MiniBooNE Cross Section Results

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NuFACT11, August 1, 2011
Outline

• MiniBooNE Description
• CC QE
• NC Elastic
• NC & CC $\pi^0$
• CC $\pi^+$
• Conclusions
MiniBooNE Experiment

- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector
ν Event Rate Predictions

#Events = Flux x Cross-sections x Detector response

External measurements (HARP, etc)
νμ rate constrained by neutrino data

External and MiniBooNE measurements
-π⁰, delta and dirt backgrounds constrained from data.

Detailed detector simulations checked with neutrino data and calibration sources.

Neutrino

Green: Effective π⁰’s
Blue: Dirt
Pink: Delta’s
Yellow: Other
Lt Blue: Nue (CCQE)

Antineutrino

Green: Effective π⁰’s
Blue: Dirt
Pink: Delta’s
Yellow: Other
Lt Blue: Nue (CCQE)
Modeling Production of Secondary Pions

- HARP (CERN)
  - 5% $\lambda$ Beryllium target (good approximation)
  - 8.9 GeV proton beam momentum
  - $\pi^+$ & $\pi^-$

Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024
Neutrino Flux from GEANT4 Simulation

Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode
Intrinsic $\nu_e$ background is ~0.5% for both Nu-Mode & Antinu-Mode
Neutrino Cross Sections

- 8 neutrino cross section publications

- have measured cross sections for 90% of $\nu$ interactions in MB
Antineutrino Cross Sections

- 2 antineutrino cross section papers

- additional antineutrino analyses currently underway
Calibration Sources

Tracker system

15% E resolution at 53 MeV

δm ~ 20%

Michel electrons

Cosmic Muon Energy

Visible energy range of oscillation signal

π^0 photon energies

Tracker & Cubes

Through-going cosmics

Visible Tank Energy (MeV)

Cube Range Energy (MeV)
Quasi-Elastic Scattering

Originated in electron-nucleus scattering, where inclusive electron scattering is expected to be dominated by knocking a single (unmeasured) nucleon out of the nucleus

\[ e^- (q, \omega) n, p \]

Expect similar response from almost all nuclei, characterized by initial momentum distribution

From Joe Carlson
Simple Fermi-Gas Model Appeared to Explain the Data Well

Moniz et al PRL 1971

Impulse Approximation
Quasi-Elastic Kinematics

Experimentally, $q$ and $\omega$ are precisely known without any reference to the nuclear final state.

FIG. 1. Schematic representation of inclusive cross section as a function of energy loss.

From Joe Carlson
ν_μ CCQE Scattering


Extremely surprising result - CCQE \( \sigma_{\nu\mu}(^{12}\text{C}) > 6 \sigma_{\nu\mu}(n) \)

How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

Look more carefully at electron scattering: Enhancement of Transverse Responses


Longitudinal scattering weakly dependent upon nucleus and momentum transfer
Transverse response depends dramatically upon $q^2$ (up to ~50%): not reproduced in FG model!
Transverse also nearly independent of nucleus.

From Joe Carlson
Nuclear Effects to the Rescue?

• possible explanation: extra contributions from two-nucleon correlations in the nucleus (all prior calculations assume independent particles)

• large enhancement from short range correlations (SRC)

• can predict MiniBooNE data without having to increase $M_A$ (here, $M_A=1.0$ GeV)

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Martini et al., PRC 80, 065001 (2009)

From Sam Zeller
Nuclear Effects to the Rescue?

• possible explanation: extra contributions from two-nucleon correlations in the nucleus (all prior calcs assume indep particles)

• could this explain the difference between MiniBooNE & NOMAD?
  
  NOMAD: $\mu$ & $\mu + p$
  MiniBooNE: $\mu$ + no $\pi$’s + any # $p$’s
  jury is still out on this

Martini et al., PRC 80, 065001 (2009)

From Sam Zeller
Comparisons to MB Double Diff’l $\sigma$

Nieves, Simo, & Vacas, arXiv:1106.5374

Accounts for long range nuclear correlations & multinucleon scattering with $M_A = 1.049$ GeV

FIG. 1. Muon angle and energy distribution $d\sigma/d\cos\theta dT_{\mu}$. Different panels correspond to the various angular bins labeled by their cosine central value. Experimental points from Ref. [3]. Green-dashed line (no it) is the full model (including multinucleon mechanisms and RPA) and calculated with $M_A = 1.049$ GeV. Red-solid line is best fit ($M_A = 1.32$ GeV) for the model without RPA and without multinucleon mechanisms.
Is the Neutrino Energy Estimated Correctly in CCQE?


