Neutrino Interactions: Puzzles and Progress

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ν Interactions: Scope

• We know a lot about neutrino interactions.
  – Weak interactions of quarks and leptons, and even neutrinos, have been extensively studied with $W^\pm$ and $Z^0$ boson precision production and decay measurements.

• Our quark targets are bound.
  – This is a problem, but not always a hard one.
  – Reactor experiments don’t have interaction problems with small momentum transfers and therefore nearly static, elastic interactions.

• GeV neutrinos on nuclei are a special pain point that nature has gifted us at accelerator neutrino oscillation experiments.
How do $\nu$ interactions matter?

• A neutrino oscillation experiment infers the parameters of interest in a single event, neutrino flavor and energy, by measuring the final state.

• Energy: detectors are imperfect and lack uniform response:
  - Energy is lost to nuclear mass, excitation.
  - Response to an energetic neutron is scant and stochastic, but energetic protons steadily lose energy by ionization.
  - A $\pi^-$ interacting in a detector tends to produce neutrons in its inelastic interactions, e.g., $\pi^- p \rightarrow \pi^0 n$. But a $\pi^+$ doesn’t.
  - A $\pi^0$ cleanly deposits all its energy, including its rest mass.

• Flavor: photons, primarily from $\pi^0$, can’t be perfectly separated from electrons.
And the $\nu_e$ Problem…

- By necessity, our $\nu_\mu$ rich beams have few $\nu_e$ in them to allow us to study any difference between $\nu_\mu$ and $\nu_e$ interactions.
- Therefore, we infer $\nu_e$ interactions from studies of $\nu_\mu$
  - But what we study can’t give us the whole picture.
  - Phase space (below), radiative corrections, etc.

O. Tomalak et al, arXiV: 2105.07939

![Graph](image)
Theory and Experiment
Failed Multi-Scale Problems

Consider a bicycle rider at right, descending the stairs of the Eiffel Tower

• A bicycle wheel is ~1m in diameter.
• If steps were ~1cm height or the steps were ramps of ~100m, we could predict the cyclist’s trajectory.
Failed Multi-Scale Problems

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- A bicycle wheel is ~1m in diameter.
- If steps were ~1cm height or the steps were ramps of ~100m, we could predict the cyclist’s trajectory.
- Since the wheel size is too close to the step size, the only reliable prediction is that it is going to be painful.
Our Failed Multi-scale Problem

- We have $E_{\nu} \sim 500 - 5000$ MeV, and therefore energy transfers from nearly zero to $\mathcal{O}(1000)$ MeV.

- Nuclear response at these neutrino energies spans elastic, metastable excitations, quasielastic (knockout), and inelastic (new particles).

- But single nucleon separation energy in $^{40}$Ar is $\sim 30$ MeV, and $m_{\Delta} - m_{N} \sim 250$ MeV.

- Processes cannot be cleanly separated, and models can’t approximate away nuclear structure nor final state degrees of freedom.

- Exact modeling of nuclear response becomes akin to equation of motion for the system above if energy required to uncouple springs is comparable to energy required to break them.
More Problems in $\nu$ Interactions

- There are other, subleading processes that are also difficult to model, but potentially important.
- Knocking out multiple nucleons ("2p2h", two-particle-two-hole, or more) is surprisingly common and difficult to model.
- Radiative corrections to neutrino interactions will be different for muon and electron neutrinos.
- Coherent $\pi^0$ production produces very energetic photons with little else in the event to warn it isn’t a $\nu_e$.
- And so forth…
Theory and Experiment

• Both are critical, and both are limited in what they can offer.

• Theory, as noted, uses necessary approximations, is limited in phase space, or calculates overly inclusive reactions ill suited to generator implementation.

• Data are good at pointing out modeling deficiencies, but often poor at pinpointing the problem.
Some Revisionist History
Hypothesis: Detector Improvements Lead to Improved Models

- Canonical exhibit is MiniBooNE.
- Primary detector capability was (excellent) lepton detection and identification.
- Single detector experiment: observed a discrepancy in the transverse momentum of muons, related to \( Q_{QE}^2 \).
  - With the data in hand, there could have been many culprits. But it was interpreted as a change in the free nucleon cross-section, as seen through \(^{12}\)C nuclei.
    - Large “axial mass”.

\[ F_A(Q^2) = F_A(0)/(1+Q^2/M_A^2)^2 \]

Phys.Rev.Lett. 100 (2008) 032301

snarky poster courtesy of Teppei Katori
Why was this important

• Response of carbon (from a GENIE model) in momentum and energy transfer is below.

