On measuring two body current contribution in neutrino-nucleus scattering

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INT Seattle
Outline:

- a very short introduction
- information contained in muon only
- pionless multinucleon knock out final states
  - pion absorption
  - CCQE followed by FSI
  - two body current events
- hadronic model for two body current events
  - a role of nucleon correlations
- possible observables
- quality of MC simulation tools
- summary
The problem: how large is two body current contribution to neutrino inclusive cross section?

- from electron scattering we know it is there
- theoretical estimates for neutrinos are uncertain and differ from each other (yesterday’s Marco Martini talk)
- most likely it was seen in MiniBooNE (only muon observable) and MINERvA (hadronic observable: vertex activity) experiments

How large it is? Which is the best approach to measure it? Is that possible at all?!

Frustrating because it is about a large contribution to the neutrino inclusive cross section!
Large CCQE $M_A$ controversy.

The experimental data is consistent with dipole axial FF and $M_A = 1.015$ GeV.

A. Bodek, S. Avvakumov, R. Bradford, H. Budd

- older $M_A$ measurements indicate the value of about 1.05 GeV
- independent pion production arguments lead to the similar conclusion

MiniBooNE reported $M_A \sim 1.35$ GeV.
The solution of the MB large axial mass puzzle?

M. Martini, G. Chanfray, M. Ericson, J. Marteau
Theoretical models

All the theoretical models provide predictions for final state muon only:

- Martini (Martea) model; two options for elementary response functions
- IFIC (Nieves) model
- transverse enhancement model
- superscaling model
- effective GiBUU model/ansatz

Is this information sufficient to identify clearly and measure a strength of the two body current contribution?

In the case of electron scattering inclusive measurements there is a significant two body current contribution in the dip region. Perhaps it is sufficient to investigate muon final state only?
Two body current contribution from muon observable

In the electron scattering there is a problem of an access of the cross section in the DIP region between QE and $\Delta$ peaks:

- there is about 30 years long discussion on the DIP region
- the extra strength is believed to come from the two-body current dynamics

Typical two body current events: no pions in the final state.

In this talk in numerical analysis we impose a strict veto on final state pions. Such events origin from:

- **CCQE with FSI effects,**
  - exception is spectral function with short range correlation part:
    - there are two nucleon knock-out events without FSI
- pion production and subsequent absorption
- two body current.

All the simulations are done in NuWro Monte Carlo event generator. Predictions will be shown for 1 GeV muon neutrinos and also for MiniBooNE flux.
NuWro

- the project started ~2005 at the Wrocław University; an important encouragement from Danka Kieselczewska from Warsaw,
- main authors: C. Juszczak, J. Nowak, T. Golan, JTS,
- the code is written in C++,
- can handle various targets, fluxes, has a detector interface,
- open source project: http://borg.ift.uni.wroc.pl/nuwro/

NuWro is not an official MC in any experiment and serves as a laboratory for new developments.

New (or relatively new) ingredients:

- random phase approximation corrections on the top of Fermi gas model,
- two body current contributions,
- in medium modifications of NN cross sections (after Pandharipande, Pieper, PRC 45 (1992) 791)
NuWro MEC models

Four options are available:

- **Nieves et al model**
  - implemented by J. Žmuda from cross section tables,
  - does not incorporate the latest upgrades of the model (work in progress)

- **microscopic models (two)**
  - similar to Marteau and Martini models,
  - $np - nh$ part expected to be very similar to Martini (Marteau) model
    - most of np-nh contribution not affected by RPA effects
  - based on: JTS, a talk at NuInt02, arXiv:nucl-th/0307047
  - two versions of elementary responses, old from the original Marteau model, new (almost) identical to those in the Martini model

- **transverse enhancement model.**

These are all models for a contribution to muon inclusive cross section. They provide no information about final state nucleons.
Models comparison – overall cross sections

New microscopic cross section larger than Martini model.
Models comparison – muon double differential cross sections
Models comparison – muon double differential cross sections

The model predictions are quite similar. Nieves model covers larger phase space.
Two body current contribution from muon observable

In attempts to identify the signal we must consider pionless events resulting from CCQE and RES dynamical mechanisms:
Two body current contribution from muon observable

