WG2 Summary - Part 2
Neutrino Scattering Physics Topics

Conveners: Makoto Sakuda and Jorge G. Morfín
Presentations and Discussions

Low energy neutrino interactions T. Sato (Osaka)
Nuclear modification of valence quark distributions and its effects on NuTeV $\sin^2 \theta_W$ S. Kumano (Saga)

DISCUSSION SESSION - WHAT IMPORTANT THEORETICAL QUESTIONS LEFT TO ANSWER

MiniBOONE scattering results H.A. Tanaka (Princeton)
K2K scattering results M. Hasegawa (Kyoto)
MINERvA expected scattering results J.G. Morfin (FNAL)
Tau production and decay via neutrino scattering K. Mawatari (Kobe)
Study of strange quark in the nucleon with neutrino scattering T-A. Shibata (TIT)
K2K NC pi0 production S. Nakayama (ICRR)
HARP result I. Kato (Kyoto)
BNL E910 result J. Link (Colombia)

DISCUSSION SESSION - WHAT IMPORTANT NEUTRINO SCATTERING PHYSICS QUESTIONS ARE UNANSWERED?

DISCUSSION SESSION - CAN SUPERBEAM OR NEUTRINO FACTORY ADDRESS THE OPEN QUESTIONS?
Neutrino Oscillation: Requirements
Dave Casper

- Neutrino energy resolution for CC interactions
  - K2K/T2K: Quasi-elastic channel
  - MINOS/NOvA: Calorimetry ($E_{\text{vis}} \rightarrow E_{\nu}$)

- Understand Nuclear Effects
  - Visible energy to neutrino energy

- Control near/far beam flux and energy spectrum differences at few percent level

- Control background for $\nu_e$ appearance signature at few per-mille level
  - Beam $\nu_e$, CC, NC contributions

- Control neutrino/anti-neutrino systematics at 1 percent level for mass hierarchy and CP studies

---

K2K

Non-QE

True - Reconstructed Energy

C. Walter, NUINT02

NOvA

($\theta_{13}$ near CHOOZ bound)

Inverted Hierarchy

Normal Hierarchy
Time Snapshot
Assume following experiments complete…

- K2K
  - HARP, BNL E910
  - Jlab High precision elastic scattering

- MiniBooNe
  - HARP, BNL E910
  - Jlab High precision elastic scattering

- MINERνA (Running parasitically to MINOS)
  - HARP, BNL E910, MIPP (E907)
  - Jlab High precision elastic scattering

- T2K-I (no input as to scattering physics expectations)
K2K Near Detectors

Extruded scintillator (15t)

Multi-anode PMT (64ch)

Wave-length shifting fiber

EM calorimeter

SciBar

SciFi

M. Hasegawa (Kyoto)

\[ E_\nu \text{ (GeV)} \]
MiniBooNE: Mini Booster Neutrino Experiment

- A search for $\nu_\mu \rightarrow \nu_e$ oscillations
- $\Delta m^2 \sim 0.1 - 10 \text{ eV}^2$
- 800 ton mineral oil target (CH$_2$)
  - 610 cm radius
  - Optical barrier at 5.75 m
  - 1280 photomultipliers in inner volume (~550 cm)
    445 ton fiducial volume
  - 240 photomultipliers in veto region

Detect neutrino interactions with $\langle E_\nu \rangle \sim 800 \text{ MeV}$

H. Tanaka, (Princeton)
Brief Introduction to the MINERνA Experiment
(Main INjector ExpeRiment ν-A)

A High-Statistics ν-Nucleus Scattering Experiment Using an On-Axis, Fine-grained Detector in the NuMI Beam

Received Stage I Approval in April
Quantitative Study of Low-energy $\nu$-Nucleus Interactions

Both HEP and NP collaborators

D. Drakoulakos, P. Stamoulis, G. Tzanakos, M. Zois
University of Athens, Athens, Greece

D. Casper
University of California, Irvine, California

E. Paschos
University of Dortmund, Dortmund, Germany

D. Boehnlein, D. A. Harris, M. Kostin, J.G. Morfin, P. Shanahan, P. Spentzouris
Fermi National Accelerator Laboratory, Batavia, Illinois

M.E. Christy, W. Hinton, C.E. Keppel
Hampton University, Hampton, Virginia

R. Burnstein, A. Chakravorty, O. Kamaev, N. Solomey
Illinois Institute of Technology, Chicago, Illinois

S. Kulagin
Institute for Nuclear Research, Moscow, Russia

I. Niculescu, G. Niculescu
James Madison University, Harrisonburg, Virginia

G. Blazey, M.A.C. Cummings, V. Rykalin
Northern Illinois University, DeKalb, Illinois

W.K. Brooks, A. Bruell, R. Ent, D. Gaskell, W. Melnitchouk, S. Wood
Jefferson Lab, Newport News, Virginia

