with ND280 data to determine/constraint the neutrino interaction parameters and neutrino flux simultaneously.

3 sub-samples from neutrino running
- Events with $\mu^-$ and no pion (CC0$\pi$) CCQE enriched
- Events with $\mu^-$ and $1\pi^\pm$ (CC1$\pi$) CC1$\pi$ enriched
- Other events with $\mu^-$ (CC Other) CCDIS enriched

For the oscillation analyses, we performed the fit with ND280 data to determine/constraint the neutrino interaction parameters and neutrino flux simultaneously.
Neutrino-nucleus interaction studies in T2K

For the oscillation analyses, we performed the fit with ND280 data to determine/constraint the neutrino interaction parameters and neutrino flux simultaneously.

2 sub-samples of $\bar{\nu}$ in anti-neutrino running period.

- Events with $\mu^+$ and only 1 track reconstructed
  CCQE enriched

- Events with $\mu^+$ and there are more than 1 track reconstructed
  Inclusive (less CCQE)

For the oscillation analyses, we performed the fit with ND280 data to determine/constraint the neutrino interaction parameters and neutrino flux simultaneously.
Neutrino-nucleus interaction studies in T2K

Neutrino interaction and flux parameter fit using the ND280 data sets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior</th>
<th>Fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE $M_A$ (GeV/c^2)</td>
<td>1.15 ± 0.07</td>
<td>1.13 ± 0.03</td>
</tr>
<tr>
<td>PF (Carbon) (MeV/c)</td>
<td>223.0 ± 12.3</td>
<td>222.7 ± 8.83</td>
</tr>
<tr>
<td>MEC fraction (%)</td>
<td>27.0 ± 29.0</td>
<td>103.1 ± 17.2</td>
</tr>
</tbody>
</table>

In the fit, not only these parameters but other parameters including flux were fit simultaneously. Therefore, these values can not be compared directly with the results from external data fits.

T2K ND280 data sets seem to require MEC-like interactions. Need further dedicated studies!
Neutrino-nucleus interaction studies in T2K
Cross-section measurements with the near detectors

• We have studied CCQE using off-axis detector. ( arXiv: 1411.6264 )
  Obtained ( effective ) $M_A = 1.26^{+0.21}_{-0.18}$ GeV/c$^2$ ( absolute ).
  *(without recent multi-nucleon interaction models.)*

• Further detailed study of CCQE and Multi-nucleon interactions are required.

• Now we are trying to use proton track information and compare with recent models with additional interactions.
Neutrino-nucleus interaction studies in T2K

Cross-section measurements with the near detectors

Data sets are compared with two model predictions:

- Martini et al. RPA + Multi-nucleon interactions

- Nieves et al. RPA + Multi-nucleon interactions
  *Phys. Rev. C* 83 045501 (2011)

Further studies are on-going to test the models and also, to estimate the contributions from multi-nucleon interactions.
Neutrino-nucleus interaction studies in T2K

Cross-section measurements with the near detectors

We also studied CCQE using proton track with T2K-INGRID detector. (on-axis ~ higher energy region)

Single track (\(\mu^-\) only) and Two track (\(\mu^- + p\)) samples gave slightly different results.

Incompleteness of the model?

Interesting to study the energy dependence using both on-axis and off-axis detector data sets.

Activities (\(\sim\) energy deposit) around the vertex is also expected to provide additional information.
Neutrino-nucleus interaction studies in T2K
Cross-section measurements with the near detectors

On-Axis detector (INGRID) has scintillator module and Iron-scintillator composite modules.

Inclusive cross-section measurement

\[
\frac{\sigma^{Fe}_{CC}}{\sigma^{CH}_{CC}} = 1.047 \pm 0.007 \text{ (stat.)} + 0.035 \text{ (syst.)}
\]


Fe/C inclusive cross-section ~ 5% difference
Neutrino-nucleus interaction studies in T2K
Cross-section measurements with the near detectors

Study of nuclear dependence ~ Use passive water layers in ND280
( One example of the on-going study ~ CC $\pi^+$ production )

Passive Water Layer

Upstream scintillator layer
Contain H$_2$O + CH interactions

Downstream scintillator layer
CH interactions

Upstream data sample

Downstream data sample

We also working on the CCQE ( -like ) interactions.
Nuclear effects ~ pion interaction in nucleus

Pion interactions in nucleus is also important because these interactions affect determination of interaction mode. However, existing data have ~30% errors. Not so much data above Δ region.
Nuclear effects ~ pion interaction in nucleus

Recently DUET experiments measured absorption + charge-exchange cross-sections.

Absorption candidate events

Almost back to back protons are observed after absorption.

