Meson Exchange Current (MEC) model in Neutrino Interaction Generator

1. Introduction
2. Leptonic simulation in GENIE
3. Hadronic simulation in GENIE
4. Comparisons
5. Discussion

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NuInt12, CBPF, Rio de Janeiro, Brazil, Oct. 22, 2012
1. Introduction

2. Leptonic simulation in GENIE

3. hadronic simulation in GENIE

4. Comparisons

5. Discussion
1. Introduction of Meson Exchange Current (MEC)

Meson Exchange Current (MEC) in e-scattering
- MEC is conceived long time to contribute at “dip” region

Inclusive electron scattering with function of energy loss

\[
\omega = E(e') - E(e)
\]

\[\theta\]

\[\text{e-beam} \quad \text{e}' \quad \text{ω} = \text{E(e') - E(e)} \quad \text{target} \quad \theta \quad \text{detector}\]
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Inclusive electron scattering with function of energy loss

\[ \omega = E(e') - E(e) \]

[e-beam] -> [target] -> [detector]

![Graph showing inclusive cross section vs. electron energy loss](image-url)

- Q.E
- DIS
- cohe
- \( \Delta \)
- \( \pi \)
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Inclusive electron scattering with function of energy loss

\[ \omega = E(e') - E(e) \]

Inclusive cross section

electron energy loss \( \omega \)

coh, \( \pi \), \( \Delta \), DIS

10/22/12
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Inclusive electron scattering with function of energy loss

\[ \omega = E(e') - E(e') \]

![Diagram showing inclusive electron scattering with function of energy loss](image)

\[ \Delta \text{-excitation} \]

\[ \pi \]

\[ A \text{ and } A' \]

\[ \text{quasi-elastic} \]

\[ e \text{ and } e' \]

\[ N \text{ and } N' \]

\[ e \text{ and } e' \]

\[ \Delta \text{ and } \pi \]

\[ A \text{ and } A' \]

\[ \text{inclusive cross section} \]
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Inclusive electron scattering with function of energy loss

![Diagram showing inclusive cross section vs. electron energy loss](image_url)

- **Q.E.** (quasi-elastic)
- **Δ**-excitation
- **DIS**
- **coherence (coh)**
- **π**
- **Δ**
- **X**

**Energy Loss Formula:**
\[ \omega = E(e') - E(e) \]
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Inclusive electron scattering with function of energy loss

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\omega = E(e') - E(e)
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dip region
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Inclusive electron scattering with function of energy loss

\[ \omega = E(e') - E(e) \]

\[ \begin{align*}
\text{e-beam} & \rightarrow \text{target} \\
\theta & \rightarrow \text{detector}
\end{align*} \]
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Meson Exchange Current (MEC) in e-scattering
- MEC is conceived long time to contribute at “dip” region
- MEC also contributes to QE peak (~10%)
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Meson Exchange Current (MEC) in e-scattering
- MEC is conceived long time to contribute at “dip” region
- MEC also contributes to QE peak (~10%)
- MEC may contribute more than we thought

Note:
Calculation with good NN potential – has correlations
Light nuclei only
Non-relativistic

Longitudinal response of $^4\text{He}$

Transverse response of $^4\text{He}$
Meson Exchange Current (MEC) in e-scattering
- MEC is conceived long time to contribute at “dip” region
- MEC also contributes to QE peak (~10%)
- MEC may contribute more than we thought
- This process may be needed to describe recent QE $\nu$-xs data

$\nu_\mu$ CCQE total xs, RPA+np-nh effect

$\nu_\mu$ Quasieelastic (QE)
Two Nucleons knock-out (2p-2h)

RPA + np-nh

RPA

$\nu_\mu$-CCQE total xs, RPA+np-nh effect
1. Introduction of Meson Exchange Current (MEC)

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- MEC may contribute more than we thought
- This process may be needed to describe recent QE $\nu$-xs data
- MEC verified in e-scattering agrees with $\nu$-scattering

Note,
Local Fermi gas with extra correlations,
MEC, pion production

More about MEC theory, see all talks on Friday
1. Introduction of Meson Exchange Current (MEC)

