General Motivation

- Aspects of neutrino-nuclear reactions
  - Hadron physics:
    - axial couplings of nucleon resonances
    - reaction rates
  - Neutrino oscillation physics:
    - energy reconstruction
  - Dark Matter Background
Neutrino-nucleon cross section

CCQE

$\nu_l \rightarrow W^+ \rightarrow l^-$

$\nu_l \rightarrow W^+ \rightarrow l^-$

$\nu_l \rightarrow W^+ \rightarrow l^-$

DIS

Note:

$10^{-36} \text{ cm}^2 = 10^{-11} \text{ mb}$

Yellow: energy range of present experiments

From: J.A. Formaggio, G.P. Zeller
Neutrino Cross Sections

- Cross sections on the *nucleon*:
  - QE
  - Resonance-Pion Production + Born terms
  - Deep Inelastic Scattering → Pions
Quasielastic Scattering

- Vector form factors from $e^-$ scattering
- Axial form factors $F_A \leftrightarrow F_P$ and $F_A(0)$ via PCAC

dipole ansatz for $F_A$ with $M_A = 1$ GeV:

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

$$J_{QE}^\mu = \left(\gamma^\mu - \frac{q^\mu}{q^2}\right) F_1^V + \frac{i}{2 M_N} \sigma^{\mu\nu} q_\nu F_2^V$$

$$+ \gamma^\mu \gamma_5 F_A + \frac{g^\mu \gamma_5}{M_N} F_P$$

Graph showing the cross-section $\sigma$ as a function of $E_\nu$ with data points from various experiments:
Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data

\[ M_A \approx 1.02 \text{ GeV world average} \]

\[ M_A \approx 1.07 \text{ GeV world average} \]

Dipole ansatz is simplification, not good for vector FF
Pion Production

- Pion production dominated by $P_{33}(1232)$ resonance
- $C^V(Q^2)$ from electron data (MAID analysis with CVC)
- $C^A(Q^2)$ from fit to neutrino data (experiments on hydrogen/deuterium), so far only $C^A_5$ determined, for other axial FFs only educated guesses
One pion puzzle solved: ANL data preferable, but only $C_5$ determined

BUT: Sato et al find extraction of p X-section from D-measurement doubtful!
Neutrino Cross Sections

- Cross sections on the *nucleus*:
  - QE + fsi
  - Resonance-Pion Production + reabsorption
  - Deep Inelastic Scattering $\rightarrow$ Pions + reabsorpt

- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., 2p-2h excitations
  - Coherent neutrino scattering and pion production
GiBUU : Theory and Event Simulation
based on a BM solution of Kadanoff-Baym equations

Physics content : Buss et al, Phys. Rept. 512 (2012) 1

code available : http://gibuu.hepforge.org

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!
Transport Equation

\[ \mathcal{D} F(x, p) + \text{tr} \left\{ \text{Re} \tilde{S}^{\text{ret}}(x, p), -i \tilde{\Sigma}^{-}(x, p) \right\}_{pb} = C(x, p). \]

\[
\left[ \left( 1 - \frac{\partial H}{\partial p_0} \right) \frac{\partial}{\partial t} + \frac{\partial H}{\partial p} \frac{\partial}{\partial x} - \frac{\partial H}{\partial x} \frac{\partial}{\partial p} + \frac{\partial H}{\partial t} \frac{\partial}{\partial p^0} + \text{KB term} \right] F(x, p) \\
= -\text{loss term} + \text{gain term}
\]

\[ F(x, p) = 2\pi gf(x, p)A(x, p). \]
CCQE and Many-Body Interactions

MiniBooNE

QE-like
= CCQE + 2p2h + stuck pions
MinervA Pions

Discrepancy at small $\Theta/T_{\pi^0}$
Coherent contribution?
Neutrino Oscillations

State of affairs:
- All mixing angles are known, with some errors
- Mass hierarchy not known
- Possible CP violating phase not known

Errors determined by total event rates and energy reconstruction:
How well do we have to know the neutrino energy?
Observable Oscillation Parameters

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right) \]
LBNE, $\delta_{\text{CP}}$ Sensitivity

Appearance probability: $P_{\mu \rightarrow e}$

Need energy to distinguish between different $\delta_{\text{CP}}$

Need to know neutrino energy to better than about 100 MeV
In QE scattering on neutron at rest, only $l + p$, $0\pi$ is outgoing. Lepton determines neutrino energy:

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos \theta_\mu)}$$

**Trouble:** all presently running exps use nuclear targets
1. Nucleons are Fermi-moving $\rightarrow$ smearing around correct energy
2. Final state interactions hinder correct event identification $\rightarrow$ wrong energy reconstructed
Complication to identify QE, **always** entangled with $\pi$ production
Both must be treated at the same time!
'pure' QE cannot be measured!!
Oscillation signal in T2K

$\delta_{\text{CP}}$ sensitivity of appearance exps

Uncertainties due to energy reconstruction (left) as large as $\delta_{\text{CP}}$ dependence (right)
QE vs. Pion Production at DUNE

Target: $^{40}\text{Ar}$

Pions: Resonance + DIS
QE: 'true' QE + 2p2h

$\text{QE} \approx \frac{1}{3} \text{ total}$
$\text{Pions} \approx \frac{2}{3} \text{ total}$
Nearly 500 MeV difference between true and reconstructed event distributions → not a useful method

Dashed: reconstructed, solid: true energy

All calculations from GiBUU

QE Energy Reconstruction for DUNE

Muon survival in $0\pi + 1p + Xn$ sample

Dashed: reconstructed, solid: true energy

Dramatic improvement in $0\pi$, $1p$, $Xn$ sample, down by only factor 3
Coherent CC Scattering

Theorie of coherent pion production in bad shape: results of PCAC based theories differ significantly
(2 curves in right figure)
Coherent NC Scattering

So far not observed

\[ \sigma \sim N^2 E^2 \]

(N = neutron number)

Recoil energy

\[ E_R \sim E^2/A \]

Higher Cross section for large N, but smaller recoil
Summary

- Elementary X-sections for neutrino-nucleon in range of 100 MeV to 20 GeV not well under control. Formfactors badly known (compared to electrons)

- Full event simulations needed to describe neutrino-nucleus interactions: quality of extracted neutrino properties depends directly on quality of generator

- No good theory for coherent pion production available, for coherent neutrino scattering so far no data

- Precision era experiments require precision era (new) generators
A wake-up call for the high-energy physics community:

Low-Energy Nuclear Physics determines response of nuclei to neutrinos

“Wake up, Dr. Erskine—you’re being transferred to low energy physics.”