Particle Physics: Neutrinos – part I

Edward Dunton

Week 8: November 10, 2018
Columbia University Science Honors Program
Course policies

- Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).

- **Attendance record counts.**
  - Up to four absences
  - Lateness or leaving early counts as half-absence
    - Send email notifications of all absences to shpattendance@columbia.edu

- Please, no cell phones during class

- **Please, ask questions!**

- Lecture materials + Research Opportunities + Resources to become a particle physicist

https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram
# Schedule

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Neutrinos in the Standard Model

What is special about neutrinos in the Standard Model?
Neutrinos in the Standard Model

- Only weak interaction.
  Only left-handed neutrinos (and right-handed antineutrinos) in the Standard Model.

- Initially implemented as massless particles.
  Neutrino oscillations show neutrinos have mass!

- Why neutrino masses are so different from the other fermions?
  Are neutrinos acquiring mass through the same mechanism (Higgs) or from something else?
Neutrino oscillations (two-neutrino example)

- Consequence of **neutrino mixing** (quantum superposition, as in Schrödinger’s cat): the neutrinos that interact are not the same kind as the neutrinos that propagate.

- Two-flavor approximation:

  
  \[
  \begin{pmatrix}
  |\nu_l\rangle \\
  |\nu_x\rangle \\
  \end{pmatrix} =
  \begin{pmatrix}
  \cos \theta & \sin \theta \\
  -\sin \theta & \cos \theta \\
  \end{pmatrix}
  \begin{pmatrix}
  |\nu_1\rangle \\
  |\nu_2\rangle \\
  \end{pmatrix}
  \]

  - **Transition** probability (derivation in blackboard):

  \[
P_{l\bar{x}, (l\neq x)}(L, E) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
  \]

  - **Survival** probability:

  \[
P_{l\bar{l}, (l\neq l)}(L, E) = 1 - P_{l\bar{x}, (l\neq x)}(L, E)
  \]

  - **Neutrino oscillation** implies neutrinos are massive and non-degenerated.
3 neutrino mixing

- **Flavor eigenstates** ($\nu_e, \nu_\mu, \nu_\tau$) ≠ **mass eigenstates** ($\nu_1, \nu_2, \nu_3$).
- Related by **Pontecorvo-Maki-Nakagawa-Sakata mixing**

**Matrix**: 3 neutrinos → 3 angles ($\theta_{12}, \theta_{23}, \theta_{13}$) + 1 CP-violating phase ($\delta$).

PMNS matrix: $U$

\[
c_{ij}=\cos\theta_{ij}, \ s_{ij}=\sin\theta_{ij}
\]

\[
\begin{pmatrix}
 1 & c_{23} & s_{23} \\
 -s_{23} & c_{23}
\end{pmatrix}
\]

Atmospheric & Long-baseline accelerator experiments

\[
\begin{pmatrix}
 c_{13} & s_{13}e^{-i\delta} & 1 \\
 -s_{13}e^{i\delta} & c_{13}
\end{pmatrix}
\]

Reactor & Long-baseline accelerator experiments

\[
\begin{pmatrix}
 c_{12} & s_{12} \\
 -s_{12} & c_{12}
\end{pmatrix}
\]

Solar & KamLAND experiments

\[
\begin{pmatrix}
 v_1 \\
 v_2 \\
 v_3
\end{pmatrix}
\]

→ $m_1$ $m_2$ $m_3$

- CP-violating phase changes sign for antineutrinos: a **source of matter-antimatter different behavior**!
- CP violation only possible if all three angles are not zero → need to **measure them all**!
Measurement of $\theta_{12}$ and $\Delta m^2_{21}$
Solar experiments
Solar neutrinos: pp chain

- pp chain produces 98.4% of Sun's fusion energy. It also produces electron neutrinos.
Solar neutrinos: CNO cycle

- CNO cycle produces 1.6% of Sun's fusion energy. It also produces electron neutrinos.

\[
\begin{align*}
^{12}\text{C} + p & \rightarrow ^{13}\text{N} + \gamma \\
^{15}\text{N} + p & \rightarrow ^{12}\text{C} + ^{4}\text{He} \\
^{15}\text{O} & \rightarrow ^{15}\text{N} + e^+ + \nu_e \\
^{15}\text{N} + p & \rightarrow ^{16}\text{O} + \gamma \\
^{16}\text{O} + p & \rightarrow ^{17}\text{F} + \gamma \\
^{13}\text{N} & \rightarrow ^{13}\text{C} + e^+ + \nu_e \\
^{13}\text{C} + p & \rightarrow ^{14}\text{N} + \gamma \\
^{14}\text{N} + p & \rightarrow ^{15}\text{O} + \gamma \\
^{17}\text{O} + p & \rightarrow ^{14}\text{N} + ^{4}\text{He} \\
^{17}\text{F} & \rightarrow ^{17}\text{O} + e^+ + \nu_e
\end{align*}
\]
Solar neutrinos: pp chain and CNO cycle
Illustrations

