CP violation in neutrino oscillations and leptogenesis

Sin Kyu Kang

9 October 2003, KIAS

T. Endoh , S. Kaneko, M. Tanimto
T. Morozumi
Phys. Rev. Lett. 89 (2002) 231601

Why do we exist ?

"Why is there only matter in Universe but no anti-matter?"
→ big question in cosmology and particle physics

- In early Universe, there was pratically equal amount of matter and anti-matter.

- As T decreased, anti-matter has annihilated with matter, leaving only radition.

- At the level of one out of ten bilions or so, there was an excess in the amount of matter over anti-matter → *the baryon asymmetry of Universe*
  We have survived *the Great Annihilation*

- " *What casued a tiny excess in the amount of matter over anti-matter ?*

Baryogenesis

baryon-antibaryon asymmetry of the universe

$$Y_B \equiv \frac{n_B}{s} \simeq (3.7 - 8.9) \times 10^{-11}$$

- **Sakharov conditions**

  1.Baryon number nonconservation
  2. C and CP violation
  3. Departure from thermal equilibrium

  It looks like neutrinos have no role...

  But, neutrinos attract much attention not only because they are windows for new physics beyond standard model, but also because they may play in important role in cosmology!!
  "Is it possible to achieve tiny masses of neutrinos and baryogenesis in a framework?" : Yes $\rightarrow$ seesaw mechanism !!

Fukugita and Yanagida suggested a nice mechanism for Baryogenesis, so called leptogenesis, and it has attracted much attention - due partly to the fact that neutrino physics is entering a flourishing era.

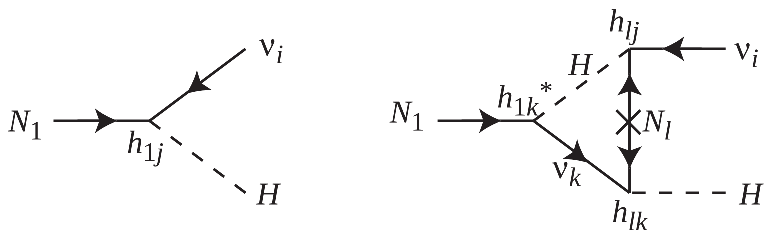
- **Leptogenesis**

  Key idea $\rightarrow$ the lepton number asymmetry Y_L is convered into a net baryon asymmetry Y_B through the $(B+L)$ violating sphaleron processes.

  Essential ingredients $\rightarrow$ heavy Majorana right-handed neutrinos N_i while $\mathcal{L}$ of the electroweak interactions keeps invariant under $SU(2)_L \times U(1)_Y$.

  The lepton number violation $\rightarrow$ induced by decays of N_i :

$$N_i \rightarrow l + \phi^\dagger, \quad N_i \rightarrow l^c + \phi$$



CP violation $\rightarrow$ arises from the interference between three level and 1-loop decay amplitudes. (source of CP violation is complex Yukawa couplings $Y_\nu \overline{l_L} \phi N_i$)

CP asymmetry ϵ_1 between $N_1 \rightarrow l + \phi^\dagger$ and $N_1 \rightarrow l^c + \phi$ decays at high energy scales :

$$\epsilon_1 = \frac{\Gamma[N_1 \rightarrow l^- \phi^+] - \Gamma[N_1 \rightarrow l^+ \phi^-]}{\Gamma[N_1 \rightarrow l^- \phi^+] + \Gamma[N_1 \rightarrow l^+ \phi^-]}$$

$$= -\frac{M_1}{2M_2} \frac{Im[(Y_\nu^\dagger Y_\nu)^2_{12}]}{V^2 (Y_\nu^\dagger Y_\nu)_{11}}, \quad (V = \sqrt{4\pi} v)$$

Condition for out-of-equilibrium decay of $N_1 \rightarrow \Gamma[N_1] < H$.

Finally, Y_L is converted into Y_B through sphaleron processes:

$$Y_B = \frac{c}{c-1} Y_L = \frac{c}{c-1} \frac{d}{g_*} \epsilon_1$$

where $c = (8N_f + 4N_\phi)/(22N_f + 13N_\phi)$

The purpose of this talk is to probe a connection between measurable CP violation in neutrino oscillations and leptogenesis.

