LEPTOGENESIS & CP VIOLATION IN NEUTRINO OSCILLATIONS

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PART A : SOME GENERAL REMARKS

★ OBSERVED MATTER-ANTIMATTER ASYMMETRY:

$$Y_B = \frac{n_B}{s} = \frac{1}{7.04} \cdot \frac{n_B}{n_\gamma} = (3.7 \sim 8.9) \times 10^{-11}$$

BBN: $\eta = \frac{n_B}{n_\gamma} = (2.6 \sim 6.3) \times 10^{-10}$

PDG2002 [OLIVE & PEACOCK]

★ BARYOGENESIS VIA LEPTOGENESIS [FUKUGITA & YANAGIDA 1986]

$$-\mathcal{L}_Y = \overline{l_L}\,\tilde{\phi}\, Y_l\, e_R + \overline{l_L}\,\phi\, Y_\nu\, \nu_R + \frac{1}{2}\overline{\nu_R^c}\, M_R\, \nu_R + h.c.$$ (LEPTON NUMBER VIOLATION)

DECAYS OF HEAVY RIGHT-HANDED MAJORANA NEUTRINOS :

$N_i \longrightarrow l + \phi^\dagger$ vs $N_i \longrightarrow l^c + \phi$ (Tree + One-loop Self-energy / Vertex)

INTERFERENCE

$\boxed{\text{CP ASYMMETRY } \epsilon_i}$

$\downarrow$ ⟵ OUT OF EQUILIBRIUM [Sakharov 1967]

$\boxed{\text{LEPTON ASYMMETRY}}$ $Y_L = \frac{d}{g_*}\epsilon_i$

$\downarrow$ ⟵ (B+L)-VIOLATING SPHALERON PROCESSES [Kuzmin et al 1985]

$\boxed{\text{BARYON ASYMMETRY}}$ $Y_B = \frac{c}{c-1} Y_L$

★ AFTER SSB, LEPTON MASS MATRICES:

$M_l = Y_l\langle\phi\rangle$, $M_D = Y_\nu\langle\phi\rangle$, $M_R = M_R$, $\boxed{M_\nu = -M_D M_R^{-1} M_D^T}$

SEESAW [Gell-Mann et al, Yanagida 1979]

DIAGONALIZATION:

$$\left.\begin{aligned} U_l^\dagger M_l \tilde{U}_l &= \bar{M}_l \equiv \mathrm{Diag}\{m_e, m_\mu, m_\tau\} \\ U_\nu^\dagger M_\nu U_\nu^* &= \bar{M}_\nu \equiv \mathrm{Diag}\{m_1, m_2, m_3\} \end{aligned}\right\}$$

MISMATCH: LEPTON FLAVOR MIXING $V = \underline{U_l^\dagger}\, \underline{U_\nu}$

$$\left.\begin{aligned} U_D^\dagger M_D \tilde{U}_D &= \bar{M}_D \equiv \mathrm{Diag}\{D_1, D_2, D_3\} \\ U_R^\dagger M_R U_R^* &= \bar{M}_R \equiv \mathrm{Diag}\{M_1, M_2, M_3\} \end{aligned}\right\}$$

MISMATCH: CP VIOLATION FOR LEPTOGENESIS ϵ_i

$$\mathrm{Im}[(M_D U_R^*)^\dagger (M_D U_R^*)]^2 = \mathrm{Im}[\underline{U_R^T \tilde{U}_D}\, \bar{M}_D^2\, \underline{\tilde{U}_D^\dagger U_R^*}]^2$$

★ In THE BASIS $U_\nu = \mathbb{1}$ [i.e. $V = U_l^\dagger$; e.g. Fritzsch & Xing 96], V AND ϵ_i DISCONNECTED

LESS FINE TUNING FOR MODEL BUILDING

★ In THE BASIS $U_l = \mathbb{1}$ AND $U_R = \mathbb{1}$, $V = U_\nu$ AND ϵ_i INDIRECTLY CONNECTED

[Buchmüller & Plümacher 96, Branco et al 01, Ellis & Raidal 02]

SEESAW: $\boxed{V \bar{M}_\nu V^T = -U_D \bar{M}_D \tilde{U}_D^\dagger \bar{M}_R^{-1} \tilde{U}_D^* \bar{M}_D U_D^T}$ MODEL BUILDING IS NONTRIVIAL!

★ LOW ENERGY EFFECTS:

LMA-MSW

(A) LIGHT NEUTRINO MASSES AND FLAVOR MIXING ANGLES ($\theta_{ATM} \sim \theta_{SUN} \gg \theta_{CHZ}$).

