Nuclear Target Cross Section Ratios at MINERvA

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How do we love MINERvA?
Let me count the ways*…

**Neutrino Physics**

“I want to measure neutrino oscillations”
MINERvA will…
- help me understand neutrino energy reconstruction
- reduce my uncertainties from cross sections and nuclear effects

**Nuclear Physics**

“I want to measure nucleon structure”
MINERvA will…
- use a probe sensitive to flavor and axial structure

*this is an incomplete list of the ways we love MINERvA
Priority: $\sigma( E_\nu )$

Neutrino-Nucleus Interactions

- Heavy nuclear targets used to get necessary statistics
  - Carbon, Iron, Lead, Water, Argon
- Nuclear effects are significant in neutrino scattering
  - Affects energy smearing and event rate
- Neutrino interaction simulation (models) rarely handle nuclear modifications well
  - They need data!

Must understand nuclear effects in neutrino scattering!
Charged lepton data show structure function $F_2$ effectively changes when nucleon bound in nucleus

Abstract:
“Using the data on deep inelastic muon scattering on iron and deuterium the ratio of the nucleon structure functions $F_2(Fe)/F_2(D)$ is presented. The observed $x$-dependence of this ratio is in disagreement with existing theoretical predictions.”

The EMC effect still puzzles after 30 years

Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

$$x = \frac{Q^2}{2M\nu}$$
Priority: $d\sigma/dx$

No comparable neutrino data!

Plot of ratio (R) of NUTEV ($\nu$-Fe) data to theoretical predictions of free nucleon $F_2$. Compared to fits to ratio from charged lepton.

Expectations for neutrino nuclear structure function modification:

- Neutrinos sensitive to structure function $F_3$
  - (Charged leptons are not)
  - Gives neutrinos ability to separate valence and sea

- Neutrinos sensitive to axial contribution of structure function $F_2$
  - (Charged leptons are not)
  - Axial effect larger at low $x$, low $Q^2$
**Inclusive Charged-Current Neutrino Cross Sections**

- **Quasi-Elastic (CCQE)**
  - knock out nucleon-

- **Resonance Production (Res)**
  - excite nucleon-

- **Deep Inelastic Scattering (DIS)**
  - destroy nucleon-

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**Graphical Representation:**

- $\nu_l \rightarrow l^-$
- $W^+$
- $n \rightarrow p$
- $\nu_l \rightarrow l^-$
- $W^+$
- $p \rightarrow p \Delta^{++}$
- $d \rightarrow W^+ u$
- $\pi^+, K, \pi^0$

**References:**


**Comments:**

- Deep Inelastic Scattering (DIS) can lead to the production of resonance states.
- Quasi-Elastic (CCQE) scattering involves the exchange of a W boson, leading to the production of a resonance state.

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**Quasi-Elastic (CCQE) Cross Section Graph:**

- $\nu_\mu$
- $\nu_e$
- $E_\nu$ (GeV)
- $\sigma / E_\nu (10^{-38} \text{ cm}^2 / \text{GeV})$

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**Moriond QCD - MINERvA Nuclear Ratios - Brian Tice**

March 26, 2014
MINERvA Detector (again)

- 120 modules for tracking and calorimetry (~32k readout channels)
  - Active element is polystyrene (plastic scintillator)
- Construction completed Spring 2010. He and Water added in 2011
- Magnetized MINOS Near Detector serves as toroidal muon spectrometer
MINERvA Detector (again)

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250 kg Liquid He

Active Scintillator Modules

1” Fe / 1” Pb
323kg / 264kg

1” Pb / 1” Fe
266kg / 323kg

3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg

0.3” Pb
228kg

500kg Water

.5” Fe / .5” Pb
161kg / 135kg

Tracking Region

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Targets used for today’s result

Active Scintillator Modules

<table>
<thead>
<tr>
<th>A</th>
<th>Mass (t)</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.16</td>
<td>6k</td>
</tr>
<tr>
<td>Fe</td>
<td>0.63</td>
<td>19k</td>
</tr>
<tr>
<td>Pb</td>
<td>0.71</td>
<td>24k</td>
</tr>
<tr>
<td>CH</td>
<td>5.48</td>
<td>189k</td>
</tr>
</tbody>
</table>

**Target 2**
- 1" Pb / 1" Fe
- 266kg / 323kg

**Target 3**
- 3" C / 1" Fe / 1" Pb
- 166kg / 169kg / 121kg

**Target 4**
- 0.3" Pb
- 228kg

**Target 5**
- .5” Fe / .5” Pb
- 161kg / 135kg
Event Topology
Muon must be matched to a momentum- and charge-analyzed track in MINOS ND

