Neutrino Oscillations

Topics

- What’s a neutrino?
- Solar Neutrino “Problem”
- Detection of Neutrinos by
  4. Superkamiokande detector
  5. Sudbury Neutrino Observatory (SNO)
  6. Kamland detector
- Quantum mechanical oscillations
- Neutrino oscillations
- Experimental results
The major players:

A neutrino ($\nu$) has almost no mass, no electric charge, and interacts only weakly (+ gravity) with other particles.
The neutrino was first postulated by Pauli in 1930 to explain the continuous energy spectrum of the electron in nuclear beta decay.

The bar in $\overline{\nu}_e$ means it is an anti-particle.
Observed Conservation Laws:

In elementary particle interactions,

3. The total number of leptons (number of leptons – number of anti-leptons) stays constant.

2. The total number of leptons of a given flavor stays constant.

Examples:

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

(Beta decay of the neutron)

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

This reaction was used by Reines and Cowan in 1956 in first direct detection of the neutrino.
Neutrinos are produced:

1) In some nuclear reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Products</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1H + p$</td>
<td>$^2H + e^+ + \nu_e$</td>
<td></td>
</tr>
<tr>
<td>$^2H + p$</td>
<td>$^3He + \gamma$</td>
<td></td>
</tr>
<tr>
<td>$^3He + ^3He$</td>
<td>$^4He + 2p$</td>
<td>85%</td>
</tr>
<tr>
<td>$^3He + ^4He$</td>
<td>$^7Be + \gamma$</td>
<td>15%</td>
</tr>
<tr>
<td>$e^- + ^7Be$</td>
<td>$^7Li + \nu_e$</td>
<td></td>
</tr>
<tr>
<td>$^7Li + p$</td>
<td>$^8He$</td>
<td></td>
</tr>
<tr>
<td>$p + ^7Be$</td>
<td>$^8B + \gamma$</td>
<td>0.02%</td>
</tr>
<tr>
<td>$^8B$</td>
<td>$^8Be^* + e^+ + \nu_e$</td>
<td></td>
</tr>
<tr>
<td>$^8Be^*$</td>
<td>$^{24}He$</td>
<td></td>
</tr>
</tbody>
</table>

(These occur in the Sun.)

This reaction is used in detection:

$$\nu_e + ^{37}Cl \rightarrow ^{37}Ar + e^+$$

2) In decays. Some examples:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$
Atmospheric Neutrinos

Primary Cosmic-ray interaction in the atmosphere.

Cascade of secondaries

Decay of secondaries

Neutrinos formed from decay of other particles

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$
• High energy particle accelerators can be used to produce beams of neutrinos. Used to study proton and nuclear structure, and other experiments.

• Supernova explosions produce bursts of neutrinos.

(SN 1987 neutrinos observed in Kamiokande (Japan) and IBM (US) detectors.)

• High energy neutrinos may be emitted from astrophysical systems such as compact binaries and AGN’s
Fundamental Questions:

Are the conservation laws absolute?

Do neutrinos have mass?*

Are neutrino and anti-neutrino distinct?

Can symmetry violations for leptons explain the matter-anti-matter asymmetry in the Universe?

*The contribution of a neutrino species to the current mass density of the Universe is

\[ \Omega_\nu h^2 = m_\nu / 92.5 \text{ eV/c}^2 \]
Neutrinos from the Sun

\[ 4p \rightarrow ^4He + 2e^+ + 2\nu_e \]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \rightarrow ^2H + e^+ + \nu_e )</td>
<td></td>
</tr>
<tr>
<td>( ^2H + p \rightarrow ^3He + \gamma )</td>
<td></td>
</tr>
<tr>
<td>( ^3He + ^3He \rightarrow ^4He + 2p )</td>
<td>85%</td>
</tr>
<tr>
<td>( ^3He + ^4He \rightarrow ^7Be + \gamma )</td>
<td>15%</td>
</tr>
<tr>
<td>( e^- + ^7Be \rightarrow ^7Li + \nu_e )</td>
<td></td>
</tr>
<tr>
<td>( ^7Li + p \rightarrow ^2^4He )</td>
<td></td>
</tr>
<tr>
<td>( p + ^7Be \rightarrow ^8B + \gamma )</td>
<td>0.02%</td>
</tr>
<tr>
<td>( ^8B \rightarrow ^8Be^* + e^+ + \nu_e )</td>
<td></td>
</tr>
<tr>
<td>( ^8Be^* \rightarrow ^2^4He )</td>
<td></td>
</tr>
</tbody>
</table>

![Neutrino Energy Spectrum](image_url)

**Neutrino Energy (MeV)**

**Solar neutrino energy spectrum**
Standard Solar Model

John Bahcall et al.

