NuWro: Wrocław Neutrino Event Generator

Tomasz Golan (University of Wrocław)
and
Paweł Przewłocki (National Center for Nuclear Research, Warsaw)

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Introduction
NuWro is a Monte Carlo neutrino event generator, which has been
developed for over 9 years at the Wrocław University by:

Cezary Juszczak  
Jan Sobczyk  
Jarosław Nowak  
Tomasz Golan  
a significant contribution from:
Krzysztof Graczyk  
Jakub Żmuda  
and others

The authors were encouraged by Danuta Kiełczewska.

The open-source C++ code is available in the repository:

http://borg.ift.uni.wroc.pl/gitweb/?p=nuwro
## Primary Interactions

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Theory/Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>quasi-elastic scattering</td>
<td>Llewellyn-Smith formalism</td>
</tr>
<tr>
<td>$\Delta(1232) \rightarrow \pi$ production</td>
<td>Adler-Rarita-Schwinger</td>
</tr>
<tr>
<td>deep inelastic scattering</td>
<td>quark-parton model</td>
</tr>
<tr>
<td>coherent $\pi$ production</td>
<td>Rein-Sehgal model</td>
</tr>
<tr>
<td>two-body current</td>
<td>IFIC (Nieves et al.) model</td>
</tr>
<tr>
<td></td>
<td>MEChM*-like model</td>
</tr>
<tr>
<td></td>
<td>Transverse Enhancement</td>
</tr>
</tbody>
</table>

*MEChM = Martini-Ericson-Chanfray-Marteau*

We thank Marco Martini for consultations in our implementation, but we also warn users that it is different than the original MEChM model.

We thank Juan Nieves and collaborators for providing us his original source code.
## General information

### Nucleus models

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi gas</td>
<td>local and “global”</td>
</tr>
<tr>
<td>Spectral function</td>
<td>for $^{12}C$, $^{16}O$, $^{40}Ar$, $^{40}Ca$, $^{56}Fe$</td>
</tr>
</tbody>
</table>

### Final state interactions

- Intra-nuclear cascade for pion:
  - Oset et al. model for kinetic energies up to 350 MeV
  - a phenomenological approach for higher energies

- Intra-nuclear cascade for nucleon:
  - a phenomenological approach with an effective nuclear potential

### Other features

- ability to use a realistic beam
- ability to use a detector geometry
Multi-nucleon knockout
Our strategy for two-body current contribution

- It is very important for the community to have a chance to use various models.
- We are very grateful to authors of theoretical models who share with us their original codes.
- In case we do not have access to important models we are trying to develop approximate approaches.
**FIRST APPROACH**

<table>
<thead>
<tr>
<th>Tables for $^{12}C(\nu_\mu, \mu^-)$</th>
<th>$\rightarrow d^2\sigma/dT_\mu d\cos\theta_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rightarrow$ 40 values for $E_\nu$ from 155 MeV to 2995 MeV</td>
<td></td>
</tr>
<tr>
<td>$\rightarrow$ for each $E_\nu$ 40x40 table for $T_\mu$ and $\cos\theta_\mu$</td>
<td></td>
</tr>
</tbody>
</table>

**Extension for higher $E_\nu$**

<table>
<thead>
<tr>
<th>Gran, Nieves, Sanchez, Vicente Vacas [PRD 88 (2013) 113007]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rightarrow$ cut in momentum transfer $</td>
</tr>
</tbody>
</table>

**CURRENT APPROACH**

<table>
<thead>
<tr>
<th>Nucleus “knows”:</th>
<th>It “does not know”:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q = (q_0, \vec{q})$</td>
<td>lepton mass</td>
</tr>
<tr>
<td>type of int.</td>
<td>its energy</td>
</tr>
</tbody>
</table>

$$
\frac{d^3\sigma}{d\Omega'dE'} \sim \sum_{i=1}^{5} W_i(q_0, \vec{q}) f_i
$$

- $f_i$ depend on lepton kinematics
- $W_i \rightarrow$ response functions depend on nucleus type, channel and four-momentum transfer

Knowing $W_i$ one can calculate double-differential cross section for each kind of neutrino and with no energy limit.

*Note, similar approach is currently used in NEUT.*
Both approaches give the same results.

\[ \frac{d\sigma}{dT \cos(\theta)} \left[ 10^{-41} \text{cm}^2/\text{GeV} \right] \text{C} \ 1.0 \text{ GeV } \nu_\mu \text{ response function} \]

\[ \frac{d\sigma}{dT \cos(\theta)} \left[ 10^{-41} \text{cm}^2/\text{GeV} \right] \text{C} \ 1.0 \text{ GeV } \nu_\mu \text{ XS tables} \]

from J. Žmuda, Vanish Valencia workshop

See J. Žmuda “Meson Exchange Currents models in NuWro Monte Carlo generator” for details.
Hadron kinematics for two-body current

All of them give predictions for lepton kinematics only!