1. Illustration of the pp chain reaction in the Sun, showing the sequence of nuclear reactions and particles involved.
2. Illustration of the CNO cycle, demonstrating the carbon, nitrogen, and oxygen reactions that contribute to solar energy production.

Legend:
- Proton
- Neutron
- Positron
- Gamma Ray
- Neutrino
- Antineutrino

These diagrams illustrate the fundamental processes that sustain the Sun's luminosity, emphasizing the role of neutrinos in these reactions.
Solar neutrinos: energy spectrum
Homestake experiment

- In the late 1960s Ray Davis and John Bahcall set up an experiment to try to detect these solar neutrinos.

- Detection of solar neutrinos using the reaction:
  \[ \nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar} \]

- Radiochemical detector.

- Ratio of observed to predicted:
  \[ \frac{R_{\text{Cl}}}{R_{\text{SSM}}} = 0.301 \pm 0.027 \]

- Missing neutrinos!
Kamiokande (1983 - 1996)
Kamiokande

- Detection of solar neutrinos using the reaction:
  \[ \nu_l + e^- \rightarrow \nu_l + e^- \]
- Water Cherenkov detector.
- Ratio of observed to predicted:
  \[ \frac{\Phi_{\text{Kamiokande}}}{\Phi_{\text{SSM}}} = 0.484 \pm 0.066. \]
- Missing neutrinos again!
Super-Kamiokande (since 1996)
Super-Kamiokande

- Detection of solar neutrinos using the reaction:
  \[ \nu_l + e^- \rightarrow \nu_l + e^- \]

- Water Cherenkov detector.

- Ratio of observed to predicted:
  \[ \frac{\Phi_{SK-I}}{\Phi_{SSM}} = 0.406 \pm 0.014 \]

- Improved result over Kamiokande, neutrinos still missing!
Super-Kamiokande
Super-Kamiokande

- **NEUTRINOGRAPHY** of the Sun. 500 days exposure!
SNO

- Detection of solar neutrinos using the reactions:
  \[ \nu_l + e^- \rightarrow \nu_l + e^- \quad \text{(ES)} \]
  \[ \nu_e + D \rightarrow e^- + p + p \quad \text{(CC)} \]
  \[ \nu_l + D \rightarrow \nu_l + p + n \quad \text{(NC)} \]

- Heavy Water Cherenkov detector.

- Ratio of observed to predicted:
  \[ \frac{\Phi_{ES}^{SNO}}{\Phi_{SSM}} = 0.406 \pm 0.046 \]
  \[ \frac{\Phi_{CC}^{SNO}}{\Phi_{SSM}} = 0.290 \pm 0.017 \]
  \[ \frac{\Phi_{NC}^{SNO}}{\Phi_{SSM}} = 0.853 \pm 0.075 \]
The SNO results (along with Super-K for atmospheric neutrinos) led to a Nobel prize in 2015.
Additional material: Reactor Experiments
$\bar{\nu}_e$ production at nuclear reactors

- Fission of nuclear fuel ($^{235}$U, $^{238}$U, $^{239}$Pu, $^{241}$Pu) produces neutron rich fission products.
- $\beta^-$ decay of fission products:
  \[ _Z^A X \rightarrow _{Z+1}^A Y + \overline{\nu}_e + e^- \]
- Average per fission:
  - 200 MeV released.
  - 6 antineutrinos.

- Nuclear power plants: greatest man-made antineutrino source.
- Need to consider nuclear fuel evolution.
KamLAND

- Detection of reactor neutrinos using the inverse beta-decay reaction:
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]
- Liquid scintillator detector.
Solar + KamLAND results
Measurement of $\theta_{23}$ and $\Delta m^2_{\text{atm}}$
NEUTRINOS FROM THE ATMOSPHERE

- The Earth is constantly being bombarded by cosmic rays (mostly protons) with astrophysical origin.
- These interact strongly with nuclei in the atmosphere, producing showers of hadrons.
- Unstable hadrons eventually decay to the lightest meson, $\pi$, which decays weakly, producing neutrinos!
ATMOSPHERIC NEUTRINO OSCILLATIONS

• Naïvely expect 2-to-1 ratio of muon to electron neutrinos.

