DISCOVERY OF NEUTRINO OSCILLATIONS

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KAMIOKANDE

- Kamioka Nucleon Decay Experiment
  - 3000 tons of water
  - 1000 50cm PMTs
  - 1000m underground
- Built in 1983 to detect proton decay, no evidence after 3 years
- Suspected that software was not good enough
- New software was tested on single Cherenkov-ring events
- Unexpected result
  - Much fewer \( \nu_\mu \) than expected

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COSMIC RAY DECAY

- Cosmic Ray enters the atmosphere
- Produces a $\pi \rightarrow \mu + \nu_\mu$
- $\mu \rightarrow e + \nu_e + \nu_\mu$
- Should expect $\sim 2\, \nu_\mu$ per $\nu_e$ for atmospheric neutrinos

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RESULTS OF KAMIOKANDE

- Monte Carlo simulation 21.8 kiloton*year
- Data from 2.86 kiloton*year exposure
- Not at 2:1 ratio due to detection efficiency of μ detection
- $\nu_e$ ratio 1.05±0.11
- $\nu_\mu$ ratio 0.59±0.07

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ events</td>
<td>93</td>
<td>88.5</td>
</tr>
<tr>
<td>$\nu_\mu$ events</td>
<td>85</td>
<td>144.0</td>
</tr>
</tbody>
</table>

WHY DOES NEUTRINO OSCILLATION IMPLY MASS

From the time-dependent Schrödinger equation:

\[
\begin{pmatrix}
\nu_1(\vec{x},t) \\
\nu_2(\vec{x},t)
\end{pmatrix}
= e^{i\vec{p} \cdot \vec{x}}
\begin{cases}
e^{-iE_1t} & \nu_1(0) \\
e^{-iE_2t} & \nu_2(0)
\end{cases}
\]

\[
= e^{i\vec{p} \cdot \vec{x}}
\begin{pmatrix}
e^{-iE_1t} & 0 \\
0 & e^{-iE_2t}
\end{pmatrix}
\begin{pmatrix}
\nu_1(0) \\
\nu_2(0)
\end{pmatrix}
\]

Using the relation between mass and flavor eigenstates:

\[
\begin{pmatrix}
\nu_\mu(\vec{x},t) \\
\nu_\tau(\vec{x},t)
\end{pmatrix}
= e^{i\vec{p} \cdot \vec{x}}
\begin{pmatrix}
\cos\theta & \sin\theta \\
-sin\theta & \cos\theta
\end{pmatrix}
\begin{pmatrix}
e^{-iE_1t} & 0 \\
0 & e^{-iE_2t}
\end{pmatrix}
\begin{pmatrix}
\cos\theta & -\sin\theta \\
\sin\theta & \cos\theta
\end{pmatrix}
\begin{pmatrix}
\nu_\mu(0) \\
\nu_\tau(0)
\end{pmatrix}
\]

If \( |\nu_\mu(0)\rangle = 1 \) and \( |\nu_\tau(0)\rangle = 0 \):

\[
|\nu_\tau(\vec{x},t)\rangle^2 = \sin^2(2\theta)\sin^2\left(\frac{E_2 - E_1)t}{2}\right) = P(\nu_\mu \rightarrow \nu_\tau)
\]
WHY DOES NEUTRINO OSCILLATION IMPLY MASS

If $E_1, E_2 \gg m_1, m_2$:

$$E_2 - E_1 = \sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2} \approx \frac{m_2^2 - m_1^2}{2p}$$

and

$$t \approx |\mathbf{x}| = L,$$
$$p \approx E$$

Therefore:

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- So, the probability of a neutrino oscillating is a function of: $\theta$, $L$, $E$, and $\Delta m$
- If $\Delta m = 0$ neutrinos will have a zero probability to oscillate
**NEUTRINO OSCILLATION CONDITIONS**

- In the case of $\nu_\mu \rightarrow \nu_\tau$ oscillation
  - Blue curve represents probability to remain $\nu_\mu$
  - Red curve represents probability to become $\nu_\tau$
- At short distances $L$, neutrinos will have a very low probability to oscillate

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NEUTRINO OSCILLATION CONDITIONS

- Should observe a deficit in $\nu_\mu$ that pass through the earth
  - Upward going $\nu_\mu$
- Want to create conditions to observe oscillations
- Kamiokande was not enough to be conclusive
- Need a much larger detector
SUPER-KAMIOKANDE

- 3000 -> 50,000 ton water Cherenkov Detector
- 1000 -> 13,000 PMT
- 1000m underground
POSSIBLE NEUTRINO EVENTS

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POSSIBLE NEUTRINO EVENTS

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RESULTS

- $\cos\theta = 1$ down-going neutrino
- Shaded boxes are predictions
- Crosses are observations
- All things considered 6.2$\sigma$
  - ~1 in 1.8 billion

MORE DATA

- 1998 data contains 531 events
- 2015 data contains 5485 events
- Heaviest neutrino ~10,000,000 times smaller than electron
- $\nu_\mu$ oscillate maximally to $\nu_\tau$

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GAUSSIAN DISTRIBUTION

<table>
<thead>
<tr>
<th>$\mu \pm N\sigma$</th>
<th>% within range</th>
<th>Daily Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.26894921%</td>
<td>Twice a week</td>
</tr>
<tr>
<td>2</td>
<td>95.44997361%</td>
<td>Every three weeks</td>
</tr>
<tr>
<td>3</td>
<td>99.73002039%</td>
<td>Yearly</td>
</tr>
<tr>
<td>4</td>
<td>99.99366575%</td>
<td>Every 43 years</td>
</tr>
<tr>
<td>5</td>
<td>99.99994267%</td>
<td>Every 4776 years</td>
</tr>
<tr>
<td>6</td>
<td>99.99999980%</td>
<td>Every 1.38 M years</td>
</tr>
</tbody>
</table>

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WHAT NEXT

- Even bigger detector, Hyper-Kamiokande
  - To start taking data in second half of 2020’s
  - 50,000 -> 260,000 tons of water
  - 11,000 -> 40,000 PMT
- Goals are to
  - Order neutrino masses
  - CP violation measurement
  - Proton decay

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ACKNOWLEDGEMENTS


THREE NEUTRINO OSCILLATIONS

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