We will look for shape modifications in 2D differential cross section introduced by two body current events:

\[
\frac{d^2\sigma_{\text{with } 2\text{body}}}{d\cos\theta_{\mu}dT_{\mu}} - \frac{d^2\sigma_{\text{without } 2\text{body}}}{d\cos\theta_{\mu}dT_{\mu}} + \frac{d^2\sigma_{\text{without } 2\text{body}}}{d\cos\theta_{\mu}dT_{\mu}}
\]

with both \(\sigma_{\text{with } 2\text{body}}\) and \(\sigma_{\text{without } 2\text{body}}\) normalized to the same value.
Two body current contribution from muon observable

We analyze (on the right) how much the shape of double differential cross section is affected by inclusion of the two body current contribution.

For monoenergetic neutrinos (1 GeV) there would be a clear and strong signal from the two body current in a region of high statistics! Analogy: dip region in electron inclusive scattering data.
Two body current contribution from muon observable

Another visualization:

CCQE is modeled by LFG+RPA.
Two body current contribution from muon observable

The pattern of modifications depends on details of the models used in numerical computations.
Another example: CCQE modeled by spectral function and MEC by (new) microscopic model.

A strong signal (in the same bin) is always there.
Two body current contribution from muon observable

Another visualization:

The CCQE model is spectral function.
Two body current contribution from muon observable

The impact of flux is devastating:

Significant shape modifications survive only in kinematical regions of low statistics. Measurement of the size of two body current contribution becomes difficult. There are big errors in MB 2D differential cross section data!
Two body current contribution from muon observable

Again, alternative visualization:
Two body current nucleon model

Perhaps there is more (or complementary) information in final state nucleons?  

Nucleon model is badly needed.

The strategy:

- start from a simple and flexible model
- identify possible observables
- identify most important assumptions
- look for observables robust wrt model assumptions
NuWro two body current nucleon model (JTS, Phys. Rev. C86, 015504 (2012))

Only muon information is used:

- muon’s kinetic energy and production angle are known as an input
- equivalently, momentum and energy transferred to the hadronic system are known
- two/three nucleons are selected from the Fermi sea
- initial hadronic system is formed by adding all the four momenta
- boost to the hadronic center-of-mass frame (CMF) is performed
- in the hadronic CMF two/three nucleons are selected isotropically as a final state configuration
- boost back to the laboratory frame is performed
- Pauli blocking may be checked
- energy balance must be consistent with the FSI (in NuWro Fermi energy and 7 MeV as a potential well is subtracted at the end of the cascade)
- events are weighted by muon double differential cross section.
**NuWro two body current nucleon model** (JTS, Phys. Rev. C86, 015504 (2012))

![Diagram of two body current nucleon model](image)

T. Katori

Strictly speaking the above figure describes GENIE nucleon model (see later) – but both are virtually identical.

The same hadronic model will be combined with four theoretical models for two body current contribution to muon inclusive cross section.
Other MC (MC like) approaches

GENIE model

- Dytman ideas for strength (based on the Lightbody model): Gaussian distribution between QE and $\Delta$ peaks

- nucleon cluster model for nucleons, very similar to NuWro approach
Other MC (MC like) approaches

GIBUU
- simple ansatz for matrix element: either a constant (model I) or transverse projection (model II), in both cases strength adjusted to the MiniBooNE data
Other MC (MC like) approaches

<table>
<thead>
<tr>
<th>Leptonic model</th>
<th>GENIE</th>
<th>NuWro</th>
<th>GiBUU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dytman model</td>
<td>TEM, np-nh model,</td>
<td>Transverse projector</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and Valencia model</td>
<td></td>
</tr>
<tr>
<td>Hadronic model</td>
<td>nucleon cluster</td>
<td>nucleon cluster</td>
<td>phase space density</td>
</tr>
<tr>
<td>initial nucleon momentum</td>
<td>Fermi sea</td>
<td>Fermi sea</td>
<td>Fermi sea</td>
</tr>
<tr>
<td>initial nucleon momentum correlation</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>initial nucleon spatial correlation</td>
<td>none</td>
<td>none</td>
<td>2 nucleons are generated</td>
</tr>
<tr>
<td>initial nucleon pair</td>
<td>n-p:n-n=1:4</td>
<td>n-p:n-n=9:1</td>
<td>at the same location</td>
</tr>
<tr>
<td>FSI model</td>
<td>isospin ansatz</td>
<td>short range correlation</td>
<td>statistical average</td>
</tr>
<tr>
<td></td>
<td>hA model</td>
<td>cascade model</td>
<td>BUU transport</td>
</tr>
</tbody>
</table>