Meson Exchange Current (MEC) in e-scattering
- MEC is conceived long time to contribute in “dip” region
- MEC also contributes to QE peak (~10%)
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- This process may be needed to describe recent QE $\nu$-xs data
- MEC verified in e-scattering agrees with $\nu$-scattering

Goal of this program
- Build the model consistent with both e-scattering and $\nu$-scattering experiments
- Implement such model in MC generator to simulate neutrino experiments
- Predict realistic signal of MEC in neutrino experiments
1. Introduction

2. Leptonic simulation in GENIE

3. Hadronic simulation in GENIE

4. Comparisons

5. Discussion
2. MEC simulation in GENIE

Currently, hadronic kinematic distributions are not available from any models in the market.

Therefore implementation of MEC takes several steps:

(1) specify leptonic model
   - Choose a model to generate lepton differential cross section
   - Energy-momentum transfer is specified from the model
   - Verify the model using e-scattering data

(2) specify hadronic model
   - Model how to pick up 2 nucleons
   - Model how to share the energy-momentum transfer, to knock-out 2 nucleons

(3) specify FSI model
   - Outgoing lepton and nucleons undertake standard FSI model in GENIE
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2. Leptonic simulation in GENIE

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

MEC model requirement
- It enhances total neutrino cross section ~30%
- It enhances more high angle scattering due to transverse nature
- It reproduces inclusive e-scattering data
2. Leptonic simulation in GENIE

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Dytman model
- First MEC model in GENIE
- Based on early work by Lightbody and O’Connell
- Easy to implement, easy to tune

Feature
- New MEC channel has only magnetic form factor (Pauli form factor)
- MEC channel is Gaussian (mean~ 1.9 GeV width~150 MeV)
- Linear A dependence to match previous studies

Lightbody model

\[ \nu \rightarrow \mu^{-} + np \rightarrow \mu^{-} + p + p \]

\[ \Delta \text{ (Cauchy)} \]

\[ \text{QE} \text{ (Gaussian)} \]

\[ \text{MEC} \text{ (Cauchy)} \]
2. Leptonic simulation in GENIE

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Dytman model
- First MEC model in GENIE
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- Easy to implement, easy to tune

\[ \nu - 12C \text{ total cross section} \]

\[ \nu - 12C \text{ total cross section} \]

\[ \text{monotonically turn off (after 1 GeV)} \]
2. Comparison with e-scattering data

In GENIE, Neutrino interaction is simulated in several steps

1. specify leptonic model
2. specify hadronic model
3. specify FSI model

Carbon target, 560MeV, 36° ($Q^2 \sim 0.1\text{GeV}^2$)

At low angle, RFG model overestimate QE peak

MEC is small contribution at low angle
2. Comparison with e-scattering data

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Carbon target, 560MeV, 60° ($Q^2 \sim 0.2\text{GeV}^2$)

MEC is related to transverse response function
More important at larger scattering angle

Pion production model is under development
2. Comparison with e-scattering data

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Carbon target, 560MeV, 145° (Q^2~0.5GeV^2)

MEC is related to transverse response function

More important at larger scattering angle

Pion production model is under development
2. GENIE prediction for neutrino experiment

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Neutrino interaction kinematics
- with NuMI low energy configuration
- matches MINERvA
2. Comparison with MiniBooNE data

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Comparison with MiniBooNE flux-folded
$\nu_\mu$ CCQE double differential cross section data

- T$\mu$ distribution, $0.8 < \cos\theta_\mu < 0.9$
- Slight over estimation at low angle muons
2. Comparison with MiniBooNE data

In GENIE, Neutrino interaction is simulated in several steps:
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Comparison with MiniBooNE flux-folded $\nu_\mu$ CCQE double differential cross section data
$\cos \theta_\mu$ distribution, $0.8 < \cos \theta_\mu < 0.9$

Decomposition of GENIE prediction
- it shows complicated mix due to flux distribution

MiniBooNE collaboration,
PRD81(2010)092005
2. Comparison with MiniBooNE data

In GENIE, Neutrino interaction is simulated in several steps:
1. Specify leptonic model
2. Specify hadronic model
3. Specify FSI model

