Neutrino Interactions with Nuclei

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Neutrino detectors contain (heavy) nuclei. Interactions of neutrinos with nuclei may make the identification of elementary processes, like knock-out, pion-production or qe scattering difficult.

Neutrino-energy must often be reconstructed from detector response (→ T. Leitner, WG2).

In-medium physics: vector and axial form factors in medium can be tested.
neutrino-nucleus reaction: $\nu_l A \rightarrow l$ hadrons

- scattering off a single nucleon
  - free nucleon
  - nucleon bound in a nucleus
- Total QE scattering off a nucleus and $\pi$ production
  - final state interactions (FSI)
    - GiBUU transport model

Results: qe scattering, $\pi$ production, nucleon knockout

Conclusions
Model Ingredients: ISI

- Impulse-Approximation: interaction with one nucleon at a time

- Nucleons move in a density-dep., momentum-dep. potential (either Skyrme or Walecka) with $p$-distribution from Local TF and realistic density distr. \(\rightarrow\) essential for qe and knock-out processes

- Fermi motion:
  - local Thomas-Fermi based on density profiles from electron scattering and Hartree-Fock calculations (for neutrons)
Model Ingredients: ISI

- Free primary interaction cross sections, no off-shell dependence, cross sections boosted to restframe of moving nucleon in Fermigas
  - Include spectral functions for baryons and mesons (free + collision broadening)
- Cross sections taken from
  - Electro- and Photoproduction for vector couplings
  - Axial couplings modeled
  - Data or models for hadronic fsi
- Pauli-principle included
- Shadowing by geometrical factor \((Q^2, \nu)\) included
Model Ingredients: FSI

- Theoretical Basis

- Kadanoff-Baym equation
  - full equation can not be solved yet
    - not (yet) feasible for real world problems

- Boltzmann-Uehling-Uhlenbeck (BUU) models
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations
  - include mean-fields
  - BUU with off-shell propagation (essential for propagating off-shell particles): GiBUU

- Cascade models (typical event generators, NUANCE, GENIE, …)
  - no mean-fields, (no) Fermi motion
what is GiBUU?
semiclassical coupled channels transport model

general information (and code available):
http://theorie.physik.uni-giessen.de/GiBUU/

GiBUU describes (within the same unified theory and code)
- heavy ion reactions, particle production and flow
- pion and proton induced reactions
- low and high energy photon and electron induced reactions
- neutrino induced reactions
  .......using the same physics input! And the same code!
GiBUU transport model – BUU equation

- time evolution of spectral phase space density
  (for $i = N, \Delta, \pi, \rho, \ldots$) given by BUU equation

$$\frac{df_i}{dt} = (\partial_t + (\nabla_\vec{p} H) \nabla_\vec{r} - (\nabla_\vec{r} H) \nabla_\vec{p}) f_i(\vec{r}, \vec{p}, \mu, t) = I_{coll} [f_i, f_N, f_\pi, f_\Delta, \ldots]$$

$f_i(\vec{r}, \vec{p}, \mu, t)$ ← one-particle spectral phase space density for particle species $i$

$$H = \sqrt{(m_i + U_S)^2 + \vec{p}^2}$$ ← Hamiltonian

- one equation for each particle species (61 baryons, 21 mesons)
- coupled through the potential $U_S$ and the collision integral $I_{coll}$
- at higher energies ($W > 2.5$ GeV) particle production through string fragmentation (PYTHIA)
Transport vs. Quantummechanics

- Fully inclusive reactions: no info on final states, both
  - Quantum-mechanical reaction theory (Relativistic Impuls Approximation RIA, Distorted Wave Impuls Approximation DWIA)
  - Transport theory applicable. Lead to same results.

- Semi-Inclusive Reactions:
  - RIA and DWIA describes only loss of flux in one channel, does not tell where the flux goes and does not contain any secondary reactions or sidefeeding of channels
  - Transport describes elastic and inelastic scattering, coupled channel effects, full event history

- Exclusive Reactions (coherent production):
  - Phase coherence: Only QM applicable
Models for neutrino-nucleus scattering

- large variety in input (QE, RES, non-RES/DIS) and treatment of FSI

**QE**
- Granada model (Nieves et al.):
  - consider correlations,
  - FSI with Valencia MC code
- Ghent model (Ryckebusch et al.) / Meucci et al.:
  - FSI: DWIA, optical potential
  - Alberico et al. /
  - van der Ventel et al.:
  - FSI via PWIA

**RES**
- Paschos et al.:
  - FSI: random walk
- Singh, Oset et al.:
  - FSI: pion absorption in eikonal approximation

**GiBUU**
- event generators:
  - FSI: ??

**non-RES / DIS**
- Bodek et al. and others

Note: This list is not exhaustive.
**Quasielastic scattering**

- **Reactions:**
  - CC: $\nu_l n \rightarrow l^- p$
  - NC: $\nu n \rightarrow \nu n$, $\nu p \rightarrow \nu p$

- **Hadronic current:**
  \[ J_{\alpha}^{QE} = \langle N' | J_{\alpha}^{QE}(0) | N \rangle = \bar{u}(p') A_{\alpha} u(p) \]

  with
  \[ A_{\alpha} = \left( \gamma_\alpha - \frac{i q \alpha}{q^2} \right) F_V^1 + \frac{i}{2M} \sigma_{\alpha\beta} q^\beta F_V^2 + \gamma_\alpha \gamma_5 F_A + \frac{q_{\alpha} \gamma_5}{M} F_F \]

