Modelling Nuclear Effects in Neutrino Scattering

Tina Leitner
Luis Alvarez-Ruso, André Peshier, Ulrich Mosel

Institut für Theoretische Physik

Overview:
- Motivation & Introduction
- Neutrino Nucleon Reactions
- BUU Transport Model
- Nuclear Effects in νA Scattering
- Summary & Outlook
Motivation & Introduction

- past, current & future experiments
  - neutrino oscillations ✓
  - neutrino mass ✓
  - precision measurement of oscillation parameters ✗
  - CP violation ✗

- problems
  - uncertainties due to neutrino cross sections & nuclear effects → detector response
  - neutrino energy reconstruction
  - proposed experiment: MINERvA

⇒ better understanding of nuclear effects is crucial for existing & future neutrino experiments
Neutrino Nucleus Scattering

- $\nu A$ reaction is factorized using **impulse approximation**:
  - $\nu_l N \rightarrow l^- X$

  with consideration of
  - Fermi motion
  - Pauli blocking
  - binding energies
  - in-medium modified $\Delta$ width

\[ \Gamma \rightarrow \Gamma_{tot}^{med} = \tilde{\Gamma} + \Gamma_{coll} \]

- propagation of final state $X$ within **BUU transport model** with consideration of FSI

- most general: all neutrino flavors, all nuclei, CC & NC
Neutrino Nucleus Scattering

- $\nu A$ reaction is factorized using **impulse approximation**:

  $\nu_l N \rightarrow l^- X$

  with consideration of
  - Fermi motion
  - Pauli blocking
  - binding energies
  - in-medium modified $\Delta$ width

  $\Gamma \rightarrow \Gamma_{\text{tot}}^{\text{med}} = \tilde{\Gamma} + \Gamma_{\text{coll}}$

- propagation of final state $X$ within **BUU transport model** with consideration of FSI

- most general: all neutrino flavors, all nuclei, CC & NC
Weak Interaction Theory

- **interaction Lagrangian:**

\[
\mathcal{L}_{\text{int}} = -\frac{g}{2\sqrt{2}} \left( (J_{\mu}^{CC} + j_{\mu}^{CC}) W^\mu + \text{h. c.} \right) - \frac{g}{2 \cos \theta_W} (J_{\mu}^{NC} + j_{\mu}^{NC}) Z^\mu + e (J_{\mu}^{em} + j_{\mu}^{em}) A^\mu
\]

- **leptonic currents:**

\[
\begin{align*}
J_{\mu}^{CC} &= \sum_{l=e,\mu,\tau} \bar{\nu}_l \gamma_\mu (1 - \gamma_5) l \\
J_{\alpha}^{NC} &= \frac{1}{2} \bar{\nu}_l \gamma_\alpha (1 - \gamma_5) \nu_l - \frac{1}{2} (1 - 2 \sin^2 \theta_W) \bar{\nu}_l \gamma_\alpha (1 - \gamma_5) l + \sin^2 \theta_W \bar{\nu}_l \gamma_\alpha (1 + \gamma_5) l
\end{align*}
\]

- **concentrate on CC in the following, but note:**

  - NC is sensitive to the isoscalar strange quark contribution to the nucleon spin
    - in particular to the strange axial vector form factor
    - complementary to parity violating electron scattering or DIS of polarized leptons
Neutrino Nucleon Scattering

- **elementary processes:** \( \sigma = \sigma(QE) + \sigma(RES) + \sigma(Non - RES/DIS) \)

- dominated by **QE & Δ resonance**

**CC:**

\[
\begin{align*}
\nu n &\rightarrow l^- p \\
\nu n &\rightarrow l^- \Delta^+ \\
\nu p &\rightarrow l^- \Delta^{++}
\end{align*}
\]
Quasielastic Scattering

- hadronic current for $\nu_l n \rightarrow l^- p$

$$J^\alpha = \cos \theta_C \bar{u}_p \left( \gamma^\alpha F_1^V(Q^2) + \frac{i \sigma_{\alpha\beta} q_\beta}{2M} F_2^V(Q^2) + \gamma^\mu \gamma^5 F_A(Q^2) + \frac{q^\alpha \gamma^5}{M} F_P(Q^2) \right) u_n$$

CVC

$$F_{1,2}^V(Q^2) = F_{1,2}^p(Q^2) - F_{1,2}^n(Q^2)$$

PCAC

$$F_P(Q^2) = \frac{2M^2}{m_\pi^2 + Q^2} F_A(Q^2)$$

- BBA-2003 parametrization for $F_{1,2}^{n,p}$ and

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$
**Resonance Production**

- hadronic current for $\nu_l n \rightarrow l^- \Delta^+$

\[ J_\alpha = \cos \theta C \bar{\psi}^\beta(p') D_{\beta\alpha} u(p) \]

with the Rarita-Schwinger spinor $\bar{\psi}^\beta(p')$ and

\[
D_{\beta\alpha} = \left( \frac{C^V_3}{M} (g_{\alpha\beta} q - q_\beta \gamma_\alpha) + \frac{C^V_4}{M^2} (g_{\alpha\beta} q \cdot p' - q_\beta p'_\alpha) + \frac{C^V_5}{M^2} (g_{\alpha\beta} q \cdot p - q_\beta p_\alpha) + g_{\alpha\beta} C^V_6 \right) \gamma_5 \\
+ \frac{C^A_3}{M} (g_{\alpha\beta} q - q_\beta \gamma_\alpha) + \frac{C^A_4}{M^2} (g_{\alpha\beta} q \cdot p' - q_\beta p'_\alpha) + C^A_5 g_{\alpha\beta} + \frac{C^A_6}{M^2} q_\beta q_\alpha
\]