Decomposition of GENIE prediction
- It shows complicated mix due to flux distribution

Decomposition of Valencia model
- Theory-based model is somewhat different

Channels (no cut)
- Total
- CCQE
- MEC
- RES
- Others

MiniBooNE collaboration, PRD81(2010)092005
2. Comparison with MiniBooNE data

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
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Comparison with MiniBooNE flux-folded
$\nu_\mu$ CCQE double differential cross section data

- Slight over estimation at low angle muons
- MC agrees with data at mild angle

![Comparison plot](image-url)
In GENIE, Neutrino interaction is simulated in several steps:
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Comparison with MiniBooNE flux-folded
\( \nu_\mu \) CCQE double differential cross section data

- T\( \mu \) distribution, 0.8 < \( \cos \theta_{\mu} \) < 0.9
  - Slight over estimation at low angle muons

- T\( \mu \) distribution, 0.5 < \( \cos \theta_{\mu} \) < 0.6
  - MC agrees with data at mild angle

- T\( \mu \) distribution, -0.1 < \( \cos \theta_{\mu} \) < 0.0
  - Slight under estimation at high angle

But remember the model is tested with electron data only!
2. Leptonic simulation in GENIE

In GENIE, Neutrino interaction is simulated in several steps:
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Kinematic constraint:
- Leptonic constraint (energy-momentum conservation)
- Hadronic constraint (model dependent kinematic constraint)
- Both CCQE and MEC show ~2% Hadronic constraint violation

\[ \nu_{\mu} - ^{12}\text{C} 800 \text{ MeV CCQE phase space} \]

\[ \nu_{\mu} - ^{12}\text{C} 800 \text{ MeV MEC phase space} \]

Ankowski et al, PRD82(2010)013002
1. Introduction

2. Leptonic simulation in GENIE

3. hadronic simulation in GENIE

4. Comparisons

5. Discussion
3. Hadron simulation in GENIE

In GENIE, Neutrino interaction is simulated in several steps:
1. specify leptonic model
2. specify hadronic model
3. specify FSI model

Kinematic distribution of nucleon need to be modelled. MEC model defines lepton kinematics, and Hadron model defines nucleon kinematics.

Nucleon cluster model
- Simple but reasonable model (GENIE, NuWro)
- it has enough flexibility to add more features later
3. Nucleon cluster model in GENIE

For a given Energy-Momentum transfer...
1. Choose 2 nucleons from specified kinematics (e.g., Fermi gas)

**Fermi gas**
- nucleon kinematics are randomly chosen from Fermi sea (GENIE, GiBUU, NuWro)

**Spectral function**
- nucleon kinematics can be chosen from spectral function

**Phase space density**
- cross section is weighted with nucleon phase space density (GiBUU)
3. Nucleon cluster model in GENIE

For a given Energy-Momentum transfer...
1. Choose 2 nucleons from specified kinematics (e.g., Fermi gas)
2. All n-n, n-p, p-p pairs are allowed, if interaction is allowed

e.g.) $\nu_\mu^{-12}$C CC MEC interaction
- It requires at least one neutron (p-p pair is forbidden)
- based on random choice, n-p : n-n $\sim$ 3 : 1 (NuWro, GiBUU)
- based on isospin conjecture, n-p : n-n $\sim$ 1 : 4 (GENIE)
- based on short range correlation n-p : n-n $\sim$ 90 : 5
Some theory also speculate n-p $\gg$ n-n (Martini model)
3. Nucleon cluster model in GENIE

For a given Energy-Momentum transfer...
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3. Energy-momentum conservation

e.g.) GENIE
- 2 nucleons make a on-shell cluster
3. Nucleon cluster model in GENIE

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- Boost back to lab frame
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Issues:
- correlations may exist in initial 2 nucleons, any models?
- certain pairs may be favoured, any models?
- separation energy, binding energy, etc, any measurements?

