The Fermilab Short-Baseline Neutrino Program: A Search for Sterile Neutrinos and A Study of $\nu$-Argon Interactions

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Neutrino Interactions
CETUP
July 22-31, 2014
Many techniques I will describe are currently being developed and used by ArgoNeut. My thanks to ArgoNeut for allowing me to use some of their data as examples.
Why look for Sterile Neutrinos?

◆ The LSND, MiniBooNE accelerator anomalies
Excess $\nu_e$ signal in $\nu_\mu$ beam. $\nu_\mu \rightarrow \nu_e$?

◆ The radioactive source anomaly:
Rate smaller by $\sim 14\%$

$\Delta m^2_{\text{new}} = 2\text{eV}^2$
$\sin^2(2\theta_{\text{new}}) = 0.12$

All $\sim 3\sigma$ effects

Could be explained by additional neutrino with a mass of $\sim 1\text{eV}/c^2$: Sterile (no $Z^0$ coupling)
Motivation or, the Genealogy of the BNB program

Interesting effect!
LSND observed a (~3.8σ) excess of $\bar{\nu}_e$ events in a pure $\nu_\mu$ beam
If due to oscillations:
L/E $\rightarrow$ High $\Delta m^2$ $\sim$ 1 eV$^2$
Can only be accomodated by a NEW and STERILE neutrino

MiniBooNE Booster Neutrino Beam at Fermilab

Excess mostly at Low energy in $\nu$ and $\bar{\nu}$.

Liquid Argon: MicroBooNE ICARUS +LAr1-ND

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July 24, 2014

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Bands at the Beach Club

Argon and the Noble Gases
Saturday, July 19th approx. 5:30pm
Why is Liquid Argon different from MiniBooNE?

- MiniBooNE searched for $\nu_\mu \rightarrow \nu_e$ oscillations
- Looked for excesses of $\nu_e$ in a $\nu_\mu$ beam and of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam.
- $\nu_e$ identified by their Charged Current Interactions $\rightarrow$ e shower in final state $\rightarrow$ Fuzzy Cerenkov Ring
- But MiniBooNE could not distinguish between a photon and an electron shower.
- Is the excess due to
  - Electrons ($\rightarrow$ oscillations to sterile)?
  - Or Photons?
- **Liquid Argon is good at**
  - Distinguishing between electrons and photons.
  - Reducing photon background
  - Neutrino energy reconstruction.

**Nature of MiniBooNE excess $\rightarrow$ Main MicroBooNE task**
What should we be looking for?

- To reproduce the same conditions as in MiniBooNE
  Locate MicroBooNE in same beam and at ~ same distance as MiniBooNE.

**MicroBooNE(170 tons) at 470m (just upstream of MiniBooNE)**

- If the LSND and/or MiniBooNE $\nu_\mu \rightarrow \nu_e$ signals are due to a sterile $\nu$
- Then: $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$
- Implies $\nu_e$ appearance AND $\nu_\mu$ disappearance
- Must look for BOTH.

What is needed?

- Determine the INTRINSIC $\nu_e$ flux in the $\nu$ beam for the $\nu_e$ appearance search
- Constrain the $\nu_\mu$ flux for $\nu_\mu$ disappearance search
- Constrain the $\nu_e$ from $\mu$ decay using the $\nu_\mu$ flux.
- Is the MiniBooNE excess intrinsic to the beam or distance dependent?

**NEAR Detector: LAr1-ND(150tons) at 110m**
What should we be looking for?

- To maximize a potential oscillation effect, increase the detector mass and its baseline:
  
  **ICARUS (760 tons) at 600m (downstream of MiniBooNE)**

- The full capabilities of a 3-detector configuration are currently being evaluated.

- Presentation at the Fermilab PAC this week.

- **For most of the rest of this talk: Concentrate on MicroBooNE and LAr1-ND.**
  - And present what could be achieved with:
    - a 3-year run of MicroBooNE (6.6 x 10^{20} POTs)
      combined with
    - LAr1-ND taking data during the 3\textsuperscript{rd} year (2.2 x 10^{20} POTs)
The Short Baseline Physics Program

- Resolve the cause and origin of the MiniBooNE low energy excess.
- Search for Oscillations at a high $\Delta m^2$.
  - $\nu_\mu - \nu_e$ appearance.
  - $\nu_\mu$ disappearance.
- Measure Neutrino-Argon interactions with high statistics in a region relevant to LBNE

- SuperNova sensitivity.

