Introduction: Neutrinos

- A neutrino ($\nu$) is an elementary particle, one of the fundamental constituents of matter.

It has almost no mass, no electric charge, and interacts only weakly (+gravity?) with other particles.
Neutrinos carry energy, momentum, angular momentum.

It was hypothesized by Pauli, in 1930, to explain a feature of nuclear $\beta$-decay.

In $\beta$-decay, an electron (or positron) is produced. If the decay were simply

$$\text{Parent} \longrightarrow \text{Daughter} + e^-$$

Then 2-body kinematics implies a single $e^-$ energy. Instead, a broad spectrum was observed.

In $\beta$-decay, the highest electron energy is sensitive to the mass of the neutrino.

Today, the $\beta$-decay experiments are being done with few-eV accuracy. The results are

$$m_{\nu_e}^2 < 1 - 2 \ (eV/c)^2$$
Sources of Neutrinos

- The Sun, and other stars. Eg.
  \[ p + p \rightarrow ^2H + e^+ + \nu_e \]

- Nuclear reactors
  Prototype reaction:
  \[ n \rightarrow p + e^- + \bar{\nu}_e \]

- Particle decays
  Eg.
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]
\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]

This type of process makes neutrinos from cosmic ray interactions in the earth’s atmospheric and possibly in some galactic neutrino sources. It is also used to make neutrino beams at accelerators.

- Supernovae. Neutrinos from Supernova 1987, in a nearby galaxy, were detected.
**Neutrino Interactions**

To predict interaction rates, we need to know the interaction **cross section**.

The average thickness of a target with atomic weight $A$, density $\rho$, for 1 interaction if the cross section is $\sigma$ is:

$$\lambda = \frac{A}{N_0 \rho \sigma}$$

Here are some neutrino cross sections measured at accelerators:

The cross section is per nucleon. For “low” energies is is directly proportional to $E_\nu$. 
Find the attenuation length of 1 \( MeV \) neutrinos in iron. The total cross section used in the above equation is just \( \sigma = A\sigma_N \). The result is:

\[
\lambda = 3 \times 10^{16} \text{ cm} \approx 2000 \text{ AU}
\]

So the earth is almost completely transparent to neutrinos of this energy.

At higher energies, the calculated cross section looks like:

The energy at which the interaction length is 1 earth radius is \( 50 - 100 \text{ TeV} \).
Solar Neutrinos

Several light-element nuclear fusion reactions in stars proceed via the weak interaction, and produce neutrinos.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Products</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>$pp \rightarrow 2\text{H} + e^+ + \nu_e$</td>
<td></td>
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<tr>
<td>$2\text{H} + p \rightarrow 3\text{He} + \gamma$</td>
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<tr>
<td>$3\text{He} + 3\text{He} \rightarrow 4\text{He} + 2p$</td>
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<td>85%</td>
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<tr>
<td>$3\text{He} + 4\text{He} \rightarrow 7\text{Be} + \gamma$</td>
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<td>15%</td>
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<tr>
<td>$e^- + 7\text{Be} \rightarrow 7\text{Li} + \nu_e$</td>
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<tr>
<td>$7\text{Li} + p \rightarrow 2^4\text{He}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p + 7\text{Be} \rightarrow 8\text{B} + \gamma$</td>
<td></td>
<td>0.02%</td>
</tr>
<tr>
<td>$8\text{B} \rightarrow 8\text{Be}^* + e^+ + \nu_e$</td>
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<tr>
<td>$8\text{Be}^* \rightarrow 2^4\text{He}$</td>
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The Standard Solar Model (SSM) predicts the energy spectra of neutrinos produced by these reactions:
The SSM correctly predicts the Sun’s luminosity.

In addition, Doppler spectroscopy of the Sun’s surface permitted the development of **helioseismology**.

The various oscillation modes are sensitive to the speed of sound in the solar interior.

The SSM makes correct predictions of this speed, as a function of radius.

**Neutrino Detectors**
Two Methods:

1. Low-energy nuclear reactions. For example

\[ \nu_e + ^{37}Cl \longrightarrow ^{37}Ar + e^- \]  \hspace{1cm} (1)

The \(^{37}Ar\) is chemically extracted, and the decay rate of \(^{37}Ar\) measured. or

\[ \nu_e + ^{71}Ga \longrightarrow ^{71}Ge + e^- \]  \hspace{1cm} (2)

Detect \(^{71}Ge\) decays.

