Introduction to Neutrino Physics

Elisabeth Falk
University of Sussex and Lund University

Lecture 2
Neutrino oscillations Part II
Recap lecture 1

• Neutrinos oscillate between different flavours because they have non-zero mass AND their mass eigenstates are different from their flavour eigenstates

• Derivation of two-flavour mixing:

\[
P_{\nu_{\alpha}\rightarrow\nu_{\beta}}(L) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
\]

• The study of neutrinos from the sun showed an apparent deficit of neutrinos – we know now that it is due to oscillations
Outline lecture 2

- Solar neutrinos (continued from yesterday)
- Atmospheric and long-baseline neutrinos
- $\theta_{13}$ and CP violation
Solar neutrinos and the solar neutrino problem

Neutrino energy $O(1 \text{ MeV})$

Solved in 2002 by SNO
SNO

- Sudbury Neutrino Observatory in Creighton nickel mine, Canada
- Tank of 1 kton of heavy water
- 2002: Explained where the missing electron neutrinos have gone
Signals in SNO

- Direct relation with $\nu_\tau$, energy spectrum
- Weak directional sens.
- Only sensitive to $\nu_e$

Equal sens. to all $\nu$

- Rel. small cross sect.
- Mainly sensitive to $\nu_\beta$
- Strong directional sens.

Different w.r.t. earlier experiments: Can measure total $\nu$ flux as well as $\nu_e$
SNO results

Flux of $\nu_{\mu\tau}$ vs flux of $\nu_e$
KamLAND

Study solar neutrino mixing parameters with reactor antineutrinos
Assumes that anti-$\nu_e$ oscillates in the same way as $\nu_e$: CPT conservation

Kamioka mine in Japan
Multiple reactors with a baseline of ~180 km
KamLAND

Liquid scintillator

Inverse beta decay on protons

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

Delayed co-incidence:

- $e^+$: prompt annihilation
- $n$: delayed capture release of 2.2 MeV $\gamma$
KamLAND result

Anti-$\nu_e$ survival probability

26 reactors from distance range 140-210 km (80% of flux)

KamLAND compared to solar results
Current knowledge

\[
U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos\theta_{23} & \sin\theta_{23} \\
0 & -\sin\theta_{23} & \cos\theta_{23}
\end{pmatrix}
\times \begin{pmatrix}
\cos\theta_{13} & 0 & \frac{e^{-i\delta_{CP}}}{\sin\theta_{13}} \\
0 & 1 & 0 \\
-\frac{e^{-i\delta_{CP}}}{\sin\theta_{13}} & 0 & \cos\theta_{13}
\end{pmatrix}
\times \begin{pmatrix}
\cos\theta_{12} & \sin\theta_{12} & 0 \\
-\sin\theta_{12} & \cos\theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\times U^{\text{diag}}_{\text{Maj}}
\]

Well measured:

\[\theta_{23} = (45 \pm 7)^{\circ}\]
\[\rightarrow \text{~equal mixing of } \nu_{\mu} \text{ and } \nu_{\tau}\]
\[\Delta m_{32}^{2} \approx \]
\[\Delta m_{\text{atm}}^{2} = 2.4 \times 10^{-3} \text{ eV}^{2}\]

Until this summer ~unknown:

\[\theta_{13} < \sim 10^{\circ}\]
\[\text{Now } \sim 3\sigma \text{ indications that } \theta_{13} < 10^{\circ}\]
\[|\Delta m_{31}^{2}| \approx \Delta m_{32}^{2}\]
\[\text{but } \Delta m_{31}^{2} > 0 \text{ or } < 0\]
\[\text{(normal or inverted hierarchy)?}\]

Well measured:

\[\theta_{12} = (34 \pm 3)^{\circ}\]
\[\rightarrow \nu_{1} \text{ is predominantly } \nu_{e}\]
\[\Delta m_{21}^{2} = 7.6 \times 10^{-5} \text{ eV}\]
\[\nu_{2} > \nu_{1} \text{ (sign of } \Delta m_{21}^{2}\text{)}\]
\[\text{from matter effects in sun}\]
Atmospheric neutrinos

