The Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Neutrino Latin America Workshop - Fermilab
April 27th, 2016
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U.S. future Accelerator Neutrino Physics: **LAr TPC Technology**

- The future U.S. accelerator neutrino program is based on the Liquid Argon Time Projection Chamber (LAr TPC) technology.

- LArTPC offers the ability to measure interactions of neutrinos and other particles in real time with sub-millimeter position resolution, allowing for
  - track reconstruction
  - particle identification and
  - electron/gamma separation

far beyond that offered by any other neutrino detection method.
The US LAr TPC Program: a path toward DUNE

A rich R&D and physics program

**R&D**
- Yale TPC and Bo (2008-2009)
- LUKE (2008)
- LAPD (2011)
- 35Ton (2013)
- CAPTAIN
  - Material Teststand
  - LAr Purity
  - Cryostat Purity
  - LArTPC Calibration

**Physics**
- ArgoNeuT (2009 - 2010)
- MicroBooNE (2015 - 2018)
- SBN (SBND, MicroBooNE, ICARUS-T600) (2018 - 2021)
- DUNE (2023+)
- v-Ar Cross Sections
- MiniBooNE
- Low Energy Excess
- Searches for Sterile Neutrino Oscillations
- CP Violation

**SBN program, this talk**
- SBND
- ICARUS-T600
- SBN - CP Violation
Why a Short-baseline accelerator neutrino program?

Physics motivations for the FNAL Short Baseline Neutrino program (SBN) - a multi-detector, LAr TPC based facility on the Booster Neutrino Beam - **Experimental Hints For Beyond Three Neutrino Mixing**
In recent years, two classes of experimental “neutrino anomalies” have been reported from measurement at short-baseline:

(I) An apparent $\nu_e$ disappearance signal in the low energy anti-neutrinos from nuclear reactors (“reactor anomaly”) and from radioactive neutrino sources in the Gallium experiments (“Gallium anomaly”).
Evidence for an electron-like excess from neutrinos from particle accelerators (the "LSND and Mini-BooNE anomalies")
Short-Baseline Accelerator Anomalies

**LSND**
- Baseline 30 m
- E = [20 – 50] MeV
- L/E ≈ 1 m/MeV

Low energy $\bar{\nu}_\mu$ beam from a decay-at-rest pion beam

167 tons liquid scintillator

Oscillation signal?

Detected an excess in the appearance of $\bar{\nu}_e$, corresponding to a $3.8\sigma$ evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation occurring at $\Delta m^2 \approx 1$ eV$^2$

This signal cannot be accommodated with the 3 SM neutrinos!
Short-Baseline Accelerator Anomalies

MiniBooNE

540 m from the target
E=[0 - 2] GeV
L/E ≈ 1 m/MeV
800 tons mineral oil

• Decay in flight neutrino source
• L/E similar to LSND
• LSND anomaly not evident in MiniBooNE where expected, but a clear excess in $\nu_\mu \rightarrow \nu_e$ (3.4 $\sigma$) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (2.8 $\sigma$) appearance is observed in a lower energy range

_PRL 110 (2013) 161801_
MiniBooNE (Cherenkov detector) cannot distinguish electron from single gamma and cannot determine the composition of the excess – Electrons or photons?
None of the SBL neutrino anomalies can be described by oscillations between the three Standard Model neutrinos.

The standard active neutrino mass splittings are way down here at $10^{-3}$ and $10^{-5}$ eV$^2$.

Hints at new physics

Atmospheric

Solar

The LSND and MiniBooNE allowed regions
Hints at new physics

None of the SBL neutrino anomalies can be described by oscillations between the three Standard Model neutrinos and ...

Could be pointing at additional physics beyond the Standard Model in the neutrino sector:

- additional neutrino states with larger mass-squared differences
- driving neutrino oscillation at small distances

Any additional neutrino doesn’t participate in weak interactions ⇒ “sterile neutrino”*

* Sterile neutrinos were introduced by Pontecorvo in 1968 as neutrinos with no standard model interaction
Sterile Neutrino Search at FNAL

- The accelerator neutrino anomalies at short-baseline hint at oscillation with very small amplitude
- Resolving small oscillation effects requires good control of systematic uncertainties

FNAL SBN: Multi-detector approach in a well characterized beam
Fermilab – aerial view
Booster Neutrino Beam (BNB)

Fermilab’s low-energy neutrino beam:

\[ \langle E_\nu \rangle \approx 700 \text{ MeV} \]
Booster Neutrino Beam (BNB)
Fermilab’s low-energy neutrino beam:
$\langle E_\nu \rangle \approx 700 \text{ MeV}$

- Beam of mostly muon neutrinos
- Search for flavor $\nu_\mu$ disappearance and $\nu_e$ appearance
- BNB stably running for a decade (well characterized)
- Anomalies exist here (MiniBooNE)

Small electron neutrino contamination: $<0.5\%$
**MicroBooNE: testing an anomaly**

**SBN program - Phase 1** - The MicroBooNE detector is taking neutrino data

- Apply the LArTPC technology to test the unexplained excess in the MiniBooNE data (on the same beam)
- Determine its composition as electrons (from $\nu_e$ appearance) or photons (from unaccounted background).
SBN program - Phase 2 - By 2018, the MicroBooNE detector will be joined by two additional LAr-TPC detectors at different baselines

- the SBND detector and
- the ICARUS-T600 detector

forming a LAr TPC trio (to sample the neutrino spectrum as a function of distance) for the SBN neutrino oscillation program
The Short-Baseline Near Detector (SBND), which will sit close to the source, plays a unique role in the chain of detectors, measuring the purity of the muon neutrino beam (it will characterize the beam before oscillations occur and address one of the dominant systematic uncertainties).
The ICARUS T600 neutrino detector — the world’s largest liquid-argon neutrino experiment — operated at Gran Sasso National Laboratory in Italy for four years on the CNGS beam, will make its way across the ocean for a new research at Fermilab.