NuWro two body current nucleon model – flexibility

Isospin correlations:
- how many n-p and n-n in pairs participate in interactions?
- no obvious theoretical argument
- a fraction of n-p pairs is a free parameter
- default value is 0.7; later some comparisons with 0.9 will be shown

Momentum correlations:
- momenta of nucleon pairs participating in interaction?
- default option (following Marteau/Martini and Nieves models): momenta are selected at random from Fermi see
- alternative: back-to-back momenta with a distribution given by spectral function – some comparisons will be shown later
Observables.

We are looking for pionless final states.

As said before, the **background** comes from:

- CCQE followed by FSI
- pion production and absorption
Two (at least) protons in the final state

The models predictions are quite different:

Predictions depend mostly on
- overall cross sections
- differential cross section in energy transfer.
Two protons in the final state

Now, include also background, i.e. similar events coming from CCQE and RES interactions. Normalization is relative wrt overall cross section.

For realistic $\rho_{thr}$ (in T2K $\sim 500$ MeV/c) the problem is background coming from pion absorption.
Reconstructed protons and vertex activity

Some information is there in vertex activity – energy deposited near interaction vertex, not identified as a proton track.

- successfully explored by MINERvA!


Below we assume that there are no pions and neutrons are not visible at all. It means, that vertex activity energy comes from low momentum protons only. It is difficult to make better without detector simulations.
Reconstructed protons and vertex activity

The simplest observable is a sum of kinetic energies of all reconstructed protons and vertex activity.

For Nieves model the shape of distribution is modified in a unique way due to the presence of two body current contribution. However, this prediction is model dependent.
On measuring two-body current contribution in neutrino-nucleus scattering.

Muon information

Single reconstructed protons and vertex activity assuming 400 MeV/c reconstruction threshold.

- There is always a large contribution from events without FSI effects.
- A structure seen in RES is in low cross section region.
Single reconstructed protons and vertex activity assuming 500 MeV/c reconstruction threshold.

- amount of vertex activity is increased
Two reconstructed protons and vertex activity assuming 500 MeV/c reconstruction threshold

- events with no vertex activity – no FSI took place
- there is nothing characteristic for two body current events
Muon and proton information put together

Finally, one can combine information from muon, reconstructed protons and vertex activity.

Using muon 3-momentum one can reconstruct its energy (CCQE assumption) and then also energy transfer. This can be compared with overall visible proton energy:
there is a kinematical region where two body current may dominate

seems to be a promising observable, but the cross section may be too low.
Correlation effects

Impact of correlation effects on number of proton pairs in the final state:

Isospin and momentum correlations are analyzed separately. A possible confusion: In above figures correlations means initial state nucleon momenta are back-to-back.

Results for (new) microscopic model.
Monte Carlo generators validation

Important question, avoided so far: how reliable are NuWro Monte Carlo simulations?

In the past MC FSI studies focused on pion cascade mainly. Performance of nucleon cascade models was not studied that much.

In what follows: some NuWro validation studies.
On measuring two body current contribution in neutrino-nucleus scattering

—Muon information

NuWro validation – pion absorption final states (LADS data)

<table>
<thead>
<tr>
<th>charge multiplicity (in %)</th>
<th>1C</th>
<th>2C</th>
<th>3C</th>
<th>≥ 4C</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon 118 MeV (LADS)</td>
<td>34.3</td>
<td>56.6</td>
<td>8.8</td>
<td>0.3</td>
</tr>
<tr>
<td>argon 118 MeV (NuWro)</td>
<td>36.6</td>
<td>54.7</td>
<td>8.2</td>
<td>0.5</td>
</tr>
<tr>
<td>argon 239 MeV (LADS)</td>
<td>18.2</td>
<td>53.8</td>
<td>24</td>
<td>3.9</td>
</tr>
<tr>
<td>argon 239 MeV (NuWro)</td>
<td>25.5</td>
<td>50</td>
<td>20.5</td>
<td>4</td>
</tr>
<tr>
<td>nitrogen 118 MeV (LADS)</td>
<td>22.8</td>
<td>63.3</td>
<td>13.2</td>
<td>0.8</td>
</tr>
<tr>
<td>nitrogen 118 MeV (NuWro)</td>
<td>25.2</td>
<td>63.3</td>
<td>10.6</td>
<td>0.9</td>
</tr>
<tr>
<td>nitrogen 239 MeV (LADS)</td>
<td>10.2</td>
<td>53.4</td>
<td>29.9</td>
<td>6.5</td>
</tr>
<tr>
<td>nitrogen 239 MeV (NuWro)</td>
<td>16.9</td>
<td>52.6</td>
<td>25.2</td>
<td>5.3</td>
</tr>
</tbody>
</table>