Interaction Material
Vertex must be in passive nuclear target or adjacent scintillator plane
Event Topology
Muon must be matched to a momentum- and charge-analyzed track in MINOS ND

Interaction Material
Scintillator events must be in the fiducial volume of the tracker
Event Reconstruction

**Hadronic Energy**
Sum of non-muon visible energy. Weight for passive material traversed.

\[ \nu = E_{recoil} = \alpha \times \sum_{i} \frac{E_i}{f_i} \]

**Muon Energy**
From range or curvature in MINOS. Add energy lost in MINERvA.

**Muon Angle**
Fitted track slopes at vertex.

**Unfold neutrino energy distributions**
Use simulation of detector smearing

**Do not unfold x distributions**
Large migration among x bins
Avoid systematic effects

\[ E_{\nu} = \nu + E_{\mu} \]

\[ x = \frac{Q^2}{2M_{\nu}} \]

\[ Q^2 = 2E_{\nu} (E_{\mu} - p_{\mu} \cos (\theta_{\mu})) \]
**Major Background - Misidentified Nucleus**

Background from other sources < 1%

**Simulation**

**Signal**

Significant impurity of scintillator events. Expect ~23% from fiducial mass of iron vs. scintillator

Few carbon/lead events migrating into iron sample
An event from Target 3

**Lead** candidate

This Event
- Run: 2014
- Subrun: 5
- Gate: 609
- Slice: 8

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An event from Target 3
Carbon candidate

This Event
Run: 2005
Subrun: 5
Gate: 111
Slice: 3

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One track events from passive target have a vertex in the first plane downstream of the target.

Tracking region used to estimate and subtract contamination from scintillator events.
Event distributions in Fe of Target 5

A separate estimated background for data and Simulation

Simulation scaled to data by total number of events passing selection. Shading on simulation is systematic uncertainty.
Kinematic Space

Event sample is a blend of interaction channels

\[ W = \sqrt{M^2 + 2M\nu - Q^2} \]
Errors on Absolute Cross Section

Flux is dominant systematic

$\frac{d\sigma_{Fe}}{dx}$
Errors on Absolute Cross Section

\[ \frac{d\sigma}{dx} = \frac{\sum_j U_{ij} (d_j - b_j)}{\epsilon_i (\Phi T) \Delta x_i} \]

Flux is the same throughout detector

\[ d\sigma^{Fe}/dx \]

Take ratio of cross sections to ~cancel flux
Errors on **Absolute Cross Section**

- $d\sigma^{Fe}/dx$

Errors on **Ratio of Cross Sections**

- $\frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx}$
Results

Charged-Current Inclusive Ratios of Cross Sections

Signal Kinematics
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 deg

Neutrino Energy

$\frac{\sigma^C}{\sigma^{CH}}$, $\frac{\sigma^{Fe}}{\sigma^{CH}}$, $\frac{\sigma^{Pb}}{\sigma^{CH}}$

Bjorken x

$\frac{d\sigma^C}{d\sigma^{CH}}$, $\frac{d\sigma^{Fe}}{d\sigma^{CH}}$, $\frac{d\sigma^{Pb}}{d\sigma^{CH}}$
Neutrino Energy

- No evidence of tension between our data and simulation here
  - Good news for oscillation experiments so far...
High $x$

- At $x=[0.7,1.5]$, we observe an excess that grows with the size of the nucleus.
- This effect is not predicted by simulation.
Low x

- At $x=[0^*, 0.1]$, we observe a **deficit** that increases with the size of the nucleus
- This effect is not predicted by simulation

**Expected Neutrino Differences**

- Neutrinos sensitive to structure function $xF_3$
- Neutrinos sensitive to axial piece of structure function $F_2$

* Simulation suggests events down to 0.005
  No events really at 0
Simulations of Nuclear Modification

Our Simulation | GENIE 2.6.2

- Fit to charged lepton DIS data
- All nuclei have same modification
  - All treated as isoscalar iron

A. Bodek, I. Park, and U.-K. Yang,

Compare to Other Models

- Kulagin-Petti (KP)
  - Microphysical model
  - Starts with neutrino-nucleon F1, F2, F3
  - Incorporates A-dependent effects

- Bodek-Yang 2013 (BY)
  - Similar to GENIE
  - Specific fits for C, Fe, Pb

Differ by only < 1%

Conclusions

- First results from nuclear targets in MINERvA
- First precise direct measurement of nuclear dependence of neutrino cross sections in the few-GeV regime
- Result submitted to PRL. Now at arXiv:1403.2103

Measurement of Ratios of $\nu_\mu$ Charged-Current Cross Sections on C, Fe, and Pb to CH at Neutrino Energies 2–20 GeV

- Our data are not reproduced by simulation
  - Available models differences are small compared to discrepancy
- Oscillation experiments should consider discrepancies in systematics
- More theoretical work is needed to improve models of neutrino-nucleus scattering in all kinematic regions
Backup
Background - Rock Muons

Affected only Target 2 in the earliest data

Uninstrumented planes reduced tracking efficiency. Veto wall was not installed yet.