(B) NEUTRINOLESS $\beta\beta$ DECAY [Xing 02] ($p, q = \pm 1$):

$$\langle m\rangle_{ee} = \left|\sum_i m_i V_{ei}^2\right| = \left| m_3 \sin^2\theta_{CHZ} + \frac{1}{2}\cos^2\theta_{CHZ}\left(\sqrt{m_3^2 + p\Delta m^2_{ATM} + q\Delta m^2_{SUN}}\, e^{2i\rho} + \sqrt{m_3^2 + p\Delta m^2_{ATM}}\, e^{2i\sigma}\right)\right.$$
$$\left. + \frac{1}{2}\sqrt{\cos^4\theta_{CHZ} - \sin^2 2\theta_{SUN}}\left(\sqrt{m_3^2 + p\Delta m^2_{ATM} + q\Delta m^2_{SUN}}\, e^{2i\rho} - \sqrt{m_3^2 + p\Delta m^2_{ATM}}\, e^{2i\sigma}\right)\right|.$$

(C) CP VIOLATION IN NEUTRINO OSCILLATIONS ($J \propto \sin\delta$ Dirac Phase).

MATTER EFFECTS: $\tilde{J} = J(\Delta m_{12}\cdot\Delta m_{23}\cdot\Delta m_{31})/(\Delta\tilde{m}_{12}\cdot\Delta\tilde{m}_{23}\cdot\Delta\tilde{m}_{31})$ [Naumov 92]

PART B: AN EXPLICIT ANSATZ

★ CONJECTURE: M_D, M_R, M_l HAVE THE SAME TEXTURE ZEROS $(1,1)=(1,3)=(3,1)=0$.
THEN M_ν MUST HAVE THE SAME ZEROS — *Seesaw Invariance*
【Fritzsch & Xing 00】

- (1) WE PROPOSE:

$$M_D = v\begin{pmatrix} 0 & \hat{\lambda}^3 & 0 \\ \hat{\lambda}^3 & x\hat{\lambda}^2 & \hat{\lambda}^2 \\ 0 & \hat{\lambda}^2 & e^{i\delta} \end{pmatrix}, \quad M_l = m_\tau \begin{pmatrix} 0 & \lambda^4 & 0 \\ \lambda^4 & y\lambda^2 & \lambda^3 \\ 0 & \lambda^3 & 1 \end{pmatrix},$$

WHERE $\hat{\lambda} \equiv \lambda e^{i\omega}$ AND x, $y \sim O(1)$, AND $v \equiv \langle\phi\rangle \approx 175$ GeV, $\lambda \approx 0.22$. NON-SO(10)!

【SO(10): $M_D = M_u$, $M_l = M_d$. Buchmüller & Wyler 01】. 【Xing, hep-ph/0206245】

- (2) TO GENERATE BIG MIXING ANGLES IN THE $\nu_\mu - \nu_\tau$ AND $\nu_e - \nu_\mu$ SECTORS,

$$M_R = M_0\begin{pmatrix} 0 & \lambda^5 & 0 \\ \lambda^5 & z\lambda^4 & \lambda^4 \\ 0 & \lambda^4 & 1 \end{pmatrix}, \quad M_\nu = \frac{v^2}{M_0}\begin{pmatrix} 0 & \hat{\lambda} & 0 \\ \hat{\lambda} & z' & 1 \\ 0 & 1 & e^{i2\varphi} \end{pmatrix}, \quad \text{WHERE} \begin{cases} z \sim O(1), \ |z'| \sim O(1), \\ z' \equiv 2x - z e^{i\omega}, \\ 2\varphi \equiv 2\delta - 5\omega . \end{cases}$$

A NECESSARY CONDITION $|z' e^{i2\varphi} - 1| \equiv \delta \sim O(\lambda)$.

- (3) AN INTERESTING PARAMETER SPASE $(x, z, \omega, \delta, M_0)$:

$$x = \frac{1}{\sqrt{2}}, \quad z = 1 + \sqrt{2}\lambda, \quad \delta = -\omega = \frac{\pi}{4} \longrightarrow \delta = \sqrt{2}\lambda, \quad \arg(z' e^{i2\varphi} - 1) \equiv 2\gamma = \frac{\pi}{2} \ !$$

★ RESULTS:

(a) MIXING ANGLES: $\sin^2 2\theta_{SUN} \approx \dfrac{8\lambda^2}{8\lambda^2 + \delta^2} \approx 0.8$, $\sin^2 2\theta_{ATM} \approx \dfrac{4}{4+\delta^2} \approx 0.98$, $\sin^2 2\theta_{CHZ} \approx \dfrac{\lambda^2}{2} \approx 0.024$.

