Sterile Neutrino and Short Baseline Neutrino (SBN) Program

Jay Hyun Jo
jjo@bnl.gov

July 10, 2023
NuSteam/NuPumas @ BNL 2023
Outline

• recap: standard model, neutrino, and neutrino oscillation
• sterile neutrino: what is it, why is it, and how do we detect it
• Short Baseline Neutrino (SBN) Program @ Fermilab
Outline

- **recap: standard model, neutrino, and neutrino oscillation**
- sterile neutrino: what is it, why is it, and how do we detect it
- Short Baseline Neutrino (SBN) Program @ Fermilab
Particle physicist trying to understand ordinary matter...

tiniest building block of matter: elementary particles of the universe

Neutrinos!
• ordinary matter is well described by **12 building blocks of matter** and the force carriers through which they interact

• **neutrinos** make up three of the 12 building blocks, with special characteristics of:
  - neutral charge
  - tiny mass
  - weakly interacting only
- the Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald “for the discovery of neutrino oscillations, which showed that **neutrinos have mass**

- neutrino morph into another kind & back again: quantum mechanical effect

- **if neutrinos oscillate, they must have mass**

- depend on neutrino flavor and neutrino energy
Crack in the Standard Model: Massive neutrinos

The most general state is a normalized linear combination:

\[ |\psi\rangle = a|1\rangle + b|2\rangle = \begin{pmatrix} a \\ b \end{pmatrix}, \quad \text{with } |a|^2 + |b|^2 = 1. \]

Suppose the Hamiltonian matrix is:

\[ H = \begin{pmatrix} h & g \\ g & h \end{pmatrix} \]

where \( g \) and \( h \) are real constants. The (time-dependent) Schrödinger equation says:

\[ H|\psi\rangle = i\hbar \frac{d}{dt}|\psi\rangle. \]

(a) Find the eigenvalues and (normalized) eigenvectors of this Hamiltonian.

(b) Suppose the system starts out (at \( t = 0 \)) in state \( |1\rangle \). What is the state at time \( t \)?

**Answer:**

\[ |\psi(t)\rangle = e^{-iHt/\hbar} \begin{pmatrix} \cos(gt/\hbar) \\ -i \sin(gt/\hbar) \end{pmatrix} \]

**Note:** This is about the simplest nontrivial quantum system conceivable. It is a crude model for (among other things) neutrino oscillations. In that case \( |1\rangle \) represents the electron neutrino, and \( |2\rangle \) the muon neutrino; if the Hamiltonian has a nonvanishing off-diagonal term \( g \), then in the course of time the electron neutrino will turn into a muon neutrino, and back again. At present this is highly speculative—there is no experimental evidence for neutrino oscillations; however, a very similar phenomenon does occur in the case of neutral K-mesons (\( K^0 \) and \( \bar{K}^0 \)).

"At present this is highly speculative — there is no experimental evidence for neutrino oscillations" 

D. J. Griffith, *Introduction to Quantum Mechanics* (p.120, 1995)
Neutrino oscillation

- neutrino flavor states are not the same as the mass states

- neutrinos generally are produced in a flavor state, which is a superposition of three mass states

- these mass states change phase over the time at different rates, leads to neutrino oscillation when viewed in the flavor basis

- this critical phenomenon is now very well known for 3-neutrino oscillation, described by PMNS matrix: and the physics parameters precisely measured with experiments in the last two decades

\[
P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 [eV]^2}{E_\nu [GeV]} \cdot L [km]\right)
\]
Recap: neutrino & neutrino oscillation

- neutrinos make up three of the 12 building blocks of the ordinary matter in the Universe

- we have found out that neutrinos oscillate; they change their states as they propagate over time
  - this quantum mechanical behavior can only happen if neutrinos have mass
  - this was not predicted in the “standard model”, cracking the otherwise almost-perfect model that describes the ordinary matter

- three-neutrino oscillation is well understood with PMNS matrix
remaining questions in \( \nu \)-physics

**standard model**
- Could **CP violation** in neutrino interactions explain the matter/antimatter asymmetry?
- What is the **ordering of the neutrino mass**?
- What is **neutrino mass**?
- Is the neutrino its own anti particle?

