Neutrino–nucleus scattering results from MINERvA

Jeff Nelson
William & Mary

UVA seminar
11/11/15
Outline

• Neutrinos Oscillations
  .... and why do we care about neutrino interactions?
• The MINERvA detector
  > Measuring a cross section
  > Need to know your flux
• Step through interaction categories & compare with current models
  > Inclusive scattering
  > Quasi-elastic and QE-like
  > Single charged/neutral pion production
  > Coherent charged pion production
  > Electron neutrino QE
  > Observation of diffractive neutral pion production
  > Inclusive and DIS nuclear effects
• Future plans
Neutrino interactions

- **Charged current (CC, W exchange)**
  - Lepton tags neutrino, all energy seen, threshold due to lepton mass

- **Neutral current (NC, Z exchange)**
  - Outgoing neutrino – no energy threshold
  - Missing energy & no flavor information

![Charged current diagram](image)

![Neutral current diagram](image)
Neutrinos oscillations
Solar neutrinos

- The Sun produces neutrinos as it converts hydrogen to helium
- The neutrino production rate is well known based on the amount of light emitted by the sun

<table>
<thead>
<tr>
<th>REACTION</th>
<th>TERM. (%)</th>
<th>( \nu ) ENERGY (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p + p \rightarrow ^2H + e^+ + \nu_e )</td>
<td>(99.96)</td>
<td>( \leq 0.423 )</td>
</tr>
<tr>
<td>( p + e^- + p \rightarrow ^2H + \nu_e )</td>
<td>(0.44)</td>
<td>1.445</td>
</tr>
<tr>
<td>( ^2H + p \rightarrow ^3He + \gamma )</td>
<td>(100)</td>
<td></td>
</tr>
<tr>
<td>( ^3He + ^3He \rightarrow \alpha + 2p )</td>
<td>(85)</td>
<td></td>
</tr>
<tr>
<td>( ^3He + ^4He \rightarrow ^7Be + \gamma )</td>
<td>(15)</td>
<td>( {0.863\ 90% } )</td>
</tr>
<tr>
<td>( ^7Be + e^- \rightarrow ^7Li + \nu_e )</td>
<td>(15)</td>
<td>( {0.385\ 10% } )</td>
</tr>
<tr>
<td>( ^7Li + p \rightarrow 2\alpha )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^7Be + p \rightarrow ^8B + \gamma )</td>
<td>(0.02)</td>
<td></td>
</tr>
<tr>
<td>( ^8B \rightarrow ^8Be^* + e^+ + \nu_e )</td>
<td></td>
<td>(&lt; 15)</td>
</tr>
<tr>
<td>( ^8Be^* \rightarrow 2\alpha )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^3He + p \rightarrow ^4He + e^+ + \nu_e )</td>
<td>(0.00003)</td>
<td>(&lt; 18.8)</td>
</tr>
</tbody>
</table>

Solar Neutrino Experiments

- Up to 2002 the data was confusing
- Solar electron neutrinos seen by 6 different experiments using 3 techniques
  > Experiments mostly sensitive to $\nu_e$ CC
- Rates and spectrum different than standard solar model
  > Problem with the neutrinos?
  > Problem with the solar model?
- Solved by the SNO experiment
  > Could see all 3 types via NC
  > It’s the neutrinos
  > They change types inside the Sun & in space
2-Flavor Oscillation Formalism

• What if there 2 neutrino basis (weak force & mass)?

\[ |\nu_i\rangle = \sum U_{li} |\nu_i\rangle \]

• The probability that a neutrino (e.g. \(\nu_\mu\)) will look like another variety (e.g. \(\nu_\tau\)) will be

\[ P(\nu_\mu \rightarrow \nu_\tau; t) = |<\nu_\tau|\nu_\mu(t)>|^2 \]

• 2–component unitary admixture characterized by \(\theta\):

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 \frac{L}{E}) \]

• Experimental parameters

  \(L\) (distance from source to detection, km)
  \(E\) (particle energy, GeV)

• Oscillation (physics) parameters

  \(\sin^2(2\theta)\) (mixing angle)
  \(\Delta m^2 = m_\tau^2 - m_\mu^2\) (mass squared difference, eV^2)
  \(E(GeV)\)

MINERvA results, Nelson
Kamland: Man–Made Neutrino Test

- Reactor experiment with a twist
  > Go a lonnnnnng long distance to test solar neutrino oscillations with man made neutrinos
  > 20% of world’s nuclear power (was) 100 - 300 km from central Japan

- Neutrinos observed: 1609

- Expectation w/o oscillations: 2450
  > Spectrum & rates fully consistent with Solar results!
  > Initial results the same year as SNO

