Neutrinos

Thanks to Ian Blockland and Randy Sobie for these slides

- spin $\frac{1}{2}$ particle with no electric charge; weak isospin partners of charged leptons
- $\nu_e$ observed in 1953, $\nu_\mu$ in 1962 and $\nu_\tau$ in the 1990s
- neutrino physics is very topical
  - solar neutrino problem, neutrino mixing, neutrino masses
$\nu_e$ discovery

Discovery of electron neutrino

- See $\nu$ to $e^+ n$
- Reines and Cowan, 1954-1957, 1 ton detector
- Nobel Prize, 1995
- Neutrinos from Nearby Fission Reactor
- Observed 1 event every few minutes

1953 Reines and Cowan (et al) at Hanford
\( \nu_\mu \) discovery

- Pions decay to muons, but again, energy was missing — must be a neutrino...
- But if \( \mu^- \rightarrow e^- \nu \nu \) then \( \mu^- \rightarrow e^- \gamma \) too unless...
- First Decay-in-flight \( \nu \) beam  BNL AGS
- 15BeV protons on Be Target
- 21m decay region, 13.5m Fe Shield, 1 Ton Detector

Discovery of muon neutrino

- 3.5x10^{17} POT
- 34 single-\( \mu \) events
- 5 background
- NO e-like events!
- Lederman, Swartz, Steinberger

1962 Lederman et al at Brookhaven
\( (10^{14} \ \bar{\nu}_\mu \) produced 29 events)
\( \nu_\tau \) discovery

- DONUT Experiment at FNAL: 1997-98
- Making a beam of \( \nu_\tau \) is hard! Want only \( D_s \)'s to decay

- Seeing \( \tau \) decay is also hard: need very sensitive detector
- 4 events seen, expect 0.34 background
Do Neutrinos Have Mass?

- Although we have always known that neutrinos are light, it is an experimental matter to determine just how light.

- As far as direct measurements go:

  \[
  \begin{array}{|c|c|c|}
  \hline
  \nu \text{ Flavor} & \text{Mass Limit} & \text{Process} \\
  \hline
  \nu_e & m_\nu < 3 \text{ eV} & ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \\
  \hline
  \nu_\mu & m_\nu < 190 \text{ keV} & \pi \rightarrow \mu + \nu_\mu \\
  \hline
  \nu_\tau & m_\nu < 18.2 \text{ MeV} & \tau \rightarrow 3\pi + \nu_\tau \\
  \hline
  \end{array}
  \]

- There is no fundamental reason (e.g., a symmetry) why \( m_\nu = 0 \).

- The Standard Model assumes that neutrinos are precisely massless; accommodating non-zero masses is in many respects straightforward.
$\nu_e$ mass measurement

Mass of Electron neutrino
Use endpoint of electron spectrum in tritium decay

\[ ^3H \rightarrow ^3\text{He} \, e^- \nu_e \]

![Graphs showing electron spectrum endpoints](image)

$m_{\nu_e} < 5.1$ ev
Mass of Muon neutrino

Use the $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay

For a pion at rest

$$m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2m_\pi \sqrt{p_\mu^2 + m_\mu^2}$$

Use the known values for the pion and muon masses

$$m_\pi = 139.56995 \pm 0.00035 \text{ MeV}$$

$$m_\mu = 105.658389 \pm 0.000034 \text{ MeV}$$

and measure the pion momentum

$$p_\mu = 29.79207 \pm 0.00012 \text{ MeV}$$

Giving an upper limit on the muon neutrino mass

$$m_{\nu_\mu} < 0.16 \text{ MeV}$$
$\nu_\tau$ mass measurement

LEP experiments measured the limit on the $\nu_\tau$ mass using $\tau \rightarrow 3\pi^- 2\pi^+ \nu_\tau$ decays.

$$M(\nu_\tau) < 18 \text{ MeV}$$
Neutrino Mixing

- Supposing that neutrinos have mass, we must now allow a mixing between the weak eigenstates and the mass eigenstates, just as we have done for the quarks.

- The neutrino analogue of the CKM matrix is the Maki-Nakagawa-Sakata (MNS) matrix.