*During* SuperNova - $\nu_e$'s detected from SN1987A
- Characteristic short burst
- Novel prize (2002)!

We *can* detect $\nu_e$ capture on Ar
- We *cannot* trigger on its own
  - ... small volume & too much cosmics!

But we *can* analyze SuperNova data upon SNEWS
- That's why we have dedicated data stream!

Using

- The Fermilab Booster Neutrino Beam
- FNAL booster (8 GeV protons)
- target and horn (174 kA)
- decay region (50 m)
- dirt (~500 m)

And, hopefully, another beam.....
The R&D Program

◆ MicroBooNE
  ▪ Cold electronics: preamps in cryostat.
    Shorter wire-preamp cables and lower temperature → Decrease noise.
  ▪ Filling without evacuation.
  ▪ Longer (2.5m) drift length. (ICARUS: 1.5m)
  ▪ TPC field calibration using a Laser.
  ▪ Reconstruction.
  ▪ Continuous readout for SuperNova purposes
  ▪ Background to proton decay studies.

◆ LAr1-ND: Closely aligned to the Long Baseline technology
  ▪ More electronics in the cold: including digitization.
  ▪ Membrane Cryostat
  ▪ TPC according to Long Baseline design.
Where are we located?

The Fermilab Booster Neutrino Beam (BNB) (and NUMI beam in off-axis configuration).

ICARUS: L=600m
476t Active volume TPC

MicroBooNE: L=470m
89t Active volume TPC

LAr1-ND: L=110m
82t Active volume TPC
Where are we located relative to an oscillation pattern?

LAr1-ND
Sample the beam
BEFORE
Oscillations

High statistics
event samples

ICARUS

MicroBooNE

FIG. 22: Top: ICARUS T600 detector schematics showing both modules and the common insulation surrounding the detector. The inner structures and feed-throughs are also shown. Bottom: A view of the detectors with the wire chambers and the high voltage system including race-tracks and cathodes.

Components with up-to-date technology in view of its future non underground operation. The refurbishing will include the following main activities:

- Realization of new vessels for LAr containment, based on aluminum extruded profiles;
- Realization of new thermal insulation, based on similar technology as foresee for LBNE and the near detector;
- Implementation of a new light collection system, that will allow automatic event localisation and disentangling from the background induced by cosmic rays;
- Implementation of new readout electronics, with new internal cabling. The possibility to...
The MicroBooNE Detector

In beam line!

June 23rd

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The MicroBooNE Liquid Argon Time Projection Chamber

Neutrinos interact in 89 tons (active volume) Liquid Argon → charged particles.

Ionization e’s drift (2.5m maximum) (1.6mm/μsec)→1.6msec.

Drift time from t⁰ gives Z t⁰ given by PMT’s

500V/cm
The MicroBooNE Photodetectors

LAr scintillates in the UV at 128nm: Use it
- To trigger on events in time with beam gate.
- To time and reject cosmic rays within drift time.

- 32 Hamamatsu R5912-02 14 stage 8 inch pm’ts.
- Located behind collection plane
- Plate coated with Tetrphenyl-butadiene (TPB)
  in front of each pm’t: to shift UV light to visible

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Triggered and SuperNova Continuous readout

Continuous readout for SuperNova

TPC

1 µs shaping time
2 MHz

PMT

60 ns shaping time
64 MHz

Beam events
Triggered by
PMT + Beam gates

Beam events
Compression
PMT trigger?

PMT trigger
Generation

PC
Cyclic (1 hr)
Data storage

50 MB/s
per PC

PC
Permanent
Data storage

PC
Permanent
Data storage

Supernova
Compression,
decimation
Reduced by
~ 80

Beam v’s: 1/ ~100secs
FIG. 19: Left: Top view schematic of the LAr1-ND membrane cryostat detector concept. Foam insulation surrounds the corrugated stainless steel membrane filling the near detector enclosure.

Right: Conceptual design of the LAr1-ND TPC. The total size of the TPC is 4.0 m (width) × 4.0 m (height) × 3.65 m (length) with the longest dimension along the neutrino beam direction. Note: the field cage panels are removed from view in this schematic.