S. Boyd, D. Naples, V. Paolone
University of Pittsburgh, Pittsburgh, Pennsylvania

University of Rochester, Rochester, New York

R. Gilman, C. Glasshausser, X. Jiang, G. Kumbartzki, K. McCormick, R. Ransome
Rutgers University, New Brunswick, New Jersey

H. Gallagher, T. Kafka, W.A. Mann, W. Oliver
Tufts University, Medford, Massachusetts

J. Nelson
William and Mary College, Williamsburg, Virginia

Red = HEP, Blue = NP, Green = Theorist
The MINERνA Detector

- Active target of scintillator bars (6t total, 3 - 5 t fiducial) - M64PMT
- Surrounded by calorimeters
  - upstream calorimeters are Pb, Fe targets (~1t each)
  - magnetized side and downstream tracker/calorimeter
Performance of the Detector:
Tracking in Active Target

- Coordinate resolution from triangular geometry is excellent
  - $\sigma \sim 2-3\text{ mm}$ in transverse direction from light sharing

- technique pioneered by D0 upgrade pre-shower detector
MINERvA preferred running is as close as possible to MINOS, (without Muon Ranger), using MINOS as high energy muon spectrometer

- If necessary, MINERvA can run stand-alone elsewhere in the hall with the muon ranger
The NuMI Neutrino Beam

Main injector: 120 GeV protons

With E-907(MIPP) at Fermilab to measure particle spectra from the NuMI target, expect to know neutrino flux to $\approx \pm 3-4\%$. 
MINERνA will have the statistics to cover a wide variety of important ν physics topics

Assume $9 \times 10^{20}$ POT: MINOS chooses $7.0 \times 10^{20}$ in LE ν beam, $1.2 \times 10^{20}$ in sME and $0.8 \times 10^{20}$ in sHE

<table>
<thead>
<tr>
<th>Process</th>
<th>νₑ Event Rates per fiducial ton</th>
<th>Typical Fiducial Volume =</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC</td>
<td>NC</td>
</tr>
<tr>
<td>Quasi-elastic</td>
<td>103 K</td>
<td>42 K</td>
</tr>
<tr>
<td>Resonance</td>
<td>196 K</td>
<td>70 K</td>
</tr>
<tr>
<td>Transition</td>
<td>210 K</td>
<td>65 K</td>
</tr>
<tr>
<td>DIS</td>
<td>420 K</td>
<td>125 K</td>
</tr>
<tr>
<td>Coherent</td>
<td>8.4 K</td>
<td>4.2 K</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>940 K</strong></td>
<td><strong>305 K</strong></td>
</tr>
</tbody>
</table>

**Main Physics Topics with Expected Produced Statistics**

- **Quasi-elastic**
  - 300 K events off 3 tons CH
- **Resonance Production**
  - 600 K total, 450 K $\pi$
- **Coherent Pion Production**
  - 25 K CC / 12.5 K NC
- **Nuclear Effects**
  - C:0.6M, Fe: 1M and Pb: 1 M
- **$\sigma_T$ and Structure Functions**
  - 2.8 M total / 1.2 M DIS event
- **Strange and Charm Particle Production**
  - > 60 K fully reconstructed events
- **Generalized Parton Distributions**
  - (few K events?)
After initial (parasitic to MINOS) run -
could add a Liquid H$_2$/D$_2$/O/Ar) Target

NOT APPROVED FOR THIS

Fid. vol:
\( r = 80 \text{ cm.} \) \( l = 150 \text{ cm.} \)

350 K CC events in LH$_2$
800 K CC events in LD$_2$

per year he-$\nu$ running. Few events with \( E \approx 1 \text{ GeV} \).

Technically easy/inexpensive to build and operate.

Meeting safety specifications the major effort.
Neutrino Scattering Topics

What will we know and not know at time snapshot?

- Quasi-elastic
- Resonance Production - 1pi
- Resonance Production - npi, transition region - resonance to DIS
- Deep-Inelastic Scattering
- Coherent Pion Production
- Strange and Charm Particle Production
- Nuclear Effects
- $\sigma_T$ and Structure Functions
  - s(x) and c(x)
  - High-x parton distribution functions
- Spin-dependent parton distribution functions
- Generalized Parton Distributions
Dominant reaction up to ~1 GeV energy

Essential for $E_\nu$ measurement in K2K/T2K

The “well-measured” reaction

- Uncertain to “only” 20% or so for neutrinos
- Worse in important threshold region and for anti-neutrinos

