太陽ニュートリノ問題の解は素粒子理論にとって何を意味するか

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「特定・宇宙ニュートリノセンター共催 第2回研究会」

目 次

1. はじめに

Solar Neutrino Deficit

V. Barger, K. Whisnant, R.J.N. Phillips
PRD24 (1981) 538

Maximal Mixing $\theta_{e\mu}^{0}$ in vacuum

MSW 効果 1985

Small Mixing $\theta_{e\mu}^{0}$

Atmospheric Neutrino Deficit

Maximal (?) Mixing $\theta_{\mu\tau}^{0}$ 1998

Model Buildings

5 options for Solar Neutrino Deficit

- SMA MSW
- LMA MSW
- LOW
- Just-so
- Sterile

大角度フレーバー混合に対する
心理的抑圧からの解放

Super-Kam 2000

Emerging default option

3 family, Bi-Maximal (LMA MSW)

↓

- Model の再検討のはじまり
- KamLAND への期待

as well as SNO

GUT

フレーバー対称性

↕

LMA MSW 解

2. 大角度フレーバー混合と質量行列の構造

ニュートリノフレーバー混合行列 (MNS 行列)

$$U_{MNS} \equiv L_E^{\dagger} L_\nu$$

$$\left.\begin{aligned} L_E^{\dagger} M_E R_E &= M_E^{diag} \\ L_\nu^{T} M_\nu L_\nu &= M_\nu^{diag} \end{aligned}\right\} \text{in some preferred basis given by underlying theory of that model}$$

o Single Large Mixing (Atmospheric Neutrinos) の場合

Large Mixing from $\underset{\sim}{M_E}$ or $\underset{\sim}{M_\nu}$

M_E : Democratic | Lopsided

$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}_{LR} \qquad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix}_{LR}$$

solar

$$L_E^{\dagger} : \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \qquad \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$M_\nu : \quad \text{See-Saw} \quad -m_D^{T} M_R^{-1} m_D = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

$$\text{Zee Mass Matrix} \quad \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & \varepsilon \\ 1 & \varepsilon & 0 \end{pmatrix}$$

○ Bi-Large (Maximal) Mixings の場合

大気ニュートリノ：	M_E	M_E	M_ν
太陽ニュートリノ：	M_E	M_ν	M_ν
	Democratic	Lopsided	Zee Matrix

LMA MSW 解

$$\Delta m^2_\odot = (2 \sim 20) \times 10^{-5}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_\odot = 0.6 \sim 0.97$$

$$\frac{\Delta m^2_\odot}{\Delta m^2_{atm}} = (1 \sim 10) \times 10^{-2} \simeq \lambda^2 \sim \lambda^3$$

$$\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_{atm}}} \simeq \frac{m_{\nu_2}}{m_{\nu_3}} \simeq \lambda \sim \lambda^{1.5} \simeq 10$$

$$\frac{m_s}{m_b} \simeq \lambda^2 \qquad \frac{m_c}{m_t} \simeq \lambda^4 \qquad \frac{m_\mu}{m_\tau} \simeq \lambda^2$$

3 Bi-Maximal Mixings と SO(10) GUT

Albright, Babu, Barr PRL81 (1998) 1167
hep-ph/9906297, 0002155

Minimal SO(10) $16_i\, 16_j\, 10_H$

$$16_i \Big(\underbrace{10_{u, u^c, d, e^c} \quad 5^*_{d^c, \ell, \nu}}_{SU(5)} \quad 1_{\nu^c} \Big)_L$$

$m_N^{\text{Dirac}} = m_U \propto m_D = m_E$ No mixings

$(16_3\, 16_3)10_H$, $(16_2\, 16_3)10_H \underline{45_H}$

$[16_3 \underline{16_H}][16_2 \underline{16'_H}]$ $[16_1 16_2][\underline{16_H}\, \underline{16'_H}]$

$[16_1 16_3][\underline{16_H}\, \underline{16'_H}]$

$$M_E = \begin{pmatrix} 0 & \delta & \delta' \\ \delta & 0 & \sigma+\varepsilon \\ \delta' & -\varepsilon & 1 \end{pmatrix}$$