• Lepton detecting experiments, like MiniBooNE and T2K/Hyper-K rely on the relationship between transverse momentum transfer and energy transfer to estimate neutrino energy.

- $W$ (recoil mass) is fixed in this space
  \[ W^2 = (M+q_0)^2 - q_3^2 \]

- Quasielastic band, at low $W$, is shown broadened by nuclear effects.

- MiniBooNE assumption was that the fix left interactions in the QE band.
How to solve this puzzle

- Easy in retrospect… correlation of recoil and the lepton to try to mimic the measurement of energy and momentum transfer.
- Requires detector technology (scintillator calorimetry) and high statistics.

![Graph showing reconstructed available energy (GeV) vs. events per GeV range](image-url)
Interpretation: Multinucleon Knockout, a.k.a., “2p2h”

- In brief, this data was interpreted as significant evidence for a large “2p2h” event rate.
- And significantly larger than predicted by models.
- Why does it matter? 2p2h sits at higher energy transfer for fixed momentum transfer.
- Interpretation of this rate as quasielastic leads to the wrong neutrino energy reconstruction.
Interpretation: Multinucleon Knockout, a.k.a., “2p2h”

- “2p2h” interpretation was corroborated by other measurements of the recoil system, in correlation with the leptons.
- Technique now used by NOvA as an important part of their oscillation analysis.

Alex Himmel, JETP Seminar, June 2018
Some Recent Results...
Result and Enabling Technology

• New MINERvA result correlating recoil with lepton kinematics.

• Key technologies: control of backgrounds, to isolate final states with only nucleons, and overwhelming statistics.

Simultaneous Measurement of Proton and Lepton Kinematics in Quasielastic like $\nu_\mu$-Hydrocarbon Interactions from 2 to 20 GeV
D. Ruterbories et al. (MINERvA Collaboration)
Phys. Rev. Lett. 129, 021803 – Published 6 July 2022
Why it matters

• Ability to compare lepton-only energy reconstruction (MiniBooNE, T2K) with calorimetric reconstruction (NOvA, DUNE) against a model, since both are accessible in this data.

• GENIE model has generally poor agreement on tails, and misses peaks by tens of MeV on recoil.

• This model can’t simultaneously be (successfully) used to estimate neutrino energies in the two types of experiments.
e4nu Energy “Feed-down”

- In electron scattering, knowledge of the true electron energy allows measurement of the difference between reconstructed and true energy.
- Model (SuSAv2 in this case) misses shape and rate in “feed-down” tail where electrons are reconstructed at much lower energy than reality, using neutrino reconstruction techniques.
Why it matters

- Although electron scattering doesn’t probe all parts of the reaction, key features, the nuclear initial state, and final state interactions, are common to electron and neutrino scattering.

- Deficiencies in the models used in neutrino scattering, when they fail to predict electron scattering, point squarely at deficiencies in the models used for $E_\nu$ reconstruction.

Figure from M. Khachatryan et al., Nature vol. 599, pp. 565–570 (2021)
Forecasting...
What can we expect before and during DUNE?

- SBN experiments are in an excellent position to exploit LAr TPC capabilities in lower energy, broadband beams.
  - Parallel to, and complimentary to MINERvA.
- Narrowband beams (off-axis) at NOvA and T2K will continue to make quasi-single energy measurements on carbon.
- Prediction: PRISM, with its ability to add information from the true neutrino energy, will generate data that solves puzzles critical for DUNE.
- Prediction: DUNE’s overwhelming near detector statistics will provide important constraints on $\nu_e$ interactions.
Closing Thoughts
Interactions: Progress on Puzzles

• Both theory and data are required to make progress on the understanding of neutrino interactions needed for precision oscillation experiments.

• New capabilities in neutrino experiments…
  – improved detectors,
  – high statistics,
  – creative analysis ideas,

• … have led to improvements in models which have proved critical for correct interpretation of oscillation data.

• Precision needs of DUNE will benefit from new capabilities, such as DUNE PRISM and electron neutrinos at high statistics, that we will use to explore neutrino interactions.
Backup
Measurements on Nucleons

- As the MiniBooNE story illustrates, a challenge data on nuclei is whether we are seeing a nucleAR effect, or a neutrino-nucleON effect.
- Mine safety considerations means we are unlikely to have significant new datasets using hydrogen targets, and nature doesn’t give us free neutrons.
- Measurements that can measure scattering on hydrogen by comparing carbon to hydrocarbon will may fill the gap.
- MINERvA is on the cusp of publishing its effort to measure $\bar{\nu}_\mu H \rightarrow \mu^+ n$.
- Capable DUNE near detectors with CH will have overwhelming statistics to exploit.