Axial form-factor not accessible to electron scattering

- Essential to modeling $q^2$ distribution

Recoil proton reconstruction requires fine-grained design - impractical for oscillation detectors

Recent work focuses on non-dipole form-factors, non-zero $G_n^E$ measurements

(88% purity)

MiniBooNe

K2K SciBar 2-ring QE

(70% purity)
MINERνA CC Quasi-Elastic Measurements

Fully simulated analysis, including realistic detector simulation and reconstruction
CC Resonant Single-Pion Production

- Existing data inconsistent (factor 2 variations)
- Treatment of nuclear effects unclear
- Renewed theoretical interest
  - Rein - Sehgal used for decades
- Sato-Uno-Lee Dynamical model gives a better fit to (poor) data

![Graphs and plots related to CC resonant single-pion production.](image)
MINERνA Resonance Production - $\Delta$

Total Cross-section and $d\sigma/dQ^2$ for the $\Delta^{++}$ assuming 50% detection efficiency

Errors are statistical only

DO NOT FORGET RADIATIVE DECAYS AS BACKGROUND TO $\nu_\mu \rightarrow \nu_e$

![Graphs showing total cross-section and differential cross-section for MINERνA Resonance Production - $\Delta$.](image)
Recent JLAB data have revived interest in quark/hadron duality

Bodek and Yang have shown that DIS cross-sections can be extended into the resonance regime, and match the “average” of the resonant cross-section.

We need more than just the “average” knowledge of the transition region - hills and valleys.

Beyond kinematic range of K2K and MiniBooNe.

MINERvA - 600K events
- Challenge to the resolution of MINERvA?
DIS: Parton Distribution Functions
What Can We Learn With All Six $\nu$ & $\bar{\nu}$ Structure Functions?

Using Leading order expressions:

\[
\begin{align*}
F_2^{\nu N}(x, Q^2) &= x\left[u + \bar{u} + d + \bar{d} + 2\bar{s} + 2c\right] \\
F_2^{\bar{\nu} N}(x, Q^2) &= x\left[u + \bar{u} + d + \bar{d} + 2s + 2\bar{c}\right] \\
xF_3^{\nu N}(x, Q^2) &= x\left[u + d - \bar{u} - \bar{d} - 2\bar{s} + 2c\right] \\
xF_3^{\bar{\nu} N}(x, Q^2) &= x\left[u + d - \bar{u} - \bar{d} + 2s - 2\bar{c}\right]
\end{align*}
\]

- Does $s = s$ and $c = c$ over all $x$?
- If so.....

\[
\begin{align*}
F_2^\nu - xF_3^\nu &= 2\left(u + \bar{d} + 2\bar{c}\right) = 2U + 4\bar{c} \\
F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} &= 2\left(u + \bar{d} + 2\bar{s}\right) = 2U + 4\bar{s} \\
xF_3^\nu - xF_3^{\bar{\nu}} &= 2\left[(s + \bar{s}) - (\bar{c} + c)\right] = 4\bar{s} - 4\bar{c}
\end{align*}
\]
Measuring Six Structure Functions for Maximal Information on PDF’s

\[
\frac{d \sigma^\nu A}{dx dQ^2} = \frac{G_F^2}{2 \pi x} \left[ \frac{1}{2} \left( F_2^\nu A(x, Q^2) + x F_3^\nu A(x, Q^2) \right) + \frac{(1 - y)^2}{2} \left( F_2^\nu A(x, Q^2) - x F_3^\nu A(x, Q^2) \right) \right]
\]

\[
\frac{d \sigma^{\bar{\nu} A}}{dx dQ^2} = \frac{G_F^2}{2 \pi x} \left[ \frac{1}{2} \left( F_2^{\bar{\nu} A}(x, Q^2) - x F_3^{\bar{\nu} A}(x, Q^2) \right) + \frac{(1 - y)^2}{2} \left( F_2^{\bar{\nu} A}(x, Q^2) + x F_3^{\bar{\nu} A}(x, Q^2) \right) \right]
\]

\[
\sigma(x, Q^2, (1 - y)^2) = \frac{G^2}{2 \pi x}
\]

\[
R = R_{\text{whitlow}} + y^2 F_L
\]

- Neutrino
  - 1 year he-beam
- Anti-Neutrino
  - 2 years he-beam

X = 0.1 - 0.125
Q^2 = 2 - 4 GeV^2
Kinematic cuts in (1-y) not shown
Coherent Pion Production

- Characterized by a small energy transfer to the nucleus, forward going $\pi$. NC ($\pi^0$ production) significant background for $\nu_\mu \rightarrow \nu_e$ oscillation search.

- Data has not been precise enough to discriminate between several very different models.

- K2K, with their SciBar detector, and MiniBooNe will attempt to explicitly measure this channel - important low $E_\nu$ measurement.