CP violation in ν oscillations

- In the above scenario, the Yukawa interactions are described BY

  $$L_Y = \overline{l_L}\tilde{\phi}Y_l e_R + \overline{l_L}\phi Y_\nu \nu_R + \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + h.c.$$

- The light neutrino mass matrix $\rightarrow$ obtained via seesaw mechanism:

  $$M_\nu \simeq -M_D M_R^{-1} M_D^T$$

- $M_\nu \rightarrow$ diagonalized by U_{MNS}
  U_{MNS} has CP-violating phases !

- **How can we measure CP violation through neutrino oscillations?**

Effects of CP violation can be measured by the asymmetry of the oscillation probability :

$$\Delta P = P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})$$
$$\sim Im(U_{e1}U^*_{e2}U^*_{\mu 1}U_{\mu 2}) \equiv J$$

How is CP violation in neutrino oscillation related to CP violation for baryogenesis ?

To achieve our goal, we consider a specific example which shows "a direct Link" between the size and sign of Baryon number and CP violation in neutrino oscillation: $\to$ the minimal seesaw model which generates $L \neq 0, \Delta P \neq 0$.

Minimal seesaw model:

$3\ light\ \ (\nu_1, \nu_2, \nu_3) + 2\ heavy\ Majorana\ (N_1, N_2):$

$$L = \quad \bar{l^i} m_{l_i} l^i + \bar{\nu^i} m_{D ij} N_{Rj} + \frac{1}{2} \bar{N}^c_{Rj} M_j N_{Rj}$$
$$(i = 1 \sim 3, j = 1, 2).$$

Dirac mass term 3×2 matrix: (in the basis where m_l, M are real diagonal.)

$$m_D = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \\ m_{31} & m_{32} \end{pmatrix}$$

$$M = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} \quad m_l = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

Note on the model:

(1) one light neutrino is exactly massless:

$$det[m_D \frac{1}{M} m_D^T] = 0$$

(2) the sign of the baryon number of the universe can be related to CP violation in neutrino oscillations ; Frampton, Glashow, Yanagida (PLB548 (2002).

(3) 3 CP violating phases

A parametrization of m_D

(6 real + 3 CP phases)

$$m_D = U_L m V_R : \qquad m = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \\ 0 & 0 \end{pmatrix}$$

$$\begin{aligned} U_L &= O(\theta_{23}) U(\theta_{13} \delta_L) O(\theta_{12}) P_L \\ P_L &= Diag.[\exp(-i\frac{\gamma_L}{2}), \exp(-i\frac{\gamma_L}{2}), 1] \\ V_R &= \begin{pmatrix} c_R & s_R \\ -s_R & c_R \end{pmatrix} \begin{pmatrix} \exp(-i\frac{\gamma_R}{2}) & 0 \\ 0 & \exp(i\frac{\gamma_R}{2}) \end{pmatrix} \end{aligned}$$

$$\begin{aligned} M_\nu &= -m_D \frac{1}{M} m_D^T \\ U_{MNS}^\dagger M_\nu U_{MNS}^* &= diag[n_1, n_2, n_3] \end{aligned} \qquad (1)$$

$$U_{MNS} = U_L K_R$$

where

$$K_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \exp[-i\phi] \\ 0 & -\sin\theta \exp[i\phi] & \cos\theta \end{pmatrix} P$$

$$P = Diag.[1, exp[i\alpha], exp[-i\alpha]].$$

Note that (θ_R, γ_R) have been transferred to (θ, ϕ, α).

1) Leptogenesis :

$\rightarrow$ depending on a CP phase γ_R in V_R

$$\begin{aligned} \epsilon_1 &\sim -Im[(m_D^\dagger m_D)_{12}^2] \\ &\sim -({m_2}^2 - {m_1}^2)^2 {s_R}^2 {c_R}^2 \sin 2\gamma_R \end{aligned}$$

2) CP asymmetry in ν oscillation :

$$\Delta P = P_{(\nu_\mu \to \nu_e)} - \bar{P}_{(\bar{\nu}_\mu \to \bar{\nu}_e)}$$
$$= 4J\{\sin[(\Delta m^2_{12} L)/(2E)] + \sin[(\Delta m^2_{23} L)/(2E)] + \sin[(\Delta m^2_{31} L)/(2E)$$