Atmospheric Neutrinos

- Primary cosmic rays strike the atmosphere and produce showers of particles including muons
- Long range of distances

Earth

\[ L \sim 20 \text{ km} \]

\[ L \sim 10^4 \text{ km} \]

Adapted from LANL

MINERvA results, Nelson
Cerenkov Rings in SuperK

4048 total p.e.
p = 689 MeV/c

MINERvA results, Nelson
SK neutrino data shows disappearance (1998)

All data (results from 7 experiments) consistent with muon neutrino $\rightarrow$ tau neutrino
NuMI Neutrino Beam at Fermilab

Target Hall

MINOS ND

120 GeV/c p from the FNAL Main Injector
Rep rate: 1 spill / 2.2 sec
3.5e13 POT/spill
10 microseconds long
Beam power: 320 kW average

MINERvA results, Nelson
Send neutrinos 735 km from Fermilab to Soudan

- There’s no tunnel — just solid rock
- Their journey takes only 0.0024 sec

2 neutrino detectors
- A small detector at Fermilab ("near detector")
- A large detector at Soudan ("far detector")
A Muon Neutrino Interaction

Resulting muon bending in the magnetic field

Debris from struck nucleus
MINOS long-baseline oscillation results (2006) (consistent results w/ K2K, T2K, NOvA)

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed</th>
<th>Predicted (w/o oscillations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam neutrinos</td>
<td>6028</td>
<td>7074</td>
</tr>
<tr>
<td>Atmospheric neutrinos</td>
<td>2072</td>
<td>2397</td>
</tr>
</tbody>
</table>

Low Energy Beam, $\nu_\mu$-mode

10.71 x $10^{20}$ POT

MINOS PRELIMINARY
Three–flavor oscillations: the last transition discovered in electron–neutrino disappearance 2012

Consistent results from 3 experiments
T2K sees equivalent in long-baseline too

MINERvA results, Nelson
The stories told...

- From the atmosphere
  - Muon neutrino goes to tau neutrino
  - And only rarely to electron neutrinos
  - Long baseline beams of neutrinos verify

- From the sun
  - Electron neutrino goes to something
  - Long baseline reactor neutrinos verify

- Last transition via precision reactor exp’s
  - Electron neutrino to muon neutrino
  - Long baseline electron appearance verifies

- What’s next?
  - Hierarchy of neutrino mass spectrum
  - CP violation in the neutrino sector
  - Requires precision comparisons of neutrino/antineutrino electron appearance

\[ \Delta m^2_{32} = m_3^2 - m_2^2 \]
NOvA – the next generation

2-detector, long-baseline experiment

Off-axis neutrinos from NuMI beam

Physics goals:

> Search for electron neutrino appearance (with both neutrinos and antineutrinos)
> Precision studies of muon neutrino disappearance
NOvA Detectors

- Designed for electron ID
- Massive, Low-Z, 65% active
- ND: 330 ton, 1 km from source
- FD: 14 kton, 810 km from source
Simulated events in NOvA
(1\textsuperscript{st} results this summer… but that’s another seminar)
Deep Underground Neutrino Experiment (DUNE) – further future

- Massive Liquid Argon TPC (up to 30 ktons)
- Almost bubble chamber-like event detail
- New beam line with higher power at a longer baseline (LBNF)
- Should start collecting data sometime in the next decade
Uncertainties on signal predictions in $\nu_e$ appearance measurements: now & goals

- **MINOS**
  - 5.6% uncertainty on signal prediction

- **T2K**
  - 6.8% uncertainty on signal prediction

- **LBNE's goal is 1% for total systematic uncertainty on signal prediction**
- **Sensitivity to CP violation is strongly impacted by uncertainties in signal & background predictions**
Neutrino interactions: why care?

• We need to estimate the energy of the incoming neutrino
  > Different from the “visible” energy seen in the detector
• Neutrino oscillation experiments use nuclei as targets (e.g. O, C, Ar)
  > This affects the visible energy …
  > Motion of struck nucleon within nucleus
  > Number of final state particles
    • We are not sensitive to their rest masses, binding energies
  > Intra-nuclear absorption and scattering
  > Nucleon itself is modified by the nucleus
Neutrino event generators

- Neutrino experiments have few in situ physics handles
  - MIP/muon, Michel electrons, Neutral Pions
  - Only know the incoming neutrino direction accurately
- We rely heavily on full simulations of neutrino interactions to understand
  - Signal selection
  - Background rejection
  - Energy reconstruction
- In the US program we most often use GENIE
- Many others exist
  - Some with fully specified final states
  - Some computed based on physics distributions
GENIE (nee NEUGEN) model & world inclusive-scattering data (ca. 2008)

Total Anti-Neutrino CC Cross Section

Total Neutrino CC Cross Section

MINERvA results, Nelson
State of scattering (ca. 2011)

- SPS and TeVatron experimental results
- Getting detailed results from MiniBooNE, K2K ND, and SciBooNE
  > Dozens of papers
  > Starting to get the right nuclei
  > Can’t fit it all on one plot anymore… a good thing
  > Dearth of antineutrino data starting to be addressed
  > All these are for ~<1 GeV
- Data disagree with models!