LADS data from Rowntree et al. PRC60 (1999) 054610

- LADS separates protons and deuterons; in NuWro only protons
- in NuWro momentum cut 200 MeV/c is imposed. Energy threshold for proton detection in LADS is 16 – 22 MeV i.e. 175 – 200 MeV/c.

LADS: [limitations of the detector] most commonly cause high final state multiplicities to be understated and also lower multiplicities to be overstated [...] Rudimentary estimates indicate that in severe cases (e.g. a three nucleon final state at 118 MeV) roughly 70% of actual strength is observed.
NuWro validation – pion absorption and charge exchange rate
NuWro validation (cont)

ArgoNeut LAr proton multiplicity data. Reconstruction threshold is 21 MeV of kinetic energy (∼ 204 MeV/c).

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Genie Expectation</th>
<th>Genie % of Total</th>
<th>DATA</th>
<th>DATA % of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0p+μ</td>
<td>28±4</td>
<td>16%</td>
<td>15±3</td>
<td>14%</td>
</tr>
<tr>
<td>1p+μ</td>
<td>80±7</td>
<td>47%</td>
<td>51±10</td>
<td>48%</td>
</tr>
<tr>
<td>2p+μ</td>
<td>23±4</td>
<td>13.4%</td>
<td>28±6</td>
<td>26%</td>
</tr>
<tr>
<td>3p+μ</td>
<td>14±3</td>
<td>8.3%</td>
<td>13±3</td>
<td>12%</td>
</tr>
<tr>
<td>4p+μ</td>
<td>8±2</td>
<td>4.5%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Total (including&gt;4p)</td>
<td>172±10</td>
<td>-%</td>
<td>107±12</td>
<td>-%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Genie Expectation</th>
<th>Genie % of Total</th>
<th>DATA</th>
<th>DATA % of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0p+ν</td>
<td>553±11</td>
<td>60%</td>
<td>422±42</td>
<td>58%</td>
</tr>
<tr>
<td>1p+ν</td>
<td>160±6</td>
<td>17%</td>
<td>266±53</td>
<td>37%</td>
</tr>
<tr>
<td>2p+ν</td>
<td>68±4</td>
<td>7%</td>
<td>30±6</td>
<td>4%</td>
</tr>
<tr>
<td>3p+ν</td>
<td>50±3</td>
<td>5%</td>
<td>3±1</td>
<td>0.4%</td>
</tr>
<tr>
<td>4p+ν</td>
<td>32±3</td>
<td>4%</td>
<td>3±1</td>
<td>0.4%</td>
</tr>
<tr>
<td>Total (including&gt;4p)</td>
<td>925±15</td>
<td>-%</td>
<td>727±68</td>
<td>-%</td>
</tr>
</tbody>
</table>

K. Partyka (ArgoNeut)
ArgoNeut proton multiplicity data – neutrino flux

<table>
<thead>
<tr>
<th># protons (%)</th>
<th>data</th>
<th>NuWro</th>
<th>GENIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14</td>
<td>15.4</td>
<td>16.3</td>
</tr>
<tr>
<td>1</td>
<td>48</td>
<td>50.8</td>
<td>46.5</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>17.8</td>
<td>13.4</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>9.6</td>
<td>8.1</td>
</tr>
<tr>
<td>≥ 4</td>
<td>0</td>
<td>6.3</td>
<td>15.7</td>
</tr>
</tbody>
</table>