From U_{MNS}, we obtain

$$J = \frac{1}{8}\sin 2\theta_{L12} \sin 2\theta_{L13} \times [c_{L13} \cos 2\theta \sin \delta_L \sin 2\theta_{L23} + c_{L12} \sin 2\theta \sin(\delta_L - \gamma_L - \phi) \cos 2\theta_{L23} - \frac{1}{2} s_{L12} s_{L13} \sin 2\theta \sin 2\theta_{L23} \sin(2\delta_L - \gamma_L - \phi)] + \frac{1}{8} \sin 2\theta \sin 2\theta_{L23} \sin(\gamma_L + \phi) \times (\sin 2\theta_{L12} c_{L13} s_{L12} - \sin 2\theta_{L13} s_{L13} c_{L12})$$

- 4 mixing angles and δ_L and $\phi + \gamma_L$ appear.
- Only ϕ and θ are related with leptogenesis
- **In order to discuss the correlation between J and leptogenesis, we need to**

determine (a) the parameter set (ϕ, θ) and (b) the parameters contained in U_L, separately.

(A) How to determine parameter set (ϕ, θ):
In our parametrization,

$$\frac{\epsilon_1}{10^{-8}} \sim -\frac{M_1}{V} 10^{-6} \sqrt{\frac{\Delta m^2_{atm}}{\Delta m^2_{sol}}} \times$$

$$\frac{n_1}{x} \sqrt{\left(1 - (\frac{x-y}{n_2 - n_1})^2\right)\left((\frac{x+y}{n_2+n_1})^2 - 1\right)}$$

where

$$x = \frac{(m_D{}^\dagger m_D)_{11}}{M_1} = \Gamma_1 \left(\frac{V}{M_1}\right)^2;$$

$$y = \frac{(m_D{}^\dagger m_D)_{22}}{M_2} = \Gamma_2 \left(\frac{V}{M_2}\right)^2$$

From neutrino mass eigenvalue equation, it follows

$$\begin{aligned} x + y &> n_2 + n_3, \\ |x - y| &< |n_3 - n_2|, \\ \rightarrow x &> min.[n_2, n_3] \end{aligned}$$

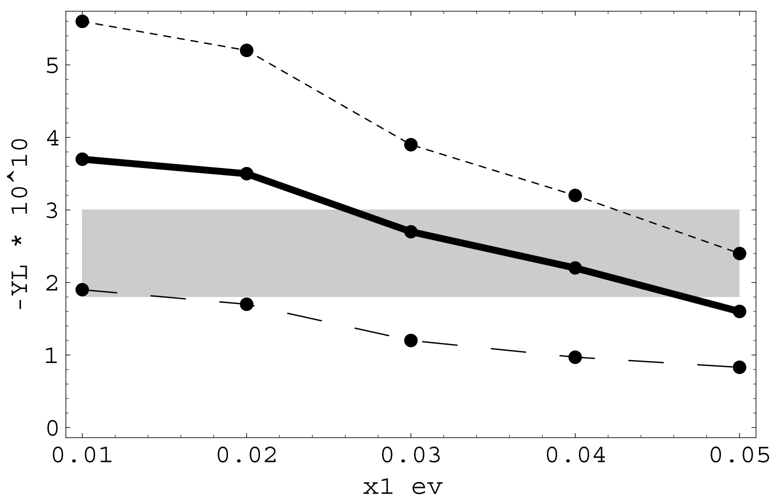
For

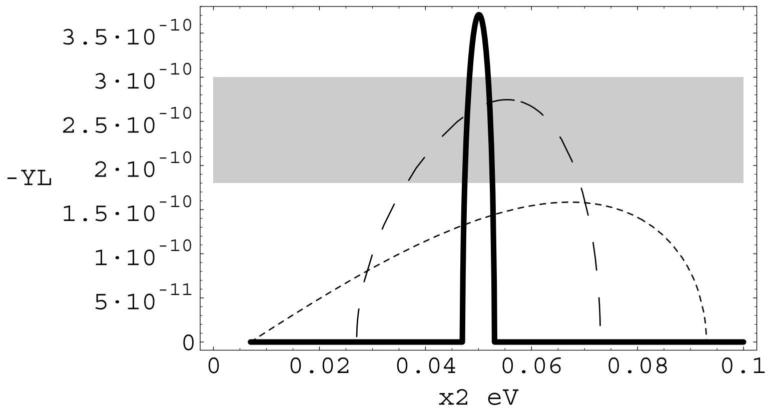
$$n_3 = \sqrt{\Delta m^2_{atom.}} \sim 5 \times 10^{-2} eV$$
$$n_2 = \sqrt{\Delta m^2_{solar}} \sim 4 \times 10^{-3} (LMA)$$

the lower bound on $x_1 \sim 4 \times 10^{-3}$.

