Neutrino-Nucleus Scattering in Neutrino Oscillation Experiments

Shirley Li (Fermilab)
3-Flavor Neutrino Oscillations

Unknown: \( \delta_{CP}, MH \)

A Few %: \( \theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{sol}, \Delta m^2_{atm} \)
3-Flavor Neutrino Oscillations

Unknown: $\delta$

A Few %: $\theta$, $\delta_{CP}$, $\Delta m_{21}^2$, $\Delta m_{31}^2$, $\theta_{12}$, $\theta_{13}$, $\theta_{23}$

Figure modified from Song et al., 20
Uncovering Neutrino-Nucleus Cross Section Problems
MiniBooNE

- Started to Produce Results in 2007
- Designed to Test Oscillations of eV Sterile Neutrinos
- 800 MeV @ 500 m
Axial Mass $m_A$ Measurement

\[ \langle N' | J_W^\mu | N \rangle \supset \bar{\mu}_N \gamma^\mu \gamma^5 F_A \mu_N, \quad F_A(Q^2) = \frac{F_A(0)}{\left(1 + \frac{Q^2}{m_A^2}\right)^2} \]

Results Disagree with Previous Experiments
Neutrino-Nucleus Cross Sections

How Do They Affect Measurements

How to Improve

How Do We Compute the Cross Sections?
1. Discussions Focus on DUNE and NOvA
2. Details Differ for Hyper-K and T2K
Measuring Neutrino Oscillation

Without Near Detector

\[
P(\nu_\mu \rightarrow \nu_e, E_\nu, l = L) = \frac{f_e(E_\nu, L)}{f_\mu(E_\nu, 0)} = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{f_\mu(E_\nu, 0)}
\]

\[
\sigma_e(E_\nu): \nu_e + ^{40}\text{Ar} \rightarrow e^- + X
\]

\[
\frac{\delta P}{P(\nu_\mu \rightarrow \nu_e, E_\nu)} \propto \frac{\delta \sigma_e}{\sigma_e(E_\nu)}
\]
Expected Accuracy

DUNE Nominal Accuracy on $\delta_{CP}$ as An Example

Need to Measure $P(E_\nu)/$Predict $\sigma(E_\nu)$ Accurately ($\leq 5\%$)
Measuring Neutrino Oscillation

With Near Detector

\[ P(\nu_\mu \rightarrow \nu_e, E_\nu, l = L) = \frac{f_e(E_\nu, L)}{f_\mu(E_\nu, 0)} = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{N_\mu(E_\nu, L)/\sigma_\mu(E_\nu)} \]

*Difference between \( \sigma_e \) and \( \sigma_\mu \) is well appreciated

Cross Section Predictions No Longer Play A Role?!?
Near/Far Cancellation?

\[ P(E_\nu) = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{N_\mu(E_\nu, L)/\sigma_\mu(E_\nu)} \]

ONE DOES NOT SIMPLY MEASURE THE TRUE NEUTRINO ENERGY
How Do Cross Section Calculations Impact Neutrino Energy Reconstruction?
How Neutrinos Are Detected

DUNE: Liquid Argon Time-Projection Chamber

Detects Charged Particle Tracks

$\nu_\mu \rightarrow 40\text{Ar} \rightarrow \pi, n, \mu, p$

-$\sim 100\text{s MeV}$

-- a few GeV
A Theorist’s View of a Neutrino Event

Only Predictions of Neutron Fraction Are Important
A Simulated Neutrino Event

- Proton vs. Pion: Quenching
- Spectrum: Thresholds
- Number of Final-State Particles: Nuclear Breakup Energy

All Exclusive Final States Play A Role

Friedland & SL, 18
The Cross Section Predictions That We Need:

\[
\frac{d\sigma}{dE_1 \, dE_2 \, ... \, dE_n}
\]

Not So Much:

\[
\sigma(E_\nu)
\]
Impact on BSM Searches

Case Study 1: Searching for Missing $p_T$

Coyle, SL, Machado, in prep

Signature:
Large Missing $p_T$

E.g., $\mathcal{O} = \frac{(L_\alpha H)(L_\beta H)}{\Lambda^2_{\alpha\beta}} \phi \rightarrow \frac{1}{2} \lambda_{\alpha\beta} \nu_\alpha \nu_\beta \phi$

After Tune:
Signature Gone
Impact on BSM Searches

Case Study 2: Sterile Neutrinos

Coyle, SL, Machado, in prep

Signature: Wiggles in Near/Far Ratios

After Tune: Slight Shift, Signature Persists
Outline

Neutrino-Nucleus Cross Sections

How Do They Affect Measurements

How to Improve

How Do We Compute the Cross Sections?
$\nu$-Nucleus Cross Sections

Beam Energy: 0.5 GeV – 5 GeV

$\nu_\mu$ + $^{40}\text{Ar}$

O or $^{12}\text{C}$, $^{16}\text{O}$ for Other Experiments

Proton or Neutron

| 20/36 |
\( \nu\text{-Nucleon Cross Sections} \)

