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

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Ornella Palamara
Fermilab & Yale University
Outline

- Why a Short-Baseline Accelerator Neutrino program?
- The Fermilab SBN Program
  - SBN physics reach
  - SBN program Status
Neutrino Oscillation - 3 neutrino mixing

- Three neutrino mixing is well established *(data from solar, atmospheric, reactor and accelerator neutrino experiments)*!
  - Picture consistent with the mixing of **3 neutrino flavors with 3 mass eigenstates** - with relatively small mass differences.

\[
\Delta m_{32}^2 \approx 2.4 \cdot 10^{-3} \text{eV}^2 \\
\frac{L}{E} = 500 \text{Km/GeV}
\]

\[
\Delta m_{21}^2 \approx 7.5 \cdot 10^{-5} \text{eV}^2 \\
\frac{L}{E} = 15,000 \text{Km/GeV}
\]

- Forthcoming experiments will address many questions related to neutrino properties:
  - What are the masses of the neutrinos?
  - Are neutrinos their own antiparticles?
  - How are the masses ordered (referred as mass hierarchy)?
  - Do neutrinos and antineutrino oscillate differently?
  - Are there additional neutrino types or interactions?

\begin{itemize}
  \item \( \beta \) and \( \beta\beta \) decay experiments
\end{itemize}
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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
Short-Baseline Neutrino Anomalies (I)

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”).

\[ R = 0.933 \pm 0.021 \]
\[ R = 0.84 \pm 0.05 \]
\[ \sim 3.2 \sigma \]
\[ \sim 2.9 \sigma \]
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

167 tons liquid scintillator

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

Oscillation signal? Backgrounds

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

MiniBooNE
Baseline 540 m
E=[0 - 2] GeV
L/E ≈ 1 m/MeV
800 tons mineral oil

- Decay in flight neutrino source (Booster Neutrino Beam - Fermilab)
- 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 $\nu_\mu \rightarrow \nu_e$ (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*

LSND and MiniBooNE allowed regions

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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: LAr TPC - multi-detector approach - in a well characterized beam
Electron-γ separation in LAr

LAr TPC offers incredible fine tracking along with electron/photon separation

Analyzing topology and dE/dx

ArgoNeuT Data

arXiv:1610.04102

Pixel size: 4mm x 0.3mm

2D views from the two wire planes
Booster Neutrino Beam (BNB)

Fermilab’s low-energy neutrino beam:
\[ \langle E_\nu \rangle \approx 700 \text{ MeV} \]
Fermilab – Neutrino beams

**Booster Neutrino Beam (BNB)**

Fermilab’s **low-energy** neutrino beam:
\[ \langle E_\nu \rangle \approx 700 \text{ MeV} \]

- Beam - mostly muon neutrinos
- BNB stably running for a decade (well characterized)
- Anomalies exist here (MiniBooNE)

Booster - 8 GeV protons

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

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

(I) BNB emits muon neutrinos ($\nu_\mu$)

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
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 $\sim 1.5$ million $\nu_\mu$ CC and $\sim 12,000$ $\nu_e$ CC interactions per year
  - $\sim 100k$ NuMI off-axis events in T600 per year
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The only existing GeV neutrino-Ar scattering data are $\sim 6000$ events from ArgoNeuT (NuMI beam, 3 GeV peak energy)
MicroBooNE experiment

MicroBooNE is taking neutrino data since Oct. 2015
(\(3.2 \times 10^{20}\) POT collected in RUN I - 7 months)

TPC Active volume: 86 t of LAr
Near and Far Detector Buildings

Near Detector
Oct. 19 2016

Far Detector
Oct. 19 2016

Ready for detector installation
Dec. 2016/early 2017
ICARUS: From Gran Sasso to Fermilab via CERN

Moving from Gran Sasso

On the road to CERN

Nov 2014

Dec 2014

Early 2017

Fermilab

New building complete late 2016

In Cleanroom @ CERN

TPC Active volume:
475 t of LAr
Largest existing LAr TPC in the world

Nov 2014

Fermilab

Jan 2015

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ICARUS T600 Refurbishment

- New thermal insulation and cold vessel
- Partial replacement of cryogenic and purification systems
- Improved planarity of TPC cathode
- Enlarged PMT system with improved electronics for surface operation
- Updated TPC electronics

360 8” PMTs (90 per chamber) coated with TPB wavelength shifter ~9 p.e./MeV at cathode
Short-Baseline Near Detector: SBND

TPC Active volume: 112 t of LAr
SBND: Detector Elements (I)

**Field Cage:** roll-formed metal profiles installed in panels (16). Some are removable for detector access. Similar to protoDUNE-SP design.

**Anode Plane Assemblies:** 4.1 x 2.5 m wire plane frames (4) tiled to create two drift regions

**HV & Cathode:** SS tubing frames with mesh panels
SBND: TPC Construction Has Begun

Wire plane frames in production

HV feed-through prototype

Cathode plane mesh prototype

Wiring procedures prototyping
Primary scintillation detection system uses 144 TPB coated 8” PMTs, same model as in ICARUS
~15 p.e./MeV at cathode

Scintillation detection R&D being pursued with acrylic light-guides & SiPM based readout system (DUNE)

Investigating possible further enhancement with reflective foils coated in wave-length shifter installed on the cathode plane. Simulations indicate much improved uniformity of collection efficiency across the drift volume.
SBND: Detector Elements (III)

Front-end electronics with cold ADC and multiplexing
11k channels → 4 feed-throughs
(MicroBooNE, 8.2k → 11 feed-throughs)

Nearly 4π coverage bi-layered external cosmic ray tracker system
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
SBN: The search for a fourth type of neutrino

The three SBN detectors will all use state-of-the-art liquid-argon time projection technology to track neutrino interactions.

The SBN research program at Fermilab will probe one enduring mystery: Are there only three types of 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!