Starting with age and the set of nuclear reactions, the model predicts:

• temperature profile
• density profile
• total power

Agrees with measurements of:

• power and surface temperature
• speed of sound as determined by helioseismology

Predicts about twice as many neutrinos as experiments observe.
Early Experiments

- Homestake Mine, South Dakota. R. Davis et al. First to detect solar neutrinos, and their deficit
- IMB Detector, Ohio. Observed SN 1987 neutrinos.
- Kamiokande, Japan. Observed SN 1987, solar neutrino deficit, atmospheric neutrinos.
Possible Reasons for the Deficit of solar neutrinos:

1. The solar model is wrong.
2. The experiments are wrong.
3. Electron neutrinos are changing to another flavor in leaving the sun and getting to the earth. -“neutrino oscillations”

Recent data provides evidence that Reason 3 is correct.

**SuperK**: Flux low; electron energy spectrum restricted the possible oscillation “parameters”.

**SNO**: Separately measured fluxes of electron neutrinos and of all neutrinos. Flux of all neutrinos agrees with solar model predictions for electron neutrinos.
Kamland: Measured anti-neutrinos from several nearby (130km) nuclear reactors.

Found flux deficit as predicted by oscillation parameters allowed by SuperK.
Challenges in ν Detection

• The earth receives about 40 billion neutrinos per second per cm$^2$ from the sun.

• If 100 billion solar ν’s hit the earth, all but \(~1\) will come out the other side without hitting anything!
  – To shield us from just 2/3 of the ν’s would take steel a light year thick.
Detection of Neutrinos

Principle: Neutrino energy transferred to some other particle in an interaction.

Because the interaction probability is so low, experiments need a large flux of neutrinos and a large detector.

Solar Neutrino Detection

1) Specific nuclear reactions, such as:

\[ \nu_e + ^{37}Cl \rightarrow ^{37}Ar + e^+ \]

(Used by Ray Davis in first solar neutrino expt.)

2) Scattering by electrons (SuperK, SNO):

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

\[ \nu_\mu + e \rightarrow \nu_\mu + e \] \hspace{1cm} (1/6)
3. Deuterium Interactions (SNO):

\[ \nu_e + d \rightarrow p + p + e^- \quad \nu_e \text{ only} \]

\[ \nu_{\text{any}} + d \rightarrow p + n + \nu_{\text{any}} \]

Other Neutrino Experiments

- Accelerator-produced neutrino beams. “Long-baseline “ (100’s of km) experiments. One (K2K) taking data, others under construction

- Detectors of very high energy neutrinos from astrophysical sources.
Super-Kamiokande

Super-Kamiokande is a 50,000 ton water detector at a depth of 1600 meters in the Kamioka Mozumi mine in Japan.

This followed the pioneering work of M. Koshiba et al. at the Kamiokande detector in the same mine.

Designed to detect solar, atmospheric, and supernova neutrinos, and proton decay.
Super-K Site in Japan

Mozumi
The Super-K Detector

Detector Characteristics

41 m h x 39 m dia.
50,000 ton (22,000 ton fiducial)
11,200 20” PMTs inner detector
1,850 8” PMTs anti-detector
40% photo-cathode coverage

Designed to detect solar, atmospheric and super-nova v’s
Photomultiplier tube:
Sensitive to very small light pulses

Can detect, with about 30% efficiency, a single photon.
When a boat moves faster than the speed of the surface waves, a wake is created.

Similarly, when a charged particle moves through a transparent medium with speed $> nc$, a shock wave is created. The shock wave is Cerenkov radiation.
Cerenkov Event Reconstruction

- Pattern of Hits
  - Where the event occurred
  - ID of particle (e or $\mu$)
- Amount of Light
  - Energy of particle
Low Energy Electron
Solar Neutrinos

Signal = 18,464 ± 204 (stat) ±646 (syst)

\[
\frac{Data}{SSM} = 0.451 \pm 0.005 (\text{stat}) \pm 0.016 (\text{syst})
\]
Add two waves of different frequency

Get beats of frequency \( f_{\text{beat}} = f_2 - f_1 \)
Frequency is related to energy:

\[ E = hf \]

h is Planck’s constant.