• However, neutrinos produced on the “far” side of the earth travel thousands of kilometres before they reach a detector.
  • So, they oscillate!

• Comparing the number of neutrinos hitting the detector from the “top” (short L) to those coming from the “bottom” (long L) gives a direct measurement of atmospheric neutrino oscillations.
SUPER-KAMIOKANDE

• The Super-Kamiokande experiment was designed to unambiguously observe oscillations in atmospheric neutrinos.
  • Following hints from its predecessor, Kamiokande.

• A tank containing 50 kilo-tons of ultra-pure water is instrumented with 11000 photo sensors to detect Cherenkov radiation emitted by relativistic charged particles.

• Excellent particle identification and directionality.
  • Crucial for oscillation measurement.
Super-Kamiokande results
SUPER-K FIRST RESULTS

- A clear deficit of “up-going” muon neutrinos was observed in the data.
  - Muon neutrinos are oscillating into tau neutrinos, which are not detected.
- Effect not seen in electron neutrinos.
  - Muon neutrino to electron neutrino oscillations are sub-dominant at this L/E.
ICECUBE ATMOSPHERIC NEUTRINOS

- Icecube sees atmospheric neutrino oscillations consistent with the Super-K results.

- Note $\Delta m^2 \sim 10^{-3}$, 100 times larger than solar mass splitting!
- Also, the mixing angle is very large – it looks like mixing is maximal or close…
NEUTRINO BEAMS

• So far, looked at experiments that use pre-existing neutrino sources.
  • Either natural: Sun, cosmic rays impinging on the atmosphere.
  • Or artificial: commercial nuclear reactors – electricity is paid for, but neutrinos are free!

• But we’ve been producing neutrino beams since the 60s.

• We can confirm neutrino oscillations using a well controlled neutrino source.

• Long baseline neutrino experiments:
  • Produce very intense muon neutrino beam
  • Point it at very large detector very far away.
  • Use well controlled beam energy, direction and timing to make very precise measurements.
    • Including searching for electron neutrino appearance from a muon neutrino beam.
      • Needs non-zero $\theta_{13}$
PRODUCING A NEUTRINO BEAM

- [https://www.youtube.com/watch?v=U_xWDWKq1CM](https://www.youtube.com/watch?v=U_xWDWKq1CM)
  1. Accelerate protons and aim them at a target.
  2. Focus the resulting pions using magnetic horns.
     - Can focus positive or negative pions to give neutrinos or anti-neutrinos.
  3. Allow pions to decay in empty volume, producing neutrinos and muons.
  4. Absorb the muons, and neutrinos will go through.
T2K & MINOS experiments
T2K & MINOS experiments
NOvA

Far Detector

5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)

Events / 0.25 GeV

Reconstructed Neutrino Energy (GeV)

Data
- Unoscillated prediction
- Best fit prediction (no sys)
- Expected 1-σ syst. range
- Best fit prediction (sys)
- Backgrounds

Normal Hierarchy
$2.74 \times 10^{20}$ POT-equiv.
Best fit $\chi^2 / N_{\text{eff}} = 19.0 / 16$

3 meters
14 meters

Top view
Beam direction
Side view
Color denotes deposited charge
THE OFF-AXIS TRICK

• Both NOvA and T2K use the “off-axis trick”.

• Don’t place the detector right in front of the neutrino beam, but a little to the side.

• Neutrinos that leave the decay pipe at a high angle have a more well defined energy.
  • Can tune $L / E$ very precisely!

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<th>T2K</th>
<th>NOvA</th>
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| $L=295$ km  
$E = 0.6$ GeV  
$L / E = 492$ km / GeV | $L=810$ km  
$E = 2.0$ GeV  
$L / E = 405$ km / GeV |

Medium Energy Tune
NEAR DETECTORS

• Want to characterise the neutrino beam as well as possible before any oscillations.
• Place neutrino detectors near the neutrino production point.
• Use data from these detectors to measure neutrino cross sections.

