Recent KamLAND Results: 3-neutrino fits

Glenn Horton-Smith

October 6, 2010

Note! This is the seminar that was given October 6, 2010. Since then, there has been an update to the KamLAND paper to include the latest MINOS data, and the result is that the "hint" of non-zero θ_{13} is much smaller. With the combination of MINOS and KamLAND, there is no longer any "enhancement" in the lower end of the 90% limit. See the latest version of the paper: arXiv:1009.4771.

1 Introduction

- Theory: neutrino oscillation – first part of talk
- Experiment: KamLAND – second part of talk
- Results: arXiv:1009.4771v1 [hep-ex] – third part of talk
- Implications for Double Chooz and LBNE (and similar experiments) – last part of talk

2 Neutrino Oscillation Theory

2.1 Neutrino mixing matrix

The three flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ can be expressed as a linear combination of three mass eigenstates (ν_1, ν_2, ν_3):

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle \quad (\alpha = e, \mu, \tau).$$

Here U is a unitary matrix conventionally defined as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{1}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$.

Note: I think it should be purely a matter of convention whether the matrix is conjugated when going from flavor- to mass-eigenstatues or when going from mass- to flavor-eigenstates. I've used the convention in Kayser's 2008 mixing review in the *Review of Particle Physics.*

2.2 Three beat frequencies

Side note: the 2010 *Review of Particle Physics* has replaced the old neutrino mixing write-up by Kayser with a new one by Nakamura and Petcov.

- "The amplitude of the probability that neutrino $\nu_{l'}$ will be observed if neutrino ν_l was produced by the neutrino source can be written as..."

$$A(\nu_l \to \nu_{l'}) = \sum_j U_{l'j}\, D_j\, U^\dagger_{jl}, \qquad l, l' = e, \mu, \tau, \tag{13.8}$$

where $D_j = D_j(p_j; L, T)$ describes the propagation of ν_j between the source and the detector, $U^\dagger_{jl}$ and $U_{l'j}$ are the amplitudes to find ν_j in the initial and in the final flavour neutrino state, respectively. It follows from relativistic Quantum Mechanics considerations that [33,35]

$$D_j \equiv D_j(\tilde{p}_j; L, T) = e^{-i\tilde{p}_j\,(x_f - x_0)} = e^{-i(E_jT - p_jL)}, \qquad p_j \equiv |\mathbf{p}_j|, \tag{13.9}$$

where [38] x_0 and x_f are the space-time coordinates of the points of neutrino production and detection, $T = (t_f - t_0)$ and $L = \mathbf{k}(\mathbf{x}_f - \mathbf{x}_0)$, $\mathbf{k}$ being the unit vector in the direction of neutrino momentum, $\mathbf{p}_j = \mathbf{k}\mathrm{p_j}$. What is relevant for the calculation of the probability $P(\nu_l \to \nu_{l'}) = |A(\nu_l \to \nu_{l'})|^2$ is the interference factor $D_j D^*_k$ which depends on the phase

$$\delta\varphi_{jk} = (E_j - E_k)T - (p_j - p_k)L = (E_j - E_k)\left[T - \frac{E_j + E_k}{p_j + p_k}\,L\right] + \frac{m_j^2 - m_k^2}{p_j + p_k}\,L. \tag{13.10}$$

$$\delta\varphi_{jk} \cong \frac{m_j^2 - m_k^2}{2p}\,L$$

$$P(\nu_l \to \nu_{l'}) = \sum_j |U_{l'j}|^2\,|U_{lj}|^2 \;+2\sum_{j>k} |U_{l'j}\,U^*_{lj}\,U_{lk}\,U^*_{l'k}| \cos\left(\frac{\Delta m^2_{jk}}{2p}\,L - \phi_{l'l;jk}\right), \tag{13.13}$$

$$P(\bar\nu_l \to \bar\nu_{l'}) = \sum_j |U_{l'j}|^2\,|U_{lj}|^2 \;+2\sum_{j>k} |U_{l'j}\,U^*_{lj}\,U_{lk}\,U^*_{l'k}| \cos\left(\frac{\Delta m^2_{jk}}{2p}\,L + \phi_{l'l;jk}\right), \tag{13.14}$$

- Please notice the important fact that there are three different "beat frequencies" corresponding to the three differences in neutrino-mass-squared.
- There is also a phase offset in the oscillations given by

  $$\phi_{l'l;jk} = \arg\left(U_{l'j}\,U^*_{lj}\,U_{lk}\,U^*_{l'k}\right).$$

  It is non-zero if and only if $l' \neq l$ and both θ_{13} and δ are non-zero in the mixing matrix.

