Short-Baseline Accelerator Neutrino Oscillations

The 2017 Tamura Symposium - Lepton and Baryon Symmetry
University of Texas at Austin
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Outline

๏ Why a Short-baseline Accelerator Neutrino program?
  • Oscillation Beyond Three-Neutrino Mixing - Status of Light Sterile Neutrinos

๏ The Fermilab SBN Program
  • Physics reach
  • Program Status
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.

\begin{align*}
\Delta m^2_{32} &\approx 2.4 \times 10^{-3} \text{eV}^2 \\
L/E &= 500 \text{Km/GeV} \\
\Delta m^2_{21} &\approx 7.5 \times 10^{-5} \text{eV}^2 \\
L/E &= 15,000 \text{Km/GeV}
\end{align*}

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?

\[ \beta \text{ and } \beta\beta \text{ decay experiments} \]
Neutrino Oscillation - 3 neutrino mixing

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Solar

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Why a Short-baseline accelerator neutrino program?

Physics motivations for a Short Baseline Neutrino program

Experimental Hints For Beyond Three Neutrino Mixing
Two classes of experimental “neutrino anomalies” have been reported from measurement at short-baseline:

(I) An apparent $\bar{\nu}_e$ disappearance signal in the low energy 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
- \( E = [20 \text{ – } 50] \text{ MeV} \)
- \( L/E \approx 1 \text{ m/MeV} \)
- 167 tons liquid scintillator

Most significant experimental hint of new physics comes from LSND

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

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 \( \Delta m^2 \approx 1 \text{ eV}^2 \)

**Oscillation signal?**

\{ Backgrounds \}

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[Diagram showing beam excess and oscillation signals]

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**PRD 64 (2001) 112007**
• 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (2.8 $\sigma$) appearance is observed in a lower energy range
MiniBooNE (Cherenkov detector) cannot distinguish electron from single gamma and cannot determine the composition of the excess – Electrons or photons?
Hints at new physics

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 $10^{-5} \text{ eV}^2$.

LSND and MiniBooNE allowed regions

Atmospheric

Solar
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
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Minimal model
• a “3+1” neutrino mixing (minimal modification of the standard three-neutrino scheme)
• the new sterile neutrino would be mainly composed by a heavy neutrino \( \nu_4 \) such that the new \( \Delta m^2 = \Delta m^2_{41} \approx [0.1 - 10] eV^2 \) and \( m_1, m_2, m_3 \ll m_4 \)

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Constraints on sterile neutrino mixing from $\nu_\mu$ disappearance data (no hints of $\nu_\mu$ disappearance in the $\Delta m^2 \sim 1 \text{ eV}^2$ region):

- Tension between when combined with appearance data analyses
- Some global analyses are performed including more than one active sterile neutrino.

Any additional neutrino doesn’t participate in weak interactions $\Rightarrow$ “sterile neutrino”*

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Global Analysis of Short-baseline Neutrino Current Exclusion Limits

“Updated Global 3+1 Analysis of Short-BaseLine Neutrino Oscillations”

\[ \nu_e \rightarrow \nu_e \] and \[ \bar{\nu}_e \rightarrow \bar{\nu}_e \]
(\[ \nu_e \] disappearance)

\[ \nu_\mu \rightarrow \nu_e \] and \[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]
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๏ Recent measurements, especially from **NEOS, IceCube and MINOS** experiments, have constrained the possible sterile neutrino parameters significantly (see later)
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**New generation of improved experiments that can rule on sterile-neutrino oscillations in exactly this region are under way or have been proposed**
FNAL Short Baseline Neutrino program

A multi-detector, LAr TPC based, facility on the Booster Neutrino Beam

*arXiv:1503.01520, January 2014*
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-$\gamma$ separation in LAr

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

Analyzing topology and dE/dx

ArgoNeuT Data

Electron Candidate

Photon Candidate

Phys. Rev. D95 (2017) 072005

Pixel size: 4mm x 0.3mm

2D views from the two wire planes
Fermilab – Neutrino beams

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

Booster - 8 GeV protons

\[ f(E_\nu) \text{ (v/POT/GeV/cm}^2\text{)} \]

\[ 10^{13} \quad 10^{11} \quad 10^{10} \]

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \quad 4 \quad 4.5 \quad 5 \]

$E_\nu$ (GeV)

- $\nu_\mu$
- $\bar{\nu}_\mu$
- $\nu_e$
- $\bar{\nu}_e$
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)

Small electron neutrino contamination: <0.5%
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 2018/19, 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 soon 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.
(II) on the way, these might be morphing into another, undetectable form (sterile neutrinos, $\nu_X$)... and eventually change again to electron neutrinos ($\nu_e$)...
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.
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Physics reach of the SBN Program
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$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity

- 3+1” Analysis
- Multi-channel approaches, with possible improvements in sensitivity from exclusive topology measurements are under study

The sensitivity of the SBN program is highest near the most favored values of $\Delta m^2$
Physics reach of the SBN Program

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

- 3+1” Analysis
- Multi-channel approaches, with possible improvements in sensitivity from exclusive topology measurements are under study

SBN will cover the LSND 99% C.L. allowed region with $\geq 5\sigma$ significance (conclusive experiment w.r.t. LSND anomaly)

S. Gariazzo et al., Global fit, arXiv:1703.00860
Physics reach of the SBN Program

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

In addition to $\nu_e$ appearance, SBN also has sensitivity to $\nu_\mu$ disappearance

- Needed to confirm an oscillation interpretation of any observed appearance signal
- Providing a more robust result on sterile-neutrino-induced oscillations
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).
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![Graph comparing cross sections for BNB on-axis and NuMI off-axis events]
MicroBooNE is taking neutrino data since Oct. 2015 ($\sim 4 \times 10^{20}$ POT collected)

TPC Active volume: 86 t of LAr
ICARUS: From Gran Sasso to Fermilab via CERN

- Removing from Gran Sasso
- On the road to CERN
- New Building at Fermilab
- In Cleanroom @ CERN

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

- Nov 2014: Removing from Gran Sasso
- Dec 2014: On the road to CERN
- 2017: In Cleanroom @ CERN
Short-Baseline Near Detector: SBND

TPC Active volume: 112 t of LAr
SBND: Detector Elements

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

4π CRT coverage
SBND: TPC Construction
Near and Far Detector Buildings

Near Detector building

Far Detector building
SBN ties to the Long-Baseline Program

- 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

Physics goals:
- Matter-antimatter (a)symmetry? (CP violation)
- Neutrinos from core-collapse supernovae
- Searching for nucleon decay
SBN: The search for a fourth type of neutrino

The three SBN detectors will sit on the Booster Neutrino Beamline at Fermilab and will all use the state-of-the-art liquid-argon time projection technology to perform the most sensitive search to date for eV-scale sterile neutrino. The SBN program will

- Follow up on hints of new physics, in particular the LNSD allowed region will be covered at $>5\sigma$
- Make high precision measurements of $\nu$-Ar cross sections
- Develop LAr TPC technology & expertise in preparation for DUNE

Well on our way to an exciting Short-Baseline Accelerator Neutrino Oscillation Program!!