• Cosmic-ray protons strike the upper atmosphere of the Earth

• End of cascade: two $\nu_\mu$ for ever $\nu_e$

• Typical energy $O(\text{GeV})$
Super-Kamiokande

- Water Cherenkov detector located in the Kamioka mine in Japan
- **1998: First evidence for neutrino flavour change**
- Preceded by “atmospheric neutrino anomaly”

![Muon Showering electron image]

Tank of 50 ktons of ultra-pure water surrounded by photo detectors
Super-Kamiokande results

Observed:
Depletion of muon-neutrino events, but not of electron-neutrino events

Later: sinusoidal survival probability as fnc of L/E
How to make a neutrino beam

- Protons strike target
- Pulsed beam (~ few ms)
- Magnetic horns focus secondary $\pi/K$
  - Decay of $\pi/K$ produces neutrinos
  - Neutrino spectrum changes with target position
Two-detector disappearance measurements

- Two-detector experiment to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated $\nu_\mu$ spectrum at Near Detector
    - Extrapolate using MC
  - Compare to measured spectrum at Far Detector

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(1.267 \Delta m^2 L / E \right) \]
MINOS

- Tracking calorimeters: alternating layers of steel and scintillator
- Magnetic field measures charge of muons
- Data-taking since 2005
- Most precise measurement of $\Delta m^2_{\text{atm}}$
- $\rightarrow$ MINOS+ next year (in higher-E NOvA beam)
Event topologies

\[ \nu_\mu \text{ CC Event} \]

\[ \nu_e \text{ CC Event} \]

\[ \text{NC Event} \]

Monte Carlo

long $\mu$ track & hadronic activity
at vertex

short event, often diffuse

short, with typical EM shower profile
MINOS $\nu_\mu$ disappearance result

$\Delta m^2 = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV$^2$ and 
$\sin^2(2\Theta) = 1.00$ ($\sin^2(2\Theta) > 0.90$ at 90% CL)

Will be overtaken by T2K, 
who already have comparable precision on $\Delta m^2$
MINOS anti-ν_µ disappearance: CPT test

- Reverse current through magnetic beam focusing horns to focus negatively charged particles → anti-ν_µ beam!

- \( \overline{\nu}_\mu \rightarrow \overline{\nu}_\mu \leftrightarrow \nu_\mu \rightarrow \nu_\mu \)

\[ 1.71 \times 10^{20} \text{ POT MINOS } \nu_e \text{ running, Far Detector} \]

\[ |\Delta m^2| = 2.32 \times 10^{-3} \text{ eV}^2, \sin^2(2\theta) = 1 \]

\[ \text{Best } \nu_e \text{ Fit} \]

\[ 1.71 \times 10^{20} \text{ POT} \]

\[ 7.24 \times 10^{20} \text{ POT} \]
Current knowledge

\[ U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i \delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{-i \delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U_{\text{Maj}}^{\text{diag}} \]

Well measured:

\[ \theta_{23} = (45 \pm 7)^\circ \]
\[ \Rightarrow \sim \text{equal mixing of } \nu_\mu \text{ and } \nu_\tau \]
\[ \Delta m^2_{32} \approx \Delta m^2_{\text{atm}} = 2.4 \times 10^{-3} \text{ eV}^2 \]

Until this summer \( \sim \) unknown:

\[ \theta_{13} \sim 10^\circ \]
\[ \text{Now } \sim 3\sigma \text{ indications that } \theta_{13} < 10^\circ \]
\[ |\Delta m^2_{31}| \approx \Delta m^2_{32} \]
\[ \text{but } \Delta m^2_{31} > 0 \text{ or } < 0 \]
\[ \text{(normal or inverted hierarchy)?} \]

Well measured:

\[ \theta_{12} = (34 \pm 3)^\circ \]
\[ \Rightarrow \nu_1 \text{ is predominantly } \nu_e \]
\[ \Delta m^2_{21} = 7.6 \times 10^{-5} \text{ eV} \]
\[ \nu_2 > \nu_1 \text{ (sign of } \Delta m^2_{21}) \]
\[ \text{from matter effects in sun} \]
Interlude:
When does the two-flavour approximation work?