$\varepsilon \simeq 0.14$
$\delta \simeq \delta' \simeq 0.008$
$\sigma \simeq 1.8$
Quarks より決まる。

$$m_s^0/m_b^0 \simeq \frac{1}{3}\varepsilon \frac{\sigma}{1+\sigma^2}$$
$$V_{cb}^0 \simeq \frac{1}{3}\varepsilon \frac{\sigma^2}{1+\sigma^2}$$
$$U_{\mu 3} \simeq -\frac{\sigma}{\sqrt{1+\sigma^2}}$$

$$|V_{cb}| = \frac{m_s^0}{m_b^0}\sigma$$

$$|U_{\mu 3}| = \frac{\sigma}{\sqrt{1+\sigma^2}}$$

$$M_N^{Dirac} = \begin{pmatrix} \eta & 0 & 0 \\ 0 & 0 & -\varepsilon \\ 0 & \varepsilon & 1 \end{pmatrix} M_{\bar{U}} \qquad SO(10)$$

$$W_{Yukawa} \ni 1_3^c\, 1_3^c\, V_M + 1_2^c\, 1_2^c \cdot V_M$$

$$M_R = \begin{pmatrix} 0 & A & 0 \\ A & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}_{RR} \Lambda_R$$

after See-Saw

$$M_\nu = m_0 \begin{pmatrix} -\left(\frac{\eta}{A}\right)^2 \varepsilon^2 & \left(\frac{\eta}{A}\right)\varepsilon^2 & 0 \\ \left(\frac{\eta}{A}\right)\varepsilon^2 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

もし $\eta/A \ll 1$ ならば maximal mixing

$$\Delta m_{21}^2 = 2\,|\eta/A|^3\, \varepsilon^4\, (M_{\bar{U}}^2/\Lambda_R)^2$$

$\Delta m_{21}^2 \simeq 4\times 10^{-10}\,\mathrm{eV}^2$ とすると $|\eta/A| \simeq 0.05$

$\Delta m_{21}^2 \simeq 2\times 10^{-5}\,\mathrm{eV}^2$ とすると $|\eta/A| \simeq 1.8$

但し、$\Delta m_{32}^2 \simeq 3.5\times 10^{-3}\,\mathrm{eV}^2$ とした。

(例) $\Delta m_{21}^2 \simeq 2\times 10^{-5}\,\mathrm{eV}^2$

$\sin^2 2\theta_{\mu\tau} \simeq 0.82 \qquad \sin^2 2\theta_{e\mu} \simeq 0.43$!!

Nomura, Yanagida, PR D59 (1999) 019303
Nomura, Sugimoto, hep-ph/9903334, PR D61 (2000) 093003

$\psi_3(16) = 10_3 + 5^*_3 + N_3$

$\psi_2(16) = 10_2 + 5^*_2 + N_2$

$\psi_1(16) \supset 10_1 + \underset{\sim}{5^*_1} + N_1$

$\underset{\sim}{\psi(10)} \supset \underset{\sim}{5_4} + 5^*_4$

$$W = \sum_{i=1}^{3} f_i \psi_i(16)\psi(10)\langle \chi(16)\rangle$$

$\langle \chi(16)\rangle \simeq 10^{15}\,\mathrm{GeV}$

$W = h_i \psi_i(16)\psi_i(16) H(10)$

5^*_4 は $H(10)$ に対して Yukawa Coupling をもたない。

$W = \kappa H(10)\underset{\sim}{\bar{H}(16^*)}\bar{\chi}(16^*) + M H(16)\underset{\sim}{\bar{H}(16^*)}$ があると

$H(10)$ と $H(16)$ は混ざる!

$$\tilde{5}^*_H = \cos\theta\, 5^*_{H(10)} + \sin\theta\, 5^*_{H(16)}$$

$$W = \sum_{i=1}^{3} g_i \psi_i(16)\psi(10) H(16)$$

$$\left.\begin{aligned} W_{\mathrm{eff}} &= \sin\theta \sum_{i=1}^{3} g_i\, 10_i\, 5^*_4\, \tilde{5}^*_H \\ &+ \cos\theta \sum_{i=1}^{3} h_i\, 10_i\, 5^*_i\, \tilde{5}^*_H \end{aligned}\right\} \text{Yukawa Coupling of } \tilde{5}^*_H$$

$$W_{eff} = \cos\theta\,(\overline{10}_1, 10_2, 10_3) \begin{pmatrix} 0 & g_1\tan\theta & 0 \\ h_2 & g_2\tan\theta & 0 \\ 0 & g_3\tan\theta & h_3 \end{pmatrix} \begin{pmatrix} 5_2^* \\ 5_4^* \\ 5_3^* \end{pmatrix} \tilde{5}_H^*$$

$$M_D = M_E^T = m_t \begin{pmatrix} 0 & x & 0 \\ m_c/m_t & y & 0 \\ 0 & z & 1 \end{pmatrix} \times \frac{\cos\theta}{\tan\beta}$$

$$x = \frac{g_1}{h_3}\tan\theta, \quad y = \frac{g_2}{h_3}\tan\theta, \quad z = \frac{g_3}{h_3}\tan\theta$$