The model can be extended to include these feature later
3. Nucleon cluster kinematics

Nucleon cluster kinematic distribution
- Isotropic momentum distribution
- Nucleon cluster has more symmetric momentum distribution than CCQE, extends to higher energy

![Diagram](image)

**Graph:**
- **Black, CCQE**
- **Red, CCMEC**

**Legend:**
- **SRC tail**

**Axes:**
- **Initial nucleon momentum**
- **Initial momentum (GeV/c)**
3. Nucleon cluster kinematics

Nucleon cluster kinematic distribution
- Isotropic momentum distribution
- Nucleon cluster has more symmetric momentum distribution than CCQE, extends to higher energy
- Isotropic angular distribution
- Nucleon cluster has no preferred direction against momentum transfer

![Graphs showing initial nucleon momentum and opening angle of initial nucleon to momentum transfer]

black, CCQE  
red, CCMEC  
SRC tail
3. Nucleon cluster model kinematics for 800 MeV $\nu_\mu$ on $^{12}$C

2 outgoing nucleon kinematics
- 2 outgoing nucleons tend to be back-to-back (model dependent feature)

opening angle of 2 outgoing nucleons (before FSI)

Opening angle of 2 nucleons are naturally large 

red, CCMEC
3. Nucleon cluster model kinematics for 800 MeV $\nu_\mu$ on $^{12}$C

In GENIE, Neutrino interaction is simulated in several steps:
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

GENIE FSI model (hA FSI model)
- After FSI, MEC still has larger opening angle for 2 nucleons than CCQE

opening angle of 2 outgoing nucleons (before FSI)
opening angle of 2 leading outgoing nucleons (after FSI)
3. Nucleon cluster model kinematics for 800 MeV $\nu_\mu$ on $^{12}$C

In GENIE, Neutrino interaction is simulated in several steps:
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GENIE FSI model (hA FSI model)
- After FSI, MEC still has larger opening angle for 2 nucleons than CCQE
- This is rare configuration for CCQE and resonance

Opening angle of 2 outgoing nucleons (before FSI)

Opening angle of 2 leading outgoing nucleons (after FSI)
3. Nucleon cluster model kinematics for 800 MeV $\nu_\mu$ on $^{12}_C$

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
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GENIE FSI model (hA FSI model)
- leading outgoing nucleon momentum
- leading outgoing nucleon angle

Nucleon cluster model may predict interesting event topologies
3. SciBooNE multi-track analysis

SciBooNE CC analysis
- total rate is normalized to CC inclusive measurement
- data is compared with NeuT prediction
- 3 track data shows excess, this can be explained by many ways
  - Resonance channel xs is underestimated?
  - FSI is not modelled correctly?
  - Indication of multi-nucleon emission?

SciBooNE CC track number
1. Introduction

2. Leptonic simulation in GENIE

3. hadronic simulation in GENIE

4. Comparisons

5. Discussion
4. MEC model in NuWro

NuWro
- 2 choices of MEC model
  - np-nh model (based on Marteau model)
  - TEM (Transverse enhancement model)
  - Nucleon cluster model similar to GENIE
    (more attention to energy balance)

Sobczyk, PRD86(2012)015504
Martini et al, PRC80(2009)065501
Bodek et al, EUJC71(2011)1726
4. Sum of all nucleon kinetic energy

**NuWro**
- 2 choices of MEC model
  - np-nh model (based on Marteau model)
  - TEM (Transverse enhancement model)
- Nucleon cluster model similar to GENIE (more attention to energy balance)

Different predictions on energy transfer provide different predictions on total kinetic energy, but after FSI, most of the structure is gone.
4. Sum of all nucleon kinetic energy

**NuWro**
- 2 choices of MEC model
  - np-nh model (based on Marteau model)
  - TEM (Transverse enhancement model)
  - Nucleon cluster model similar to GENIE (more attention to energy balance)

For GENIE, Dytmn model has Gaussian energy transfer, therefore has symmetric kinetic energy distribution.

**GENIE $\nu_\mu$-$^{12}$C 800 MeV total outgoing nucleon kinetic energy**
4. Max nucleon momentum

NuWro
- 2 choices of MEC model
  - np-nh model (based on Marteau model)
  - TEM (Transverse enhancement model)
  - Nucleon cluster model similar to GENIE (more attention to energy balance)

For GENIE, Dytman model has Gaussian energy transfer, therefore has symmetric kinetic energy distribution.

