KING'S College LONDON Founded 1829

String Theory and CPT Violating Baryon Asymmetry in the Universe

Sarben Sarkar
Theoretical Particle Physics and Cosmology Group
Department of Physics
King's College London

London Institute for Field Theory and Particle Physics

LIFTaPP

Baryogenesis

Problem:

- Standard model has symmetry between matter and antimatter
- In the universe there is no significant primordial antimatter

Standard model symmetry

$$SU(3)_c \times SU(2)_W \times U_Y$$

$$\text{Triangle anomaly} \Longrightarrow B - L \text{ conserved}$$

Sakharov's conditions

$$X \to Y + B$$
$$\bar{X} \to \bar{Y} + \bar{B}$$

1. Need mechanisms that violate B
2. C and CP not conserved
3. Departure from thermal equilbrium

$$X \to Y_{\begin{pmatrix} R \\ L \end{pmatrix}} + B_{\begin{pmatrix} R \\ L \end{pmatrix}}$$
$$\bar{X} \to \bar{Y}_{\begin{pmatrix} L \\ R \end{pmatrix}} + \bar{B}_{\begin{pmatrix} L \\ R \end{pmatrix}}$$

$$L \text{ violation} \Rightarrow B \text{ violation}$$

Leptogenesis to Baryogenesis

Measure of Baryon Asymmetry

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}$$

n_B is number density of baryons

$n_{\bar{B}}$ is number density of antibaryons

s is the entropy density

$$Y_{\Delta B} = O\left(10^{-10}\right)$$

In era of nucleosynthesis

Problem: standard sources CP violation many orders of magnitude too small to give magnitude of (although clever schemes such as resonant leptogenesis.

$Y_{\Delta B}$

New source of CP violation from gravitational physics in string theory

The lowest lying energy multiplet in superstring theory:
bosonic part:

g_{MN} graviton

ϕ spin 0 scalar

B_{MN} antisymmetric tensor

String theory propagation in such background fields

Impose conformal invariance

vanishing of Weyl anomaly coefficients

Target space Framework

$d = 4$ large (non-compact) dimensions

remaining $D - 4$ *conformal* field theory

$$g_{\mu\nu}(x), B_{\mu\nu}(x), \phi(x)$$

$$H^{\lambda}_{\mu\nu} = e^{2\phi} \varepsilon^{\lambda}_{\mu\nu\rho} \partial^{\rho} b$$

Vanishing of Weyl anomaly coefficients

$$R_{\mu\nu} = \frac{1}{2}\partial_\mu\phi\,\partial_\nu\phi + \frac{1}{2}g_{\mu\nu}\nabla^2\phi + \frac{1}{2}e^{2\phi}\left[\partial_\mu b\,\partial_\nu b - g_{\mu\nu}(\partial b)^2\right]$$

$$\nabla^2 b + 2\,\partial_\lambda b\,\partial^\lambda\phi = 0$$

$$\delta c = -3e^{-\phi}\left[\begin{array}{l} -R + \nabla^2\phi + \\ \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}e^{2\phi}(\partial b)^2 \end{array}\right]$$

A possible background

$$ds_E^2 = -(dt)^2 + t^2\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

$$\phi = -2\log t + \phi_0$$

$$b = 2e^{-\phi_0}\sqrt{kt}$$

I Antoniadis, C Bachas, J R Ellis and D V Nanopoulos, Nucl Phys B 328 117 (1989)

Investigate consequences of this background

Low energy string effective action

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left(\boldsymbol{R} - 2\partial^\mu\phi\partial_\mu\phi - \boldsymbol{e^{-4\phi}H_{lmn}H^{lmn}}\right)$$

Terms in bold can be rewritten as *R* *but* with a modified Christoffel symbol

D J Gross and J H Sloan, Nucl Phys B 291 41 (1987)

$$\overline{\Gamma}^{\lambda}_{\mu\nu} = \Gamma^{\lambda}_{\mu\nu} + e^{-2\phi}H^{\lambda}_{\mu\nu}$$

$$\overline{\Gamma}^{\lambda}_{\mu\nu} \neq \overline{\Gamma}^{\lambda}_{\nu\mu}$$