Our generators (models) do not accurately reflect recent cross section data

Adapted from PRD 81, 092005 (2010)
by P. Rodrigues

Adapted from PRD 83, 052007 (2011)
by P. Rodrigues
MINERvA

- Finely segmented solid scintillator (CH) detector on axis in NuMI
  - Active tracker is all scintillator
  - Calorimeters are scintillator w/ Fe or Pb
- Targets of Iron, Pb, C, Fe, H$_2$O & He
- MINOS detector for muon spectrometer
- Test beam program for energy scale/detector model
A MINERvA event
Active scintillator modules

- **250 kg Liquid He**

- **500 kg Water**

- **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

- **.5” Fe / .5” Pb**
  - 161kg / 135kg

MINERvA results, Nelson
The MINERvA Collaboration
Measuring a cross section

\[ \sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E} \]

- D is data event yield
- B is background estimate
- \( U(\ ) \) an unfolding operation
- \( \Phi \) is flux
- \( \epsilon \) is the acceptance correction
- \( \Delta E \) is the bin width
- T is the number of target nucleons
Flux tools: flux critical for any absolute measurement

- **Hadron production data**
  - External thin & thick target hadron production data
  - Legacy data, NA49, MIPP
  - Future: US-NA61

- Can also use standard–candle cross sections
  - Neutrino–electron scattering
  - Low $v$ (low recoil) events rates

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Final MINERvA constrained flux to be unveiled at 12/17 FNAL seminar by Leo Aliaga (W&M)

Preview next week at NuInt2015 (<8% errors)
Flux: GEANT4 corrected with external data (preliminary: used for almost all MINERvA results)

GEANT4 FTFP-based flux turned using NA49 thin-target $\pi/k/\rho$ data and MIPP thin-target $k/\pi$ ratios; corrected for $\eta$ production
Flux tools: flux critical for any absolute measurement

- Hadron production data
  - External thin & thick target hadron production data
    Legacy data, NA49, MIPP
  - Future: US–NA61

- Can also use standard–candle cross sections
  - Neutrino–electron scattering
  - Low v (low recoil) events rates
$\nu$-e scattering

- Signal is a single electron moving in beam direction
  - purely electro-weak process
  - Cross section is smaller than nucleus scattering by a factor of 2000
- Improves MINERvA's flux uncertainties
  - Statistically limited (~8% error)
  - Results are consistent with new flux calculations
- Important proof of principle for future experiments
  - Especially for higher energy beams
Flux: low $\nu$

- Charged-current scattering with low hadronic recoil energy ($\nu$) is flat

$$\frac{d\sigma}{d\nu} = A(1 + \frac{B\nu}{AE} - \frac{C\nu^2}{A2E^2})$$

- Gives a measurement of the flux’s shape
- Normalization tied to external measurements at high energy
NuMI on–axis neutrino flux from the low–nu method

Results are consistent with the neutrino-electron scattering and ex situ fluxes
NuMI on–axis antineutrino flux from the low–nu method

To be unveiled at 1/8/16 FNAL wine & cheese
Simplest thing…
inclusive charged current scattering

Results use low-nu flux
MINERvA CC inclusive neutrino cross section & world data

\[ \sigma / E \left( 10^{-38} \text{ cm}^2 / \text{GeV} / \text{nucleon} \right) \]

-neutrino energy (GeV)

-data
-simulation
-NOMAD
-MINOS
-T2K

\[ \nu_\mu \text{ in FHC} \]

fractional uncertainty

-neutrino energy (GeV)

Total
-Statistical
-MCStatistical
-GENIE
-Flux
-RecoilReconstruction
-MuonReconstruction
-CrossNormalization
-Normalization
MINERvA CC inclusive antineutrino cross section & world data

\[ \sigma/E \left( 10^{-38} \text{ cm}^2 / \text{GeV} / \text{nucleon} \right) \]

- **data**
- **MINOS**
- **IHEP-JINR**
- **simulation**

**neutrino energy (GeV)**
Neutrino Quasi-Elastic Candidate

\[ \nu \rightarrow \mu^{-} \]