This detector will soon be exposed to an intense low energy neutrino source. MicroBooNE is approved to receive an exposure of $6.6 \times 10^{20}$ protons on target from the existing on-axis Fermilab Booster neutrino beam. It will also record interactions from an off-axis component of the NuMI neutrino beam. During MicroBooNE running, the BNB will be operated in the same configuration that successfully delivered neutrino and antineutrino beam to MiniBooNE for more than a decade, thereby significantly reducing systematic uncertainties in the comparison of MicroBooNE data with that from MiniBooNE.

As of the writing of this document, construction of the MicroBooNE TPC has been completed and on June 23, 2014, the MicroBooNE vessel was moved to the Liquid Argon Test Facility (LArTF), a new Fermilab enclosure just upstream of the MiniBooNE detector hall in the Booster neutrino beamline (Figure 21). Final installation and detector commissioning has begun. MicroBooNE is on schedule to begin taking neutrino data in early 2014.

C. Far Detector: ICARUS T600

The ICARUS T600 detector installed in the underground INFN-LNGS Gran Sasso Laboratory has been the first large-mass Liquid Argon TPC (LAr-TPC) operating as a continuously drifting detector.
LAr1-ND Cold Electronics

LAr1-ND Light Collection

Compact light-guide collection system to detect LAr scintillation light.
ICARUS

- Gran Sasso: Dismantling and move to
- CERN: Refurbishing
  - New electronics
  - New containment vessel
  - New insulation
  - New light collection.
- Fermilab:
  - New Building
  - New cryogenics

4 anode wire planes
- Same 3mm wire spacing as MicroBooNE and LAr1-ND
- 2 cathodes
What is the MiniBooNE excess due to? Electrons or Photons?

**Electron**: Connected to primary vertex
And singly ionizing track in first ~ 2.4 cm before shower develops.

**Photons from \( \pi^0 \) rejection:**
- Recognize 2 photons \( \rightarrow \pi^0 \) mass

**Single Photon** rejection:
- Gap between primary vertex and conversion point

- and doubly ionizing track in first ~ 2.4 cm
- \( \rightarrow \) 94% rejection of “single \( \gamma \)”.
ArgoNeut validates the technique

electron vs gamma Reco

Average $dE/dx$ over the first 2.4 cm of shower

Electron showers: Connected to vertex

Photon showers: Separated from vertex

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BNB Flux Spectra in $\nu$ mode

Flux from BNB in $\nu$ mode at MicroBooNE (470m)

MicroBooNE

Peaks at $\sim 600$ MeV
$\sim 1\% \nu_e$ content
MiniBooNE Low Energy Excess

Scaling signal from MiniBooNE: Down for Mass, up for Efficiency
Scaling backgrounds according to better PID and better flux knowledge

Assuming no distance dependence: (NOT an oscillation)

<table>
<thead>
<tr>
<th></th>
<th>MicroBooNE</th>
<th>LAr1-ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Events</td>
<td>97</td>
<td>775</td>
</tr>
<tr>
<td>“Low-energy Excess”</td>
<td>47.6</td>
<td>380</td>
</tr>
<tr>
<td>Background</td>
<td>49.4</td>
<td>394.6</td>
</tr>
<tr>
<td>Statistical Error</td>
<td>7.0</td>
<td>19.9</td>
</tr>
<tr>
<td>Systematic Error</td>
<td>6.6</td>
<td>52.2</td>
</tr>
<tr>
<td>Total Error</td>
<td>9.6</td>
<td>55.9</td>
</tr>
<tr>
<td>Statistical Significance of Excess</td>
<td>6.8 σ</td>
<td>19.1 σ</td>
</tr>
<tr>
<td>Total Significance of Excess</td>
<td><strong>5.0 σ</strong></td>
<td><strong>6.8 σ</strong></td>
</tr>
</tbody>
</table>

6.6 x 10^{20} POTs  2.2 x 10^{20} POTs

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If Excess due to Photons.

Different Cuts to Select Photons, Reject e’s

Excess is NOT due to photons

Excess IS due to photons $\rightarrow 4.1\sigma$

Background: $\gamma$ or $\pi^0$

OR

Radiative $\nu$ interaction

Examples:

- R. Hill arXiv: 0905.0291
- Jenkins et al arXiv: 0906.0984
- Serot et al arXiv: 1011.5913

(Estimated from MiniBooNE rates)
What would we expect for an oscillation at the Global best fit?

