NuSOng:
Neutrino Scattering on Glass

Janet Conrad, Peter Fisher
Autumn 2007 PAC Meeting
Nov 2, 2007
EOI

Authors

T. Adams\textsuperscript{4}, L. Bugol\textsuperscript{2}, J.M. Conrad\textsuperscript{2}, P.H. Fisher\textsuperscript{6}, J.A. Formaggio\textsuperscript{6}, A. de Gouvêa\textsuperscript{9}, W.A. Loinaz\textsuperscript{1}, G. Karagiorgi\textsuperscript{2}, T.R. Kobilarce\textsuperscript{3}, S. Kopp\textsuperscript{13}, G. Kyle\textsuperscript{8}, D.A. Mason\textsuperscript{3}, R. Milner\textsuperscript{6}, R. Moore\textsuperscript{3}, J. G. Morfin\textsuperscript{3}, M. Nakamura\textsuperscript{7}, D. Naples\textsuperscript{10}, P. Nienaber\textsuperscript{11}, F.I Olness\textsuperscript{12}, J.F. Owens\textsuperscript{4}, W.G. Seligman\textsuperscript{2}, M.H. Shaevitz\textsuperscript{2}, H. Schellman\textsuperscript{9}, M.J. Syphers\textsuperscript{3}, T. Tait\textsuperscript{9}, C.Y. Tan\textsuperscript{3}, R.G. Van de Water\textsuperscript{5}, R.K. Yamamoto\textsuperscript{6}, G.P. Zeller\textsuperscript{5}

\textsuperscript{1}Amherst College, Amherst, MA 01002
\textsuperscript{2}Columbia University, New York, NY 10027
\textsuperscript{3}Fermi National Accelerator Laboratory, Batavia IL 60510
\textsuperscript{4}Florida State University, Tallahassee, FL 32306
\textsuperscript{5}Los Alamos National Accelerator Laboratory, Los Alamos, NM 87545
\textsuperscript{6}Massachusetts Institute of Technology, Cambridge, MA 02139
\textsuperscript{7}Nagoya University, 464-01, Nagoya, Japan
\textsuperscript{8}New Mexico State University, Las Cruces, NM 88003
\textsuperscript{9}Northwestern University, Evanston, IL 60208
\textsuperscript{10}University of Pittsburgh, Pittsburgh, PA 15260
\textsuperscript{11}Saint Mary’s University of Minnesota, Winona, MN 55987
\textsuperscript{12}Southern Methodist University, Dallas, TX 75205
\textsuperscript{13}University of Texas, Austin TX 78712

9 Universities • 2 Undergraduate Colleges • 2 National Labs
Outline:

Janet:
1. Intro
2. Physics Opportunities

Peter:
1. Design
2. Future Plans
A high-statistics, high energy neutrino experiment...

Neutrino Mode

NUTEV + CHARM II

High energy, very pure beam (×20 POT)

Fine-grained, massive detector (×6 mass)

We are in the process of exploring the best run-plan
Physics in this talk assumes 1.5E20 POT in $\nu$, 0.5E20 POT in $\bar{\nu}$
Very high statistics!

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ CC Deep Inelastic Scattering</th>
<th>$\nu_\mu$ NC Deep Inelastic Scattering</th>
<th>$\nu_\mu$ electron NC elastic scatters</th>
<th>$\nu_\mu$ electron CC quasielastic scatters (IMD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75k</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700k</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7k</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0k</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A unique opportunity for these channels!
As many thesis topics as I can type in 5 minutes…

1. The weak mixing angle measure from neutrino-electron scattering
2. The weak mixing angle measured from neutrino-quark scattering
3. New physics limits probed through coupling to the $Z$
4. New physics limits from the inverse muon decay cross section
5. Cross section measurement of neutrino and antineutrino electron scattering
6. A search for $N \rightarrow \mu \mu \nu$ decay in the 5 GeV mass range
7. Searches for light mass neutrissimos
8. $\nu_\mu$ disappearance at very high $\Delta m^2$
9. A search for evidence of nonunitarity of the 3 neutrino matrix
10. A search for neutral heavy leptons in the 5 GeV mass range
11. Constraints on muonic photons
12. Measurement of the CCQE cross section at high energy
13. Measurement of the NC$\pi^0$ cross section at high energy
14. A study of the transition from single pion to DIS production at high energy
15. Measurement of $F_2$ and $xF_3$ at very high statistics
16. Comparisons of $F_2$ on nuclear targets from low to high $x$
17. High precision measurement of $R$ from neutrino scattering
18. Constraint on isospin violation from $\Delta xF_3$
19. Charm production in the emulsion target and a measure of $B_c$
20. Measurement of the strange sea and $\Delta s$ from dimuon production
21. Measurement of the charm sea from wrong-sign single muon production in DIS
22. Neutrino vs antineutrino nuclear effects
Physics Opportunities

