CP violation in leptogenesis and at low energy

Federica Palorini
in collaboration with Sacha Davidson, Julia Garayoa, Nuria Rius

Institut de Physique Nucléaire de Lyon

GDR neutrino - June 2007

Introduction

The problem :

Relation between low energy CP violation and CP violation in flavoured leptogenesis

Summary :

- Baryon asymmetry
- Thermal leptogenesis
- Effect of flavours in leptogenesis
- Sensitivity of flavoured leptogenesis from low energy CP-odd observables
- Conclusions

Cosmological matter excess

Observations :

- The known universe is made of matter (no γ rays from annihilations)

$\Rightarrow$ there is an excess of matter over anti-matter

- Matter $\simeq H = p + e^-$, implying a baryon asymmetry :

$$Y_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} \neq 0$$

Measurements of baryon number density :

- Luminous matter : $Y_B \sim$ few $\times 10^{-11}$
- BBN : $Y_B \sim 2 - 6 \times 10^{-10}$
- WMAP : $Y \sim 6.15 \pm .025 \times 10^{-10}$

No definite information on lepton asymmetry (there is an undetectable CMB of νs which could contain a large lepton asymmetry)

Sakharov conditions

If Universe was born with a baryon asymmetry
$\Rightarrow$ BA would have been diluted during *inflation*

Dynamical baryon asymmetry production after inflation :

1. B violation : to evolve from a state with $B = 0$ to $B \neq 0$
2. C and CP violation : different behaviour of particles and anti-particles
3. out-of-equilibrium dynamics : CPT conservation $\Rightarrow$ particles and antiparticles with same mass $\Leftrightarrow$ same abundance

Sakharov conditions

In the Standard Model :

1. B violation from quantum anomalies and non perturbative processes (sphalerons)
2. C and CP violation (in the CKM matrix), but CP violation is too small
3. out-of-equilibrium in electroweak phase transition, but too smooth the shift of the Higgs vev for $m_h > 70$ GeV

$\Rightarrow$ Extension of the Standard Model scenario

Seesaw

$$\mathscr{L}_{seesaw} = (\overline{\ell}^i_L H^*_d)\mathbf{Y}^*_{\mathbf{e}ij} e^j_R + (\overline{\ell}^i_L H^*_u)\lambda^*{}_{iJ} N^J + \overline{N^c}^J \frac{\mathbf{M}^*{}_{JK}}{2} N^K + h.c.$$

At low energy ($\ll M_1$) :

- Heavy degrees of freedom are integrated out
- $[m_\nu] = \lambda M^{-1} \lambda^T v_u^2 = U D_\nu U^T$: effective light neutrino mass matrix
- D_e : charged Yukawa couplings

$\Rightarrow$ 12 parameters in the lepton sector

Type 1 seesaw has 21 parameters (bottom-up parametrisation) :

- D_ν : 3 light neutrino masses
- U_{MNS} : 3 mixing angles, Dirac phase δ, Majorana phases α and β
- $\lambda\lambda^\dagger = V_L^\dagger D_\lambda^2 V_L$: 3 neutrino Yukawa couplings, 3 mixing angles, 3 phases
- D_{Y_e} : 3 charged Yukawa couplings

Thermal leptogenesis

$$\mathscr{L}_{seesaw} = (\bar{\ell}_L^i H_d^*)\mathbf{Y}_{\mathbf{e}ij}^* e_R^j + (\bar{\ell}_L^i H_u^*)\lambda^*{}_{iJ} N^J + \overline{N^c}^J \frac{\mathbf{M}^*{}_{JK}}{2} N^K + h.c.$$

- Hierarchical N masses : $M_1 \sim 10^9$ GeV $\gg M_2, M_3$
- Thermal production of the N_1 (and negligeable production of N_2)

The process :

- N_1 produced by scattering processes at $T \sim M_1$
- N_1 decay violating CP $\Rightarrow$ production of lepton asymmetry
- If inverse decays are out of equilibrium the asymmetries may survive
- The lepton asymmetry is converted into baryon asymmetry by sphalerons