( Correlated pair nucleon absorbed $\pi^+$ ?)

Error has shrunk less than 10%

Simulation parameter tuning has been started.

Study to separate charge exchange from absorption is on-going.

Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity

(personal thoughts)

1) **CCQE and Multi-nucleon CCQE-like interactions**
    1. Measured interaction rates:
        MiniBooNE found larger interaction rate of CCQE(+like ) interactions.
        Atmospheric sub-GeV $\nu_e$ event rate seems to be consistent with $M_A=1.2\text{GeV}/c^2$.
        (simple relativistic Fermi-Gas model)
        But there are uncertainties of $\nu$ fluxes.
    2. Suppressions in the small $q^2$ region / forward going leptons have been observed in various experiments:
        K2K, MiniBooNE, MINOS (preliminary), T2K.

$Larger M_A$ (with simple Fermi-Gas model)
seems to reproduce these to some extent.
Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity
(personal thoughts)

1) **CCQE and Multi-nucleon CCQE-like interactions.**
   Even though, low energy data (somewhat) agrees
   with expectations with simple Fermi-Gas + larger $M_A$,
   it is far from satisfactory.

   **Because possible contributions are neglected in the model:**
   RPA, multi-Nucleon interactions,
   Local density effects (local Fermi-Gas) or
   Spectral function (momentum-potential distributions)
   etc...

   **And assumed true $E_\nu$ and reconstructed $E_\nu$ relation
   are incorrect for Multi-nucleon interactions.**

   However, current data sets are not sufficient
   to justify or reject the models.
Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

( personal thoughts )

1) **CCQE and Multi-nucleon CCQE-like interactions.**
   1) Further improvements of reconstruction tools and analyses ( in T2K ND280 ) are essential.
      
      Example)
      
      Extensive use of the proton tracks and the energy deposit around the vertex will provide useful information. ( Some indications in MINERνA results. )

2) More neutrino and anti-neutrino data ( of the T2K ND280 ) Still statistically limited to perform detailed analyses.
   Neutrino and anti-neutrino interactions have different $dq^2/d\sigma$.
   This may provide additional information on nuclear effects and dependences.

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Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

( personal thoughts )

1) **CCQE and Multi-nucleon CCQE-like interactions.**
   With the current T2K ND280,
   energy/momentum threshold ( from track ID )
   or energy resolution ( from vertex activity ) of protons
   may not be sufficient to give definite answer.
   Also, we need to understand the nuclear dependence,
   i.e. difference between Carbon and Oxygen.
   ( Current ND280 can provide some info. but may not be sufficient. )
   Therefore, we need additional information.
   Experiments like MINERνA and MicroBooNE
   will provide useful information.
   However, the current issues seem to have energy dependence.
   Also, Ar may be too large nucleus, unfortunately.
   **We need a sets of new detectors!**
Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity

( personal thoughts )

1) **CCQE and Multi-nucleon CCQE-like interactions.**
   Several new detectors have been proposed. Among of them,
   a) Water + Scintillator 3D grid tracking detector
      (WAGASCI )
   b) Introducing water based scintillator cells in FGD
   c) Emulsion detector with water target
   d) High pressure gas TPC with Neon
   seem to be quite interesting and promising.

   a) and b) are quite straight forward
   and will improve understanding of C/O differences.

   c) and d) are really attractive
   because they have low momentum threshold
   with fine tracking capabilities.

   d) may need ( quite a lot ) of R&D, though.
Cells are filled with $\text{H}_2\text{O}$ or $\text{CH}$

(Cell size is 5 x 5 x 2.5 cm$^3$)
Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

( personal thoughts )

2) $\nu_\mu/\nu_e$ ratio

Low energy $\sigma$ ( < 0.5 GeV ) has nuclear model dependence.
It may not have large impact but need to be studied.

3) **Single $\pi$ production cross-section and $\pi$ momentum distribution**

Rein-Sehgal ( FKR ) model is known to have problem in reproducing electro-pion production data.
Modified ( improved ) structure function is used in Neut but it is time to try more sophisticated models for comparison.
( At this moment, there seems no significant difference, though. )
Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

\((\text{personal thoughts})\)

4) \(\pi\) interactions in/with Carbon and Oxygen

DUET experiment is expected to provide cross-sections of \(\pi + C\) scattering. However, \(p_\pi < 300\ \text{MeV/c}\).

We need to have higher \(P_\pi\) data for the improvements of

a) \(\pi\) secondary interactions (FSI) in nucleus and

b) \(\pi\) interactions in the detectors.

GEANT4 is used to simulate detector responses.