Only a few highlights from three main categories…

1. Indirect Searches for New Physics
2. Direct Searches
3. Parton Distribution Studies
Indirect Searches:  
Physics reach of 5.6TeV!

NuSOnG will work with ratios….

New!

\[ \nu_\mu \rightarrow \nu_\mu \]
\[ Z \rightarrow e^- e^- \]

Purely leptonic

\[ \nu_\mu \rightarrow \mu^- \]
\[ W \rightarrow e^- \nu_e \]

NuTeV-style

“Paschos-Wolfenstein”
NuTeV:
νq scattering ("PW")
is 3σ off SM…

New Physics
or
"Standard Model"?

Constrain nuclear isospin violation
through QCD measurements
(specifically: $\Delta x_{F_3} = x_{F_3}^u - x_{F_3}^d$)

$u^p \neq d^n$
Take $\sin^2 \theta_W$ and $\rho$ and map them to

$S = \text{weak isospin conserving}$

$T = \text{weak isospin violating}$

Very roughly:

- extra $Z$’s
- extra families
- Heavier Higgs

$m_t = 175$ GeV,

$m_H = 100$ GeV.
Our Expression of Interest provides a general discussion of the physics value of this measurement, both on its own and within the context of LHC.

Here we show specific models on how NuSOnG complements LHC in the case of new physics.
A Chiral 4th Generation Model

Degenerate-mass families are highly constrained. Families with isospin violation are not!

- Quark mixings < 0.01
- A heavy $\nu_4$ appears which can be dark matter (a “neutrissimo”)

• The Higgs can be ~300 GeV
LHC:

- Highly enhanced $H \rightarrow ZZ$
- The Higgs mass,
  lets say 300 GeV
- complex decay modes
  (e.g. $6W$’s and $2b$’s)

And what it doesn’t...

- Measure mass of new quarks
- Observe new charged leptons
  (off mass shell Drell-Yan produced)
- Reconstruct the decay modes fully

NuSOnG:

Large isospin violation is measured via $\Delta x F 3$, allowing NuTeV to be corrected.

A Chiral 4th generation ($\Delta S=0.2$)
with isospin violation ($\Delta T=0.2$)
A Z’ Model (B-3L_μ)

for Z’ models see, e.g., Carena, Daleo, Dobrescu and Tait, hep-ph/0408098

LHC:

• Z’ → μμ -- clearly!
• The mass (let’s say 3 TeV)
• Missing Z’ → ee
• Z’ → tt
• Z’ → ττ difficult!

...A 3 TeV Z’ with B-3L_μ coupling
(hep-ph/9903362; 0209316)

NuSOnG:

• Measure Coupling to light quarks & ν_μ.
• No coupling to e

nuclear isospin violation is ruled out and...
The “God-forbid” Scenario

LHC sees a standard model Higgs and no signs of new physics

But if NuSOnG sees this…

There is new physics in the neutrino sector!
Direct Tests for New Physics  
e.g. “Matrix Freedom”

Nonunitarity of the 3 neutrino mixing matrix
\[ \sum_j |U_{\alpha j}|^2 = 1 - X_\alpha, \]

\[ P_{\alpha\alpha}^{\text{general}} = P_{\alpha\alpha}^{\text{unitary}} - 2X_\alpha [1 - 2|U_{\alpha 3}|^2 \sin^2 \Delta_{31}] + X_\alpha^2. \]

L/E dependent  \[ \text{Not!} \]

Appearance has same effect!

At L=0 there will be an instantaneous transition between neutrino species!