$x \simeq m_c/m_t \quad y \simeq \sqrt{m_c/m_t} \quad z \simeq 1 \Rightarrow$ nice fits

$\theta_{\mu\tau} \simeq \pi/4$ from $z = 1$

Neutrino Sector はどうなるか？ 5_4^* never couples to N_i in $\psi_i(16)$

$$W = \sum_{i=1}^{3} K_i \psi_i(16)\,\psi(10)\,H(10)\,\frac{\bar{\chi}(16^*)}{M_G}$$

5_H

$$M_\nu^{Dirac} = m_t \begin{pmatrix} 0 & \delta_1 & 0 \\ m_c/m_t & \delta_2 & 0 \\ 0 & \delta_3 & 1 \end{pmatrix} \quad \delta_i = \frac{K_i}{h_3}\,\frac{\langle \chi(16) \rangle}{M_G}$$

$$\delta_1 \simeq \delta_3 \simeq 0 \qquad \delta_2 \simeq m_c/m_t$$

$$W = \dot{\lambda}_{ij}\,\frac{1}{M_G}\,\psi_i(16)\,\psi_j(16)\,\bar{\chi}(16^*)\,\bar{\chi}(16^*)$$

$$(M_R)_{ij} = \frac{\langle \bar{\chi}(16^*) \rangle^2}{M_G}\,\underbrace{\dot{\lambda}_{ij}}_{???} \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_\nu = \frac{(m_t)^2}{M_N}\begin{pmatrix} r^2 & \delta_2 r & 0 \\ \delta_2 r & \delta_1^2+\delta_2^2+\delta_3^2 & \delta_3 \\ 0 & \delta_3 & 1 \end{pmatrix} \quad r = \frac{m_c}{m_t}$$

今, $\delta_1 \simeq \delta_3 \simeq 0$ $\delta_2 \simeq r$ ととると

$$M_\nu \propto \begin{pmatrix} r^2 & r^2 & 0 \\ r^2 & r^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \theta_{e\mu} = \frac{\pi}{4} \;!$$

$$U_{MNS} = L_E^\dagger L_\nu \simeq \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & \varepsilon \\ 1/2 & 1/2 & -1/\sqrt{2} \\ 1/2 & 1/2 & -1/\sqrt{2} \end{pmatrix} \quad \text{Bi-Maximal}$$

Neutrino Masses

$$m_2^\nu / m_3^\nu \simeq \delta_2^2 \simeq \frac{m_c^2}{m_t^2} \simeq 5\times10^{-5}$$

$$\Delta m_{21}^2 \simeq 10^{-11}\,\mathrm{eV}^2 \longrightarrow \text{Just-So Solution}$$

However

$$(M_R)_{ij} \propto \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \quad \text{ならば}$$

$\Delta m_{21}^2 \simeq 10^{-5}\,\mathrm{eV}^2$ が得られる。

LMA MSW

4 Bi-Maximal Mixings とフレーバー対称性

Prototype としての Democratic Matrix

"flavor - democratic" $S_{3L} \times S_{3R}$

$$M_{FD} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}_{LR} m$$

rank 1

$(0, 0, 3) m$

$$\Downarrow$$

$$U_{FD} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{6} & 1/\sqrt{3} \\ -1/\sqrt{2} & 1/\sqrt{6} & 1/\sqrt{3} \\ 0 & -2/\sqrt{6} & 1/\sqrt{3} \end{pmatrix}$$

$$M_E = C_E M_{FD} + m_E^{break}$$ $S_{3L} \times S_{3R}$

$$M_\nu = C_\nu I + \underbrace{C'_\nu}_{small} M_{FD} + m_\nu^{break}$$ S_{3L} Majoranas

$$m_{\nu_1} \simeq m_{\nu_2} \simeq m_{\nu_3}$$

$$U_{MNS} = L_E^\dagger L_\nu \simeq U_{FD}^T \simeq \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}$$

$$\sin^2 2\theta_{\mu\tau} \simeq \frac{8}{9} \qquad \sin^2 2\theta_{e\mu} \simeq 1$$

