Neutrino Mass Measurements from Oscillation Experiments

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The Future of Neutrino Mass Measurements
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Neutrino Oscillation Experiments measure flavor oscillations.
Homestake Experiment was First…

Davis experiment in Homestake mine

Estimated rate: 10 atoms per week!

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

615 ton $C_2\text{Cl}_4$ (bleaching solution)

1 SNU = 1 interaction/$10^{36}$ target atoms/sec
Result considered a Failure

• **1968: Davis's initial results**
The much-touted experiment appears a failure. Davis announces that he has detected only about one third as many radioactive argon atoms as Bahcall predicted. Scientists call the discrepancy "The Solar Neutrino Problem." The press calls it "The Mystery of the Missing Neutrinos."

**Decades of Doubt**
In the two decades following their disappointing results, Davis fine-tunes his solar neutrino detector, and Bahcall refines and checks his calculations. Hundreds of other physicists, chemists, and astronomers also examine Bahcall and Davis's work. No one can find significant fault with either the apparatus or the calculations.

**1969: A possible explanation**
Physicists Vladimir Gribov and Bruno Pontecorvo, working in the Soviet Union, suggest that Davis and Bahcall's missing neutrinos can be explained by "neutrino oscillations"
Proton Decay Experiments (save the day)

1985: More missing particles
In an experiment called Kamiokande, sited in the Kamioka Mozumi mine in Japan, Masatoshi Koshiba and colleagues detect far fewer atmospheric neutrinos than they expect to see. While atmospheric neutrinos are a different type from those produced by the sun, the so-called "atmospheric neutrino anomaly" is similar to the solar neutrino problem. Where are the missing neutrinos?

One of 3 detectors to observe neutrinos from SN1987a
The Super-Kamiokande Collaboration
MEDIA ADVISORY FOR JUNE 5, 1998
EVIDENCE FOR MASSIVE NEUTRINOS

We announce today at "Neutrino '98", the international physics conference underway in Takayama, Japan, that the Super-Kamiokande Experiment has found evidence for non-zero neutrino mass.

“Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.”
Neutrino Mixing

- If neutrinos have mass, it is possible that the weak eigenstates are not the same as the mass eigenstates:

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\(\Delta m^2_{12}, \Delta m^2_{23}\)
More On Neutrino Mixing

• Parametrize the mixing matrix as:

\[
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\]

solar $\nu$  reactor $\nu$  atmospheric $\nu$

• For reactor experiments, the probability of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ is:

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E}\right)
\]

where $\Delta m^2_{ij} = |m_i^2 - m_j^2|$
How Does It Work?

\[ P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]

\[ \Delta m_{31}^2 = 3 \times 10^{-3} \text{eV}^2 \]

\[ \Delta m_{31}^2 = 1 \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 2\theta_{13} = 1 \]

\[ \sin^2 2\theta_{13} = 0.2 \]
Initial results do not provide strong bounds…
but we know that the mass differences are small.
At this point, most experiments consisted of a single detector and did not control their neutrino source.
But a new generation of oscillation experiments changed everything.

Begin the era of precision oscillation experiments

KamLAND
Accelerator Experiments

- Two magnetic focusing horns
- Moveable target relative to horn 1 (variable neutrino spectrum)
- Long decay region followed by absorbers
- ~95% $\nu_\mu$, ~4% $\bar{\nu}_\mu$, ~1.3% $\nu_e$
MINOS OVERVIEW

- Main Injector Neutrino Oscillation Search
- Accelerator-based long-baseline neutrino experiment
- Precision experiment at the atmospheric $\Delta m^2$
- One $\nu_\mu$ beam: NuMI
  - 120 GeV protons from Fermilab Main Injector
- Two detectors
  - Near Detector: measure beam composition and spectrum
  - Far Detector: search for evidence of oscillations
Identical Detectors

**NEAR DETECTOR**
- 1 km from target
- 1 kton
- 282 steel planes
- 153 scintillator planes

**FAR DETECTOR**
- 735 km from target
- 5.4 kton
- 484 steel/scintillator planes
- GPS time-stamping to synchronise FD data to beam

Steel/scintillator tracking calorimeters
- Functionally identical
- Magnetised to 1.2 T
Statistics

- Very large event rates in the Near Detector (~$10^7$ events in the fiducial volume for $10^{20}$ POT)

→ High-statistics dataset:
  - Understand performance of Near Detector
  - Check level of agreement between data and Monte Carlo

Distribution of reconstructed event vertices in the x-y plane

Reconstructed track angle with respect to vertical

Beam points down 3 degrees to reach Soudan

Chi2/NDF = 44.77/39
νμ Disappearance - Energy Spectrum

This plot compares the 848 events in MINOS Far Detector (black points) to the expected neutrino energy distribution (1065 ± 60 events) in the absence of neutrino disappearance (red histogram). While most of the events are expected to be charged-current neutrino interactions, 5.9 neutral current (NC) background events are expected (shaded histogram barely visible in bottom corner), as well as 1.5 nu-tau interactions, 2.3 events from upstream neutrino interactions in the rock, and 0.7 cosmic ray events.

The data showing a clear deficit relative to the expected rate, we fit these data for the hypothesis of two-flavor oscillations, and the black histogram shows the expected spectrum corresponding to $\Delta m^2 = (2.43 \pm 0.11) \times 10^{-3}$ and $\sin^2(2\Theta) = 1.00 \pm 0.05$ which gives the best fit to the data, with a $\chi^2$/dof=90/97.
Neutrino Oscillation Data Summary

Neutrino Mixing: PMNS Matrix

\[
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\]

Solar
KamLAND
\(\theta_{12} \sim 30^\circ\)

Reactor
Accelerator
\(\theta_{13} < 12^\circ\)

Atmospheric,
K2K, MINOS, T2K, etc.
\(\theta_{23} \sim 45^\circ\)

\[
\sin^2(2\theta_{23}) > 0.92
\]

\[
\Delta m_{32}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2
\]

\[
\sin^2(2\theta_{12}) = 0.87 \pm 0.03
\]

\[
\Delta m_{21}^2 = (7.59 \pm 0.20) \times 10^{-5} \text{ eV}^2
\]

\[
\sin^2(2\theta_{13}) < 0.19\ , \quad \text{CL}=90\%
\]

Unknown: \(\sin^2 2\theta_{13}, \ \delta_{CP}, \ \text{Sign of } \Delta m_{32}^2\)
Mass Hierarchy

\[ \Delta m_{21}^2 = (7.59 \pm 0.20) \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{32}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{ij} = |m_i^2 - m_j^2| \]
Intensity Frontier

The Intensity Frontier, accessed with a combination of intense particle beams and highly sensitive detectors offers the possibility of resolving the hierarchy issue.
Thank You