2.3 "Wash out" of high frequencies

- At large L, the oscillations as E varies are so rapid that the detector can't resolve them.
- In this limit, only the slowest oscillation can be seen.
- The lowest Δm^2 is Δm^2_{21}.
- For electron neutrino (or antineutrino) oscillations, we have

$$\nu_e = U^*_{e1}\nu_1 + U^*_{e2}\nu_{e2} + U^*_{e3}\nu_{e3}$$

and we get

$$P(\nu_e \to \nu_e) = P(\bar\nu_e \to \bar\nu_e) \cong |U_{e3}|^4 + \left(1 - |U_{e3}|^2\right)^2\; P^{2\nu}(\nu_e \to \nu_e)\,,$$

where $P^{2\nu}$ is the 2-neutrino oscillation formula, $P^{2\nu} = 1-\sin^2 2\theta_{12}\sin^2\Delta m^2_{12}L/(4p)$.

2.4 Matter effects

Electrons in matter affect the "index of refraction" of the neutrinos: their phase changes with distance differently due to interactions with the electrons.

$$\widetilde{P}_{ee}^{2\nu} = 1 - \sin^2 2\theta_{12M} \sin^2 \left(\frac{1.27 \Delta m_{21M}^2 L}{E} \right) , \qquad (4)$$

where L is the electron antineutrino ($\overline{\nu}_e$) flight distance in meters from the source to the detector, E is the $\overline{\nu}_e$ energy in MeV, and Δm_{21}^2 is in eV^2. θ_{12M} and Δm_{21M}^2 are the matter-modified mixing angle and mass splitting defined by

$$\sin^2 2\theta_{12M} = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} , \qquad (5)$$

$$\Delta m_{21M}^2 = \Delta m_{21}^2 \sqrt{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} . \qquad (6)$$

$A = -2\sqrt{2} G_F \widetilde{N}_e E$, and has a negative sign for antineutrinos; G_F is the Fermi constant. The matter effect modifies the expected reactor $\overline{\nu}_e$ event rate by up to 3%, depending on the oscillation parameters.

3 KamLAND experiment

(Refer to paper.)

3.1 Overall scheme

3.2 Expected events

3.3 Candidate selection

3.4 Efficiency model (Fig. 1 of paper)

3.5 Backgrounds

3.6 Fit to theory

4 Results

4.1 Best fit and confidence regions (Figs. 2-4)

4.2 Survival probability visualization and fit (Figs. 5-6)

4.3 Interpretation of θ_{13} confidence region.

5 Implications for future experiments

In general, the "hints" of non-zero θ_{13} is good news for these experiments:

- Upcoming reactor experiments: Double Chooz, Daya Bay, RENO.
- Upcoming accelerator experiments: T2K, NOνA, LBNE.

5.1 Reactor experiments: Double Chooz, Daya Bay, RENO

- Look for $\bar{\nu}_e$ disappearance over ~1 km baseline:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4p}.$$

- Note magnitude of disappearance $\propto \sin^2 2\theta_{13}$. (Not $\sin^2 \theta_{13}$.)
- Double Chooz ultimately sensitive (@90%) down to $\sin^2 2\theta_{13} = 0.03$; Daya Bay and RENO aim for 0.01.

Math for θ_{13}:

$$\begin{aligned} \sin^2 2\theta &= [2 \sin\theta \cos\theta]^2 \\ &= 4(\sin^2\theta)(1 - \sin^2\theta) \\ \sin^2\theta = 0.017^{+0.010}_{-0.009} &\Leftrightarrow \sin^2 2\theta = 0.067^{+0.038}_{-0.035} \end{aligned}$$

- Of course θ_{13} is what it is. But if you believe the error bars and interpret them as "odds", then 84% confident that $\sin^2 2\theta_{13} > 0.067 - 0.035 = 0.032$. This is encouraging.

5.2 Accelerator experiments

- T2K, NOvA, and LBNE look for both θ_{13} and δ. Can only see the later if the former is non-zero.
- Sensitivity....