(注) $\sin^2 2\theta_{e\mu} = 1 - \frac{4}{3}\left(L_E^{Br}\right)^2_{21} \simeq 1 - \frac{4}{3}\frac{m_e}{m_\mu} \gtrsim 0.99$

Miura, Takasugi, Yoshimura, hep-ph/0003139 Z_3 symmetry

$O(3)_L \times O(3)_R$ フレーバー対称性をもつモデル

$S_{3L} \times S_{3R}$ モデル ⇒ flavor democratic for M_Q, M_E

マジョラナ ニュートリノ M_ν

$$M_\nu = C_\nu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + C_\nu r \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \quad S_{3L}$$

Large MNS Mixing ⇒ $r \ll 1$ ⇒ $m_{\nu_1} = m_{\nu_2} = m_{\nu_3}$

ν_i $(i=1\sim3)$ Degenerate
Q_i, E_i Hierarchical
} unified picture?

$O(3)$ フレーバー対称性が必要

$O(3)$ Symmetric Limit

$$\psi_3^Q = (q_1, q_2, q_3)^T \quad \psi_3^L = (l_1, l_2, l_3)^T$$

ν_i : Degenerate Masses

Q_i, E_i are massless

M.T, Watari, Yanagida
PLB 461 (1999) 345

$O(3)$ Breaking

ν_i Degeneracy is lifted

Q_i, E_i have hierachical masses.

Δm_{ij}^2 are related with m_{Q_i}, m_{E_i}.

$O(3)_L \times O(3)_R$ Flavor Symmetry

$\ell_L^i\,(i=1\sim3)$ $O(3)_L$ triplet, $e_R^i\,(i=1\sim3)$ $O(3)_R$ triplet

$3\times3 = 1+3+5$

$$\Sigma^{(1)}_{L,R} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \omega^{(1)}_{L,R}$$

Symmetric traceless tensor's

$$\Sigma^{(2)}_{L,R} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \omega^{(2)}_{L,R}$$

$(5_L, 1_R)$

$(1_L, 5_R)$

Explicit Breakings to avoid unwanted massless Nambu-Goldstone Bosons.

$$\sigma^{(1)}_{L,R} \equiv \frac{\Sigma^{(1)}_{L,R}}{M_f} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & -2 \end{pmatrix} \delta_{L,R}$$

$$\sigma^{(2)}_{L,R} \equiv \frac{\Sigma^{(2)}_{L,R}}{M_f} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \varepsilon_{L,R}$$

$\delta_{L,R} \lesssim 1$

$\varepsilon_{L,R} \lesssim 1$

$$\delta_{L,R} \equiv \omega^{(1)}_{L,R}/M_f \qquad \varepsilon_{L,R} \equiv \omega^{(2)}_{L,R}/M_f$$

$$W = \frac{H^2}{M}\ell\left(1 + \alpha_{(1)}\sigma_L^{(1)} + \alpha_{(2)}\sigma_L^{(2)}\right)\ell$$

$$\hat{m}_\nu = \frac{\langle H\rangle^2}{M}\left\{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \alpha_{(1)}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}\delta_L + \alpha_{(2)}\begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}\varepsilon_L\right\}$$

Almost degenerate neutrino masses.

Quarks and charged lepton are still massless.

$$\phi_L(3,1) \qquad \phi_R(1,3) \Rightarrow \text{mass}$$

VEV are determined by superpotential

$$W = Z_L(\phi_L^2 - 3v_L^2) + Z_R(\phi_R^2 - 3v_R^2)$$
$$+ X_L(a_{(i)}\phi_L \sigma_L^{(i)} \phi_L) + X_R(a'_{(i)}\phi_R \sigma_R^{(i)}\phi_R)$$
$$+ Y_L(b_{(i)}\phi_L \sigma_L^{(i)}\phi_L) + Y_R(b'_{(i)}\phi_R \sigma_R^{(i)}\phi_R)$$

$X_{L,R}$ $Y_{L,R}$ $Z_{L,R}$ are $O_{3L} \times O_{3R}$ singlets.