- Experimental errors are of the order of 20%.
- GENIE predicts too many protons in the final state; NuWro had similar problems – Pandharipande, Pieper modifications are important.
ArgoNeut proton multiplicity data – antineutrino flux

<table>
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<th>data</th>
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<tr>
<td>0</td>
<td>58</td>
<td>64.9</td>
<td>59.8</td>
</tr>
<tr>
<td>1</td>
<td>36.6</td>
<td>22.7</td>
<td>17.3</td>
</tr>
<tr>
<td>2</td>
<td>4.1</td>
<td>8.0</td>
<td>7.3</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>2.8</td>
<td>5.4</td>
</tr>
<tr>
<td>≥ 4</td>
<td>0.4</td>
<td>1.6</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Below also GIBUU results (seem to be similar to NuWro)

Tingjun Yang
On measuring two body current contribution in neutrino-nucleus scattering

Muon information

ArgoNeut proton multiplicity data – antineutrino flux

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<td>1.6</td>
<td>10.2</td>
</tr>
</tbody>
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Below also GIBUU results (seem to be similar to NuWro)

Tingjun Yang

Yesterday Ornella told me that the data should be modified!
ArgoNeut proton multiplicity data – antineutrino flux

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<tr>
<th># protons (%)</th>
<th>data</th>
<th>NuWro</th>
<th>GENIE</th>
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<tbody>
<tr>
<td>0</td>
<td>67.7</td>
<td>64.9</td>
<td>59.8</td>
</tr>
<tr>
<td>1</td>
<td>23.7</td>
<td>22.7</td>
<td>17.3</td>
</tr>
<tr>
<td>2</td>
<td>6.4</td>
<td>8.0</td>
<td>7.3</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>2.8</td>
<td>5.4</td>
</tr>
<tr>
<td>≥ 4</td>
<td>1.0</td>
<td>1.6</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Below also GIBUU results (seem to be similar to NuWro)

With the new data agreement is even better
Summary:

- In order to measure two body current contribution final state nucleons should be investigated.
- It is necessary to separate background from pion absorption and FSI effects.
- Reliable MC simulation tools are required.
- A role of nucleon-nucleon correlations should be understood.
- Experimental searches combined with further MC studies must be done.
Thank you!
Nuclear correlations

Fermi gas model completely neglects nucleon-nucleon correlations.

From electron scattering experiments we know that $\sim 20\%$ of time nucleons are strongly correlated in pairs with large $\sim$ back to back momenta.

- for $|\vec{p}| \lesssim 600$ MeV/c corrections are expected to be due to tensorial nuclear force and pairs to be deuteron like with isospin $I = 0$ (proton-neutron only).

A typical distance between nucleon is 1.7 fm

A correlated pair:

Three nucleon correlations are very unlikely (0.5%).
On measuring two body current contribution in neutrino-nucleus scattering

Back-up slides

Two body current neutrino computations

- inclusion of the two body current contribution leads to good agreement with the MB CCQE data with $M_A \sim 1.05$ GeV.
- neutrino energy unfolding procedures should be accordingly modified
- difficult to get predictions for final state nucleon momenta (JTS, PRC86, 015504 (2012)), important ArgoNeut data discussed in Dave’s talk

Microscopic model prediction for isospin of the initial state nucleons:

Microscopic models can be extended to energies up to 10 GeV (R. Gran, J. Nieves, F. Sanchez, M.J. Vicente-Vacas, arXiv:1307.8105 [hep-ph])

- important role of correlations introduced within the random phase approximation (RPA) approach and 2p-2h contribution
- RPA brings in a strong suppression at $Q^2 \sim 0$ (a factor of 0.6) and some enhancement for $Q^2 \geq 0.4$ GeV$^2$.
Beyond Fermi gas ground state computations

- Results from J. Carlson, J. Jourdan, R. Schiavilla, I. Sick, Phys. Rev. C65 (2002) 024002 for electron scattering suggest that it is very important to consider a realistic ground state.

- Non-relativistic computations done for light nuclei: $^3$H, $^4$H and $^6$Li in the language of Euclidean responses and sum rules:
  - Almost all the enhancement of the strength due to two-body current comes from proton-neutron, and not from proton-proton or neutron-neutron pairs.
  - When ground state correlations are neglected (Fermi gas model) the extra strength due to two-body current contributions becomes very small.