*Precisions of \(\pi\) interactions in the detector are important to study neutrino interactions.*
Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

( personal thoughts )

5) *nucleon interactions in/with Carbon and Oxygen*
   We need to find the way to improve nucleon interactions in the nucleus or in the detector.

6) *Improvements of the neutrino interaction simulation programs*
   Recently, collaborations with theorists are really working well to improve our understanding of the models and the simulation software.

   We have to continue and expand these activities not only for the neutrino oscillation studies but also for the better understanding of the neutrino-nucleus interactions.
Summary

Uncertainties of
• neutrino-nucleus interactions,
• hadron interactions in nucleus and
• hadron interactions in detectors
  are expected to be the largest sources
  of the systematic errors in the oscillation analyses.

We have to improve analysis tools of ND280
  for further detailed analyses of various interactions.

Already running or starting experiments in the world
  are also expected to provide useful information.

However, we also need `optimized’ detectors
  with sufficient statistics
  for better understandings of these interactions
  in the T2K energy region.
Summary

Recently, we are collaborating with theorists to understand the interactions and it is really helpful. We have to expand this kind of activities to develop more accurate and reliable neutrino-nucleus and detector simulation programs and to assign appropriate systematic uncertainties.

All the studies of these interactions will help in improving the atmospheric neutrino oscillation analyses and proton decay search sensitivities.
backups and memos
Study of neutrino interactions

Past experiments
  Bubble chamber ~ D_2 target
  ( quasi- ) free neutron data as reference

Recent experiments
  MiniBooNE
    Mineral Oil Cherenkov detector
    4\pi coverage

  MINERnA
    Fine grained tracking detector
    Scintillator + other target material
    Limited acceptance ( < ~ 20 degree for \mu etc. )
    but sensitive to the heavy particles.
Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

Vector & Axial form factors

**Vector part**: Determined using electron scattering data

**Axial part**: Determined using neutrino scattering data (dipole form, parameter is $M_A$)

**BNL, D2**

$M_A = 1.07 \pm 0.06$ GeV/c$^2$

1,236 events


**ANL, D2**

$M_A = 1.00 \pm 0.05$ GeV/c$^2$

1,737 events

Miller, PRD 26, 537 (1982)
The K2K experiment

Comparison with K2K 1kt detector and simulation data

Fully contained 1 ring $\mu$-like events

Direction of $\mu$ w.r.t. beam

Forward deficit

slightly larger
# of events in backward

NEUT-1211

$M_A=1.1$ GeV/c$^2$ for CCQE
$M_A=1.2$ GeV/c$^2$ for $1\pi$
GRV94 with Bodek-Yang corr.
Coherent $\pi$ by Marteau et.al.

Important to measure large angle scattering!
Charged current Quasi-elastic scattering

\[ M_A = 1.20 \pm 0.12 \text{ GeV} \]
\[ (\chi^2 = 261/235 \text{ dof}) \] shape only

Most significant errors:

- Muon momentum scale 0.07
- Relative flux and normalization 0.06
- \( M_A \) 1\( \pi \) 0.03
- relative non-QE fraction 0.03
- Nuclear re-scattering 0.03
- Statistics only 0.03

R.Gran, E.Jeon, et al., accepted by PRD (hep-ex/0603034)
Charged current Quasi-elastic scattering

MiniBooNE

Axial vector form factor parameter $M_A$

$$F_A(Q^2) = \frac{g_A}{(1 + Q^2 / M_A^2)^2}$$

Need to be determined from the neutrino scattering data.

$M_A = 1.35 \pm 0.17$ GeV

- **World avg.**
  $M_A = 1.02 \pm 0.17$ GeV

- **K2K SciFi** $(^{16}\text{O}, Q^2 > 0.2)$
  $M_A = 1.20 \pm 0.12$ GeV

- **K2K SciBar** $(^{12}\text{C}, Q^2 > 0.2)$
  $M_A = 1.14 \pm 0.11$ GeV
Charged current quasi-elastic scattering

\( \nu + n \rightarrow l^- + p \)

NOMAD experiment

Carbon target, \(<E_\nu> \sim 24 \text{ GeV}\)

\[ M_A(\nu) = 1.06 \pm 0.02 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \text{ GeV/c}^2 \]

\[ M_A(\bar{\nu}) = 1.06 \pm 0.07 \text{ (stat.)} \pm 0.10 \text{ (syst.)} \text{ GeV/c}^2 \]

Consistent with Bubble chamber results.
Charged current quasi-elastic scattering $\nu + n \rightarrow l + p$

MINERvA Experiment $< E_\nu > \sim 3.5$ GeV

Simple relativistic Fermi Gas model $M_A = 0.99$ GeV/c$^2$

did not give the best fit result. Need some modification.