Minimizing potential $|F_X|^2 = 0$ $|F_Y|^2 = 0$ $|F_Z|^2 = 0$

$$\langle\phi_L\rangle = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} v_L \qquad \langle\phi_R\rangle = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} v_R$$

For charged lepton,

$$W = \frac{K_\ell}{M_f^2}(\bar{e}_R \underbrace{\phi_R)(\phi_L}_{} \ell_L)\bar{H} \qquad \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}(1\ 1\ 1)$$

$$\hat{m}_\ell = K_\ell \left(\frac{v_L v_R}{M_f^2}\right) \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \langle\hat{H}\rangle$$

assume $v_L \sim v_R \sim M_f$ $\quad m_\tau \simeq 3K_\ell \frac{v_L v_R}{M_f^2}\langle\hat{H}\rangle$

Minimizing Potential

$$\phi_L^2 - 3v_L^2 = 0 \qquad \phi_R^2 - 3v_R^2 = 0$$

$$\phi_L \sigma_L^{(1)} \phi_L = 0 \qquad \phi_R \sigma_R^{(1)} \phi_R = 0$$

$$\phi_L \sigma_L^{(2)} \phi_L = 0 \qquad \phi_R \sigma_R^{(2)} \phi_R = 0$$

def.

$$\phi_L = \begin{pmatrix} x_L \\ y_L \\ z_L \end{pmatrix} v_L \qquad \phi_R = \begin{pmatrix} x_R \\ y_R \\ z_R \end{pmatrix} v_R$$

$$\sigma_{L,R}^{(1)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \delta_{L,R} \quad \sigma_{L,R}^{(2)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \varepsilon_{L,R}$$

$$x_L^2 + y_L^2 + z_L^2 = 3 \qquad x_R^2 + y_R^2 + z_R^2 = 3$$

$$x_L^2 + y_L^2 - 2z_L^2 = 0 \qquad x_R^2 + y_R^2 - 2z_R^2 = 0$$

$$x_L^2 - y_L^2 = 0 \qquad x_R^2 - y_R^2 = 0$$

$$x_L = y_L = z_L = 1 \qquad x_R = y_R = z_R = 1$$

$$\sigma^{(i)} = \begin{pmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & -a-b \end{pmatrix}$$

$$\delta W = \frac{K_\ell}{M_f^2}\Big\{ A_i^\ell (\bar{e}\,\sigma_R^{(i)}\phi_R)(\phi_L \ell)$$

$$+ B_i^\ell (\bar{e}\,\phi_R)(\phi_L \sigma_L^{(i)} \ell) + C_{ij}^\ell (\bar{e}\,\sigma_R^{(i)}\phi_R)(\phi_L \sigma_L^{(j)} \ell)\Big\} \bar{H}$$

$$U_{FD}^T \hat{m}_\ell U_{FD} = K_\ell \left(\frac{v_L v_R}{M_f^2}\right) \langle \bar{H} \rangle \times$$

$$\begin{pmatrix} 2 C_{22}^\ell \varepsilon_L \varepsilon_R & 2\sqrt{3}\, C_{21}^\ell \varepsilon_R \delta_L & \sqrt{6}\, A_2^\ell \varepsilon_R \\ 2\sqrt{2}\, C_{12}^\ell \varepsilon_L \delta_R & 6\, C_{11}^\ell \delta_L \delta_R & 3\sqrt{2}\, A_1^\ell \delta_R \\ \sqrt{6}\, B_2^\ell \varepsilon_L & 3\sqrt{2}\, B_1^\ell \delta_L & 3 \end{pmatrix}_{RL}$$

μ and e get masses!

$m_\mu / m_\tau \simeq \delta_L \delta_R \qquad m_e / m_\tau \simeq \varepsilon_L \varepsilon_R$

Quark Mass Matrices

$A_i^\ell \to A_i^{U,D} \quad B_i^\ell \to B_i^{U,D} \quad C_{ij}^\ell \to C_{ij}^{U,D}$

$V_{us} \simeq \dfrac{\varepsilon_L}{\delta_L}\,, \quad V_{cb} \simeq \delta_L\,, \quad V_{ub} \simeq \varepsilon_L$

$\delta_L \simeq \lambda^2 \qquad \varepsilon_L \simeq \lambda^3 \qquad \delta_R \simeq 1 \qquad \varepsilon_R \simeq \lambda$

Δm_{ij}^2 are related with δ_L and ε_L

$$\delta W = \frac{H^2}{M} \ell \left(\beta \frac{\phi_L}{M_f} \frac{\phi_L}{M_f} \right) \ell$$

$$\hat{m}_\nu = \frac{\langle H \rangle^2}{M} \left\{ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + d_{(1)} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \delta_L \right.$$

$$\left. + d_{(2)} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \varepsilon_L + \beta \left(\frac{v_L}{M_f} \right)^2 \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \right\}$$