- $\nu_\mu \rightarrow \nu_e$ appearance in the context of 3 active + 1 sterile neutrino model (3+1)

Example Signal: $\Delta m^2 = 0.43$ eV$^2$, $\sin^2 2\theta_{\mu e} = 0.013$

Cuts to Select Electrons, Reject $\gamma$’s

2.2 x $10^{20}$ POT exposure for LAr1-ND

6.6 x $10^{20}$ POT exposure for MicroBooNE

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The power of a Three Detector Combination: \( \nu_\mu \rightarrow \nu_e \) sensitivity

**Preliminary**

**Statistical Uncertainty Limit**
for 6.6e20 POT exposure
On all 3 detectors

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\( \nu_\mu \) Disappearance

- Testing \( \nu_\mu \) disappearance with a near detector constraint
  \[ \Delta m_{41}^2 = 1.2 \text{ eV}^2 \quad \sin^2 2\theta_{\mu\mu} = 0.09 \]

- LAr1-ND: \( 2.2 \times 10^{20} \) POTs

- MicroBooNE: \( 6.6 \times 10^{20} \) POTs

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$\nu_\mu$ Disappearance

6.6x10$^{20}$ POT exposure for MicroBooNE

2.2x10$^{20}$ POT exposure for LAr1-ND

$\nu_\mu$ disappearance not a statistics limited search. Here shown with a 4% systematic uncertainty on the near to far extrapolation.

Previous limit at high $\Delta m^2$ limited by near and far detectors being different technologies.
Exploiting the full correlations

- The observed electron candidate event rate in LAr1-ND at 110m is used to constrain the expected rate in MicroBooNE and ICARUS.

- The $\nu_\mu$ are also used as a constraint as they have the same parent as the $\mu$’s that generate part (75%) of the intrinsic $\nu_e$ background.

- Simultaneous fit to Near, Far, $\nu_\mu$ and $\nu_e$ data sets is used to apply the constraints.

Using a Flux Correlation Matrix between Far (600m) and Near(110m) detectors and between $\nu_\mu$ and $\nu_e$.

Obtained using Reweighting Technique
Vary flux: reweight simulated events of BOTH ND and FD detectors.
with each variation

Strong Correlation between Far (600m) and Near(110m) detectors $\nu_e$ fluxes.
Neutrino – Argon Interactions
Neutrino-Argon Interactions at low energy (~ 1 GeV).

Why are they important?
- Only measurements on Argon: ArgoNeut.
- Few measurements in this energy range.
- Not very consistent.

Important
- In their own right.
- For LBNE 2nd max.
- HyperK

Expected Data Sample

**MicroBooNE:** 6.6 x 10^{20} protons on target: ~ 120k CC + NC  
**LAr1-ND:** 2.2 x 10^{20} protons on target (ONE year of data taking): ~1.1M CC + NC

<table>
<thead>
<tr>
<th>Process</th>
<th>Reaction</th>
<th>MicroBooNE 6.6 x 10^{20} POT</th>
<th>LAr1-ND 2.2 x 10^{20} POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE</td>
<td>$\nu_\mu \ n \rightarrow \mu^- \ p$</td>
<td>48,276</td>
<td>470,497</td>
</tr>
<tr>
<td>CC RES</td>
<td>$\nu_\mu \ N \rightarrow \mu^- \ N$</td>
<td>26,852</td>
<td>220,177</td>
</tr>
<tr>
<td>CC DIS</td>
<td>$\nu_\mu \ N \rightarrow \mu^- \ X$</td>
<td>10,527</td>
<td>82,326</td>
</tr>
<tr>
<td>CC Coherent</td>
<td>$\nu_\mu \ Ar \rightarrow \mu^- \ Ar+\pi$</td>
<td>376</td>
<td>3004</td>
</tr>
</tbody>
</table>
Data presentation.

Instead of unravelling specific “true at production” final states taking into account reinteractions