**CVC & M_{1+} dominance**

\[
C^V_4 \sim C^V_3 \quad C^V_5 = 0 \quad C^V_6 = 0 \\
C^V_3 \rightarrow eN
\]

**PCAC**

\[
C^A_6 \sim C^A_5
\]

**parametrization**

\[
C^V_3 \\
C^A_5 \quad C^A_4 \quad C^A_3
\]

- $\Delta$ width: $p$-wave $\Gamma \sim q_{CM}^3$
Resonance Production Cross Section

- double differential cross section $\frac{d^2\sigma}{dQ^2dW}$ for $\nu_\mu p \rightarrow \mu^- \Delta^{++}$

![Graphs showing the double differential cross section for different values of $Q^2$ and $W$.](image)
Neutrino Nucleus Scattering

- \( \nu A \) reaction is factorized using **impulse approximation**:
  - \( \nu_l N \rightarrow l^- X \)
  - With consideration of
    - Fermi motion
    - Pauli blocking
    - Binding energies
    - In-medium modified \( \Delta \) width
  - \[ \Gamma \rightarrow \Gamma_{tot}^{med} = \tilde{\Gamma} + \Gamma_{coll} \]

- Propagation of final state \( X \) within **BUU transport model** with consideration of FSI

- Most general: all neutrino flavors, all nuclei, CC & NC
Neutrino Nucleus Scattering

- $\nu A$ reaction is factorized using **impulse approximation**:
  - $\nu_l N \rightarrow l^- X$
  - with consideration of:
    - Fermi motion
    - Pauli blocking
    - binding energies
    - in-medium modified $\Delta$ width
    - $\Gamma \rightarrow \Gamma_{med}^{tot} = \tilde{\Gamma} + \Gamma_{coll}$

- propagation of final state $X$ within **BUU transport model** with consideration of FSI

- most general: all neutrino flavors, all nuclei, CC & NC
**Neutrino Nucleus Scattering**

- $\nu A$ reaction is factorized using **impulse approximation**:
  - $\nu_l N \rightarrow l^- X$
  - with consideration of
    - Fermi motion
    - Pauli blocking
    - binding energies
    - in-medium modified $\Delta$ width
    $$\Gamma \rightarrow \Gamma^{med}_{tot} = \tilde{\Gamma} + \Gamma_{coll}$$

- propagation of final state $X$ within **BUU transport model** with consideration of FSI

- most general: all neutrino flavors, all nuclei, CC & NC
BUU Transport Model

- description of heavy ion collisions, $e A$, $\gamma A$ and $\nu A$ reactions with one code
- well tested against experimental data, in particular for $\gamma^{(*)} A$
- coupled channel semiclassical transport model

- **Boltzmann-Uehling-Uhlenbeck equation**
  for each particle species $i$ ($i = N, R, \pi, \rho, K, \ldots$):

$$\frac{df_i}{dt} = (\partial_t + (\nabla_{\vec{p}} H) \nabla_{\vec{r}} - (\nabla_{\vec{r}} H) \nabla_{\vec{p}}) f_i(\vec{r}, \vec{p}, t) = I_{\text{coll}} [f_1, \ldots, f_i, \ldots, f_M]$$

Hamilton function: $H = \sqrt{(\mu + U_s)^2 + \vec{p}^2}$

- $f_i$ : phase space density

  **mean field for baryons**
  Skyrme type with momentum dependence

- set of BUU equations coupled via $I_{\text{coll}}$ and mean field
- off-shell transport, in-medium widths
BUU Transport Model – Collision Term

- **collision integral** accounts for changes in $f_i$ due to 2 particle collisions:
  - elastic and inelastic scattering (coupled channels)
  - Pauli blocking for fermions

- **FSI**
  - absorption
  - charge exchange
  - redistribution of energy
  - production of new particles

- most important scattering processes:
  
  \[
  \begin{align*}
  NN & \leftrightarrow NN & NR & \leftrightarrow NR' \\
  NN\pi & \leftrightarrow NN & mB & \leftrightarrow R, \text{ in particular } \pi N \leftrightarrow \Delta \\
  NN & \leftrightarrow NR & \pi N & \leftrightarrow \pi N \\
  NN & \leftrightarrow \Delta \Delta & \pi N & \leftrightarrow \pi \pi N 
  \end{align*}
  \]
Neutrino Nucleus Scattering