Two orders of magnitude difference:
\[ \Delta m_{\text{atm}}^2 \sim O(10^{-3} \text{ eV}^2) \quad \text{and} \quad \Delta m_{21}^2 \sim O(10^{-5} \text{ eV}^2) \]

At L/E\sim 100 \text{ km}:
\( \Delta m_{21}^2 \) oscillations fully developed
\( \Delta m_{\text{atm}}^2 \) oscillations “averaged out:”

At L/E\sim 1 \text{ km}:
\( \Delta m_{\text{atm}}^2 \) oscillations developed
\( \Delta m_{21}^2 \) not yet kicked in

Must use 3-flavour mixing for %-level precision

Example:
\( \nu_e \) from a reactor
Leptonic CP violation

• Remember:
  CP violation in quarks not sufficient to explain the matter/antimatter asymmetry of the universe

• Leptogenesis:
  A heavy, right-handed, CP-violating neutrino could have created the asymmetry just after the Big Bang

• $\delta_{CP}$ can only be non-zero if all three mixing angles are non-zero $\rightarrow$ grouped with $\theta_{13}$, as we know the other two are $> 0$
$\theta_{13}$: Long-baseline accelerator vs. reactor experiments

LBL accelerator experiments:
- Look for appearance ($\nu_\mu \to \nu_e$) in pure $\nu_\mu$ beam vs. $L$ and $E$
- Near detector to measure background $\nu_e$s (beam + mis-id)
- $P (\nu_\mu \to \nu_e) = f (\delta, \text{sign} (\Delta m_{31}^2))$

Reactor experiments:
- Look for disappearance ($\overline{\nu}_e \to \overline{\nu}_e$) as a fnc of $L$ and $E$
- Near detector to measure unoscillated flux
- $P (\overline{\nu}_e \to \overline{\nu}_e)$ independent of $\delta$; matter effects small

Combination of appearance and disappearance
very powerful if comparable sensitivity

MINOS, T2K, NOvA

Double Chooz, Daya Bay, RENO

29/11/11
T2K

- FD: Super-Kamiokande
  Water Cherenkov detector 22.5 kton fiducial mass
- ND280: TPC + plastic scintillator
  Flux and cross-sections
- INGRID:
  beam intensity/direction
Off-axis beam reduces high-energy tail:
- Narrow-band beam around oscillation maximum
- Reduces feed-down from mis-reconstructed higher-E events
T2K $\nu_e$ appearance analysis

- **Basic idea**
  - Apply selection criteria to Super-K data to isolate $\nu_e$-CCQE events
  - Compare with expected number of background events $\rightarrow$ measure appearance probability

- **Backgrounds**
  - **Intrinsic $\nu_e$ contamination** from $\mu$, $K$ decays in decay pipe
  - **NC-$\pi^0$** interactions of $\nu_\mu$ (missed or merged gamma-rays $\rightarrow$ single e-like ring detected)
T2K first result (Jun 2011)

~ 1 year’s worth of data
6 candidate $\nu_e$ events
Expected BG of 1.5+/−0.3 events for $\sin^2 2\theta_{13} = 0$
P-value of 0.7 % for null hypothesis

2.5σ indication for $\theta_{13} > 0$

MINOS result from summer 2011:
Excludes for $\sin^2 2\theta_{13} = 0$ at 89% CL
Prefers smaller $\theta_{13}$ : $\sin^2 2\theta_{13} = 0.04(0.08)$ NH(IH)
NO\(\nu\)A

- Expected start in 2013
- Also sensitive to mass hierarchy: can make use of MSW effect over 810 km baseline
- Forward scattering of (anti) neutrinos in matter differ because of the extra diagram for scattering off electrons
- Oscillation probabilities: \(P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\)
- Normal hierarchy: \(P(\nu_\mu \rightarrow \nu_e) > P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\); inverted hierarchy: the other way around
Recap and outlook

- Neutrino mixing parameters ($\theta, \Delta m^2$) for “solar” and “atmospheric” neutrino sectors have been well measured

- We are seeing the first results from experiments that will tell us about the subdominant $\theta_{13}$

- $\theta_{13}$ must be $> 0$ for $\delta$ to exist
  - But there is another possibility for leptonic CP violation if neutrinos are Majorana particles

- $\sin^2 2\theta_{13}$ must be $> \sim 0.01$ to be experimentally accessible
  - This would open up an avenue for leptonic CPv

- $\theta_{13}$ with reactors first in Lecture 3

- Then on to Majorana neutrinos and neutrinoless double beta decay
Back-ups