Thermal leptogenesis

- Produce the maximal thermal N density if production rate is fast enough (e.g. $\Gamma(q_L t_R \to \phi \to \ell N)$) :

$$\Gamma_{prod} \sim \frac{h_t^2 \lambda^2}{4\pi} T > H$$

- Lepton asymmetry produced if N decay are CP violating and out of equilibrium and inverse decays are turn off :

$$\epsilon = \frac{\Gamma(N_1 \to \phi\ell) - \Gamma(N_1 \to \overline{\phi}\,\overline{\ell})}{\Gamma(N_1 \to \phi\ell) + \Gamma(N_1 \to \overline{\phi}\,\overline{\ell})}$$

$$\Gamma_{ID} \equiv \Gamma(l\phi \to N_1) = \Gamma_{decay} e^{-M1/T} = \frac{[\lambda\lambda^\dagger]_{11} M_1}{8\pi} e^{-M_1/T} < H = \frac{10T^2}{m_{pl}}$$

- When $\Gamma_{ID} \sim H \quad \Rightarrow \quad n_N/n_\gamma \simeq e^{-M_1/T} \simeq H/\Gamma_{decay}$
- Lepton asymmetry $\to$ baryon asymmetry :

$$Y_B \sim \frac{1}{3} Y_L = \frac{n_l - n_{\bar{l}}}{n_N} \frac{n_N}{n_\gamma} \sim \frac{H}{3g_*} \frac{\epsilon}{\Gamma_{decay}}$$

Flavour in leptogenesis

- Rates for interactions involving charged lepton yukawas :

$$\Gamma_\alpha \sim 5 \times 10^{-3} h_\alpha^2 T$$

If this rates are in equilibrium $\Rightarrow$ flavours become distinguishable[1][2][3] :

- $\Gamma_\tau > H$ for $T < 10^{12}$ GeV
- $\Gamma_\mu > H$ for $T < 10^{9}$ GeV

$\Rightarrow$ Between 10^9 GeV and 10^{12} GeV we can distinguish the τ flavour (which is in equilibrium) from the others :

$$\hat{\ell}_o = \frac{\lambda_{\mu 1}\hat{\mu} + \lambda_{e1}\hat{e}}{\sqrt{|\lambda_{\mu 1}|^2 + |\lambda_{e1}|^2}}$$

- The lepton asymmetries ϵ_τ and ϵ_0 evolve separately

[1] R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, hep-ph/9911315
[2] A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0601083
[3] E. Nardi, Y. Nir, E. Roulet and J. Racker, hep-ph/0601084

Flavour in leptogenesis

- Produce the maximal thermal N density if production rate is fast enough (e.g. $\Gamma(q_L t_R \to \phi \to \ell_\alpha N)$) :

$$\Gamma_{prod} = \sum_\alpha \Gamma_{prod}(\to \phi \ell_\alpha) \sim \sum_\alpha \frac{h_t^2 |\lambda|^2_{\alpha 1}}{4\pi} T > H$$

- Lepton asymmetry in flavour α (produced in N decay) survives when inverse decays from flavour α are turn off :

$$\epsilon_{\alpha\alpha} = \frac{\Gamma(N_1 \to \phi \ell_\alpha) - \Gamma(N_1 \to \overline{\phi}\, \overline{\ell}_\alpha)}{\Gamma(N_1 \to \phi \ell_\alpha) + \Gamma(N_1 \to \overline{\phi}\, \overline{\ell}_\alpha)}$$

$$\Gamma_{\alpha\alpha} \equiv \Gamma(l_\alpha \phi \to N_1) \simeq \frac{|\lambda|^2_{\alpha 1} M_1}{8\pi} e^{-M_1/T} < H = \frac{10 T^2}{m_{pl}}$$

- At T_α, when inverse decays from flavour α turn off :

$$\frac{n_N}{n_\gamma}(T_\alpha) \simeq e^{-M_1/T_\alpha} \simeq \frac{H}{\Gamma_{\alpha\alpha}}$$

$$Y_B \sim \frac{1}{3} \sum_\alpha \frac{n_l - n_{\bar{l}}}{n_N} \frac{n_N}{n_\gamma} \sim \frac{H}{3 g_*} \sum_\alpha \frac{\epsilon_{\alpha\alpha}}{\Gamma_{\alpha\alpha}} \neq \frac{H}{3 g_*} \frac{\sum_\alpha \epsilon_{\alpha\alpha}}{\sum_\beta \Gamma_{\beta\beta}}$$

The question

- The relation between CP violation at low energy (measurable in neutrino oscillations) and CP violation at high energy ?

