(Status of ) The search for $\nu_\mu$ to $\nu_e$ oscillations at MiniBooNE

Andrew Bazarko – Princeton University
9 October 2003
WIN03 – Weak Interactions and Neutrinos
Lake Geneva, Wisconsin
MiniBooNE status snapshot

MiniBooNE has been running for 1 year at Fermilab
acquired 15% of goal $10^{21}$ protons on target
At the moment (Sept – mid Nov) accelerator is shutdown
important accelerator improvements are underway

Outline

Overview of the experiment
   (preview of tomorrow’s tour)
First neutrino events and analysis

Outlook
LSND: Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\bar{\nu}_\mu$ beam from $\mu^+$ decay at rest
energy 20-53 MeV
baseline 30 m
$L/E \sim 1 \text{ m/MeV}$

87.9\pm22.4\pm6.0$ events

$\Delta m^2 \sim 0.2-10$ eV$^2$
(Bugey is $\bar{\nu}_e$ disappearance)
Too many $\Delta m^2$’s?

3 light neutrino flavors

Solar (+KamLAND) neutrinos:
- $\Delta m^2 \approx 7 \times 10^{-5} \text{ eV}^2$
- mostly $\nu_e \rightarrow \nu_{\mu,\tau}$

Atmospheric (+K2K) neutrinos:
- $\Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2$
- mostly $\nu_\mu \rightarrow \nu_\tau$

Where does LSND’s $\Delta m^2 \sim 0.2-10 \text{ eV}^2$ fit in this picture??
ν Oscillation Scenarios:

With current results from solar, atmospheric, and LSND ν–oscillation searches (3 $\Delta m^2$s), we have an interesting situation:

**Only 3 active $\nu$:**

```
ν mass
ν₁ = ν₂ = ν₃
```

OR...

**3 active+1 sterile $\nu$:**

```
ν mass
ν₁ = ν₂ = ν₃ = ν₄
```

OR...

**CPT violation:**

```
ν mass
ν₁ = ν₂ = ν₃
```

OR...

```
ν mass
ν₁ = ν₂
```

- solar: $\nu_e \rightarrow \nu_\mu$
- atmos: $\nu_\mu \rightarrow \nu_e, \nu_\tau$
- LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \rightarrow \bar{\nu}_e$
- not a good fit to data

- solar: $\nu_e \rightarrow \nu_\mu, \nu_\tau$
- atmos: $\nu_\mu \rightarrow \nu_\tau$
- LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_s \rightarrow \bar{\nu}_e$
- possible(?)

- solar: $\nu_e \rightarrow \nu_\mu$
- atmos: $\nu_\mu \rightarrow \nu_\tau$
- LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- possible(?)

Need to definitively check the LSND result.
Goal: test LSND with 5-$\sigma$ sensitivity over whole allowed range

- higher statistics
- different signature
- different backgrounds
- different systematics

MiniBooNE!
BooNE: Fermilab Booster Neutrino Experiment

First phase: “MiniBooNE”

- Single detector, $\nu_\mu \rightarrow \nu_e$ appearance
- $L/E=500 \text{ m}/500 \text{ MeV} = 30 \text{ m}/30 \text{ MeV (LSND)}$
MiniBooNE

8-GeV protons on Be target $\rightarrow$  
$\pi^+, K^+, \ldots$, focused by horn  
decay in 50-m pipe, mostly to $\nu_\mu$  
all but $\nu$ absorbed in steel and dirt  
$\nu$'s interact in 40-ft tank of mineral oil  
charged particles produce light  
detected by phototube array

Look for electrons produced by mostly-$\nu_\mu$ beam
The Booster

8 GeV proton accelerator supplies beam to all Fermilab experiments

It must now run at record intensity

MiniBooNE runs simultaneously with the collider program; goals:

- antiproton source
- TeVatron
- NuMI
- 120 GeV fixed target

MiniBooNE: negligible impact on collider; improvements to Booster good for NuMI
Booster performance

We are pushing the Booster hard

Must limit radiation damage and activation of Booster components:
  increase protons
  but decrease beam loss

~steady improvements
  careful tuning
  understanding optics

need factor of 2-3 to reach goal $10^{21}$ p.o.t. by early 2005

further improvements coming
  collimator project (now)
  large-aperture RF cavities

red: Booster output (protons/minute)
blue: energy loss per proton
(W-min/proton)
Target and magnetic horn