MINERvA Data

Muon

Proton

Neutrino beam

MINERvA results, Nelson
Long-standing problem in $\nu_\mu$ CCQE

- NOMAD, bubble chambers
  - Used two-track topology with low thresholds
  - Consistent with RFG (like GENIE’s model) with $M_A=1$ GeV but prefer a better nuclear model
- K2K, MiniBooNE, MINOS, SciBooNE
  - Fine-grained scintillator so higher proton tracking threshold
  - Look for a muon and low recoil; use muon kinematics for energy
  - See a higher rate and different $Q^2$ distributions consistent with a higher $M_A$ + low $Q^2$ suppression
- By 2010: becoming clear that this was probably due to an extra unmodeled process well known in electron scattering
  - 2 particle, 2 hole (2p2h)
  - Models include MEC & TE

NOMAD: EPJ C 63, 355 (2009)
MB: PRD 81, 092005 (2010)
SB: J. Walding, IC thesis (2009)
2-track QE, proton-based reconstruction

- Select events based on 1 PID’d stopping proton & 1 muon
- Reconstruct kinematics quantities using proton angle and energy
- Very sensitive to final state interactions
- Shape-only comparison
- In proton kinematic variables, see relatively good agreement with Relativistic Fermi Gas (RFA) model for QE scattering
- These 2-track QE make a pretty good standard candle
QE-like with lepton-based kinematics

- Reconstruct the muon
  > Require not too much energy beyond a box around the vertex
- Relatively insensitive to final state interactions (only enter via the background estimate)
- Disagreement with Fermi Gas model seen in total cross section, shape of cross section
  > Shape alone (right) has model discriminating power
  > Favors 2p2h contribution
  > TEM = Transverse Enhancement Model
Search region around the vertex for QE-like events for signs of extra particles

- The model is that a \((np)\) pair are coupled via initial-state pion exchange
  - Like a deuteron within the nucleus
  - Neutrino scattering should look like 2 protons in the final state
  - Antineutrino scattering should look like 2 neutrons in the final state
- Measure distance of extra energy in annuli around the vertex to measure the energy spectrum of the extra particles
  - Consistent with extra proton production \((2p-2h)\) for \((25\pm9)\)% of neutrino QE-like events with range up to 250 MeV/c
  - No excess in antineutrinos QE-like
- GENIE underestimates energy of QE-like hadronic system which will cause biases in neutrino energy reconstruction
Electron neutrino CC QE:
Large signal for electron appearance
The first time this channel has been measured

- Isolate the small electron neutrino sample (2% of beam)
- Rely on electrons having one prompt track while neutral pions start their shower with 2 tracks’ ionization ($e^+e^-$ pair)
Electron neutrino CC QE is consistent with muon neutrino CC QE

- Constrains differences the between nuclear effects to the 15% level
Unmodeled background: NC diffractive scattering from $H$

- Little momentum transfer to target
- Vector meson emitted in forward direction

**Unique to diffractive scattering from $H$:**
- Recoiling $H$ nucleus (single proton) sometimes visible

Not in (default) GENIE model
Results: pion production

MINERvA Data

Neutrino resonant charged pion production candidate

neutrino beam

MINERvA results, Nelson
Results: pion production

MINERvA Data

Antineutrino resonant neutral pion production candidate
Pizero mass peak after sideband fits

\[ \bar{\nu}_\mu \text{ Tracker} \rightarrow \mu^+ \pi^0 X \text{ (X has no mesons)} \]

\( m_{\gamma\gamma} \) (MeV/c^2)
Results: resonant charged pion production

- Differential cross sections with respect to muon kinematics
  - Muon is not FSI sensitive
  - Shapes vs both energy and angle are in reasonable agreement with GENIE
- GENIE over-predicts the resonance rate for charged pions by 25%
  - Charge pion is FSI sensitive
- GENIE mildly over-predicts the rate for neutral pions
  - Neutral pion is mildly FSI sensitive (Largely through charge exchange)
- The difference in agreement suggests possible FSI deficiency

B. Eberly FNAL JTES, Feb 7 2014
T. Le, FNAL JTES, Jan 9, 2015
C. McGivern, FNAL JTES, June 26, 2015
Pion production cross sections vs $E_\nu$

$\bar{\nu}_\mu$ Tracker $\rightarrow \mu^+ 1\pi^0 X$ ($W < 1.8$ GeV)

$\nu_\mu$ Tracker $\rightarrow \mu^- N\pi^\pm X$ ($W < 1.8$ GeV)
Resonant Pion Production