T2K: Complex of general purpose detectors

NOvA: Miniaturized version of far detector
T2K AND NOVA NEUTRINO EVENTS
T2K AND NOVA DATA

Muon neutrinos disappear

Electron neutrinos appear

NOvA Preliminary

T2K Preliminary

NOvA Preliminary
T2K AND NOVA DATA

Muon neutrinos disappear

Electron neutrinos appear

T2K observed electron neutrinos appearing from a muon neutrino beam for the first time in 2013

$\theta_{13} \neq 0$
SK (atm), T2K, MINOS, IceCube (atm), NOvA
Measurement of $\theta_{13}$
Measurement of $\theta_{13}$ with reactors

- For baselines of $\sim 1$ km, the probability can be approximated by:

$$P_{ee}(L, E) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$\approx 1 - \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2_{31}}{E}[\text{eV}^2][\text{km}][\text{MeV}]\right)$$
Measurement of $\theta_{13}$ with two-detector reactor experiments

- Antineutrinos detected by inverse $\beta$-decay:
  on Gd-loaded liquid scintillator calorimeters.
- Reactor prediction and the antineutrino detection systematic uncertainties can be reduced if **two identical detectors**, one near and one far from the reactors, are built.

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<th>Reactor power (GW$_{th}$)</th>
<th>Distance (m)</th>
<th>Depth (mwe)</th>
<th>Target mass (ton) $\times$ detectors</th>
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<td>8.5</td>
<td>400 / 1050</td>
<td>120 / 300</td>
<td>8 $\times$ 2</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>17.4</td>
<td>470, 576 / 1648</td>
<td>260 / 860</td>
<td>20 $\times$ 8</td>
</tr>
<tr>
<td>RENO</td>
<td>16.5</td>
<td>294 / 1383</td>
<td>120 / 450</td>
<td>16 $\times$ 2</td>
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Double Chooz: a two-detector experiment

Near Detector
L ~ 400 m
~ 300 ν/day
120 mwe
December 2014

Far Detector
L ~ 1050 m
~ 40 ν/day
300 mwe
April 2011

Chooz-B reactors
PWR N4s
2 × 4.25 GW$_{th}$
~ $10^{21}$ ν/s
100%ν$_e$

nuclear power plant (Ardennes, France)
Electron antineutrino detection

**Inverse Beta Decay (IBD):**
- Reaction threshold: $E_\nu \geq 1.806$ MeV.
- Disappearance experiment.
- Well known cross-section (0.2%).
- Coincidence of 2 signals: background suppression.

**Prompt signal:**
- Positron kinetic energy + $\gamma$’s from annihilation.
- $E_{\text{prompt}} \approx E_\nu - 0.782$ MeV
- $E_{\text{prompt}} \sim 1 - 9$ MeV

**Delayed signal:**
- $\gamma$’s from radiative neutron capture.
- **Gd:** $\Delta T \sim 30$ μs, $E_{\text{delayed}} \sim 8$ MeV.
- **H:** $\Delta T \sim 200$ μs, $E_{\text{delayed}} = 2.22$ MeV.
The Double Chooz Far Detector

Inner Detector:
- **Neutrino Target**: acrylic vessel (8 mm) with 10.3 m³ Gd-loaded (1 g/l) liquid scintillator.
- **Gamma-Catcher**: acrylic (12 mm) vessel with 22.5 m³ of liquid scintillator.
- **Buffer**: stainless steel (3 mm) vessel supporting 390 10” PMTs, with 110 m³ of non-scintillating mineral oil.

Outer Detector:
- **Inner Veto**: steel (10 mm) vessel supporting 78 8” PMTs, with 90 m³ of liquid scintillator.
- **Shielding**: 15 cm steel.
- **Outer Veto**: plastic scintillator strips.
Latests measurements of $\theta_{13}$

$\theta_{13}$ unknown until 2011. Huge progress in a few years.

- **Double Chooz**
  - JHEP 1410, 086 (2014)

- **Preliminary (Moriond)**

- **Daya Bay**
  - PRL 115, 111802 (2015)

- **RENO**
  - Preliminary (arXiv:1511.05849)

- **T2K**
  - PRD 91, 072010 (2015)
  - $\Delta m^2_{32} > 0$
  - $\Delta m^2_{32} < 0$

A. Cabrera, FNAL seminar 03/25/2016
SHORT(ER) BASELINE REACTOR EXPERIMENTS

- Daya Bay experiment, south China.
- $L \sim 1.5 \text{ km}; \ E \sim 1 \text{ MeV}; \ \text{Minimum } \Delta m^2 \sim 10^{-3} \text{ eV}^2$
SHORT(ER) BASELINE REACTOR EXPERIMENTS

• In 2012, $\theta_{13}$ went from being the least well known of the mixing angles to the most precisely measured!