Increases neutrino intensity by 7x

170 kA in 140 µsec pulses @ 5 Hz

Currently positive particles are being focused, selecting neutrinos $\pi^+ \rightarrow \mu^+ \nu_\mu$

the horn current can be reversed to select antineutrinos $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

Prior to run, tested to 11M pulses
has performed flawlessly:
40M pulses in situ

World’s longest-lived horn
Intrinsic $\nu_e$ in the beam

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \]

\[ K^+ \rightarrow \pi^0 e^+ \nu_e \]

\[ K_L \rightarrow \pi^- e^+ \nu_e \]

important bkgd to osc search

Tackle this background with half-million $\nu_\mu$ interactions in detector HARP experiment (CERN) E910 (Brookhaven) “Little Muon Counter” 25 m / 50 m decay length option
Little Muon Counter (LMC)

- off-axis ($7^\circ$) muon spectrometer
- $K$ decays produce higher-energy wide-angle muons than $\pi$ decays
- clean separation of muon parentage
- scintillating fiber tracker

Muon momentum at $7^\circ$ (GeV)

Monte Carlo

Data from temporary LMC detector

53 MHz beam RF structure seen

[Image of decay channels: $K$ and $\pi$]
The MiniBooNE detector
MiniBooNE detector

pure mineral oil (Cherenkov:scint \(\sim 3:1\))

total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5 m radius)

Phototube support structure provides opaque barrier between veto and main volumes

1280 20-cm PMTs in detector at 5.5 m radius
\[\rightarrow\] 10% photocathode coverage
(330 new tubes, the rest from LSND)

240 PMTs in veto
Pattern of hit tubes (with **charge** and **time** information) allows reconstruction of track location and direction and separation of different event types.

e.g. candidate events:

- muon from $\nu_\mu$ interaction
- Michel electron from stopped $\mu$ decay after $\nu_\mu$ interaction
- $\pi^0 \rightarrow$ two photons from $\nu_\mu$ interaction
measure:
  PMT charge and time response
  and oil attenuation length

397 nm laser (no scintillation!) modeling other sources of "late light"
Stopping muon calibration system

Optically isolated scintillator cubes in tank:
  six 2-inch (5 cm) cubes
  one 3-inch cube

Scintillator tracker above the tank:

Stopping muons with known path length

Calibration sample of muons up to 700 MeV
Michel electrons
(electrons from the decay of stopped muons)

plentiful source from cosmosics
and beam-induced muons

cosmic muon lifetime in oil
measured: $\tau = 2.15 \pm 0.02$ $\mu$s
expected: $\tau = 2.13$ $\mu$s
(8% $\mu^-$ capture)

Energy scale and resolution
at Michel endpoint (53 MeV)

Michel electrons throughout
detector ($r<500$ cm)
Neutrino events

beam comes in spills @ up to 5 Hz
each spill lasts 1.6 $\mu$sec

trigger on signal from Booster
read out for 19.2 $\mu$sec; beam at [4.6, 6.2] $\mu$sec

no high level analysis needed to see neutrino events

backgrounds: cosmic muons
decay electrons

simple cuts reduce non-beam backgrounds to $\sim 10^{-3}$

160k neutrino candidates
in $1.5 \times 10^{20}$ protons on target
The road to $\nu_\mu \rightarrow \nu_e$ appearance analysis

Blind $\nu_e$ appearance analysis
  you can see all of the info on some events
  or
  some of the info on all events
  but
  you cannot see all of the info on all of the events

Early physics: other analyses before $\nu_\mu \rightarrow \nu_e$ appearance interesting in their own right
relevant to other experiments
necessary for $\nu_\mu \rightarrow \nu_e$ search
  vets data-MC agreement (optical properties, etc.)
  and reliability of reconstruction algorithms
  progress in understanding backgrounds
Early physics

**CC quasi-elastic**

- $\nu_\mu, \theta_\mu \rightarrow E_\nu, Q^2$
- relatively well-known $\sigma$: $\nu_\mu$ disappearance

**NC $\pi^0$ production**

- resonant:
  \[ \nu + (p/n) \rightarrow \nu + \Delta \]
  \[ \Delta \rightarrow (p/n) + \pi^0 \]
- coherent:
  \[ \nu + C \rightarrow \nu + C + \pi^0 \]
- abundance $\sim 7\%$
- $\pi^0 \rightarrow \gamma \gamma$
- two rings
- E1, E2 from $\bar{C}$ intensities
- select “sharp” events
- $\sim 88\%$ purity
- reconstruct invariant mass of two photons
- background to $\nu_e$ appearance and limits on sterile $\nu$