Given its **large mass and far location** ICARUS-T600 will provide high sensitivity to oscillated neutrinos allowing for a precision search.
The search for the forth neutrino in SBN

\( (\text{II}) \) on the way, these might be morphing into another, undetectable form (sterile neutrinos, \( \nu_X \))... and eventually change again to electron neutrinos (\( \nu_e \))...

\( (\text{I}) \) BNB emits muon neutrinos (\( \nu_\mu \))

\( \nu_\mu \)\n
\( \nu_e \)\n
\( \nu_X \)\n
600 m

470 m

110 m

Appearance \( \nu_e \)?

Disappearance \( \nu_X \)?:

Having multiple detectors allows simultaneous searches for oscillations in appearance and disappearance channels, a very important constraint for interpreting the experimental observations.
A large mass far detectors and a near detector of the same technology is the key to large reductions of both statistical and systematic uncertainties (reduced to % level) in SBN oscillation searches, allowing to address region of interest at 5σ.
Physics reach of the SBN Program

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity

SBN will cover the LSND $99\%$ C.L. allowed region with $\geq 5\sigma$ significance

(conclusive experiment w.r.t. LSND anomaly)
Physics reach of the SBN Program

$\nu_\mu \rightarrow \nu_x$ Disappearance sensitivity

SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of SciBooNE and MiniBooNE
A correct interpretation of the outcome of ν oscillation experiments requires precise understanding of ν interaction cross sections.

SBN detectors will provide huge data sets of ν-Ar interactions from the BNB on-axis and the NuMI off-axis fluxes.

- Large samples in MicroBooNE are coming!
- SBND will record ~1.5 million νμ CC and ~12,000 νe CC interactions per year.
- ~100k NuMI off-axis events in T600 per year.
Not only oscillation physics: Cross Sections at the SBN

- A correct interpretation of the outcome of $\nu$ oscillation experiments requires precise understanding of $\nu$ interaction cross sections
- SBN detectors will provide **huge data sets of $\nu$-Ar interactions** from the BNB on-axis and the NuMI off-axis fluxes
  - Large samples in MicroBooNE are coming!
  - SBND will record $\sim1.5$ million $\nu_\mu$ CC and $\sim12,000$ $\nu_e$ CC interactions per year
  - $\sim100k$ NuMI off-axis events in T600 per year
- The only existing GeV neutrino-Ar scattering data are $\sim6000$ events from ArgoNeuT (NuMI beam, 3 GeV peak energy)
MicroBooNE experiment

**MicroBooNE** installs time projection chamber inside vessel, prepares for move

**TPC Active volume:**
86 t of LAr

MicroBooNE is taking neutrino data since Oct. 2015

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**Image 1:** MicroBooNE experiment setup.

**Image 2:** TPC Active volume.

**Image 3:** MicroBooNE data visualization.
Near Detector: SBND

See presentation from T. Miao

SBND design is in final stages and starting construction

TPC Active volume: 112 t of LAr
ICARUS: From Gran Sasso to Fermilab via CERN

Removing from Gran Sasso

On the road to CERN

Nov 2014

Dec 2014

TPC Active volume: 475 t of LAr

Early 2017

Fermilab

In Cleanroom @ CERN

New building complete late 2016

Fermilab

Jan 2015
SBN: International collaboration

55 institutions, 8 countries
Five U.S. national laboratories plus CERN

Institutions | SBN | SBN-DUNE Overlap
---|---|---
US | 27 | 25
Non-US | 28 | 24
SBN: International collaboration

Latin America institutions

Over 225 Authors Total

University of Puerto Rico
[3 collaborators - SBND experiment]

University of Campinas
Federal University of ABC
Federal University of Alfenas
[13 collaborators - SBND experiment]

Brasil 3
Latin America institutions

Greater participation by Latin American groups is welcome!

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SBN ties to the Long-Baseline Program

Physics goals:
- Matter-antimatter (a)symmetry? (CP violation)
- Neutrinos from core-collapse supernovae
- Searching for nucleon decay

- SBN provides an excellent opportunity for the continued development of the liquid argon TPC technology toward the DUNE long-baseline program
- SBN data also presents important physics opportunities valuable to the future LBL program
  - Measurements of neutrino-argon interactions
  - Execution of precision oscillation searches will drive the development of sophisticated reconstruction and data analysis techniques using TPC data
The three SBN detectors will all use state-of-the-art liquid-argon time projection technology to track neutrino interactions.

The international SBN research program at Fermilab will probe one enduring mystery: Are there only three types of ghostly neutrinos, or is a fourth type waiting to be discovered?

In the coming years we will know if the neutrinos have still more surprises for us!

Finding Sterile Neutrinos Would be Revolutionary!