**beyond the standard model**
- Are there **new interactions** we could discover via neutrino?
- Are there **additional neutrinos** beyond known three types?
remaining questions in $\nu$-physics

**standard model**

- could CP violation in neutrino interactions explain the matter/antimatter asymmetry?
- what is the ordering of the neutrino mass?

**beyond the standard model**

- are there new interactions we could discover via neutrino?
- are there additional neutrinos beyond known three types?

- what is neutrino mass?
- is the neutrino its own anti particle?
Outline

- recap: standard model, neutrino, and neutrino oscillation
- **sterile neutrino:** what is it, why is it, and how do we detect it
- Short Baseline Neutrino (SBN) Program @ Fermilab
Why add extra neutrino?

- since the detection of neutrino and oscillation, many experiments start to collect & analyze neutrino data

- several experiments have found series of anomalous results

- anomalous in a way that “observation” (detected/measured data) does not agree with “prediction” (simulation/model generated with the current best of our knowledge)

  - LSND: measured more $v_e$ than predicted
  - MiniBooNE: measured more $v_e$ than predicted
  - GALLEX/SAGE/BEST: measured less $v_e$ than predicted

\[\text{Phys. Rev. D 64 112007, 2001}\]
\[\text{Phys. Rev. D 103, 052002 (2021)}\]
• taken individually, each anomaly is not significant enough to be convincing: but they all are pointing toward the similar thing

• most commonly interpreted as hint for one or more new “sterile" neutrino (oscillates but does not interact weakly)
Why add extra neutrino?

- The number of weakly interacting “active” neutrino flavors is fixed to three, by the Z width measurements (LEP).
- But additional, non-interacting “sterile” neutrino states could still exist.
- Potentially detectable through impact on neutrino oscillations.
- Q: can this new type of neutrino be solution to these anomalies?
- A: unfortunately, it’s not so simple… there are severe tension between different measurements & channels.

Potential flavor transitions via this new mixing:

$$P_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2 \sin^2 \left(1.27 \frac{\Delta m^2_{41} L}{E}\right)$$
How can we detect sterile neutrino?

- sterile neutrino does not interact weakly, only experience gravity: no way to *directly* detect it

- but it still oscillates like other neutrino species, hence affecting neutrino oscillation pattern
  - oscillation probability of how one neutrino state morphs into the other state will be different if extra neutrino exists (i.e. PMNS matrix changes)

- \( \nu_e \) disappearance channel: \( \nu_e \rightarrow \nu_e \)
  - how many \( \nu_e \) has been oscillated into other (including \( \nu_s \)) neutrino types?

- \( \nu_e \) appearance channel: \( \nu_u \rightarrow \nu_e \)
  - how many \( \nu_e \) has been oscillated from \( \nu_u \)?
The MiniBooNE Anomaly: Low Energy Excess (LEE)

- MiniBooNE observed low-energy excess (LEE) of electron-neutrino-like events
  - LEE: more events measured/detected than predicted, in the low energy region
- eV-scale sterile neutrino could explain this excess
  - the excess is due to sterile neutrino oscillated into electron neutrino
  - prediction is lower than observed because the prediction is made based on 3-neutrino paradigm
• MiniBooNE is a Cherenkov detector
  - mostly detecting outgoing leptons (electrons, muons, etc)
  - cannot distinguish between electrons and photons
• this limitation makes it hard to interpret the origin of LEE
  - if electrons, this can be explained by sterile neutrino oscillated into electron neutrinos
  - if photons, this can be explained by underestimated prediction of single-photon-producing SM process
LArTPC: Liquid Argon Time Projection Chamber

- Liquid argon (LAr) as total absorption calorimeter
  - dense, abundant, cheap
  - ionization and scintillation signals
- Time Projection Chamber (TPC) as 4\pi charged particle detector
  - 3D reconstruction with a fully active volume
- LAr+TPC: fine-grained 3D tracking with local dE/dx information and fully active target medium
at MicroBooNE's core is an 85 ton LArTPC
at MicroBooNE’s core is an 85 ton LArTPC
the MicroBooNE detector

in addition there is a light detection system consisting of 32 8-inch PMTs.
Cryostat

TPC

Liquid Argon @ 89 K

Charged particles!