Present topological final states based on number of protons, number of pions

<table>
<thead>
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<th>LAr1-ND 2.2 x 10^{20}POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC Inclusive</td>
<td></td>
<td>88,098</td>
<td>787,847</td>
</tr>
<tr>
<td>CC 0π</td>
<td>ν_μ N→μ^- + Np</td>
<td>56,580</td>
<td>535,673</td>
</tr>
<tr>
<td></td>
<td>.ν_μ N→μ^- + 0p</td>
<td>12,680</td>
<td>119,290</td>
</tr>
<tr>
<td></td>
<td>.ν_μ N→μ^- + 1p</td>
<td>31,670</td>
<td>305,563</td>
</tr>
<tr>
<td></td>
<td>.ν_μ N→μ^- + 2p</td>
<td>5,803</td>
<td>54,287</td>
</tr>
<tr>
<td></td>
<td>.ν_μ N→μ^- + ≥3p</td>
<td>6,427</td>
<td>56,533</td>
</tr>
<tr>
<td>CC 1 π±</td>
<td>ν_μ N→μ^- + nucleons + 1 π±</td>
<td>21,887</td>
<td>176,361</td>
</tr>
<tr>
<td>CC ≥2π±</td>
<td>ν_μ N→μ^- + nucleons + ≥2π±</td>
<td>1,953</td>
<td>14,659</td>
</tr>
<tr>
<td>CC ≥1π^0</td>
<td>ν_μ N→μ^- + nucleons + ≥1π^0</td>
<td>9,678</td>
<td>76,129</td>
</tr>
</tbody>
</table>

Similarly for Neutral Current Interactions
Inclusive cross section

Will measure in a region where
- there are no Argon points and
- some inconsistent results
- 2nd oscillation maximum at LBNE

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Charged Current Inclusive in LAr1-ND: Muon measurement.

- **Contained muons**: Momentum measured through range and dE/dx with 5% Resolution
- Can we also use **non-contained muons**?
  - Identification through dE/dx as a function of distance from exit point.
  - Momentum measurement: through multiple scattering.
  - For contained tracks > 1m according to ICARUS data: Resolution: 30%.

![Graph showing events vs. true neutrino energy](image)

- Contained: 50%
- Non-contained (Long > 1m): 34%
- Total: 84%.
QuasiElastic

Questions:
QE is an easy topology: 1 muon + 1 proton → Or is it?
Nuclear Reinteractions

Nuclear reinteractions $\rightarrow$ NO proton or MANY Nucleons in Final State

How do we know they are treated correctly in the simulation?

No proton

In NOMAD, the nuclear formation length was tuned such as to equalize the cross sections calculated from the 2 samples:

- One Muon and No Proton sample
- One Muon and One Proton sample
Two-protons

Can we identify them?

Use \(dE/dx\) as a function of residual range (distance from stopping point).

Minimum Kinetic energy: \(T_p > 20\text{ MeV}\)

\(~ 2\text{ wires} = 6\text{mm}\)

Build likelihoods using several measurements along track.

Example: Simulation and Truth

ArgoNeut Data

**ArgoNeut Data**

**ArgoNeut** (8 protons)

**ArgoNeut** (8 protons)
Can we also count neutrons?

![ArgoNeut Data](image)

proton
(from neutron conversion)

Allows:

- Better Nucleon multiplicity measurement in several reactions.
- Better hadronic energy measurement.
Coherent production at $E_\nu < 2$ GeV.

$\nu_\mu$ interacts with Ar nucleus as a whole.

$\textbf{CC } \pi^+: \nu_\mu + \text{Ar} \rightarrow \text{Ar} + \mu^- + \pi^+$

NO evidence at low energy:

SciBooNE: $\sigma(\text{coh.}\pi^+)/\sigma(\nu_\mu \text{ CC}) < 0.67 \times 10^{-2}$ at 90% C.L. at $<E_\nu> = 1.1$ GeV

K2K: $\sigma(\text{coh.}\pi^+)/\sigma(\nu_\mu \text{ CC}) < 1.36 \times 10^{-2}$ at 90% C.L. at $<E_\nu> = 2.2$ GeV

Above 2 GeV:

Minerva: New data showing signal.

ArgoNeut: First Argon data.

LAr1-ND: $\sim 3000$ events according to GENIE. Good accuracy measurement.

Excellent for extra activity at vertex.

Pion $dE/dx$ identification and full containment.

$\textbf{NC } \pi^0: \nu_\mu + \text{Ar} \rightarrow \text{Ar} + \nu_\mu + \pi^0$

SciBooNE and MiniBooNE found definite signal at $E_\nu \sim 1$ GeV.

LAr1-ND: $\pi^0$ very good signature in LAr. Vertex activity.

