New Opportunities in Neutrino Physics

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Brief Review

Description of Oscillations

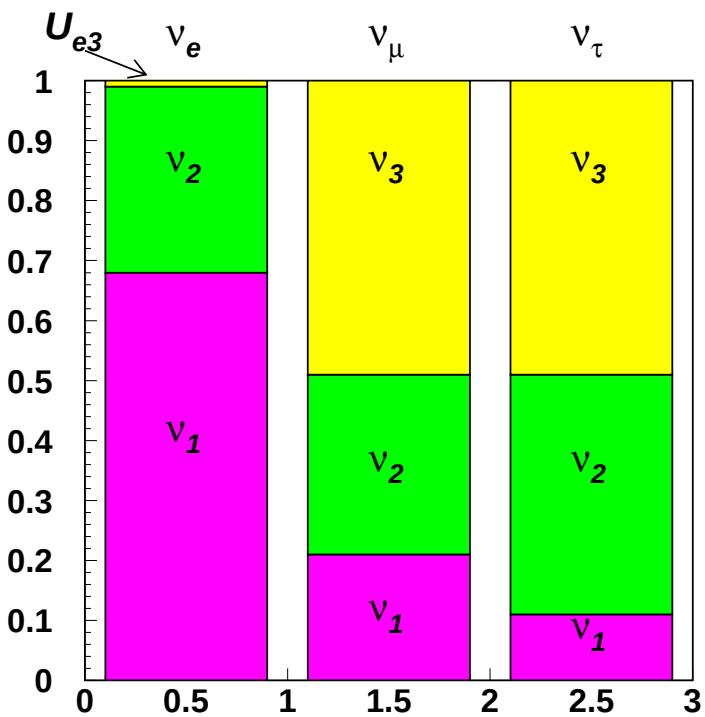
Recent Progress and Implications

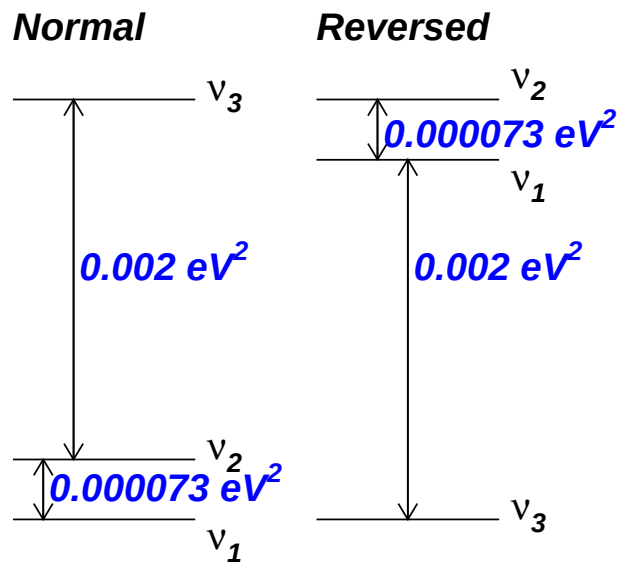
What to Expect in 5 years

Ambitions !

Particle Chart

Big Picture





Difference in mass squares: $(m_2^2 - m_1^2)$

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 $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$,

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

- 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:

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

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

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J. Alessi, et al., ”The AGS-based Super Neutrino Beam Facility, Conceptual Design Report,” BNL-73210-2004-IR, 1 Oct. 2004.

W. T. Weng *et al.*, J. Phys. G **29**, 1735 (2003).

W. J. Marciano, “Extra long baseline neutrino oscillations and CP violation,” BNL-HET-01-31, Aug 2001. 11pp. arXiv:hep-ph/0108181.

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M. Diwan *et al.*, BNL-71228-2003-IR, May 2003. 114pp. arXiv:hep-ex/0305105.

M. Diwan *et al.*, BNL-69395, Oct 2002. 100pp. arXiv:hep-ex/0211001.

M. V. Diwan *et al.*, "Megaton modular multi-purpose neutrino detector for a program of physics in the Homestake DUSEL," arXiv:hep-ex/0306053.

Conclusion