NO\textsuperscript{A}A

\textbf{NuMI Off-Axis $\mu$e Appearance Experiment}

APS Neutrino Workshop
Brookhaven
5 March 2004

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NO$
\sigma$A

Organization

- Concept
- Detector
- Site
- Beam
- Backgrounds
- Simulations
- Physics Potential
- Status and Schedule
Phase 1

- Goals:
  - Verify atmospheric results and improve parameter measurement.
  - Low sensitivity search for $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations.

- Time scale: Now to next two years.

- Examples:
  - K2K
  - MINOS
  - CNGS
Phase 2 Experiments

Phase 2

Goals:
- Extend the search for $\nu_\mu \rightarrow \nu_e$ oscillations by an order of magnitude.
- Start to gather information on the mass hierarchy and CP violation.

Time scale: By the end of the decade

Cost: NuMI scale (~150 M$)

Examples
- JPARC Phase 1
- NO\~A
- Reactor Experiments
Phase 3 Experiments

● Phase 3
  ● Goals:
    • Resolve the mass hierarchy
    • Measure the CP phase
  ● Time scale: Next decade
  ● Cost: B$ range (proton driver and massive detector)
  ● Examples:
    • JPARC Phase 2
    • CERN SPL and beta beam
    • Brookhaven proposal
    • Extensions to NO\(A\)
    • Neutrino factories (phase 4?)
How Do We Achieve Our Phase 2 Goals?

- Go off-axis to get a low-energy narrow-band beam near the atmospheric oscillation maximum (proposed by Brookhaven in 1995)
  - $\nu_e$ appearance maximum
  - $\bar{\nu}_e$ CC largely disappears
  - Higher-energy NC disappears
- Build a detector optimized for electron detection
- Increase the beam flux times detector mass
- Work at a long baseline to maximize matter effects
Off-Axis Kinematics

\[
E_\nu = \frac{0.43 m_{\odot}}{1 + Q^2 Q^2}
\]

\(E_\nu\) versus \(E_\pi\) for different values of \(\theta\):
- \(\theta = 0\) mrad
- \(\theta = 7\) mrad
- \(\theta = 14\) mrad
- \(\theta = 27\) mrad

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Off-Axis Spectrum (No oscillations)
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A is proposed to be
- 50 kT
- Medium-Z sandwich detector
  - Particle board absorber
  - Liquid scintillator strip detectors with APD readout
  - Glass RPC detectors fallback option
- 810 km baseline, about 12 km off-axis (Ash River, MN)
Why a Medium-Z Sandwich Detector?

- Water Cerenkov does not provide sufficient NC rejection at NuMI energies (~2 GeV).
- Liquid Argon requires R&D beyond the Phase 2 time scale.
- Medium-Z sandwich detectors provide good $p^0$-electron discrimination.
Electron Track

 Hits per plane > 1
Muon track

Hits per plane \sim 1
Two tracks with different starting points leading to a “gap”
Detail of NC with leading $\pi^0$
Monolithic structure

Liquid Scintillator:
1.2 m x 3 cm x 14.4 m
30-cell PCV extrusions,
24 extrusions/plane,
750 planes
= 18,000 extrusions
= 540,000 channels
APD readout

Absorber:
20 cm particleboard/plane (~1/3 $X_0$)

TASD being studied

800 planes X, absorber, Y, absorber, … = detector
We are now focusing on the Ash River site.
Beam Prospects

- MINOS will start next year with $2 \times 10^{20}$ pot/yr.
- By 2009, we expect that the MI should deliver $4 \times 10^{20}$ pot/yr. Will most likely require more magnet and RF power to increase the MI cycle rate.
- Further increases in proton intensity requires replacing the 8 GeV Booster. Best option is a superconducting linac (a.k.a. proton driver). A proton driver is being recommended by the Fermilab Long Range Planning Committee and is on the Secretary of Energy’s facilities plan (although generic and very long range). A proton driver would allow $20 \times 10^{20}$ pot/yr.
Backgrounds to $\bar{\nu}_e$ 

- Scale of background problem: statistical error on background in 5 yr run is about 15%.