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Resonance production.

\[ \nu_\mu + p \rightarrow \mu^- + \Delta^{++} (\rightarrow p\pi^+) \]

\[ \nu_\mu + n \rightarrow \mu^- + \Delta^+ (\rightarrow p\pi^0) \]  
\[ (\rightarrow n\pi^+) \]

LAr1-ND: With good proton and p/\pi^+ identification should contribute at low energy.
Resonance cross section (NOMAD Preliminary)

\[ \sigma(\nu, p \rightarrow \mu^+ \pi^+) \text{ (10}^{-38} \text{ cm}^2/\text{nucleon)} \]

Carbon results
Black points: NOMAD preliminary

LAr1-ND: Good accuracy on Argon, below the NOMAD points.

Presented at CETUP
Last week

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SuperNovae neutrino’s

Neutrino events were observed for SN1987a

Between 10 and 20 Absorption events
In each of MicroBooNE and LAr1-ND
About 100 events in ICARUS

\[ \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \]

expected for a **galactic** supernova

Electron Energy: **tens of MeV**

Cannot trigger on these: Data continuously stored in a cyclic buffer
For ~ a few hours, waiting for a SNEWS alert \(\rightarrow\) store data permanently.

I. Gil-Botella and A. Rubbia JCAP 10(2003)009

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R&D: Background to Proton Decay $\rightarrow K^+ \nu_\mu$

1. Identify $K^+$

Example: Simulation Studies $\rightarrow$ Measurements

**Separating** 339 MeV/c $K^+$ from protons of equal range: 15 cm

Likelihood: 4 $dE/dx$ measurements along track

2. Measure background from cosmic rays

Cosmic $\mu$

Granite block installed near MicroBooNE

TPC

Charge exchange
Background to Baryon Non-Conservation: $\bar{n}n$ oscillations $\rightarrow$ annihilation

**Oscillation** of neutron to antineutron followed by **annihilation** of antineutron with an Argon nucleus nucleon.

- Spherical
- Zero NET momentum
- Total energy
- $= 2 \, M_n$

**Annihilation**

- Atmospheric $\nu$ (Main background)
  - Linear
  - Non-zero momentum
  - No constraint on energy

Is there additional background from cosmic rays?
Neutral particles entering detector Depositing 2 GeV?

Measure it in the 3 detectors.

*Simulation using Truth*
Status and Schedule

- **MicroBooNE:**
  - Installation in Progress.
  - Cryostat (with TPC+PMT’s) moved to final position June 23rd.
  - Insulation, electronics platform and filling next.
  - Data-taking as of End 2014; 3 years for a total of $6.6 \times 10^{20}$ POT’s

- **LAr1-ND and ICARUS:**
  - Going through approval process
  - Data Spring 2018?
Possible Extensions of the Program

◆ Anti Neutrino running.

◆ Magnetizing one or more detectors
  ▪ Reduces “wrong” sign background
    (especially interesting in antineutrino running).
  ▪ Better momentum measurements.

◆ “Beam OFF-target” running.
  ▪ Searches for exotic particles produced absorber
LAr1-ND Collaboration


¹ Yale University, New Haven, CT
² University of Liverpool, Liverpool, UK
³ Syracuse University, Syracuse, NY
⁴ Fermi National Accelerator Laboratory, Batavia, IL
⁵ Brookhaven National Laboratory, Upton, NY
⁶ Massachusetts Institute of Technology, Boston, MA
⁷ Columbia University, Nevis Labs, Irvington, NY
⁸ University of Chicago, Enrico Fermi Institute, Chicago, IL
⁹ University of Bern, Laboratory for High Energy Physics, Bern, Switzerland
¹⁰ University of Manchester, Manchester, UK
¹¹ Los Alamos National Laboratory, Los Alamos, NM
¹² University of Oxford, Oxford, UK
¹³ Center for Neutrino Physics, Virginia Tech, Blacksburg, VA
¹⁴ University of Sheffield, Sheffield, UK
¹⁵ Indiana University, Bloomington, IN
¹⁶ CERN, Geneva, Switzerland
¹⁷ University of Cambridge, Cambridge, UK

*Spokespersons

10 US institutions
- 3 DOE National Laboratories
- 6 NSF institutions

7 European institutions
- 5 UK institutions
- 1 Swiss institution
- CERN

11 institutions also on MicroBooNE. Most also LBNE collaborators.
MicroBooNE Collaboration