Beam Energy: 0.5 GeV – 5 GeV

- Deep Inelastic Scattering
- Resonance Production
- Quasi-Elastic Scattering

Multiple Particles
Nucleon + Meson
Single Nucleon

No Controlled Expansion
\( Q^2 \approx 1 \text{ GeV}^2 \)
Kinematic Region

- **DIS:** $\nu_\mu + d \rightarrow \mu + u$
  
  Energy Too Low for Factorization

- **RES:** $\nu_\mu + n \rightarrow \mu + \Delta$
  
  30+ Resonance States, Not Enough Data

- **QE:** $\nu_\mu + n \rightarrow \mu + p$
  
  $$Q^2 = -q^2, \quad x = \frac{Q^2}{2p \cdot q}$$

All Channels Are Important

Ankowski, Friedland, SL, in prep
Compare $\sigma(E_\nu)$

Informative, But Not Adequate
Generator vs. $\nu$ Data

Experiments Use Generators, Mostly GENIE

- NOvA, 20
- T2K, 20
- MINERvA, 19
- MicroBooNE, 19

$\chi^2/N_{\text{bins}}$
- 245.9/42
- 108.8/42
- 172.9/42
- 126.5/42
Generator vs. $\nu$ Data

Experiments Use Generators, Mostly GENIE

No Models/Tunes Can Reproduce All Data Sets
Outline

Neutrino-Nucleus Cross Sections

How Do They Affect Measurements

How Do We Compute the Cross Sections?

How to Improve
Quasi-Elastic And Meson-Exchange Current Channels Are Important

What About Resonance Production and DIS?
MiniBooNE Setting the Tone

Quasi-Elastic and Meson-Exchange Current Channels Are Important

What About Resonance Production and DIS?
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Quasi-Elastic And Meson-Exchange Current Channels Are Important

What About Resonance Production and DIS?
**ν-A Generators vs. e-A Data**

- 2.4 GeV $e$
- $p/A$

- **Same Primary Vertex Models, Only Vector Couplings**

- **Same Final-State Interactions / Nucleon Distributions**

**E.g., Elastic Scattering:**

\[
\begin{align*}
\langle N'|J_γ^μ|N \rangle &= \bar{μ}_N' \left\{ γ^μ F_1 + \frac{iσ^{μν}q_ν}{2M} F_2 \right\} μ_N \\
\nu - p
\langle N'|J_γ^μ|N \rangle &= \bar{μ}_N' \left\{ γ^μ F_1 + \frac{iσ^{μν}q_ν}{2M} F_2 \right\} μ_N \\
\end{align*}
\]
**Neutrino Generators vs. Data**

$$\omega = E_e - E_{e'}$$

Ankowski, Friedland, SL, in prep

Data from Niculescu et al., 00
### Generator Treatment

<table>
<thead>
<tr>
<th>GENIE</th>
<th>GiBUU</th>
</tr>
</thead>
<tbody>
<tr>
<td>RES relativistic quark model</td>
<td>fit for form factors from single-pion prod. data</td>
</tr>
<tr>
<td>DIS PDF modified from GV98 that aims to work down to $Q^2 \rightarrow 0$</td>
<td>PYTHIA</td>
</tr>
</tbody>
</table>

$$
\langle \Delta|J^\mu|N \rangle = \bar{u}_\Delta^\alpha \left[ \gamma_5 (q g^\alpha \mu - q^\alpha \gamma^\mu) G_1 \\
+ \gamma_5 (q^\alpha p'^\alpha - q \cdot p' g^\alpha \mu) G_2 \\
+ \gamma_5 (q^\alpha q'^\mu - q^2 g^\alpha \mu) G_3 \right] u_N
$$
Neutrino Generators vs. Data

3.245 GeV @ 26.98°
GENIE

30/36
Ankowski, Friedland, SL, in prep
Data from Niculescu et al., 00
Neutrino Generators vs. Data

- GENIE: 50—80% error
- GiBUU: 20—30% error
- RES vs. DIS: Not a Good Separation
- Major Implementation Errors

Ankowski, Friedland, SL, in prep
Data from Niculescu et al., 00
Cross Section Calculations

Observables Are High-Dimensional

\[ \frac{d\sigma}{dE_1 dE_2 \ldots dE_n} \] (Exclusive), not \[ \frac{d\sigma}{dE} \] (Inclusive)

Much Harder to Compute Exclusive Cross Sections
More Data Is Needed!

Existing Coverage Is Poor

- Only 1 Set of Argon Data
- Little Coverage of Phase Space Important for DUNE
- Only Inclusive Data

Ankowski et al., 19
Light Dark Matter eXperiment

Planning Stage Funded!
Important Design Features

Ankowski et al., 19
Also: CLAS12

- Good Coverage
- Different Nuclei
- All Outgoing Particles in the Forward Region

Large Overlap with DUNE Phase Space
Conclusions

1. GeV Neutrino-Nucleus Scattering is Crucial to the Success of Long-Baseline Neutrino Experiments

2. No Complete Theoretical Framework Available; Difficult to Assess Uncertainties

3. More Scattering Data is Needed

4. New Theoretical Ideas Are Needed
Thank you