- Background composition (typically)
  - Beam $\bar{\nu}_e$ CC 54%
  - NC 34%
  - $\bar{\nu}_\mu$ CC (with unidentified $\nu$) 12%

- Most direct approach is an off-axis near detector
  - Beam $\bar{\nu}_e$ CC and NC scale approximately as $1/L^2$.
  - $\bar{\nu}_\mu$ CC does not, due to oscillations. Correct by extrapolating identified muons to unidentified muons.
  - Useful cross section measurements from the MINER$\bar{A}$ experiment
Simulations

- We have done full simulations, starting with raw hits. The hits are reconstructed and the signal events are separated from the various backgrounds with the use of a cut on a likelihood function, based on topological characteristics.
- I have added 5% systematic uncertainty to the background determinations.
- New beam and physics simulations give less sensitive results by a factor of about 1.5. Graphs that have not been redone yet are labeled “Old”.

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\[ P(\nu_l \nu_e) \]
\[ (\text{in Vacuum}) \]

- \[ P(\nu_l \nu_e) = P_1 + P_2 + P_3 + P_4 \]
  - \[ P_1 = \sin^2(\theta_{23}) \sin^2(\theta_{13}) \sin^2(1.27 \Delta m_{13}^2 L/E) \]
  - \[ P_2 = \cos^2(\theta_{23}) \sin^2(\theta_{12}) \sin^2(1.27 \Delta m_{12}^2 L/E) \]
  - \[ P_3 = \mp J \sin(\theta_{23}) \sin(1.27 \Delta m_{13}^2 L/E) \]
  - \[ P_4 = J \cos(\theta_{23}) \cos(1.27 \Delta m_{13}^2 L/E) \]

where \[ J = \cos(\theta_{13}) \sin(\theta_{12}) \sin(\theta_{13}) \sin(2\theta_{23}) \times \]
\[ \sin(1.27 \Delta m_{13}^2 L/E) \sin(1.27 \Delta m_{12}^2 L/E) \]
In matter, $P_1$ will be approximately multiplied by $(1 \pm 2E/E_R)$ and $P_3$ and $P_4$ will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\sqrt{m_{13}^2}}{2\sqrt{2}G_F} \approx 11 \text{ GeV for the earth's crust.}$$

About a ±23% effect for NuMI, but only a ±10% effect for JPARC.
Probability Plots

- Probability plots assume a particular result for a measurement of $P(\bar{\nu}_\mu \rightarrow \nu_e)$ and show:
  - The possible values of $\sin^2(2\theta_{13})$, $\text{sign}(m_{13}^2)$, and $\bar{\nu}$ consistent with this measurement, and
  - How another measurement would discriminate among them.
\[ P(\bar{\nu}_e) = 0.02 \text{ at 820 km} \]

Note

(1) Effect of \( \cos(\theta) \) term
(2) Ambiguities
  (Hidden ambiguity: \( P1 \mu \sin^2(\theta_{23}) \); if \( \sin^2(2\theta_{23}) = 0.95 \), \( \sin^2(\theta_{23}) = 0.39 \) or 0.61)

(1) Rough equivalence of reactor and antineutrino measurements
$P(\bar{\nu}_1, \bar{\nu}_3, \bar{\nu}_e) = 0.05, 0.02, 0.01, \text{ and } 0.005 \text{ at } 820 \text{ km}$
\[ P(\bar{\nu}_e = \bar{\nu}_e) = 0.02 \]

at 820 and 295 km
$P(\bar{\nu}_e) = 0.02$ at 820 km

Note ambiguities between normal hierarchy and inverted hierarchy.

Can combining JPARC and NuMI data help?
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.02$ at 820 km vs. $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 295 km

Ambiguous points are still fairly close together
A 2nd Detector at the 2nd Maximum?

$\sin^2(2\theta_{13})$ vs. $P_{\text{2nd max}}(\nu_e)$ for $P(\nu_e) = 0.02$

- $L = 820$ km, 10 km off
- $L^* = 710$ km, 30 km off
- $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$

- $\Delta m^2 < 0$
- $\Delta m^2 > 0$

- $\delta = 0$
- $\delta = \pi/2$
- $\delta = \pi$
- $\delta = 3\pi/2$
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u$A Goals

- **Primary (Phase 2) goal:** Find evidence for $\nu_\mu \rightarrow \nu_e$, determining $\sin^2(2\theta_{13})$ to a factor of 2.

- **Longer term goal:** Determine the mass hierarchy.

- **Ultimate goal:** Precision measurement of the CP-violating phase $\delta$. 

