Super-Kamiokande Physics II: Long Baseline Beams
Neutrino Oscillations

Assume

**FLAVOR STATES**

\[
| \nu_f >
\]

are superpositions of

**MASS STATES**

\[
| \nu_m >
\]

weakly interacting

\[
| \nu_f > = \sum_{i=1}^{N} U_{fi} | \nu_i >
\]

unitary mixing matrix

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate
Simple two-flavor case

\[ |\nu_f> = \cos \theta |\nu_1> + \sin \theta |\nu_2> \]
\[ |\nu_g> = -\sin \theta |\nu_1> + \cos \theta |\nu_2> \]

Propagate a distance \( L \):

\[ |\nu_i(t)> = e^{-iE_i t} |\nu_i(0)> \sim e^{-im_i^2 L/2p} |\nu_i(0)> \]

Probability of detecting flavor \( g \) at \( L \):

\[
P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right)
\]

Parameters of nature to measure: \( \theta, \Delta m^2 = m_1^2 - m_2^2 \)
The Experimental Game

- Start with some neutrinos (natural or artificial)
- Measure (or calculate) flavor composition and energy spectrum
- Let them propagate
- Measure flavor and energies again

Have the flavors and energies changed?
If so, does the change follow
\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

Disappearance: \( \nu \)'s oscillate into 'invisible' flavor
- e.g. \( \nu_e \rightarrow \nu_\mu \) at \( \sim \text{MeV} \) energies

Appearance: directly see new flavor
- e.g. \( \nu_\mu \rightarrow \nu_\tau \) at \( \sim \text{GeV} \) energies
Oscillation Parameter Space

Twiddle L/E

Frequency $\propto \Delta m^2 L/E$

Amplitude $\propto \sin^2 2\theta$

Experimental statistics

$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2(\frac{1.27 \Delta m^2 L}{E})$
Zenith angle distribution

1489 days of SK data (SKI)

FC

FC+PC

Deficit of $\nu_\mu$

from below

(long pathlength)

e-like

$\mu$-like

up-going

down-going
Next: INDEPENDENT TEST of atmospheric neutrino oscillations using a well-understood $\nu$ beam

$E_\nu \sim \text{GeV, } L \sim 100\text{'s of km for same } L/E$

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right)$$

LONG BASELINE EXPERIMENTS

Compare flux, flavor and energy spectrum at near and far detectors
K2K (KEK to Kamioka) Long Baseline Experiment

~ 1 GeV muon neutrinos

12 GeV protons on Al target
+ $\pi$ focusing horn
+ decay pipe for pions
Events matched w/GPS
The Neutrino Beamline at KEK
The Near Detector (300 m away)

Characterize the $\nu$ beam for extrapolation to SK
Suppression observed, spectral distortion consistent with oscillations

Results from K2K

Total 107 beam events observed; expect 149.7

Single-ring \( \mu \)-like events

\[ \Delta m^2 = 2.8 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\Theta) = 1.0 \]
K2K Allowed Oscillation Parameters

Best Fit Results:
\[ \Delta m^2 = 2.8 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\theta) = 1.0 \]
(constrained to physical region)

Consistent with SK atmospheric
Future Long Baseline Experiments

start 2005-6, 730 km distance

MINOS: Fermilab to Soudan

CNGS: CERN to Gran Sasso
NuMI Beamline at Fermilab

MINOS Detector at the Soudan mine

iron plates + scintillating fibers w/ magnetic field
CNGS
CERN Neutrinos to Gran Sasso

Look for $\tau$ neutrinos explicitly

Decay “kink”

$\nu_\tau$
ICARUS Liquid Argon Time Projection Chamber

"Digital Bubble Chamber"
OPERA

lead/emulsion sandwich + scintillator planes

Extract bricks for scanning if electronic detector indicates τ-like event
T2K: "Tokai to Kamioka"

Existing detector: Super-K
295 km, about 30 times K2K flux
2.5 deg. off axis
T2K ("Tokai to Kamioka") 2° off-axis

Near
+ 2 km
detectors,

Super-K
refurbished
by 2006

Start 2009

Beam
neutrino
ergy
tuned to
oscillation
minimum
J-PARC beamline under construction now
T2K Detectors

1. Near detector at 280 m: fine-grained tracker

2. Intermediate detector at 2 km
   Water Cherenkov + fine-grain tracker (LAr) + muon ranger
   Beam spectrum looks more like beam at SK
   \(\Rightarrow\) cancel systematics

3. Super-K III at 295 km, fully refurbished
Summary

Atmospheric muon neutrinos are changing flavor ('disappearing') as they travel through the Earth:

This measurement in SK was the first clear indication of neutrino mass and oscillation

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

This oscillation disappearance has now been confirmed with a long-baseline beam of neutrinos: K2K results are consistent

Next generation: MINOS, CNGS, T2K