- Like the CKM matrix, the MNS matrix can be parametrized in terms of 3 mixing angles and 1 CP-violating complex phase.

- We label the neutrino mass eigenstates (in order of ascending mass) as $\nu_1$, $\nu_2$, and $\nu_3$. 
Neutrino Deficits

• In 1967, Ray Davis put 100,000 gallons of dry-cleaning fluid in a tank a mile underground to try to measure the solar neutrino flux.

• The measured flux (inferred from 1 Cl to Ar conversion every 2 days) was about a factor of 3 below the theoretical expectations from the Standard Solar Model.

• Similar neutrino deficits were later observed for the atmospheric neutrinos generated by cosmic rays.

• Surprisingly, both experiment and theory turned out to be right and these effects are now understood as neutrino oscillation effects.
Solar Neutrinos

The Sun is an intense source of MeV neutrinos!

\[ 4p + 2e^{-} \rightarrow ^{4}\text{He} + 2\nu_{e} + 26.731 \text{ MeV} \]

Solar models let us predict the rates of each neutrino-producing reaction.
Solar Neutrino Flux Measurements

Two Classes of Experiment (so far)

- Radiochemical
  - $\nu_e$ interactions convert target nuclei
  - Radioactive products extracted and counted after exposure time
- Water Cerenkov
  - Real-time detection of scattered atomic $e^-$'s
  - Mixed CC and NC sensitivity

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detection Reaction</th>
<th>Threshold</th>
<th>Primary Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>$\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$</td>
<td>0.8 MeV</td>
<td>$^7\text{Be}, ^8\text{B}$</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>$\nu_e, (\mu, \tau) + e \rightarrow \nu_e, (\mu, \tau) + e$</td>
<td>7.3 MeV</td>
<td>$^8\text{B}$</td>
</tr>
<tr>
<td>SAGE, GALLEX/GNO</td>
<td>$\nu_e + ^{71}\text{Ga} \rightarrow e^+ + ^{71}\text{Ge}$</td>
<td>0.23 MeV</td>
<td>$pp, ^7\text{Be}, ^8\text{B}$</td>
</tr>
<tr>
<td>Super-K</td>
<td>$\nu_e, (\mu, \tau) + e \rightarrow \nu_e, (\mu, \tau) + e$</td>
<td>5 MeV</td>
<td>$^8\text{B}$</td>
</tr>
</tbody>
</table>
Neutrino Oscillations: 2 Flavor Model

- We will now illustrate how neutrino oscillations work in the context of a 2-neutrino model.

- Neutrinos are always produced as weak eigenstates. Suppose that at $t = 0$ we produce an electron neutrino:

$$|\nu(0)\rangle = |\nu_e\rangle$$

- Neutrinos propagate as mass eigenstates. In a 2-neutrino model, the weak eigenstates and the mass eigenstates are related by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$
Neutrino Oscillations: Propagation

- In terms of the mass eigenstates, our original $\nu_e$ is

$$|\nu(0)\rangle = \cos \theta \ |\nu_1\rangle + \sin \theta \ |\nu_2\rangle$$

- When a particle propagates in free space, it accumulates a phase of $e^{-iEt}$.

- Assuming that the spatial momentum of the original $\nu_e$ is passed on to $\nu_1$ and $\nu_2$, the energy of each neutrino is given by

$$E_i = \sqrt{p^2 + m^2_i}$$

$$\simeq |p| \left( 1 + \frac{m^2_i}{2p^2} \right)$$
Neutrino Oscillations: $|\nu(t)\rangle$

- The two mass eigenstates pick up different phases as they propagate, so that

$$|\nu(t)\rangle = e^{-iE_1 t} \cos \theta \ |\nu_1\rangle + e^{-iE_2 t} \sin \theta \ |\nu_2\rangle$$

- Going back to flavor eigenstates, this is

$$|\nu(t)\rangle = e^{-iE_1 t} \cos \theta \ (\cos \theta \ |\nu_e\rangle - \sin \theta \ |\nu_\mu\rangle) + e^{-iE_2 t} \sin \theta \ (\sin \theta \ |\nu_e\rangle + \cos \theta \ |\nu_\mu\rangle)$$