Meson Exchange Diags.

2p-2h fin. sts.

Correlation Diags.

Electron Scattering

$^{56}$Fe, $q=0.55\text{GeV/c}$

$$E_{\nu}^{QE} = \frac{(2m'_nE_\mu-(m'_n^2+m_\mu^2-m_p^2))}{2.\sqrt{(m'_n-E_\mu)^2+m_\mu^2}\cos(\theta)}}$$

One body RFG

Meson exchange

Correlation
$\bar{\nu}_\mu$ CCQE Scattering

Enhancement also observed in antineutrino scattering
Data/MC integrated ratio: $1.39 \pm 0.14$

J. Grange, NuINT11
Neutrino Neutral Current Elastic


- Neutral current elastic process probes similar formalism as charged-current quasi-elastic
  - sensitive to structure of both nucleon types.

- Proton fitter developed that reconstructs protons with Scintillation & Cherenkov light ($T_p > 350$ MeV)
- 94,531 events (~65% purity)
- Measured quantities:
  - $d\sigma/dQ^2$
  - $\Delta s = 0.08+0.26$ (strange quark contribution to proton spin)
  - $M_A = 1.39+0.11$

From D. Perevalov
Antineutrino Neutral Current Elastic

- 21,500 events (4.48x10^{20} POT)
- 57% $\nu$NC EL purity

(R. Dharmapalan, NuInt11)
Final State Interactions (FSI): Once produced, hadrons have to make it out of the target nucleus. There can be nucleon rescattering and \( \pi \) absorption & charge exchange. Therefore, we measure final state kinematics in detail and report what we observe.
Charged-Current $\pi^+$


- Crucial channel for $\nu_\mu$ disappearance measurements
  - can bias CCQE signal if $\pi^+$ lost

- First tracking of charged pions in a Cherenkov detector!

- Measured quantities:
  - $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$
  - $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\mu d\theta_\mu$
  - $d^2\sigma/dT_\pi d\theta_\pi$ (many firsts)

Custom 3 Cherenkov-ring fitter developed to reconstruct both $\mu$, $\pi^0$

- Resonant-only process

- Measured quantities:
  - $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/dp_\pi$, $d\sigma/d\theta_\mu$, $d\sigma/d\theta_\pi$
  - (many firsts)

Neutral-Current $\pi^0$


- Background measurement very important for $\nu_e$ appearance analysis
  - NC$\pi^0$ signature electron-like if lose $\gamma$
  - NC$\pi^0$ constrains $\Delta$ production which allows for a "measurement" of $\Delta$ rad. decay background

- Valuable input for $\theta_{13}$ Cherenkov-based measurements
  - T2K, LBNE

- Measured quantities:
  - $d\sigma/dp_\pi$, $d\sigma/d\theta_\pi$
    (for both $\nu$, $\bar{\nu}$ data)

From Joe Grange
NC$\pi^0$ Scattering


coherent fraction=19.5+-1.1+-2.5%
Single Pion Cross Sections

(R. Nelson, NuInt11)
Conclusions

• MiniBooNE Neutrino Cross Sections are more interesting than expected!
• Theorists & Experimentalists must carefully specify what they mean by QE & $E_\nu$ and what is assumed.
• Fermi Gas Model is inadequate for $\nu$-nucleus inclusive scattering.
• Realistic models are required and have to include initial and final state correlations and 2-body currents.
• Differences between neutrino & antineutrino cross sections and energy reconstruction must be better understood when searching for CP Violation.
Backup
Super Scaling


A new dimensionless scaling variable is employed

$$\psi = \frac{y_{RFG}}{k_{Fermi}} = \frac{m_N}{k_{Fermi}} \left( \lambda \sqrt{1 + \tau^{-1}} - \kappa \right)$$

$$\lambda = \frac{\omega}{2m_N}, \tau = \frac{Q^2}{4m_N^2}, \kappa = \frac{q}{2m}$$

Note linear scale: not bad for

$$\psi < 0$$

Serious divergence above

$$\psi = 0$$
Diagrams of Some Short Range Correlations

Some RPA p-h diagrams from Martini et al. PR C80, 065501

Exchange Current and pionic correlation diagrams in Amaro et al. PR C82 044601
Comparisons to MB Double Diff’l $\sigma$

- underestimate the data at large scattering angles particularly for small $T_\mu$

Martini, FNAL PPD $\nu$ dept. presentation, 09/30/10

- need more measurements of muon (and proton) kinematics!

From Sam Zeller

Amaro et al., arXiv:1104.5446 [nucl-th]