Neutral, absolute

Charged, absolute

Charged, shape

MINERvA results, Nelson
Coherent charged pion production

Neutral pion NC analog is a background to electron neutrino appearance measurements
Prior results: coherent charged pion production results

- Clear signal seen by high energy experiments
- No signals seen in recent low-energy experiments

PLB 313, 267 (1993)

PRD 78, 112004 (2008)

K2K

SciBooNE
Coherent charged pion production

- MINERvA sees clear signal of neutrino and antineutrino coherent pion production
- Reconstruct $|t|
  - The 4-momentum transfer to nucleus (including masses)
  - Minimal model dependence in signal prediction
  - Large background suppression

\[ Q^2 \geq m^2_{\mu}[y/(1-y)] \]
\[ |t| \geq [(Q^2 + m^2_\pi)/(2yE_\nu)]^2 \]

PRL 113, 261802 (2014)
Coherent charged pion production

- Data begin to probe kinematic predictions used to model this signal
- See indications that model does not accurately reflect energy or angle of pion
  > Harder
  > More forward

PRL 113, 261802 (2014)
Coherent charged pion production

\[ \nu_\mu + A \rightarrow \mu^- + \pi^+ + A \]

\[ \bar{\nu}_\mu + A \rightarrow \mu^+ + \pi^- + A \]

\begin{itemize}
  \item MINERvA \(<A> = 12\)
  \item SciBooNE \(<A> = 12\)
  \item K2K \(<A> = 12\)
  \item T2K \(<A> = 12\)
  \item BEBC \(<A> = 20\)
  \item CHARM III \(<A> = 21\)
  \item SKAT \(<A> = 30\)
  \item ArgoNeuT \(<A> = 40\)
  \item GENIE v2.6.2
\end{itemize}


PRL 113, 261802 (2014)
Probing Nucleon Structure
Deep Inelastic Scattering (DIS)

- Lepton strikes quark, breaks apart nucleon
- Cross section a function of
  - Probe (lepton) momentum
  - Interaction kinematics
  - Target (quark) momentum

Encoded in structure functions – $F_1$, $F_2$, $F_3$

\[
\frac{d^2\sigma_{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 M_n E_\nu}{\pi (1 + Q^2/M_W^2)^2} \left[ \frac{y^2}{2} 2x F_1(x, Q^2) + \left( 1 - y - \frac{xy M_n}{2E_\nu} \right) F_2(x, Q^2) \pm y \left( 1 - \frac{y}{2} \right) x F_3(x, Q^2) \right]
\]

$\nu = E - E'$

$Q^2 = -q^2 = 2E \left( E' - p' \cos (\theta) \right)$

$y = \frac{E_h}{E}$

Inelasticity

$x = \frac{Q^2}{2M_\nu}$

Bjorken scaling variable
Fraction of nucleon’s momentum carried by the struck quark

MINERvA results, Nelson
Inclusive cross section ratios on various nuclei

No tension between data and generator vs $E_\nu$

**GENIE 2.6.2**

PRL. 112 (2014) 231801
High $x$ summary

- At $x = [0.7, 1.1]$, observe an **excess** that grows with the size of the nucleus
- This effect is not modeled in simulation

**GENIE 2.6.2**

PRL. 112 (2014) 231801

MINERvA results, Nelson
Low $x$ summary

- At $x = [0.0,0.1]$, observe a **deficit** that grows with the size of the nucleus
- This effect is not modeled in simulation

We expected neutrino differences

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

MINERvA results, Nelson
DIS version – might be better than inclusive but stats in LE sample are limited

J. Mouseau, JTES 5/15
MINERvA ME Program

- 3 times the POT of low-energy sample by FY16 shutdown
- 3.5 times more events/POT
- These statistics will allow study of nuclear effects in exclusive states
- Wider ranges of energies means wider range of kinematics to probe and discriminate between models
CAPTAIN–MINERvA

- Proposed extension to program (2017–2020)
- Add a LArTPC with MINERvA for downstream containment
- 1st dedicated Ar cross sections in few-GeV region
- Supports the DUNE program
Synopsis

- Future long-baseline neutrino oscillation experiments, including the US-flagships of NOvA and DUNE, need to know cross sections in the few GeV region at unprecedented precision
  - Requires systematics at least a factor of six smaller than the current state of the art
- MINERvA is leading the way in neutrino–nuclear scattering in this energy regime
  - Initial results focus on $\nu$–C
  - A number of new results coming later this month at NuInt2016
  - Near future: evolution of nuclear effects in exclusive channels over a range of nuclei
  - Further future: dedicated liquid argon program
- These results need to be incorporated into models (event generators) for the US neutrino oscillation program to succeed