Observation of Electron Antineutrino Disappearance at Daya Bay

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016{\text{(stat)}} \pm 0.005{\text{(syst)}}$$
First glimpse of $\delta$

- $\nu_\mu \rightarrow \nu_e$ depends on the mass hierarchy and CP-violating phase.

\[
P_{\mu e}(L, E) = \frac{1}{(A-1)^2} \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2 [(A-1)\Delta] + \frac{\alpha}{A(1-A)} \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \times \sin(\delta) \sin(\Delta) \sin(A\Delta) \sin [(1-A)\Delta] + \frac{\alpha^2}{A^2} \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(A\Delta),
\]

\[
\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{32}} \quad \Delta \equiv \frac{\Delta m^2_{32}L}{4E} \quad A \equiv 2\sqrt{2}G_F N_e \frac{E}{\Delta m^2_{32}}
\]

**Critical input:** Using the $\theta_{13}$ from the reactor experiments, the mass hierarchy and the CP-violating phase can be studied.
3 neutrinos: mixing matrix

\[
\begin{pmatrix}
V_e \\
V_\mu \\
V_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
c_{23} & s_{23} & 0 \\
-s_{23} & c_{23} & 0
\end{pmatrix}
\begin{pmatrix}
c_{13} & s_{13} e^{i\delta} & 0 \\
-s_{13} e^{i\delta} & c_{13} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
v_1 \\
v_2 \\
v_3
\end{pmatrix} \rightarrow \begin{pmatrix} m_1 \\
m_2 \\
m_3 \end{pmatrix}
\]

- **3 angles measured (mnemonic approximation):**
  - \( \theta_{12} \approx 34^\circ \)
  - \( \theta_{23} \approx 45^\circ \) (symmetry?)
  - \( \theta_{13} \approx 9^\circ \)
- **CP-violating phase** \( \delta ? \)
- Why so different from quark mixing?

\[ \Delta m^2_{jk} \equiv m_j^2 - m_k^2 \]
3 neutrinos: mass ordering

- 3 mass eigenstates $\rightarrow$ **2 independent squared-mass differences:** $\Delta m_{32}^2 + \Delta m_{21}^2 = \Delta m_{31}^2$
- But which is on top of which?
- **Matter effects within the Sun show the mass eigenstate $\nu_2$ is heavier than $\nu_1$.**
- Which is the **lightest neutrino**? Two possibilities left:

![Diagram of mass squared vs. neutrino energy](image_url)

- Normal
- Inverted

**Normal:**
- $m_1^2$ to $m_2^2$ (solar $\sim 7 \times 10^{-5}$ eV$^2$)
- $m_2^2$ to $m_3^2$ (atmospheric $\sim 2 \times 10^{-3}$ eV$^2$)

**Inverted:**
- $m_1^2$ to $m_3^2$ (atmospheric $\sim 2 \times 10^{-3}$ eV$^2$)
- $m_2^2$ to $m_3^2$ (solar $\sim 7 \times 10^{-5}$ eV$^2$)
Future: $\delta$ and mass hierarchy

- Both CP-violating phase and the mass hierarchy can be measured in a long-baseline accelerator experiment.
- Need a long baseline and a broad-energy beam to disentangle CP violation caused by matter effects (Earth is made only from matter) from the intrinsic CP violation.

Neutrino beam expected by 2026.
> 5σ measurement of CP-violating phase if CP violation is close to maximal.
  > 3σ measurement for 65% of δ range.
> 5σ determination of mass hierarchy for any value of CP-violating phase.
> 2017: Far Laboratory construction started.
> 2018: DUNE detector prototypes (protoDUNE) at CERN test beam.
> 2021: Far Detector installation begins.
> 2024: Beginning of Physics data taking.
> 2026: First neutrinos from Fermilab beam.
Proton decay at DUNE

- $p \rightarrow e^+ \pi^0$
- $p \rightarrow e^+ K^0$
- $p \rightarrow \mu^+ K^0$
- $n \rightarrow \bar{\nu} K^0$
- $p \rightarrow \bar{\nu} K^+$

- Predictions:
  - Minimal SU(5)
  - SUSY SO(10)
  - Non-SUSY SO(10) G_{224D}
  - 6D SO(10)
  - Minimal SUSY SU(5)
  - Flipped SU(5)
  - Non-minimal SUSY SU(5)
  - SUSY SO(10)

- Experiments:
  - Soudan
  - Frejus
  - Kamiokande
  - IMB
  - Super-K
  - Hyper-K

- DUNE (40 kt)
Core-collapse supernova neutrinos at DUNE