In the case of $\beta \left(\frac{v_L}{M_f} \right)^2 \ll d_{(2)} \varepsilon_L$

$$m_{\nu_3} = m_0 \, (1 - 2 d_{(1)} \delta_L) \qquad m_0 \equiv \frac{\langle H \rangle^2}{M}$$

$$m_{\nu_2, \nu_1} = m_0 \, (1 + d_{(1)} \delta_L \mp d_{(2)} \varepsilon_L)$$

$$\Delta m^2_{31} \simeq 6 \, | d_{(1)} \delta_L | \, , \quad \Delta m^2_{21} \simeq 4 \, | d_{(2)} \varepsilon_L |$$

$$\Delta m^2_{21} \simeq \frac{\varepsilon_L}{\delta_L} \Delta m^2_{31}$$

Input: $\delta_L \simeq 0.1 \quad \varepsilon_L \simeq 10^{-3} \sim 10^{-2}$

$\Delta m^2_{31} = 10^{-3} \, \mathrm{eV}^2$

$\Delta m^2_{21} \simeq 10^{-5} \sim 10^{-4} \, \mathrm{eV}^2$ (prediction)

$$U_{MNS} = (A B_\ell^\dagger) = B_\ell^\dagger A^T = B_\ell^\dagger \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}$$

$$B_\ell^\dagger \simeq \begin{pmatrix} 1 & -\lambda & \lambda^3 \\ \lambda & 1 & -\lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

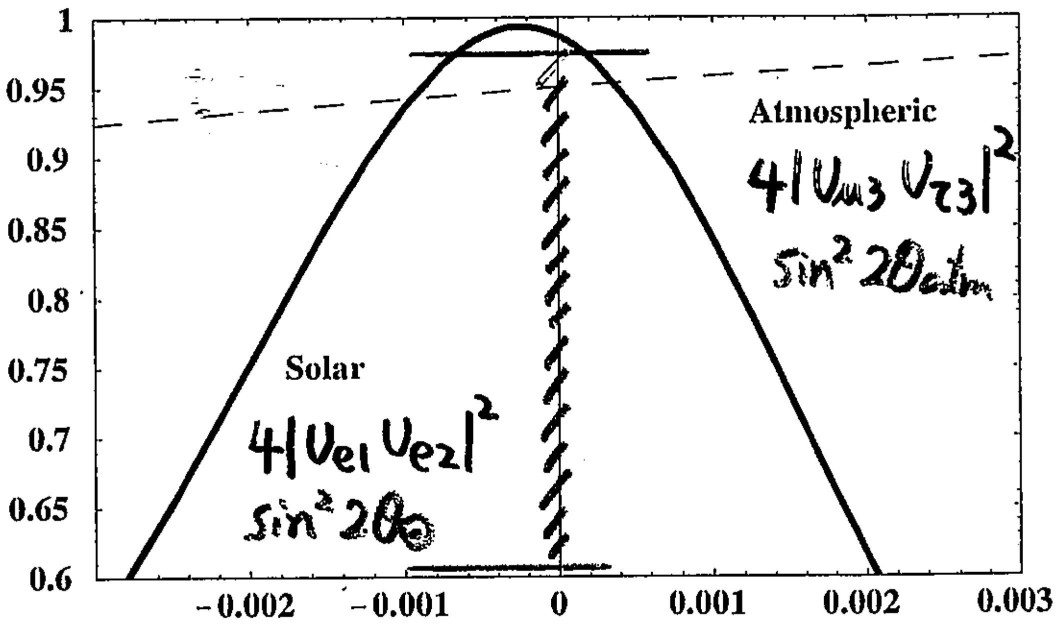
Large Mixing Angle MSW solution !!