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3 $\odot$ Discovery Potential for $\bar{\nu}_e$

$3 \odot$ Sensitivity to $\sin^2(2\theta_{13})$

$L = 810$ km, 10 km off
$\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$

100$x10^{30}$ pot (Proton Driver)

$\Delta m^2 > 0$
$\Delta m^2 < 0$

JPARC Phase 1

20$x10^{20}$ pot

$\Delta m^2 > 0$
$\Delta m^2 < 0$
Study Points

\[ \sin^2(2\theta_{13}) \text{ vs. } P(\bar{\nu}_e) \text{ for } P(\nu_e) = 0.02 \]

- L = 820 km, 10 km off
- \( \Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2 \)

- \( \Delta m^2 > 0 \)
- \( \Delta m^2 < 0 \)

- \( \delta = 0 \)
- \( \delta = \pi/2 \)
- \( \delta = \pi \)
- \( \delta = 3\pi/2 \)
Point 1: NuMI 3 yr $\square$, 3 yr $\square$ 4 $10^{20}$ and 20 $10^{20}$ pot/yr

1, 2, 3 $\sigma$ Contours for Starred Point, Neg $\Delta m^2$

$L = 820$ km, 10 km off
$\Delta m_{32}^2 = 2.5 \times 10^{-3}$ eV$^2$
12 $10^{20}$ pot $\nu$, 12 $10^{20}$ pot $\bar{\nu}$

Proton Driver

Old

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NuMI 3 yr, 3 yr
4 $10^{20}$ and 20 $10^{20}$ pot/yr

1, 2, 3 $\sigma$ Contours for Starred Point, Pos $\Delta m^2$

$\sin^2(2\theta_{13})$

$L = 820$ km, 10 km off
$\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$
$12 \times 10^{20}$ pot $\nu$, $12 \times 10^{20}$ pot $\bar{\nu}$

Old

$\delta (\pi)$

Proton Driver

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NuMI 3 yr $\nu$, 3 yr $\bar{\nu}$, 2 Detectors and Proton Driver

1, 2, 3 $\sigma$ Contours for Starred Point, Pos $\Delta m^2$

$\sin^2(2\theta_{13})$

$\delta (\pi)$

$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV$^2$
$L = 820$ km, $10$ km off
$L = 710$ km, $30$ km off
$60 \times 10^{20}$ pot $\nu$, $60 \times 10^{20}$ pot $\bar{\nu}$

Old
95% CL Resolution of the Mass Hierarchy

\[ L = 810 \text{ km, } 10 \text{ km off} \]
\[ \Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2 \]

- Each \( \nu \) and \( \bar{\nu} \)
- 12x10^{20} \text{ pot, } \Delta m^2 > 0
- 12x10^{20} \text{ pot, } \Delta m^2 < 0
- 60x10^{20} \text{ pot, } \Delta m^2 > 0
- 60x10^{20} \text{ pot, } \Delta m^2 < 0

(Proton Driver)
2 o Resolution of the Mass Hierarchy

L = 810 km, 10 km off
L = 710 km, 30 km off
$\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$

Each $\nu$ and $\bar{\nu}$

- $60 \times 10^{20} \text{ pot, } \Delta m^2 > 0$
- $60 \times 10^{20} \text{ pot, } \Delta m^2 < 0$ (Proton Driver)
**Status**

- R&D proposal submitted to the NSF in September.
- Progress Report submitted to the Fermilab PAC in December; full proposal will follow in March.
- PAC reaction:
  - “This can potentially become the future flagship experiment in an exciting neutrino physics program at Fermilab.”
  - “Given the physics potential of the experiment and the significant detector cost involved, the Committee feels that some assistance from Fermilab for time-critical R&D needs leading to the proposal are justified.”
- Temporary governance of the collaboration set up at February collaboration meeting.
- Next collaboration meeting May 15-16.
Possible Time Scenario

- Spring 2004 - R&D funds from NSF
- June 2004 - Stage 1 Approval from Fermilab
- Summer 2004 - APS study report finished
  - Initial funding proposed for FY06 (Oct. 1, 2005)
- Dec 2004 - Final technology decision
  - Proposal update document submitted to Fermilab
- June 2005 - Final approval by Fermilab
  - Construction funds requested for FY07
- Oct 2006 - Start of construction
- Sept 2008 - Start of data with 25% of detector
- Sept 2010 - Detector construction completed
Comments on Schedule

● The schedule outlined is the technically feasible one with some optimistic assumptions about flow of funds.

● The NO\textsuperscript{A} projected cost is essentially the same as the cost of the whole NuMI project - beam, detectors, conventional construction (~$150M).

● NuMI will take 5 years of funding to complete - mainly because of delay in completion of underground excavation work.
Conclusion

- NO\(A\) is the right next step for the US in the context of a world-wide phased investigation of neutrino physics.
- In conjunction with other efforts, it will provide the information necessary to plan for Phase 3 activities.