Target 2 ≈ 50% of iron, 33% of lead. Early data ≈ 30% of all neutrino data.

→ < 1% flat correction
Background - Neutral Current and $\bar{\nu}_\mu$ Events

Small backgrounds (<0.5%)
Subtract using simulation prediction for fractional background

Wrong sign contamination is smaller in the beam’s focusing beam
Kinematic Space

Shows all analyzed events from all nuclei

- DATA
- Soft DIS
- Inelastic Continuum
- DIS
- Resonances
- Quasi-elastic

Reconstructed \( Q^2 \) (GeV/c)^2 vs. Reconstructed Bjorken \( x \)

- \( W = 2 \) GeV
- \( W = 1.3 \) GeV
Forming a Cross Section

\[
\left( \frac{d\sigma}{dx} \right)_i = \frac{\sum_j U_{ij} (d_j - b_j)}{\epsilon_i (\Phi T) \Delta x_i}
\]

- **data – background = signal**
- **Unfolding matrix**
  - From reco bin j to “true” bin i
- **Efficiency for bin i**
- **Flux times target number**
  - Flux may depend on bin
- **Bin width**
Bin Migration

\[
\left( \frac{d\sigma}{dx} \right)_i = \sum_j U_{ij} (d_j - b_j) \epsilon_i (\Phi T) \Delta x_i
\]

- Unfold in neutrino energy
  - Iterative Bayesian unfolding with 4 iterations

- Fold true x distributions
  - Multiply by this matrix \( \rightarrow \)
  - Avoids model dependence
  - Migration in x is significant
Reconstruction Efficiency

Signal Kinematics
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 deg

MINOS-match requirement
Muon momentum threshold ~ 2 GeV

(plots made with Target 5 lead events)

\[
\left( \frac{d\sigma}{dx} \right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}
\]
Subtract the Plastic Background

- Predict spectrum of background using:
  - Events in the Tracker
  - Geometric Acceptance
  - Reconstruction Efficiency

Found this event in scintillator of tracker

Pretend the same event happened in plastic background
Predict spectrum of background using:

Events in the Tracker

Selection of events in tracker volume done in both data.
Does not use cross section model.

Data-driven background
Predict spectrum of background using:

- Geometric Acceptance

Muon-only Geant4 simulation measures probability muon will hit MINOS

- Function of muon energy, muon angle, vertex
- Does not use neutrino interaction model
Predict spectrum of background using:

**Geometric Acceptance**

- Muon-only Geant4 simulation measures probability muon will hit MINOS
  - Function of muon energy, muon angle, vertex

- Apply reweight factor to each event in tracker
  - “For every 1 event like this in the tracker, there will be X in the background”

\[
RW = \frac{f_{\text{target}}(E_\mu, \theta_\mu)}{f_{\text{tracker}}(E_\mu, \theta_\mu)}
\]
Predict spectrum of background using:

- Efficiency also depends on hadronic energy
  - Shower can obscure muon. Not addressed by geometric acceptance.
- Measure remaining efficiency with simulation
  - GENIE 2.6.2 and Geant4
Accuracy of Background Estimation

Events in the Tracker
Geometric Acceptance
Reconstruction Efficiency

Plastic BG Prediction for Iron of Target 5 (MC)

Stat. Errors Only

$\chi^2/\text{ndf} = 18.69/8 = 2.34$

Plastic BG Prediction for Iron of Target 5 (MC)

Stat. Errors Only

$\chi^2/\text{ndf} = 6.04/5 = 1.21$
Errors on Absolute Cross Section

\[ \sigma_{Fe} \]

Errors on Ratio of Cross Sections

\[ \frac{\sigma_{Fe}}{\sigma_{CH}} \]
Form Ratios

- Combine targets
  - E.g. Add events from all lead pieces after efficiency correction
- Divide C, Fe, Pb cross sections by scintillator cross section
  - Each nucleus divided by a statistically independent scintillator measurements
  - Scintillator measurement is specific for each nucleus, to use the same transverse area