MicroBooNE Collaboration + Project Team


University of Cambridge: A. Blake, J. Marshall, M. Thomson

University of Chicago: W. Foreman, J. Ho, D. Schmitz, J. Zennamo

University of Cincinnati: R. Grosso, J. St. John, R. Johnson, B. Littlejohn


Kansas State University: T. Bolton, S. Farooq, S. Gollapinni, G. Horton-Smith


Michigan State University: C. Bromberg, D. Edmunds

New Mexico State University: T. Miceli, V. Papavassiliou, S. Pate, K. Woodruff

Otterbein University: N. Tagg

total team (collaboration + project):

3 countries
23 institutions
134 collaborators (includes project team)

University of Oxford: G. Barr, M. Bass, R. Guenette

University of Pittsburgh: S. Dytman, D. Naples, V. Paolone

Princeton University: K. McDonald, B. Sands

Saint Mary's University of Minnesota: P. Nienaber

SLAC: M. Convery, B. Eberly, M. Graham, D. Muller, Y-T. Tsai

Syracuse University: J. Asaadi, J. Esquivel, M. Soderberg

University of Texas at Austin: S. Cao, J. Huang, K. Lang, R. Mehdiyev


INFN, Italy: F. Cavanna, O. Palamara (currently at Yale)

Virginia Tech: M. Jen, L. Kalousis, C. Mariani

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* spokespersons, + project manager
ICARUS Collaboration


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Conclusions

◆ Looking forward to start data taking within 6 months with MicroBooNE:
  ▪ Minimum low energy excess.
  ▪ First look at LSND excess
  ▪ Cross sections.

◆ Hoping for approval of extra 2 detectors by PAC soon,

◆ Next 3 years:
  ▪ Build LAr1-ND
  ▪ Refit ICARUS
  ▪ Analyze MicroBooNE data
Back Up
Magnetized LAr1-ND

• Two possible detector designs
  – Configuration A: The return yoke downstream of the neutrino beam and be instrumented with scintillator modules to form a muon spectrometer increasing the detector acceptance and allowing for particle ID for escaping charged pions
  – Configuration B: Compared to (A) there is an extended detector volume but contains no downstream spectrometer
Wrong Sign Contamination

• Charge selection (in antineutrino mode) is one of the main motivating factors for a magnetized detector
  – Neutrino background in the antineutrino beam

[Graphs showing event distributions with different energy scales and event counts for LAr1-ND and MicroBooNE]
Laser Calibration in MicroBooNE

- Field non-uniformity arise
  - Distortion expected by Ar$^+$ accumulation @ cathode
  - Needs to be calibrated out

- Laser Calibration System (LCS)
- LCS inject laser to ionize Ar along the path
  - $\lambda \approx 266$ nm, need high intensity to ionize
  - Distortion shows up in the reconstructed signal path

Plot & Diagram ... courtesy of C. Rudolf

Laser path @ ArgonTube (Uncalibrated)

Laser path @ ArgonTube (Calibrated)
Cold Electronics Performance

16 channel/chip charge amplifier: Adjustable Gain 4.7, 6.8, 14.0, 25.0 mV/fC
Adjustable peaking time 0.5, 1, 2, 3 μs, 5.5 mW/channel

Prototype Vertical Cold Mother Board with prototype ASICs

Crosstalk < 0.3%

Noise ~550 e⁻ with $C_D = 150 \text{pF}$ in $\text{LN}_2$

Channel-to-channel gain variation for two chips is < +/-2%

32 overlaid unipolar Channels in $\text{LN}_2$
Gain 4.7 mV/fC
Membrane Cryostat

Original thought:
Locate LAr1-ND in the SciBooNE Hall at 100m
# MiniBooNE Low Energy Excess