GENIE $\nu_\mu^{12}$C 800 MeV total outgoing nucleon kinetic energy
4. MEC model in GiBUU

Triple differential cross section
- A special care is paid for the phase space
- 2 nucleons start from same location (effect of nuclear density is squared)

Symmetry factor
(n-n, p-p pair=1/2, n-p pair=1)

\[ \frac{d^3\sigma^{(3)}}{d\Omega' \, dE'} = \frac{|k'|}{|k|} g_{12} S_{34} S_{12} \frac{1}{(2\pi)^4} \int d^3x \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} f_1(x, p_1) f_2(x, p_2) \]

One-particle phase space density
(solution of coupled Kadanoff-Baym eqn.)

Lalakulich et al, PRC86(2012)014614
4. Total cross section, with N-nucleons

**GiBUU**
- A special care is paid for the phase space
- 2 nucleons start from same location)
- hadronic tensor is transverse projector (model II)
- FSI controls final state particles

2p-2h doesn’t contribute to 1 nucleon knockout
- MEC model shouldn’t enhance 1-nucleon knock out

![Diagram of nucleon knockout](image)

**GiBUU $\nu^{-12}\text{C}$ total cross section for multi-nucleon knockout (after FSI)**
4. Total cross section, with N-nucleons

**GiBUU**
- A special care is paid for the phase space
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**GENIE** $\nu_\mu^{12}\text{C}$ total xs for multi-nucleon knockout (after FSI)
## 4. Summary

<table>
<thead>
<tr>
<th>What kind of Leptonic model?</th>
<th>GENIE</th>
<th>NuWro</th>
<th>GiBUU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dytman model</td>
<td>np-nh model and TEM</td>
<td>Transverse projector for hadronic tensor</td>
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<table>
<thead>
<tr>
<th>how to choose 2 nucleon momentum?</th>
<th>GENIE</th>
<th>NuWro</th>
<th>GiBUU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From Fermi sea, independently</td>
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</table>

<table>
<thead>
<tr>
<th>how to choose 2 nucleon location?</th>
<th>GENIE</th>
<th>NuWro</th>
<th>GiBUU</th>
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<tbody>
<tr>
<td></td>
<td>both are random</td>
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<td>both are random, but same location</td>
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</table>

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<thead>
<tr>
<th>Any correlations?</th>
<th>GENIE</th>
<th>NuWro</th>
<th>GiBUU</th>
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<td>no</td>
<td>no</td>
<td>no, but $x_s$ is weighted by phase space density</td>
</tr>
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<table>
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<tr>
<th>what kind of pairs? n-p or n-n?</th>
<th>GENIE</th>
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<td>n-p : n-n = 1 : 4</td>
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<th>How to share energy-momentum transfer by 2 nucleons?</th>
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<tr>
<td></td>
<td>nucleon cluster model</td>
<td>nucleon cluster model</td>
<td>not clear</td>
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1. Introduction

2. Leptonic simulation in GENIE

3. hadronic simulation in GENIE

4. Comparisons

5. Discussion
5. Discussion

The effort to implement MEC model in MC is just started..., with many open questions
- How to choose 2 initial nucleon kinematics?
- How to implement 2 final nucleon FSI?
- What kind of pairs are preferred, n-n, or n-p, or p-p?
- Where are 2 nucleons generated?
- Do we assume any correlation of initial nucleon? (momentum and location)

Some of them may be described in theoretical models, but what is best way to
implement in MC? (can have significant effect on predictions!)

e.g.) Short Range Correlations (SRC)
  - Initial nucleons can be off-shell
  - from hadron experiments, n-p pair is preferred
  - 2 nucleons are close
  - initial momenta are correlated (back-to-back)

We need more input for a realistic prediction
5. Discussion

GENIE v2.7.2
- First tagged version with MEC
- Lepton kinematic is based on Dytman model, tests are ongoing with e-scattering data
- Hadron kinematic is based on GENIE nucleon cluster model
- Will be available Mar. 2013

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Muito obrigado!
Backup