**NC elastic**

- abundance $\sim 15\%$
- usually sub-$\bar{C}$
- dominated by scintillation
- low Ntank (pmt hits)
- high late light fraction
- understanding of scintillation
- sensitive to nucleon strange spin component
CC $\nu_\mu$ quasi-elastic events

selection: topology
  ring sharpness
  on- vs. off-ring hits
  timing
  single $\mu$-like ring
  prompt vs. late light

⇒ variables combined
  in a Fisher discriminant

PRELIMINARY

$E_{\text{vis}}$

PRELIMINARY

$\cos \theta_\mu$

data and MC relatively normalized

yellow band: Monte Carlo with current uncertainties from
  • flux prediction
  • $\sigma_{\text{CCQE}}$
  • optical properties
Neutrino energy

kinematic reconstruction:
assume $\nu_\mu n \rightarrow \mu^- p$
use $E_{\nu_\mu}$, $\theta_{\mu}$ to get $E_{\nu}$

sensitive to $\nu_\mu$ disappearance

Monte Carlo

\[
\left( \frac{\Delta E_{\nu}}{E_{\nu,\text{gen}}} \right)^2 = a^2 + \left( \frac{b}{\sqrt{E_{\nu,\text{gen}}}} \right)^2 + \left( \frac{c}{E_{\nu,\text{gen}}} \right)^2
\]

\begin{align*}
a & = 3.788008 \times 10^{-2} \\
b & = 8.364264 \times 10^{-2} \\
c & = 0.000000 \times 10^{00}
\end{align*}

$<10\%$ for $E_{\nu} > 800$ MeV

PRELIMINARY
Preliminary $\nu_\mu$ disappearance sensitivity

systematics dominated:

from uncertainty in flux prediction
NC $\pi^0$ production

$N_{TANK} > 200$, $N_{VETO} < 6$, no decay electron

perform two ring fit on all events
require ring energies $E_1, E_2 > 40$ MeV

fit mass peak to extract signal yield
including background shape from Monte Carlo

Preliminary

Mass = $0.1356 \pm 0.0009$ GeV/$c^2$
Width = $0.0209 \pm 0.0009$ GeV/$c^2$
Num. $\pi^0 = 2425 \pm 107$ Events
\( \pi^0 \) production angle

sensitive to production mechanism

coherent is highly forward peaked

data and MC are relatively normalized

MC shape assumes Rein-Sehgal cross sections
\( \pi^0 \) decay angle

and

\( \pi^0 \) momentum

CM frame | lab frame
---|---
\[ \theta_{\text{CM}} = \pi/2 \] | small \( \gamma \gamma \) opening angle
\[ \cos \theta_{\text{CM}} = 0 \] | photon energies asymmetric
\[ \theta_{\text{CM}} = 0 \] | \[ \cos \theta_{\text{CM}} = 1 \]

PRELIMINARY

- Data w/ statistical errors
- MC w/ statistical + yield extraction systematic errors

PRELIMINARY
Now select $N_{\text{TANK}} < 150$

$N_{\text{VETO}} < 6$

Background subtraction

clear beam excess

use random triggers to subtract non-beam background
$\nu_{\mu}$ NC elastics

Consider $N_{\text{TANK}}$ spectrum
MC and data shapes agree qualitatively for $N_{\text{TANK}}>50$
Unknown component $N_{\text{TANK}}<30$

data and MC relatively normalized for $N_{\text{TANK}}>50$

Late light selection:
fit event vertex for $N_{\text{TANK}}>50$
calculate fraction of late hits
select events with significant late light
ν\textsubscript{e} appearance sensitivity

preliminary estimates, backgrounds and signal

1500 intrinsic ν\textsubscript{e}
500 μ mis-ID
500 π\textsuperscript{0} mis-ID
1000 LSND-based ν\textsubscript{μ}→ν\textsubscript{e}

cover LSND allowed region at 5 σ
updated estimates coming
currently expect results in 2005
Conclusions
steadily taking data
currently at 15% of $10^{21}$ p.o.t
beam is working well, but still need higher intensity
improvements underway (shutdown) will be key
first sample of neutrino physics
detector and reconstruction algorithms are working well