- The probability of an oscillation from $\nu_e$ to $\nu_\mu$ is then

$$P_{osc}(t) = |\langle \nu_\mu | \nu(t) \rangle|^2$$

$$= |\sin \theta \ \cos \theta \ (-e^{-iE_1 t} + e^{-iE_2 t})|^2$$
Neutrino Oscillations: $P_{osc}$

$$P_{osc}(t) = \left| \sin \theta \cos \theta \left( -e^{-iE_1 t} + e^{-iE_2 t} \right) \right|^2$$

$$= \frac{1}{4} \sin^2 2\theta \left[ 2 - \left( e^{i(E_2-E_1)t} + e^{-i(E_2-E_1)t} \right) \right]$$

$$= \frac{1}{2} \sin^2 2\theta \left[ 1 - \cos(E_2 - E_1)t \right]$$

- With $\Delta E = \Delta m^2 / 2p$ and

$$E \simeq pc \quad \& \quad L \simeq tc \quad \Rightarrow \quad \frac{t}{p} \simeq \frac{L}{E}$$

$$P_{osc}(t) = \frac{1}{2} \sin^2 2\theta \left[ 1 - \cos \left( \Delta m^2 L / 2E \right) \right]$$

$$= \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (eV^2) \cdot L (km)}{E (GeV)} \right)$$
\[ P_{\text{osc}} = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E) \]

...Depends Upon Two Experimental Parameters:
- \( L \) – The distance from the \( \nu \) source to detector (km)
- \( E \) – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:
- \( \Delta m^2 = m_1^2 - m_2^2 \) (eV²)
- \( \sin^2 2\theta \)
Curves (red, blue, black) for $2\theta = 0.14, 0.1, 1.57$ and frequency $5, 0.15, 0.01$, respectively. A detector might sample the region 8-12.
Oscillation Plots...

\[ P_{osc} = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L / E) \]

No oscillation signal \( \rightarrow \) limit at some Confidence Level
Example: \( P_{osc} > P \) at 90\% CL

\[ \Delta m^2 \text{ (eV}^2) \]

90\% CL
Excluded Region

\[ \sin^2 2\theta_{\text{min}} = 2*P \]

\[ \Delta m^2_{\text{min}} = (E/(1.27L)) \sqrt{P} \]

Signal \( \rightarrow \) “allowed region”
Ways of Observing Neutrino Oscillations

- The oscillation probabilities depend on $\theta$, $\Delta m^2$, $L$, and $E$.
- We can either look for the appearance of a different neutrino flavor (usually limited by background) or we can measure the disappearance of the expected flavor (limited by calibration of source and target).

<table>
<thead>
<tr>
<th>Source</th>
<th>$\nu$ Types</th>
<th>Mode</th>
<th>Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>$\nu_e$</td>
<td>Disappearance</td>
<td>Great distance</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>$\nu_e$, $\bar{\nu}<em>e$, $\nu</em>\mu$, $\bar{\nu}_\mu$</td>
<td>Disappearance</td>
<td>Variable distance</td>
</tr>
<tr>
<td>Reactor</td>
<td>$\bar{\nu}_e$</td>
<td>Disappearance</td>
<td>Low energy</td>
</tr>
<tr>
<td>Accelerator</td>
<td>$\nu_\mu$, $\bar{\nu}_\mu$</td>
<td>Either</td>
<td>Control $E$ and $L$</td>
</tr>
</tbody>
</table>
Current Status

- The mixing matrix appears to feature very large mixing angles (LMA); the following gives a crude view of the sizes of the matrix elements:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
0.35 & 0.95 & < 0.2 e^{i\delta} \\
-0.35 & 0.25 & 0.70 \\
0.65 & -0.25 & 0.70
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
\[(\text{Mass})^2\]

\[\Delta m_{\text{atm}}^2 \quad \Rightarrow \Delta m_{0}^2\]

- Green hatch: \(\nu_e\)
- Red right: \(\nu_\mu\)
- Blue left: \(\nu_\tau\)
Cl
Ga

\[ \Delta m^2 \] [eV^2]

\[ \tan^2 \theta \]

http://hitoshi.berkeley.edu/neutrino

SuperK
LSND
CHOOZ
Bugey
KARMEN2
PaloVerde
CDHSW
BNL E776
K2K
KamLAND
SNO
Super-K+SNO+KamLAND
http://hitoshi.berkeley.edu/neutrino
Sudbury Neutrino Observatory