2. Neutrino scatters from electron or nucleus. Scattered particles detected. Some detectors use Cerenkov light to detect and track the neutrinos.

**First Experiments**

1. First experiment by R. Davis et al, in Homestake gold mine (S.D.)
   
   Used reaction 1. Ran for \(\approx 30\) years. Consistently found fewer neutrinos than predicted by SSM.

2. Gallex (Gran Sasso) Gallium detector. Threshold low enough to detect pp \(\nu\)'s.

3. SAGE (USSR) Gallium. “

4. KamioKande (Japan) Water. \(Sees^8B \nu\)'s.

5. (IMB detector, Ohio, saw supernova 1987, but did not measure solar neutrinos.)
Results

1. These experiments reported fluxes lower than predicted by SSM. This was the “solar neutrino problem”.

\[ ^8B \quad 1/3 - 1/2 \quad \text{SSM} \]
\[ pp \quad 2/3 \quad \text{SSM} \]

2. Can we raise \( T_{\text{sun}} \) to increase the \( \nu \) flux?

   No. \(^8B\) is \textbf{much} more sensitive to \( T_{\text{sun}} \) than \( pp \)

3. No one found a way to adjust the solar model to agree with the experiments.
Remaining possibility:
Flux suppression with possible energy dependence.

- Can get this with $\nu$ “oscillations”. In certain energy ranges, $\nu_e$’s are transformed to $\nu_{other}$, which are detected with much lower (or zero) probability. This mechanism requires the neutrinos to be produced as a coherent superposition of two or more mass eigenstates. It requires that at least one neutrino has mass.

**Neutrino Flavor Oscillations**

To get $\nu$ oscillations,

1. There are different masses for the neutrinos: $\nu_1, \nu_2, \nu_3$. Eigenstates of the weak Hamiltonian, eg. $\nu_e, \nu_\mu, \text{ and } \nu_\tau$ are superpositions of $\nu_1, \nu_2, \nu_3$.

2. The simplest description (2-component):

\[
|\nu_e> = \cos \theta |\nu_1> + \sin \theta |\nu_2>
\]
\[
|\nu_\mu> = - \sin \theta |\nu_1> + \cos \theta |\nu_2>
\]

For a neutrino propagating in vacuum, we expect an oscillation at a frequency proportional to:

\[
E_2 - E_1 \approx \frac{m_2^2 - m_1^2}{2E}
\]
The survival probability after a length $L$ can be shown to be:

$$P(\nu_x \rightarrow \nu_x) = 1 - \sin^2 2\theta \sin^2 \left[1.27\Delta m^2 L/E\right]$$

where $L$ is in km, $E$ in GeV, and $\Delta m^2$ in $[eV/c^2]^2$.

3. In addition, in matter, $|\nu_e>$ has an interaction which $|\nu_{\mu}>$ does not. This creates a new term in the Hamiltonian matrix. Oscillations are “stimulated” by passage through matter.
Consequences of Neutrino Mass

- Dark Matter. The contribution of neutrinos would be

\[ \Omega_\nu \approx \frac{m_{\text{total}}}{30\text{eV}} \]

So a few-eV mass would be significant.

- The “Standard Model” assumes massless \( \nu \)'s. They are in a eigenstate of helicity (\( \sigma p/p \))

Massive \( \nu \)'s would alter the fundamental symmetries of the weak Hamiltonian.

Neutrino oscillations also imply lepton flavor violation.

These can be accommodated with the Minimal SuperSymmetric Model.

- For every Fermion there is a Boson, and vice versa.
Detection Principle: neutrino energy transferred to some other system.

Examples: Electron Scattering

The reaction

\[ \nu_e + e^- \rightarrow \nu_e + e^- \]  \hspace{1cm} (3)

proceeds via either the charged or neutral current process.

\[ \nu_\mu + e^- \rightarrow \nu_\mu + e^- \]  \hspace{1cm} (4)

goes only via the neutral current process.
Reaction 3 is \( \approx 6 \) times more likely than reaction 4.

The scattered electron is then detected.