By solving the Boltzmann equation, we can obtain Y_L.

Since $\phi, \theta \to$ functions of x and y, we can estimate the allowed regions ψ, θ.




3.5·10^-10
3·10^-10
2.5·10^-10
2·10^-10
1.5·10^-10
1·10^-10
5·10^-11
0
-YL
0
0.02
0.04
0.06
0.08
0.1
x2 eV

(B)The parameters in U_L are partially determined from the neutrino oscillation experimental results.

In particular, for the case with small θ_{13}, θ which is consistent with CHOOZ experiment, the MNS mixing matrix is given, in the leading order, by

$$U_{MNS} \simeq \begin{pmatrix} c_{L12} & s_{L12} & s_{L13}e^{-i\delta_L} + s_{L12}s_\theta e^{-i\phi'} \\ -s_{L12}c_{L23} & c_{L12}c_{L23} & s_{L23} \\ s_{L12}s_{L23} & -c_{L12}s_{L23} & c_{L23} \end{pmatrix} P(\alpha', -\alpha').$$

where

$$\phi' = \phi + \gamma_L, \quad \alpha' = \alpha - \frac{\gamma_L}{2}$$

$$P(\alpha', -\alpha') = diag.[1, e^{i\alpha'}, e^{-i\alpha'}]$$

Taking $\theta_{23} \simeq \theta_{12} \simeq \pi/4$, we obtain

$$J \simeq \left(s_{L13} \sin\delta_L + \frac{s_\theta}{\sqrt{2}} \sin(\phi + \gamma_L) \right) /4$$

$$|(U_{MNS})_{e3}| \simeq |s_{L13}e^{-i\delta} + \frac{s_\theta}{\sqrt{2}} e^{-i\phi'}|,$$

$$|(m_{eff})_{ee}| \simeq |\frac{n_2}{2} e^{4i\alpha'} + n_3(s_{L13}e^{-i\delta_L} + \frac{s_\theta}{\sqrt{2}} e^{-i\phi'})^2|.$$

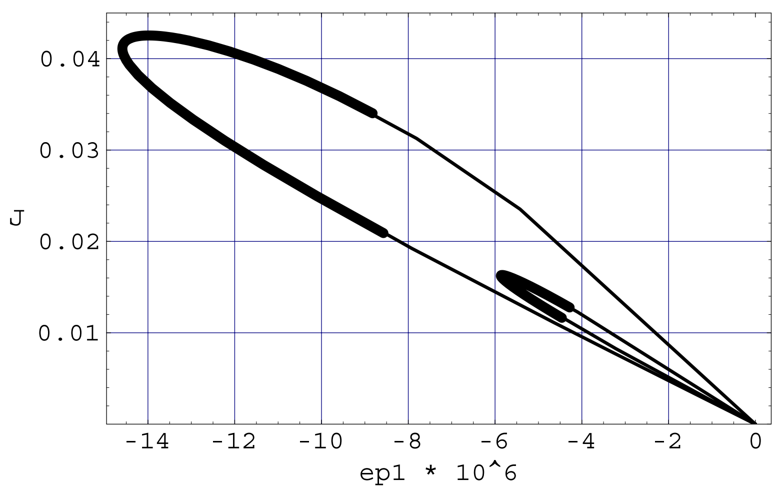
When $\theta_{L13} << \theta$,

$$J \simeq \sin 2\theta \sin(\phi + \gamma_L) \frac{1}{8\sqrt{2}}$$

Using the allowed values for (ϕ, θ), we can investigate how J can be affected by γ_L.

If γ_L $\rightarrow$ much smaller than ϕ, the measurement of CP violation in low energy experiment may directly indicate leptogenesis.

The correlation between ϵ_1 and J with $\gamma_L = 0$ $\rightarrow$ Figure



When $\theta << \theta_{L13}$, J mainly depends on δ_L, which has nothing to do with leptogenesis.

Summary

- leptogenesis phase (γ_R) certainly affects the CP violation measurable in the neutrino oscillations through (ϕ).

- We examined the connection between the CP violation in the neutrino oscillations and leptogenesis in the minimal seesaw model.

- To see how the CP violation in the light neutrino sector can be related to the CP violation for leptogenesis, we numerically determined the mixing angles and CP phases appeared in high energy scale.