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
<th>Events</th>
<th>MiniBooNE</th>
<th>dE/dx</th>
<th>Total</th>
<th>Error</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(µB)</td>
<td>(LAr1-ND)</td>
<td>dE/dx unc.</td>
<td>dE/dx unc.</td>
<td>unc.</td>
<td>(µB)</td>
<td>(LAr1-ND)</td>
</tr>
<tr>
<td>$\mu \rightarrow \nu_e$</td>
<td>21.5</td>
<td>171.3</td>
<td>0.26</td>
<td>0.1</td>
<td>0.28</td>
<td>6.0</td>
<td>47.7</td>
</tr>
<tr>
<td>$K^+ \rightarrow \nu_e$</td>
<td>6.4</td>
<td>51.3</td>
<td>0.22</td>
<td>0.1</td>
<td>0.24</td>
<td>1.55</td>
<td>12.4</td>
</tr>
<tr>
<td>$K^0 \rightarrow \nu_e$</td>
<td>1.8</td>
<td>14.7</td>
<td>0.38</td>
<td>0.1</td>
<td>0.39</td>
<td>0.73</td>
<td>5.79</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>4.9</td>
<td>38.9</td>
<td>0.26</td>
<td>0.0</td>
<td>0.26</td>
<td>1.27</td>
<td>10.1</td>
</tr>
<tr>
<td>$\nu_\mu e \rightarrow \nu_\mu e$</td>
<td>3.8</td>
<td>30.7</td>
<td>0.25</td>
<td>0.1</td>
<td>0.27</td>
<td>1.03</td>
<td>8.26</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>6.7</td>
<td>53.4</td>
<td>0.13</td>
<td>0.1</td>
<td>0.16</td>
<td>1.10</td>
<td>8.77</td>
</tr>
<tr>
<td>Dirt</td>
<td>0.9</td>
<td>6.9</td>
<td>0.16</td>
<td>0.1</td>
<td>0.19</td>
<td>0.16</td>
<td>1.31</td>
</tr>
<tr>
<td>$\Delta \rightarrow N\gamma$</td>
<td>2.5</td>
<td>19.8</td>
<td>0.14</td>
<td>0.1</td>
<td>0.17</td>
<td>0.43</td>
<td>3.40</td>
</tr>
<tr>
<td>Other</td>
<td>0.9</td>
<td>7.6</td>
<td>0.25</td>
<td>0.1</td>
<td>0.27</td>
<td>0.26</td>
<td>2.04</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>49.4</td>
<td>322.1</td>
<td></td>
<td></td>
<td>6.55</td>
<td>52.23</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MicroBooNE</th>
<th>LAr1-ND</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Events</strong></td>
<td>97</td>
</tr>
<tr>
<td>“Low-energy Excess”</td>
<td>47.6</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>49.4</td>
</tr>
<tr>
<td><strong>Statistical Error</strong></td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Systematic Error</strong></td>
<td>6.6</td>
</tr>
<tr>
<td><strong>Total Error</strong></td>
<td>9.6</td>
</tr>
<tr>
<td><strong>Statistical Significance of Excess</strong></td>
<td>6.8 σ</td>
</tr>
<tr>
<td><strong>Total Significance of Excess</strong></td>
<td>5.0 σ</td>
</tr>
</tbody>
</table>
Probing Active to Sterile Oscillations with Neutral-Currents

➢ A unique probe of sterile neutrino oscillations, directly sensitive to any “sterile" flavor content, is available through neutral-current (NC) neutrino interactions. In this type of search, one looks for an overall depletion of the flavor-summed event rate.

➢ We have considered the NC $\pi^0$ channel, due to its characteristic event topology and kinematics.Unlike other NC channels, the presence of the two photons from the $\pi^0$ decay pointing back to a common vertex, with an invariant mass corresponding to $m_{\pi^0}$, provides a powerful discriminant against potential backgrounds.
Dark Matter Searches with Booster Beam Off-Target Running

BNB has the capability to steer the protons past the target and onto the 25m or 50m iron dump.

Beam spot position in beam off target mode (~1 mm spread)

- Target is 1 cm diameter
- Air gap between target and horn inner conductor is ~1 cm

In the target/absorber:

In the detector:

Electron Elastic scattering Nucleon Elastic scattering

Background events: 1600
Excess:
1-10  light green
10-1000 Green
>1000  dark green

Electrons and nucleons can be reconstructed in MiniBooNE with ~35% efficiency. For MicroBooNE assume 70%.

For MicroBooNE nucleon (electron) systematics errors 20% (12%).

Will eventually need similar estimates for MicroBooNE.

Low energy (<200 MeV) regime is important.

Electron Elastic scattering Nucleon Elastic scattering

July 24, 2014
Leslie Camilleri, CETUP


2 APA’s  
Anode Plane Assembly  
(wires)

1 CPA  
Cathode Plane Assembly

Membrane cryostat  
as in LBNE

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The cryostat is designed so that the bulk of the cryostat surface is immersed with liquid (signal feedthrough immersed in liquid, to limit outgassing from signal cables). Only a small volume of gas is contained in an insulated "expansion" tank, sitting on the top of the cryostat.

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Leslie Camilleri, CETUP