One common detection method is **Cerenkov radiation**, electromagnetic radiation produced by a particle moving in a transparent medium at a speed faster than \( c/n \). The emission is at an angle given by

\[
\cos \theta = 1/n\beta
\]

For water, for \( \beta \approx 1 \), this angle is about 42°. Cerenkov light is used to detect neutrinos in the **SuperKamiokande** detector.
The detector contains 50,000 tonnes of water. It is 40 meters high and 30 meters in diameter.
The 20-inch photomultipliers can detect a single optical photon (with \( \approx 25\% \) efficiency.) There are 11,400 of these tubes, looking inward. An additional 2200 smaller PMT’s look outward at a 1\( m \) layer of water to veto charged particles entering from the outside.
The time and photoelectron output of the tubes are used to reconstruct the electron position, direction and energy.
Cerenkov light detection is also used in the SNO detector. This detector, located in Ontario, Canada, contains 1000 tonnes of heavy water, surrounded by a layer of light water.
The PMT’s are mounted on a geodesic dome.
And installed in an underground chamber.
SNO detects neutrinos mainly by a nuclear reaction.

It also detects electron scattering.

The nuclear reaction probability is much larger than that for electron scattering. The low-energy detection rates for SNO and SuperK are comparable.

The electron energy in the CC reaction is close to the incident $\nu$ energy.
Neutrino Oscillation Parameter Space
SuperKamiokande Results

Distribution of angle between scattered electron and Sun direction:
Fluxes, at 1 AU:

SuperK, (assuming all incident neutrinos are $\nu_e$):

$$\phi = (2.32 \pm 0.03 + 0.08 - 0.07) \times 10^6 / cm^2 s$$

(the first uncertainty is statistical, the next systematic)

This is 45.2% of the SSM prediction.

The SuperK flux includes detection of $\nu_\mu$ at $\approx 1/6$ efficiency.

SNO, from CC events (from $\nu_e$ only)

$$\phi = (1.75 \pm 0.07 + 0.12 - 0.11 \pm 0.05) \times 10^6 / cm^2 s$$

So SuperK is measuring more $\nu$'s than SNO!

The difference is 3.3$\sigma$. 
Other Evidence for Neutrino Oscillations

1. KamLand. At KamioKande site. 1000 tonnes liquid scintillator. Look for oscillations of $\bar{\nu}_e$ from several reactors. Is sensitive to “Large Mixing Angle” oscillations. New results published Jan 08:
   $\Delta m^2 = 2.95 \pm .21 \times 10^{-5} (eV/c)^2$ Agrees with solar result.

2. BOREXINO. Gran Sasso. 300 tonnes liquid scintillator. Looks for .862 MeV $\nu_e$ from $^7Be$ reaction in Sun. Results (2007) agree with SSM.

3. SuperK atmospheric neutrino data.

4. KtoK experiment: neutrino beam from KEK accelerator, near Tokyo, directed at SuperK, 250 km away.

5. MINOS Experiment: Neutrino beam from Fermilab to underground detector in Soudan
mine in Minnesota. Results agree with SuperK atmospheric neutrino results.

6. LSND (Los Alamos) experiment results:

\[ \nu_e - \nu_\mu \text{ oscillations. } \Delta m^2 \approx 1eV^2 \]

Oscillation not seen by KARMEN, a similar experiment, but no significant disagreement. A positive result leads to introduction of a 4th \( \nu \), a “sterile” neutrino. An experiment at FNAL “MiniBoone”, has recently ruled out this result.
SuperK atmospheric neutrino data.

- Atmospheric $\nu$’s are produced in decays of particles produced in cosmic ray-induced showers in the atmosphere.
- SuperK is sensitive to energies from a few hundred MeV to several GeV.
- The detector is able to distinguish muons from electrons.
- This capability was verified with an accelerator test of a prototype.
- The experiment studies the $\nu$ flux flavor composition vs. path length.
Detector response to an electron (top) and a muon (bottom).
Different zenith angles correspond to different path lengths.
The survival probability for a $1 - GeV \nu_\mu$, with $\Delta m^2 = .003(eV/c^2)^2$, is:
Dotted lines are for oscillation with $\Delta m^2 = .003(eV/c^2)^2$, $\sin^2(2\theta) = 1$. 
Current results:

- Solar: $\Delta m^2 = 8.0 \pm .5 \times 10^{-5} (eV/c^2)^2$
  $\theta = 33.9 \pm 2.2^\circ$
- Atmospheric: $\Delta m^2 = 1.9 - 3.0 \times 10^{-3} (eV/c^2)^2$
  $\theta > 36^\circ$