**Extra Term**
- Ensures vector current conservation for nonequal masses

**Axial Form Factors**
- Related by PCAC
- Dipole ansatz

**Vector Form Factors**
- Related to EM form factors by CVC
- BBBA-2007 parametrization

In addition:
- **Strange** vector and axial form factors for NC
Quasielastic scattering

\[ \nu_\mu \, n \rightarrow \mu^- \, p \]

\( \sigma \left[ 10^{-38} \text{ cm}^2 \right] \)

5% error in \( M_A \)

Barish, PRD 16 (1977)
Mann, PRL 31 (1973)
Baker, PRD 23 (1981)
CC pion production on free nucleons

- CC production of $\Delta^+$ and $\Delta^{++}$
  - subsequent decay into 3 channels: $\nu_l p \rightarrow l^- p \pi^+$
    - including higher resonances (isospin $\frac{1}{2}$):
      \[
      P_{11}(1440), D_{13}(1520), S_{11}(1535)
      \]
      \[
      \nu_l n \rightarrow l^- n \pi^+
      \]
      \[
      \nu_l n \rightarrow l^- p \pi^0
      \]

[Graphs showing cross sections as functions of $E_\nu$ for $\pi^+$ and $\pi^0$]
Medium modifications of the inclusive cross section

- All cross sections Fermi smeared
- $\Delta$ cross section is further modified in the nuclear medium:
  - $\pi$ decay might be Pauli blocked: decrease of the free width $\Gamma \rightarrow \Gamma_P$
  - additional "decay" channels in the medium: collisional width $\Gamma_{\text{coll}}$

\[
\begin{align*}
\Delta N &\rightarrow NN \quad \text{"pion-less decay"} \\
\Delta NN &\rightarrow NNN
\end{align*}
\]

- overall effect: increase of the width
  
  \[
  \Gamma \rightarrow \Gamma^{\text{med}} = \Gamma_P + \Gamma_{\text{coll}}
  \]

collisional broadening
Necessary check for inclusive cross section:
Electroproduction
CC pion production: $\nu_\mu^{56}\text{Fe} \rightarrow \mu^- \pi X$

$E_\nu = 1 \text{ GeV}$
Effects of FSI on pion kinetic energy spectrum at $E_\nu = 1$ GeV

- strong absorption in $\Delta$ region
- side-feeding from dominant $\pi^+$ into $\pi^0$ channel
- secondary pions through FSI of initial QE protons

Significant distortion of spectra by FSI
CC nucleon knockout: $\nu_\mu^{56}\text{Fe} \rightarrow \mu^- \text{N} \ X$

$E_\nu = 1\ \text{GeV}$

w/ o FSI

w FSI

Dramatic FSI Effect
NC nucleon knockout: $\nu_\mu \ ^{56}{\text{Fe}} \rightarrow \nu_\mu \ ^{N}X$

- NC: starts with comparable yields $p : n \sim 1 : 1$
  (remember: CC $p : n \sim 10 : 1$)
  $\rightarrow$ Sidefeeding less important

- FSI dominant
QE and $\Delta$ contributions to NC knock-out

At $E_\nu \approx 1.3$ GeV
$\Delta$ contribution to knock-out equals QE contrib
Result: Identification of QE events, MiniBooNE vs. K2K

Commonly used identifications for QE events have 20 – 30% error

- **K2K**: misses secondary neutrons
- **MiniBooNE**: counts also pion-kicked nucleons
Result: MiniBooNE

\[ \nu_\mu + ^{12}C \rightarrow \mu^- + 0 \pi + X \]

averaged over MiniBooNE flux - \( M_A = 1.0 \) GeV

Problem in peak height sensitive to vertex corrections and details of potential
Coherent Pion Production

Room for improvement: all calcs on coherent production use static approximation
Extension to higher energy

- **GiBUU model**
  - Extension to neutrino energies of up to \(\sim 100 \text{ GeV}\) straightforward
  - Elementary cross section then dominated by DIS

- **GiBUU** has been successfully applied to (Gallmeister, Kaskulow et al.) high energy electro-production:

  
  ![Graphs showing hadron and pion attenuation](image)

  - Hadron Attenuation at 27 – 280 GeV
  - Pion Attenuation at 5 GeV

Extension to neutrinos straightforward
GiBUU is a multi-purpose theory and tool to describe final state interactions, consistently in very different reactions. Includes

- Elastic scattering
- Inelastic scattering
- Sidefeeding (cc effect)

Inclusive electroproduction cross sections described quite well

- Potential, and in particular momentum dependence (FSI), essential already for primary interaction
- Method allows to propagate particles out to detector
Conclusions

- Particle production at neutrino energies of ~1 GeV
  - Inclusive cross section dominated by Δ excitation, with QE contribution, good description of electroproduction data
  - Semi-inclusive particle production incl. coupled channel FSI in GiBUU straightforward, tested against γA and πA
  - Δ excitations affect nucleon knockout, may contaminate QE experiments
  - Extension to higher energies (5 – 280 GeV) successful for electroproduction, for neutrinos to be done, straightforward
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