(b) NEUTRINO MASSES:

NORMAL HIERARCHY
$m_3 \approx \sqrt{\Delta m^2_{ATM}} \approx (4.0 \sim 6.2) \times 10^{-2}$ eV.

$$\begin{cases} m_1 \approx \left(\dfrac{\lambda}{2\sqrt{2}} \tan\theta_{SUN}\right) m_3 \approx (1.9 \sim 3.0) \times 10^{-3}\ \text{eV}, \\ m_2 \approx \left(\dfrac{\lambda}{2\sqrt{2}} \cot\theta_{SUN}\right) m_3 \approx (5.0 \sim 7.8) \times 10^{-3}\ \text{eV}, \\ m_3 \approx 2\dfrac{v^2}{M_0} \approx (4.0 \sim 6.2) \times 10^{-2}\ \text{eV} \longrightarrow M_0 \approx 2\dfrac{v^2}{m_3} \approx (4.9 \sim 7.6) \times 10^{14}\ \text{GeV} \end{cases}$$

(c) RATIO: $R_\nu \equiv \frac{\Delta m^2_{SUN}}{\Delta m^2_{ATM}} \approx \frac{\delta}{16}\sqrt{8\lambda^2+\delta^2} \approx 1.4\times10^{-2}$.

(d) NEUTRINOLESS $\beta\beta$ DECAY: $\langle m\rangle_{ee} \approx \frac{\lambda^2}{8} m_3 \approx (2.4\sim3.8)\times10^{-4}\,\mathrm{eV}$ TOO SMALL!

(e) CP VIOLATION: $J \approx \frac{\lambda^2 \sin 2\gamma}{4\sqrt{8\lambda^2+\delta^2}} \approx 2\%$. [NOTE: $\sin 2\gamma \approx \frac{2x}{\delta}\sin 2\varphi - \frac{z}{\delta}\sin(2\varphi+\omega)$]

$$= \frac{2x}{\delta}\sin(2\zeta-5\omega) - \frac{z}{\delta}\sin(2\zeta-4\omega)$$

(f) HEAVY NEUTRINO MASSES: HIERARCHY!

$M_1 \approx \frac{\lambda^6}{z}M_0 \approx 5.2\times10^{10}\,\mathrm{GeV}$, $M_2 \approx z\lambda^4 M_0 \approx 1.8\times10^{12}\,\mathrm{GeV}$, $M_3 \approx M_0 \approx 6.0\times10^{14}\,\mathrm{GeV}$.

(g) CP ASYMMETRY ϵ_1 (OUT-OF-EQUILIBRIUM DECAY OF THE LIGHTEST HEAVY NEUTRINO):

$$\epsilon_1 \approx -\frac{3}{16\pi v^2}\cdot\frac{M_1}{[U_R^T M_D^\dagger M_D U_R^*]_{11}}\sum_{j=2}^{3} \frac{\mathrm{Im}([U_R^T M_D^\dagger M_D U_R^*]_{1j})^2}{M_j}$$

$$\approx -\frac{3\lambda^6}{16\pi}\cdot\frac{x^2 z\sin 2\omega - 2x(1+x^2)\sin\omega + \sin 2(2\omega-\zeta)}{z(1+x^2+z^2-2xz\cos\omega)}$$

WHERE $U_R \approx \begin{pmatrix} i & \frac{\lambda}{z} & 0\\ -i\frac{\lambda}{z} & 1 & \lambda^4 \\ i\frac{\lambda^5}{z} & -\lambda^4 & 1\end{pmatrix}$.

$$\approx -\frac{\lambda^6}{4\pi}\left(1-\frac{23\sqrt{z}}{12}\lambda+\frac{67}{18}\lambda^2\right)\approx -5.2\times10^{-6}.$$ (TYPICAL NUMBER)

LOOK AT THE PHASES IN J AND ϵ_1 — INDIRECTLY RELATED! (ζ, ω)

(h) WASH-OUT [Kolb & Turner 90]:

$d \approx \frac{0.3}{K}\cdot\frac{1}{(\ln K)^{0.6}} \approx 1.7\times10^{-3}$, WHERE $K \equiv \frac{[U_R^T M_D^\dagger M_D U_R^*]_{11}}{8\pi v^2}\cdot\frac{M_{PL}}{1.66\sqrt{g_*}M_1} \approx \frac{3-\sqrt{z}\lambda+6\lambda^2}{16\pi}\cdot\frac{M_{PL}}{1.66\sqrt{g_*}M_0} \approx 73$.

(i) BARYON ASYMMETRY: $Y_B = \frac{c}{c-1}\cdot\frac{d}{g_*}\epsilon_1 \approx 4.7\times10^{-11}$, WHERE $g_*\approx 100$, $c \approx 8/23$.

★ CONCLUSION: GOOD AGREEMENT WITH EXPERIMENTAL AND OBSERVATIONAL DATA.