Strongest constraints (from rare decays) for instantaneous $\nu_\mu \rightarrow \nu_e$ are at the $1 \times 10^{-4}$ level
• Look for excess $\nu_e$’s in a range not expected

Instantaneous $\nu_\mu \rightarrow \nu_e$ at the $1 \times 10^{-4}$ level gives an $\sim 10\%$ increase in $\nu_e$ rate at $E_\nu \sim 350$ GeV

Seeing both would be a striking signature!

• Look for “wrong sign” IMD

$\bar{\nu}_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$ -- this should not occur!

But if $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, then $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$ … same signature!

improve the present limit by a factor of 10, and reach few $\times 10^{-4}$ level

Unique Capability!
NuSOnG will have SiO$_2$, C, Al, Fe and Pb targets, Kinematic range matches eRHIC and complements Minerva

QCD Studies
e.g. $x F_3$

- $F_2^\nu(\overline{\nu})(x, Q^2) = \sum [x q^\nu(\overline{\nu}) + x \overline{q}^\nu(\overline{\nu}) + 2x k^\nu(\overline{\nu})]$
- $x F_3^\nu(\overline{\nu})(x, Q^2) = \sum [x q^\nu(\overline{\nu}) - x \overline{q}^\nu(\overline{\nu})]$

- $x F_3$ uniquely determined by $\nu$DIS
- Sensitive to valence quarks
- Nonsinglet QCD evolution (theoretically robust)
- $\Delta x F_3 = x F_3^\nu - x F_3^{\overline{\nu}}$ can be used to constrain isospin violation (1st opportunity!)
- Test if $\nu$, $\overline{\nu}$ nuclear effects are the same.
As many thesis topics as I can type in 5 minutes…

1. The weak mixing angle measure from neutrino-electron scattering
2. The weak mixing angle measured from neutrino-quark scattering
3. New physics limits probed through coupling to the Z
4. New physics limits from the inverse muon decay cross section
5. Cross section measurement of neutrino and antineutrino electron scattering
6. A search for $N \rightarrow \mu \mu \nu$ decay in the 5 GeV mass range
7. Searches for light mass neutrissimos
8. $\nu_\mu$ disappearance at very high $\Delta m^2$
9. A search for evidence of nonunitarity of the 3 neutrino matrix
10. A search for neutral heavy leptons in the 5 GeV mass range
11. Constraints on muonic photons
12. Measurement of the CCQE cross section at high energy
13. Measurement of the NCπ0 cross section at high energy
14. A study of the transition from single pion to DIS production at high energy
15. Measurement of $F_2$ and $xF_3$ at very high statistics
16. Comparisons of $F_2$ on nuclear targets from low to high $x$
17. High precision measurement of $R$ from neutrino scattering
18. Constraint on isospin violation from $\Delta xF_3$
19. Charm production in the emulsion target and a measure of $B_c$
20. Measurement of the strange sea and $\Delta s$ from dimuon production
21. Measurement of the charm sea from wrong-sign single muon production in DIS
22. Neutrino vs antineutrino nuclear effects

This is a very physics-rich experiment!
Our detector design draws on the heritage of FMMF, CDHS, CHARM, CCFR and NuTeV. NuSOnG combines and advances the best ideas of these experiments:
1. High granularity, X₀/4
2. Simple, robust, design
3. Isoscalar target
4. Modularity: active elements could be fabricated at universities for assembly at Fermilab
5. Low risk: well known elements that can be engineered for cost
6. High luminosity, high energy
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total target mass</td>
<td>3.49 kt</td>
</tr>
<tr>
<td>Fiducial mass</td>
<td>2.97 kt</td>
</tr>
<tr>
<td>Total length</td>
<td>192 m</td>
</tr>
<tr>
<td>Number glass planes</td>
<td>2500</td>
</tr>
<tr>
<td>Proportional counter planes</td>
<td>2000</td>
</tr>
<tr>
<td>Scintillator planes</td>
<td>500</td>
</tr>
<tr>
<td>Toroid washers</td>
<td>96</td>
</tr>
<tr>
<td>Drift planes</td>
<td>60</td>
</tr>
</tbody>
</table>
Proportional tubes
ArCo2 (80:20)
Gain of 3000 gives 52 fC
250 tubes per plane
500k-1000k total channels