→ Four-momentum transfer \( q \) is shared by two nucleons with four-momenta \( p_1 \) and \( p_2 \).

→ In the CMS frame the direction of momentum \( \vec{p} \) is selected uniformly:

\[
q + p_1 + p_2 \xrightarrow{\text{CMS}} (E^{CMS}, 0)
\]

\[
p_{3}^{CMS} = (E^{CMS}/2, \vec{p})
\]

\[
p_{4}^{CMS} = (E^{CMS}/2, -\vec{p})
\]

→ \( p_3 \) and \( p_4 \) are obtained by preforming boost back to the LAB frame.
Spectral function:

\[ P_{\text{total}}(\vec{p}, E) = P_{\text{MF}}(\vec{p}, E) + P_{\text{corr}}(\vec{p}, E) \]

About 20% of interactions occur on a correlated nucleon.

The spectator is now also knock out in NuWro.

to be improved.
→ Usually, free nucleon-nucleus cross sections are used in nucleon cascade models.

→ Effective density dependent NN cross section:

_Pandharipande, Pieper PRC45 (1992) 791_

→ In medium NN cross section becomes much smaller.

Important in MEC studies!
Protons multiplicity

ArгоNeуT preliminary results

→ K. Partyka “Exclusive 1mu+np topologies in ArgoNeuT” NuInt12
→ O. Palamara “QE or not QE, that is the question” INT workshop, Seattle, 2013

Observable

→ number of protons ($T_k \gtrsim 22$ MeV) in the final state
→ no pion in the final state

<table>
<thead>
<tr>
<th>No. of protons</th>
<th>Data</th>
<th>NuWro</th>
<th>Data</th>
<th>NuWro</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14</td>
<td>15.4</td>
<td>67.7</td>
<td>64.9</td>
</tr>
<tr>
<td>1</td>
<td>48</td>
<td>50.8</td>
<td>23.7</td>
<td>22.7</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>17.8</td>
<td>6.4</td>
<td>8.0</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>9.6</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>more</td>
<td>0</td>
<td>6.3</td>
<td>1.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>

errors are of the order of 20%
Detector geometry
Detector geometries and flux information in NuWro

- NuWro can now make simulations in a real detector environment
  - ROOT geometry definitions supported
    - spatial distribution of materials with given density and composition
  - extremely fast simulation code
  - vertex position/outgoing particles are saved
    - can be further used in detector simulation software
- This feature has already been used in T2K experiment (see next slide)

- Beam flux files are supported
  - NuWro can read neutrino by neutrino from flux files generated by beam MC
  - important for off-axis experiments
Detectors in NuWro – ND280@T2K

• An example of usage: simulation for ND280 near detector of the T2K experiment
• A set of samples prepared to study possibilities of multi-nucleon (np-nh, MEC) events’ selection
  – NuWro has got implementations of two multi-nucleon models: Nieves and Martini-Marteau
• Several samples generated in different regions of the detector
• and subsequently processed using full detector simulation
  – Output can be directly compared with data
  – Analysis in progress

**Vertex distribution (left)** of NuWro simulated events using the ND280 geometry (left: full inner detector and right: FGD1 only - single scintillator bars visible). The denser parts contain more vertices
Detectors in NuWro – ND280@T2K (2)

An example event display (above) of a NuWro generated event (CCQE), a muon and a proton are visible (both are properly reconstructed)

ND280 NuWro simulation workflow

1. Flux
2. NuWro neutrino interaction generation
3. ND280 detector simulation and reconstruction
4. Analysis, comparison with data

NuWro-generated samples are used in the T2K studies of np-nh contribution in ND280 tracker data. For details, see Peter Sinclair’s talk.

Above: an example of distribution that can be used for np-nh search – cosine of angle between muon and proton (visible differences between CCQE and mec events)
NuWro online
The on-line graphical interface for NuWro is now available:

http://nuwro.ift.uni.wroc.pl

→ setting parameters
→ running simulations
→ making plots
NuWro online

Introduction
Multi-nucleon
Detector geometry
NuWro online
Summary

T. Golan and P. Przewłocki NuWro 14 / 16
1. The simulation is done on our server

2. The output ROOT file is stored on our server, but one can download it.
One can use already defined types of charts or define its own.
1. NuWro is a complete tool to analyze the data.

2. All major neutrino interaction types are included.

3. There are several models of two-body current contribution.

4. The realistic beam as well as detector geometry can be used.

5. There is a graphical on-line interface.