- $\nu A$ reaction is factorized using **impulse approximation**:
  - $\nu_l N \rightarrow l^- X$
  - with consideration of:
    - Fermi motion
    - Pauli blocking
    - binding energies
    - in-medium modified $\Delta$ width
    \[ \Gamma \rightarrow \Gamma_{tot}^{med} = \tilde{\Gamma} + \Gamma_{coll} \]

- propagation of final state $X$ within **BUU transport model** with consideration of FSI

- most general: all neutrino flavors, all nuclei, CC & NC
**Neutrino Nucleus Scattering**

**νA reaction is factorized using impulse approximation:**

- $\nu_l N \rightarrow l^- X$

  with consideration of
  
  - Fermi motion
  - Pauli blocking
  - binding energies
  - in-medium modified $\Delta$ width
  
  $$\Gamma \rightarrow \Gamma_{med}^{tot} = \tilde{\Gamma} + \Gamma_{coll}$$

- propagation of final state $X$ within **BUU transport model** with consideration of FSI

**most general: all neutrino flavors, all nuclei, CC & NC**

---

Tina Leitner, Universität Giessen

Modelling Nuclear Effects in Neutrino Scattering
Neutrino Nucleus Scattering

- $\nu A$ reaction is factorized using **impulse approximation**:
  - $\nu_l N \rightarrow l^- X$
  - with consideration of
    - Fermi motion
    - Pauli blocking
    - binding energies
    - in-medium modified $\Delta$ width
    - $\Gamma \rightarrow \Gamma_{med}^{tot} = \tilde{\Gamma} + \Gamma_{coll}$

- propagation of final state $X$ within **BUU transport model** with consideration of FSI

**exemplarily:** $\nu_\mu ^{56}\text{Fe} \rightarrow \mu^- X$ for $E_\nu = 0.4 - 2$ GeV
**Inclusive Cross Section** \( \nu_\mu^{56}\text{Fe} \rightarrow \mu^- X \)

- double differential cross sections per nucleon: \( \frac{d^2\sigma}{dE_\mu dQ^2 A} \)
- inclusive cross section:

\[
d^2\sigma/(dE_\mu dQ^2 A) \left[ 10^{-38} \text{ cm}^2/\text{GeV}^3 \right]
\]

\( E_\mu = 0.41 \text{ GeV} \)
Pion Production $\nu_\mu^{56}\text{Fe} \rightarrow \mu^- \pi X$

- $E_\mu = 0.41$ GeV, $Q^2 = 0.21$ GeV$^2$
  - $\pi^+$ without FSI
  - $\pi^+$ with FSI

- $E_\mu = 0.41$ GeV, $Q^2 = 0.61$ GeV$^2$
  - $\pi^+$ without FSI
  - $\pi^+$ with FSI
  - $\Delta$
  - QE

- $E_\mu = 0.41$ GeV, $Q^2 = 0.21$ GeV$^2$
  - $\pi^0$ without FSI
  - $\pi^0$ with FSI

- $E_\mu = 0.41$ GeV, $Q^2 = 0.61$ GeV$^2$
  - $\pi^0$ without FSI
  - $\pi^0$ with FSI
  - $\Delta$
  - QE
Pion Momentum Distribution $\nu_\mu^{56}\text{Fe} \rightarrow \mu^- \pi X$

$E_\nu = 1.2\text{ GeV}, E_\mu = 0.41\text{ GeV}, Q^2 = 0.21\text{ GeV}^2$

$E_\nu = 1.2\text{ GeV}, E_\mu = 0.41\text{ GeV}, Q^2 = 0.61\text{ GeV}^2$

$\pi^+$

$\pi^0$

$\sigma/(d\pi dE_\mu dQ^2 A) \times 10^{-38}\text{ cm}^2/\text{GeV}^4$

$p_\pi [\text{GeV}]$

E. Leitner, Universität Giessen

Modelling Nuclear Effects in Neutrino Scattering
Nucleon Knockout  $\nu_\mu^{56}\text{Fe} \rightarrow \mu^- N X$

$E_\nu = 0.41 \text{ GeV}, Q^2 = 0.21 \text{ GeV}^2$

$E_\mu = 0.41 \text{ GeV}, Q^2 = 0.61 \text{ GeV}^2$

$E_\nu = 0.41 \text{ GeV}, Q^2 = 0.21 \text{ GeV}^2$

$E_\mu = 0.41 \text{ GeV}, Q^2 = 0.61 \text{ GeV}^2$
Summary & Outlook

- **neutrino nucleus scattering**
  - impulse approximation
  - 2 steps: νN & FSI

- **neutrino nucleon reactions**
  - dominated by quasielastic scattering & Δ production
  - vector form factors obtained from electron scattering

- **BUU model**
  - well approved model for eA, γA → extended to νA
  - all important in-medium effects are taken into account

- **nuclear effects in νA scattering**
  - inclusive scattering, pion production & nucleon knockout
  - in-medium effects, in particular FSI, are not negligible

- **work in progress & future plans**
  - inclusion of higher resonances & non-resonant background
  - extraction of better N-Δ transition form factors from new eA data