$m_0 = 0.1\ \mathrm{eV} \quad \delta_L = 0.05 \quad \varepsilon_L = 0.003$

$\Delta m^2_{31} = 3.1 \times 10^{-3}\ \mathrm{eV}^2$ (Atmospheric)

$\Delta m^2_{21} = 1.1 \times 10^{-4}\ \mathrm{eV}^2$ (Solar)

Effect of $\beta \left(\frac{v_L}{M_f}\right)^2 \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$



PL B483 (2000) 417

hep-ph/0001306 Large Mixing Angle MSW solution

$$\left\{ \begin{array}{l} \sin^2 2\theta_\odot = 0.60 \sim 0.97 \quad (3\sigma) \\ \Delta m^2_\odot = (1.4 \sim 18) \times 10^{-5}\ \mathrm{eV}^2 \end{array} \right.$$

Wait KamLAND

5 Bi-Maximal Mixings とその他のモデル

= Non See saw = $\underline{M_E : \text{Diagonal}}$

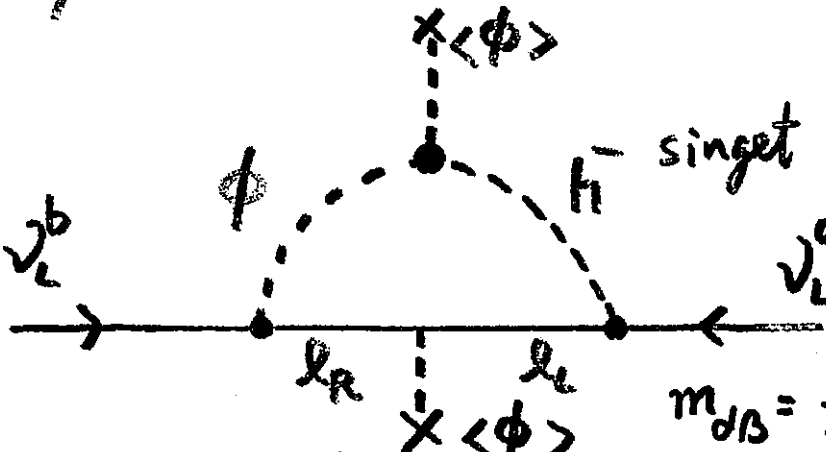
Left handed majorana masses are given

by $\nu_L^T C \langle \Delta^0 \rangle \nu_L$ SU(2) triplet Higgs

$2 \times 2 = 1,\ 3$

Additional Symmetry : $L_e - L_\mu - L_\tau$, ...

by Zee-like models SU(2) singlet scalar



$$m_{\alpha\beta} = f^{\alpha\beta}(m_{L\alpha}^2 - m_{L\beta}^2) \times \frac{v_2}{v_1} \mu F(M_1^2, M_2^2)$$

by R-parity and lepton-number-violation in SUSY $\boxed{\varepsilon_i L_i H}$

+ loop diagrams

Typical form for M_ν

$$M_\nu = \begin{pmatrix} m_{11} & cM & sM \\ cM & m_{22} & m_{23} \\ sM & m_{23} & m_{33} \end{pmatrix}$$

$M \gg m_{ij}$, $s \equiv \sin\theta$ $c \equiv \cos\theta$ $\theta \sim \frac{\pi}{4}$

$\Downarrow$ rotation in the 2-3 plane by θ

$$M'_\nu = \begin{pmatrix} m_{11} & M & 0 \\ M & m'_{22} & m'_{23} \\ 0 & m'_{23} & m'_{33} \end{pmatrix}$$ 1-2 plane Large Mixing

$m_1 \simeq m_2 \gg m_3$

$\theta_{e\mu} \simeq \frac{\pi}{4}$ $\theta_{\mu\tau} \simeq \frac{\pi}{4}$

$\Delta m^2_{12} \simeq 4 M m_{ij}$ $\Delta m^2_{23} \simeq M^2$ $M \simeq 0.05\,\text{eV}$

LMA MSW : $m_{ij} \simeq 10^{-4} \sim 10^{-3}\,\text{eV}$

$\sin^2 2\theta_{e\mu} \gtrsim 0.99$

6 まとめ

太陽ニュートリノ options

- SMA MSW　many models
- Just - SO　Nomura - Yanagida $SO(10)$
  Albright - Barr
  $S_{3L} \times S_{3R}$, Z_3
  Zee - like (Radiative, R-..)
  ⋮
- LMA MSW
  $SO(10)$?
  $S_{3L} \times S_{3R}$, Z_3
  $O_{3L} \times O_{3R}$　Quark - Lepton Unification

$\Delta m^2_{12} / \Delta m^2_{23} \sim m_s / m_b$

$m_1 \simeq m_2 \simeq m_3 \longrightarrow \beta\beta_{0\nu}$

(Non-Abelian Flavor Symmetry)

Need KamLAND !!