- Expect 25K events and roughly (30-40)% detection efficiency with MINERvA.

- Can also study A-dependence with MINERvA.
MINERνA: Coherent Pion Production

25 K CC / 12.5 K NC events off C - 8.3 K CC/ 4.2 K NC off Fe and Pb

CC Coherent Pion Production Cross Section

\[ \sigma(\nu_\mu + A \rightarrow \mu^- + \pi^+ + A) \]

Expected MiniBooNe and K2K measurements

Rein-Seghal
Paschos-Kartavtsev

- MINERνA
- CHARM (CC), Bergsma, Phys. Lett. 157B, 489 (1985)
Include hadron formation length corrections

K2K QE analysis

MINERvA can measure $L_H$ off of C, Fe and Pb
Nuclear Effects - modified interaction probabilities

EXPECTED to be different for ν!!
Nuclear Effects - Low $\nu$, low $Q^2$ shadowing

All “known” nuclear effects taken into account:
Pauli suppression, Fermi Motion, Final State Interactions
They have **not included** low-$\nu$ shadowing that is only allowed with axial-vector (Boris Kopeliovich at NuInt04)

$$L_c = \frac{2\nu}{(m_{\pi}^2 + Q^2)} \geq R_A \quad (\text{not } m_A^2)$$

$L_c$ 100 times shorter with $m_\pi$ allowing low $\nu$-low $Q^2$ shadowing

ONLY MEASURABLE VIA NEUTRINO - NUCLEUS INTERACTIONS! **MINER$\nu$A WILL MEASURE THIS** ACROSS A WIDE $\nu$ AND $Q^2$ RANGE WITH $C : Fe : Pb$
List of items to be considered

- **Is Coherent pion suppressed?**
  - K2K will use PID to disentangle $1\pi$/coherent pion (Hasegawa)
  - New data (e-N, $\gamma$–C) on coherent pion production. $\gamma C \rightarrow \pi^0 C$ from Mainz MAMI Accelerator may tell us something.

- **Change in Elastic form factors**
  - Cause A few % effect on $d\sigma/dq^2$ in low$q^2$ region

- **N\Delta form factor coupled with $M_A$**
  - Sato (Nufact04), Paschos (NuInt04)
  - Old Rein-Sehgal N\Delta form factor does not agree with data.

- **Uniform Fermi momentum distributions in MC?**
  - Electron scattering data show large $kf$ component. Benhar(NuInt04) and Nakamura (NuInt04). QE peak cross section 10-20% higher with Fermi Gas than with Spectral Functions which agrees better with electroproduction data.
What will we need beyond MiniBooNe, K2K and MINERνA parasitic run for neutrino scattering?

- **ANTINEUTRINO EXPOSURE**
  - Need to improve purity - NuFact05 design efficient $\nu$ beam (with plug)

- **HYDROGEN AND DEUTERIUM EXPOSURE FOR $\nu$ and $\bar{\nu}$**
  - Need reasonable event rates at $E \approx 1$ GEV

- **NARROW BAND BEAM FOR DETAILED LOOK AT NC?**
  - NuFact05 - Is off-axis beam sufficiently narrow?

- **IMPROVED DETECTOR TECHNIQUES**
  - PARTICULARLY GOOD NEUTRON DETECTION FOR $\bar{\nu}$
What can Superbeams and Neutrino Factories Add to $\nu$ Scattering Measurements?

Debbie Harris

- Neutral Current Measurements vs $E_\nu$
- Anti-neutrino cross sections & interactions
- $H_2, D_2$ Measurements
- Polarized Target Measurements (spin structure functions)
- Narrow Band $\nu$ Beams
  - How narrow is narrow?
  - Are there tricks to get more narrow beams?
- Broad Band $\nu$ Beams
  - Largest rate
  - No NC vs $E_\nu$ available
- Beta-beams
  - Broad band, Low Energy
- Neutrino Factories
  - Broad Band
  - Neutrino and antineutrino at the same time, if you can reconstruct $\nu_\mu$ and $\nu_e$ CC
  - NO NC vs $E_\nu$ or even vs neutrino helicity!
At the completion of MiniBooNe, K2K and the MINERνA parasitic run we will have reasonable results for neutrino-nucleus interactions including cross-sections, form factors and nuclear effects.

We will need a SuperBeam to have similarly reasonable results for $\nu$ cross-sections, hydrogen and deuterium cross-sections for both $\nu$ and $\bar{\nu}$, high-statistics narrow-band studies of NC (and CC) channels.

We will need a Neutrino Factory for neutrino-polarized target experiments (T-A. Shibata) to understand the spin-dependent pdfs and generalized parton distributions.