Given the measured value of the baryon asymmetry, can an allowed range for the U_{MNS} phases be predicted ?

- First answer in Branco et al.[4] in leptogenesis without flavour
- Easily seen with Casas-Ibarra parametrisation and hierarchical RH neutrinos :

$$\lambda = U D_k^{1/2} R D_M^{1/2} \quad \Rightarrow \quad \epsilon = -\frac{3M_1}{16\pi v^2} \frac{\Im(\sum_\rho m_\rho^2 R_{\rho 1}^2)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

$\Rightarrow$ ϵ is independent of U_{MNS} phases

- We want to address the same problem in flavoured leptogenesis

[4] Branco, Morozumi, Nobre and Rebelo, hep-ph/0107164

Analytic result

In flavoured leptogenesis :

$$\epsilon_{\alpha\alpha} = -\frac{3M_1}{16\pi v^2}\frac{\Im(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{\beta 1} R_{\rho 1})}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

We look for an area of the parameter space where :

- We have enough baryon asymmetry
- Y_B is independent from low energy phases

It is found :

- In strong wash-out regime
- Using a simple form for R :

$$R = \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix}$$

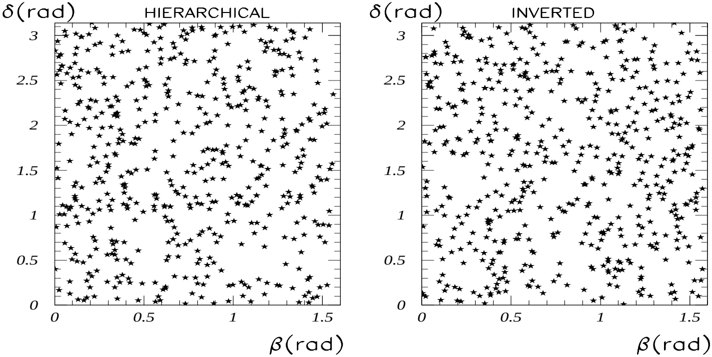
We can write Y_B independentely from the low energy phases (with $\phi = \rho + i\omega$) :

$$Y_B \simeq 10^{-10}\left(\frac{M_1}{10^{11}\mathrm{GeV}}\right)\frac{\sin\rho\cos\rho\sinh\omega\cosh\omega}{\sin^2\rho\cosh^2\omega + \cos^2\rho\sinh^2\omega}$$

Parameter scan

- Random selection of points where the baryon asymmetry is large enough
- Neutrino masses are taken non degenerate
- Dirac phase defined such that $U_{e3} = \sin\theta_{13}^{-i\delta}$
- The baryon asymmetry arises in the decay of N_1 with mass $M_1 = 10^{10}$ GeV

Parameter scan



A large enough baryon asymmetry can be obtained

for any values of the U_{MNS} phases

Leptogenesis in minimal supergravity

Next step :

- Analysis performed in leptogenesis with minimal supergravity
- Enhanced flavour violating processes due to RGE running of the sneutrino mass matrix, e.g. :

$$BR(\mu \to e\gamma) = \frac{\alpha^3 \tan^2\beta}{G_F^2 m_{SUSY}^8} \left| \frac{1}{8\pi^2}(3M_0^2 + A_0^2)\lambda_{ek}\lambda^\dagger_{k\mu} \log(\frac{M_X}{m_{M_k}}) \right|^2$$

$\Rightarrow$ Measurable observables : $\lambda\lambda^\dagger = V_L^\dagger D_\lambda^2 V_L$

- Effects on electric dipole moments
- Parameter scan with Markov Chain Monte Carlo
- Results soon...

Conclusions

- The relevant question in discussing “relation” between CP violation in the U_{MNS} matrix :

Is the baryon asymmetry *sensitive* to the U_{MNS} phases ?

- The answer was *NO* for unflavoured leptogenesis in the SM seesaw (Branco et al.)

- We argue that the answer does not change also with the inclusion of flavour effects in leptogenesis :

For any value of the U_{MNS} phases it is possible to find a point in the space of unmeasurable seesaw parameters such that leptogenesis works