ν_e Appearance

Backgrounds

- beam ν_e
- Neutral current events

ν running

- measure $\sin^2 2\theta_{13}$
  and δ_{CP}.
- resolve mass hierarchy for
  $\sin^2 2\theta_{13} > 0.01$
- with $\bar{\nu}$ running
  $\sin^2 2\theta_{13} > 0.003$ at 90% C.L.

If $\sin^2 2\theta_{13}$ too small δ_{CP} cannot be measured. (See Patrick's curves).

ν_μ Disappearance

Neutrino Running

- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

- 1% determination of Δm^2_{32}
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.

New Opportunities in Neutrino Physics

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March 5, 2006

Stonybrook University

Brief Review
Description of Oscillations
Recent Progress and Implications
What to Expect in 5 years
Ambitions !

Particle Chart

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \tag{1}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned} \tag{2}$$

Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, ...$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$,

$$E = 1GeV,\ L = 494km\ .$$

- The Standard Model has no ν_R field, only ν_L, and no neutrino mass. $L = L_e + L_\mu + L_\tau$ always conserved
- Because the currents destroy as many particles as they create.
- But presence of mass forces us to add ν_R to the fields.
- ν_R carries no Electroweak Isospin and therefore can be created and destroyed by itself ($m_M \bar{\nu}_R^c \nu_R$).
- Therefore the neutrino mass most likely implies non-conservation of L and neutrinos are most likely Majorana particles.

Oscillations in presence of matter

Propogation equation.

$$i\frac{d}{dx}\nu_f = HR_\theta\nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.

Additional potential for ν_e $(\bar{\nu}_e)$: $\pm\sqrt{2}G_F N_e$

N_e is electron number density.

Oscillations in presence of matter

$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i\frac{d}{dx}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{4E}\left(R_\theta \begin{pmatrix} m_2^2 - m_1^2 & 0 \\ 0 & m_1^2 - m_2^2 \end{pmatrix} R_\theta^T + 2E \begin{pmatrix} \sqrt{2}G_F N_e & 0 \\ 0 & -\sqrt{2}G_F N_e \end{pmatrix}\right)\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad (3)$$

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta} \times \sin^2 \frac{L\Delta m^2}{4E}\sqrt{(a - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6 \times 10^{-5} \times D/(gm/cc) \times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \quad (4)$$

3-generation formula without matter effect:

$$\begin{aligned} P(\nu_a \to \nu_b) \quad = \quad & \sum_i |U_{ai}|^2 |U_{bi}|^2 \\ & 2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E \\ & 2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E \\ & 2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2 L/2E \end{aligned} \tag{5}$$

For anti-neutrinos take complex conjugate of matrix. Difference from 2 generations: phases.

Brief review of key evidence

Super KamiokaNDE

Sudbury Neutrino Oberservatory (SNO)

KamLand

3-generation oscillations

3-generations in matter

New Neutrino Agenda

MINOS

T2K

A new reactor experiment

Super-Neutrino-Beam with a Large detector

Status of new projects

Conclusion