If a quantum mechanical state is a superposition of two states with different energies, quantum beats occur, with beat frequency

\[ f_{\text{beat}} = \frac{(E_2 - E_1)}{h} \]

**Example:**

Excite Helium atoms to states with Several energy components.

Look at photon emission vs distance.
Berry et al., 1971:

FIG. 1. Intensity profile of the 1s^3p^43p^- 1s^23s^- transition. The beam energy is 200 keV. The foil is located at the half-intensity point on the foil-screen side. The circles and the triangles are the measurements in light polarized parallel and perpendicular to the beam, respectively. The residual longitudinal polarization is 0.1 ± 0.1%.
Example: 1-dimensional box with a particle. Probability distributions for lowest two energy states separately.
Now combine the two states:

Oscillation frequency is proportional to

$$E_2 - E$$
Neutrino Flavor Oscillations

$\nu_1$, $\nu_2$, $\nu_3$ have definite masses

And, for example,

$$\nu_e = \cos(\theta) \nu_1 + \sin(\theta) \nu_2$$

$\theta$ gives the strength of mixing.
The beat frequency is proportional to

\[ m_2^2 - m_1^2 = \Delta m^2 \]

So the oscillation is characterized by the coupling strength and \( \Delta m^2 \).

An electron neutrino produced in the Sun, can “oscillate” into a neutrino of another type on its way to the Earth.

A detector of electron neutrinos will find less than expected.
Why $\Delta m^2$?

Special relativity:

$$E = \sqrt{p^2 + m^2} \quad \text{(c=1)}$$

$$= p \sqrt{1 + m^2 / p^2}$$

$$\approx p(1 + m^2 / 2p^2) \quad \text{(Taylor exp)}$$

$$E_2 - E_1 \approx (m_2^2 - m_1^2) / 2p$$
Complications:

- Traversal of matter, in the Sun or Earth provides extra stimulation of the oscillations.

  (Mikelaev, Smirnov, Wolfenstein)

- Oscillations occur among 3 neutrinos.
  (But the couplings are generally unequal, and 2-neutrino oscillations are a good approximation.

- 4 neutrinos?
Probability that a neutrino at the earth is an electron neutrino

Spectral distortion (at highest energy)

Night /Day enhancement

Night /Day enhancement

Spectral distortion

MSW

Vacuum

Seasonal variation (at highest energy)

Spectral distortion (at highest energy)
Finding Oscillation Parameters from the data:

1. Pick values of “beat frequency” and coupling strength.

2. Predict the experimental results on zenith angle and energy distributions with these values.

3. Compare data with predictions. If they disagree, the values are excluded.

12. Make a “map” of allowed values.
Oscillation parameters determined from energy spectrum and day-night difference

Blue and green regions are allowed.
SuperK found strong evidence for neutrino oscillations in atmospheric neutrinos.

There is also evidence that this oscillation is from $\nu_\mu \rightarrow \nu_\tau$. 
Sudbury Neutrino Observatory (SNO)

Uses D2O instead of water.
About 1/50 SuperK size, but detection rate about the same.
SNO Results

1. Flux from $\nu_e$-only reaction is less by appropriate amount than SuperK flux for $\nu_e + (1/6)\nu_\mu$

1. Flux of all-flavor neutrinos agrees with solar model calculations.
Kamland Detector

Also in Mozumi mine. At site of original Kamiokande experiment.

Detector is **liquid scintillator**, in which a moving charged particle produces a light flash.

Radioactivity background a serious Problem which was overcome.
Kamland detected reactor-produced anti-neutrinos. Average distance 130 km.

\[
\bar{\nu}_e + p \rightarrow n + e^+
\]

The \( e^+ \) annihilation was detected, and, after some delay, the \( \gamma \) from the reaction

\[
n + p \rightarrow \gamma + d
\]

produced an electron-positron pair.
Kamland oscillation parameters

Agrees with one of the SuperK-allowed parameters!
Oscillation parameters determined from energy spectrum and day-night difference

Blue and green regions are allowed.
Conclusions

1. The standard solar model is basically correct.

2. Neutrino oscillations exist.

3. Neutrinos have mass.

Current and planned accelerator experiments will address interesting and complex questions about coupling strengths, and make more precise mass measurements.

More data from solar and atmospheric Experiments will further confirm and extend the current results.