Scintillator planes
18k photons
100 fibers per plane
50k-100k total channels
Key Issues for study in the next few months
• Optimize granularity for good signal efficiency, low background vs. channel count
• Optimize ratio of proportional tubes (good spatial resolution) vs. scintillator (good energy resolution, timing)
• Flux determination using inverse muon decays
• Ability to detect Michel electrons
• Calibration beam requirements
• Shielding and veto requirements
• Cost and schedule
Some Development Projects are just starting

1. Stack of five 1” glass planes with active detectors for cosmic ray studies (Columbia/MIT)
2. Instrumenting the glass targets (Columbia)
3. Liquid scintillator with glass beads to provide high density, isoscalar target - Northwestern
4. Measurement of neutrino cross sections on glass with Minerva
5. Alternatives to toroidal focussing
NuSOnG will provide new measurements in three areas: *electroweak measurements* of neutrino neutral current couplings, *sensitive searches* for new neutrino properties and high *precision studies of quarks* inside the nucleus. The experiment itself is *simple, robust* and could draw in a large university based community. NuSOnG places modest demands on protons from the accelerator complex and, in return, will provide a very broad physics program.
Backup
What is nuclear isospin violation?

\[
\delta u_v(x, Q^2) = u^p_v(x, Q^2) - d^n_v(x, Q^2)
\]

\[
\delta d_v(x, Q^2) = d^p_v(x, Q^2) - u^n_v(x, Q^2)
\]

Why?
- u and d quarks have different masses
  (biggest effect in “bag model”)
- Difference in the virtual meson (pion) cloud
- QED corrections (different because u is +2/3, d is -1/3)

Why does it matter?

CC interactions are flavor-dependent!

\[
\begin{array}{ccc}
\nu_\mu & \mu^- & \bar{\nu}_\mu \\
W & W & W \\
d & u & u \\
d & u & d
\end{array}
\]
Sources of information on nuclear isospin violation:

**Past experiments:**
F₂ in charged lepton vs neutrino scattering
(comparison will be improved by NuSOnG, which will extend to lower x due to higher stats and less dense target)
W lepton charge asymmetry from the TeVatron
Drell-Yan 866

**Proposed Experiments:**
NuSOnG ΔxF₃ (1st real opportunity due to high stats!)
Drell-Yan: E906 (approved -- run date?)

**Possible Experiments** (suggested in hep-ph/0507029)
π⁺D scattering
Semi-inclusive deep inelastic scattering
Why NuSOnG can do better than CCFR (only previous attempt)?

1. Higher stats
   (stat error determined by the $\bar{\nu}$ events: $\sim 33$M vs 250k)

2. Better reach in $y = E_{\text{had}}/E_{\nu}$
   less material from front face to toroid,
   wider detector (5m vs 3m)

3. Isoscalar target
   (no correction for excess neutrons)

4. Improved measurements of s and c seas

5. Range of nuclear targets to study $\nu$ vs $\bar{\nu}$ nuclear effects

A first opportunity for a significant result!
The upcoming NuTeV-reanalysis  
(likely available in late winter)

Will include…

The new Ke3 branching ratio which moves \( \sin^2 \theta_W \) away from the SM
The new strange sea asymmetry which moves \( \sin^2 \theta_W \) toward the SM

Net expectation: No change, but small increase in error due to strange sea
Other improvements coming soon…
(but not included in NuTeV re-analysis)

NLO calculations are now available but are awaiting resolution on nuclear effects in PDFs

Radiative corrections are being recalculated (available next spring?)
Other experiments measuring $\sin^2 \theta_W$

**JLAB:**
DIS-Parity (needs the 12 GeV upgrade)

**QWEAK**

---

**Important!**
... and complementary

(Figure from QWEAK website)

PW error $\sim$QWEAK, but in the neutrino sector (and higher $Q^2$)
Challenges for the Tevatron...

1. Instabilities at high luminosity and energy.
2. Repeated ramping.

These questions have to be answered by the Tevatron Dept.

On our experiment, we have expertise:
   Ron Moore
   Mike Syphers
   C.Y. Tan