Neutrino cross sections

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September 21, 2015
Remember: We love Neutrinos!

Motivation- Why are neutrino cross sections important?
  - Oscillation experiments
  - Why am I focusing on CCQE

CCQE Scattering
  - What is CCQE?
  - What do we know?
  - Ah.... do we know it?
  - Potential problems and things to look at

Experiment- Minerva
  - NUMI beamline and detector
  - Differential cross section measurement
More than three type of neutrinos?
Majorana neutrinos? Dirac neutrinos?
Mass hierarchy
CP violation
Oscillation experiments

- Focus on mass hierarchy, CP violation
- Find appearance or disappearance
- Oscillation probability depends on neutrino energy

\[ P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E_\nu) \]

- Need cross section to reconstruct energy

Quality of cross section is important to reduce systematic errors

<table>
<thead>
<tr>
<th>Source of uncertainty (number of parameters)</th>
<th>( \delta n_{SK} ) / ( n_{SK} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-independent cross section (11)</td>
<td>4.9%</td>
</tr>
<tr>
<td>Flux and ND280-common cross section (23)</td>
<td>2.7%</td>
</tr>
<tr>
<td>SK detector and FSI+SI systematics (7)</td>
<td>5.6%</td>
</tr>
<tr>
<td>( \sin^2(\theta_{13}), \sin^2(\theta_{12}), \Delta m^2_{31}, \delta_{CP} ) (4)</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total (45)</td>
<td>8.1%</td>
</tr>
</tbody>
</table>

arxiv1403.1532v
Oscillation experiments

We don’t see neutrino with detector! We don’t know the energy it has when it interacts

What we need to know to reconstruct energy

- Probability of neutrino interacting
- Nuclear modifications
- Relation between neutrino energy and quantities observed
Oscillation experiments

How many neutrino interactions should I see?

\[ N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target} \]

Need to know information of detector and source of neutrinos

Cross section pretty much "translates" event rate to appearance probability
Why CCQE?
What is CCQE Scattering?

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

QE: Neutrino scatters off an entire nucleon  
In CCQE neutrino interaction: target neutron is converted to a proton  
No pions in final state
CCQE - Model

Llewellyn-Smith (1972)

\[
\frac{d\sigma}{dQ^2} = \frac{G_F^2 M^2}{8\pi E^2_p} \left[ A \pm \frac{s-u}{M^2} B + \frac{(s-u)^2}{M^4} C \right]
\]

Vector form factors obtained from electron scattering
Axial-vector form factor depends on empirical parameters

\[
F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}
\]
CCQE - results

![Graph showing CCQE results](image-url)
CCQE - new questions

- Both on C, appear to differ on 30
- New measurements not coming as expected
- Nuclear effects?
Measurement of Muon Neutrino Quasielastic Scattering on a Hydrocarbon Target at $E_{\nu} \sim 3.5$ GeV
\[ \nu_\mu + n \rightarrow \mu^- + p \]
\[
\left( \frac{d\sigma}{dQ_{QE}^2} \right)_{i} = \frac{\sum_j U \left( N_{data,j} - N_{bkgd} \right)}{\epsilon_i (\Phi T) \Delta Q_{QE,i}^2}
\]
Differential cross section measurement

\[ \frac{d\sigma}{dQ^2_{QE}} (\text{cm}^2/\text{GeV}^2/\text{neutron}) \]

\[ 1.5 < E_\nu < 10 \text{ GeV} \bullet \text{Absolutely Normalized} \]

- data
- NuWro RFG \( M_A = 1.35 \)
- NuWro RFG \( M_A = 0.99 + \text{TEM} \)
- NuWro RFG \( M_A = 0.99 \)
- GENIE RFG \( M_A = 0.99 \)
- NuWro SF \( M_A = 0.99 \)

\[ \text{Ratio to GENIE} \]

\[ 10^{-2} < Q^2_{QE} (\text{GeV}^2) < 1 \]

\[ 10^{-1} < Q^2_{QE} (\text{GeV}^2) < 1 \]

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