2092 m to Surface

18 m Diameter Support Structure for 9500 PMTs, 60% coverage

1000 Tonnes D₂O

12 m Diameter Acrylic Vessel

1700 Tonnes Inner Shielding H₂O

5300 Tonnes Outer Shield H₂O

Urylon Liner and Radon Seal
Event Display–Neutrino Event
Solar $\nu$ Interactions in SNO

**Elastic Scattering (ES)** \( \nu_x + e^- \rightarrow \nu_x + e^- \)
- Same way Super-K saw neutrinos
- Mostly measures $\nu_e$, plus a little of $\nu_\mu$ or $\nu_\tau$

**Charged Current (CC)** \( \nu_e + d \rightarrow p + p + e^- \)
- See only the electron neutrinos here

**Neutral Current (NC)** \( \nu_x + d \rightarrow n + p + \nu_x \)
- Measures total flux of all neutrino types!
- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons if they are captured on other nuclei (e.g. $n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \gamma$’s)
Physics of Long Baseline $\nu$ Experiments

Basic idea: shoot a man-made neutrino beam through the Earth, and study neutrino oscillations in controlled way

K2K: KEK to Kamioka
T2K: J-PARC to Kamioka
($\times 50$ stats.)

Far detector: Super-K

<table>
<thead>
<tr>
<th>Measure</th>
<th>Determine</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(\nu_\mu \to \nu_\mu)$</td>
<td>$\Delta m^2_{23}, \theta_{23}$</td>
</tr>
<tr>
<td>$P(\nu_\mu \to \nu_e)$</td>
<td>$\theta_{13}$</td>
</tr>
<tr>
<td>$P(\bar{\nu}<em>\mu \to \bar{\nu}</em>\mu)$</td>
<td>CPT</td>
</tr>
<tr>
<td>$P(\bar{\nu}_\mu \to \bar{\nu}_e)$</td>
<td>$\delta_{CP}, \text{sign}(\Delta m^2_{23})$</td>
</tr>
</tbody>
</table>
Neutrino Mass Terms

- If neutrinos do have a small mass, we could create Dirac mass terms (just like for $m_\ell$ and $m_q$).
- Since neutrinos do not carry non-zero quantum numbers, it is possible that a neutrino is its own antiparticle. Such a neutrino is known as a Majorana neutrino.
- Incorporating both Dirac and Majorana mass terms leads to the seesaw mechanism, whereby the presence of a right-handed neutrino at the GUT scale leads to

$$m_\nu \sim \frac{m_D^2}{M_{GUT}}$$

where $m_D$ is the Dirac mass of a typical Standard Model fermion and $M_{GUT}$, as we’ll soon see, is approximately $10^{15}$ GeV.
Double $\beta$ Decay

- Certain unstable atoms, such as $^{136}\text{Xe}$ and $^{76}\text{Ge}$, can decay to elements with two additional protons via double $\beta$ decay.
- These decays cannot be regarded as two separate $\beta$ decays because the intermediate state is energetically off limits.
- As a result, double $\beta$ decay is one big process in which two separate neutrons simultaneously decay via $n \rightarrow p + e^- + \bar{\nu}_e$.
- Because $\beta$ decay is a 3-body decay, the energy of the emitted electron is not fixed.
0νββ

- Supposing that neutrinos are Majorana particles, the two neutrinos involved in double β decay can actually be merged into an internal line so as to produce neutrinoless double β decay.

- The × denotes the “transition” from ν to ν̄. This leads to a suppression of $m_\nu/E_\nu$.

- Now that each β decay is essentially a 2-body decay, the energy of the electrons is fixed.
$2\nu\beta\beta$ vs. $0\nu\beta\beta$
Summary

- Neutrino masses, although not present in the SM, can easily be incorporated, along with the MNS mixing matrix.
- \( m_\nu \neq 0 \) leads to neutrino oscillations (observed) and may lead to \( 0\nu\beta\beta \) (searched for).
- Structure of the MNS matrix is becoming better known; next generation experiments will possibly measure CP violation in neutrinos