$\nu_\mu$
Scintillation light

TPC

32 PMT's

Liquid Argon @ 89 K

Cryostat
Scintillation light
Ionization Charge

Meanwhile

3 Wire planes
8192 wires

TPC

Liquid Argon @ 89 K

Cryostat

Liquid Argon @ 89 K

Cryostat
Scintillation light
Ionization Charge

Liquid Argon @ 89 K
Cryostat

TPC

Cathode
3 Wire planes
8192 wires

Electric Field

Anode

e^-
e^-
e^-
e^-

Liquid Argon @ 89 K
Cryostat
Scintillation light
Ionization Charge

TPC
Cryostat
Liquid Argon @ 89 K

Cathode
Electric Field
Anode

3 Wire planes 8192 wires

Jay Hyun Jo
Scintillation light
Ionization Charge

TPC

Liquid Argon @ 89 K

Cryostat

3 Wire planes
8192 wires

Cryostat

Cathode

Electric Field

Anode

8192 wires
Scintillation light
Ionization Charge

TPC

Cryostat

Liquid Argon @ 89 K

3 Wire planes
8192 wires

Cathode

Electric Field

Anode
Scintillation light
Ionization Charge

Liquid Argon @ 89 K
Cryostat

TPC

3 Wire planes
8192 wires

Cathode
Electric Field

TPC

Liquid Argon @ 89 K
Cryostat
- capable of separating electrons from photons, with gap and calorimetry information
Outline

- recap: standard model, neutrino, and neutrino oscillation
- sterile neutrino: what is it, why is it, and how do we detect it
- Short Baseline Neutrino (SBN) Program @ Fermilab
Fermilab SBN program

- three LArTPC detectors, with same neutrino beamline and different baseline
- reduce statistical uncertainties with large mass far detector (ICARUS)
- reduce systematic uncertainties with same LArTPC detector technology
Fermilab SBN program

- three LArTPC detectors, with same neutrino beamline and different baseline
- reduce statistical uncertainties with large mass far detector (ICARUS)
- reduce systematic uncertainties with same LArTPC detector technology
MicroBooNE

- started taking data since 2015
- finished operation in 2021
- accumulated the world's largest sample of neutrino interaction on argon
- one of the first LArTPC detectors with many new features
  - cold, low noise electronics
  - excellent LAr purity
  - pioneered LArTPC detector physics
  - stable & long-term running
The MiniBooNE Anomaly: recap

- this limitation makes it hard to interpret the LEE
  - if electrons, this can be explained by sterile neutrino oscillated into electron neutrinos
  - if photons, this can be explained by underestimated prediction of single-photon-producing SM process
MicroBooNE LEE result

- first MicroBooNE result probed both electron-like and photon-like signals, with LArTPC's ability of e/γ separation

- photon analysis targets NC Δ→Nγ channel
  - test if this channel is underestimated in the standard model
  - result shows no evidence for enhanced rate of single photons from NCΔ decay
MicroBooNE LEE result

- first MicroBooNE result probed both electron-like and photon-like signals, with LArTPC's ability of e/γ separation
- electron analysis selects electron neutrino events
- test if the MiniBooNE low energy excess can be seen
  - probes 4 different topologies
  - result shows the observation is in agreement with prediction, no sign of MiniBooNE LEE
• LEE results are re-interpreted under a sterile neutrino oscillation hypothesis

• MicroBooNE could reject some portion of LSND and GALLEX/SAGE/BEST allowed region

• updated result is aiming to exclude most of the allowed region
Short Baseline Neutrino Detector: SBND

- same LArTPC technology with some upgrade
- closer to the target: much more neutrinos detected
- will start taking data in late 2023
ICARUS

- 2 LArTPC modules
- Total of 760t LAr (467t active)

- shipped from Europe (LSNG), refurbished & upgraded
- farther away from the target, but much larger volume
- started taking neutrino data since 2021
• main goal is to definitively test sterile neutrino hypothesis
  - confirm or dispute anomalies that can be explained by sterile neutrino hypothesis
• also will measure & study how neutrino interacts with argon: important input to future DUNE experiment
neutrinos oscillate, and three-neutrino oscillation is well understood

however several neutrino experiments showed anomalies, which could be explained by postulating an additional neutrino: **sterile neutrino**

Fermilab SBN program consists of three LArTPC neutrino detectors, MicroBooNE, SBND, ICRAUS, with a goal to tackle this topic

- MicroBooNE result showed that MiniBooNE anomaly is not from electron neutrinos & excluded some sterile neutrino-allowed region

- ICARUS started taking data in 2021 and SBND will be taking data in 2023

- together, SBN program will search for eV-scale sterile neutrino
Backup slides
LSND & MiniBooNE anomaly

- **LSND** (1990-2001)
  - $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ excess over background suggests evidence for oscillation at $\Delta m^2 \sim 1$eV$^2$

- **MiniBooNE** (1998-2020)
  - measured $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \nu_e$ appearance
  - the excess of events at low energy
LArTPC: Liquid Argon Time Projection Chamber

charged particle enters detector

\[ \downarrow \]

scintillation light emitted by excited Ar, detected by PMTs

\[ \downarrow \]

ionization electrons drift to anode plane, detected by sense wires
**LSND & MiniBooNE anomaly**

- **LSND (1990-2001)**
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess over background suggests evidence for oscillation at $\Delta m^2 \sim 1\text{eV}^2$

- **MiniBooNE (1998-2020)**
  - measured $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \nu_e$ appearance
  - the excess of events at low energy

---

**Yale**

Jay Hyun Jo

arxiv:2006.16883

$4.8 \sigma$
unfortunately, it’s more complicated than that…

• significant tension between $\nu_e$ appearance and $\nu_e$ and $\nu_\mu$ disappearance

• lots of different independent observations currently unexplained

• we need to understand the anomalies better!

From Pedro Machado’s Neutrino 2020 talk: Sterile Neutrino Global Picture
short-baseline anomalies

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 \\
0 & +c_{23} & +s_{23} \\
0 & -s_{23} & +c_{23}
\end{pmatrix}
\begin{pmatrix}
+c_{13} & 0 & +s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & +c_{13}
\end{pmatrix}
\begin{pmatrix}
+c_{12} & +s_{12} & 0 \\
-s_{12} & +c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- three flavor neutrino states is well established by neutrino oscillation physics in solar, atmospheric, reactor, and accelerator domains

- puzzling collection of short-baseline anomalies: reactor anomaly, gallium anomaly, LSND & MiniBooNE anomaly
  
  - possible portal for new physics: the holy grail of the particle physics community
  
  - correctly estimating backgrounds/oscillation is important for the future neutrino program such as DUNE
  
  - need to resolve the anomalies -> MicroBooNE & SBN program
Neutrino Oscillations

- Neutrino flavor eigenstates are not the same as the mass eigenstates

- Neutrinos generally are produced in a flavor eigenstate, which is a superposition of three mass eigenstates

- These mass eigenstates have different energies, and therefore change phase over time at different rates according to Schrodinger’s equation

- This leads to neutrino oscillations when viewed in the flavor basis

- The existence of sterile neutrinos (additional mass eigenstates) would change the details of this picture

MicroBooNE: ~0.5 km / ~1GeV, negligible neutrino oscillation expected

from https://en.wikipedia.org/wiki/Neutrino_oscillation