Torsion

Action for Fermions in Background

Ψ is a 4-spinor

$$\gamma^{\mu}(x) = e_a^{\mu}(x)\gamma^a$$

$$g_{\mu\nu}(x) = \eta_{ab} e_{\mu}^{a}(x) e_{\nu}^{b}(x)$$

$$e_a^{\mu} e_{b\mu} = \eta_{ab}$$

$SO(3,1)$ gauge symmetry

$$\bar{\nabla}_a \psi = e_a^\mu \left(\partial_\mu + \frac{i}{2} \varpi_{a\mu b} \Sigma^{ab} \right) \psi$$

$$\varpi_{a\mu b} = e_\nu^a \left(\partial_\mu e^{b\nu} + \bar{\Gamma}^\nu_{\mu\lambda} e^{b\lambda} \right)$$

$$S_{Dirac} = \frac{1}{2} \int d^4x \sqrt{-g} i \left(\bar{\psi} \gamma^a \bar{\nabla}_a \psi - \bar{\nabla}_a \bar{\psi} \gamma^a \psi - 2im \bar{\psi} \psi \right)$$

Equivalent to

$$S_{Dirac} = \frac{1}{2} \int d^4x \sqrt{-g} \bar{\psi} \left(i \gamma^a \partial_a + B_d \gamma^5 \gamma^d - m \right) \psi$$

$$B^d = \frac{1}{4} \varepsilon^{abcd} e_a^\mu e_{b\nu} \left(\partial_\mu e_c^\nu + e^{-2\phi} H^\nu_{\mu\lambda} e_c^\lambda \right)$$

Spinors in an Axial Background Field

B^0 Is a constant $B^i = 0$

Dispersion relations:

$$U_\mu U^\mu V_\nu V^\nu - 2m^2 U_\mu V^\mu + m^4 = 0$$

where $U_\mu = p_\mu - B_\mu$ $V_\mu = p_\mu + B_\mu$

$$E_r^2 = m^2 + \left(B_0 + \lambda_r \left|\vec{p}\right|\right)^2 \qquad \lambda_r \equiv (-1)^{r-1} \qquad r = 1,2$$

λ_r helicity eigenvalues

Based on work with Ellis, Mavromatos and de Cesare

1. M Fukugita and T Tanagida, Phys. Lett. B174 45 (1986)
2. N E Mavromatos and S Sarkar , Eur Phys J C 73 2359 (2013)
3. J Ellis, N E Mavromatos and S Sarkar, Phys Lett B 725 407 (2013)
4. M de Cesare, N E Mavromatos and S Sarkar, Tree Level Leptogenesis from Kalb-Ramond Torsion Background

Universality of torsion coupling to fermions

Transformation properties of $\bar{\psi}\gamma^a\gamma^5\psi$ under,C, P,T and CPT

C	1
P	$-(-1)^a$
T	$(-1)^a$
CPT	-1

$$(-1)^a = \begin{cases} 1 & for\ a = 0 \\ -1 & for\ a \neq 0 \end{cases}$$

B_0 CP violating

PT violating always

Leptogenesis model

$$L = i\bar{N}\partial N - \frac{M}{2}\left(\bar{N}^c N + \bar{N}N^c\right) - \bar{N}B\gamma_5 N - Y_k \bar{L}_k \tilde{\phi} N + h.c.$$

where $\tilde{\phi}_i = \varepsilon_{ij}\phi_j$ $N^c = -i\gamma^2 N^*$

N right-chiral Majorana neutrino

L_k is left-chiral Standard Model lepton doublet

$$\left(Y_k \bar{L}_k \tilde{\phi} N\right)^\dagger = Y^* \bar{L}_c \tilde{\phi}^\dagger N^c$$

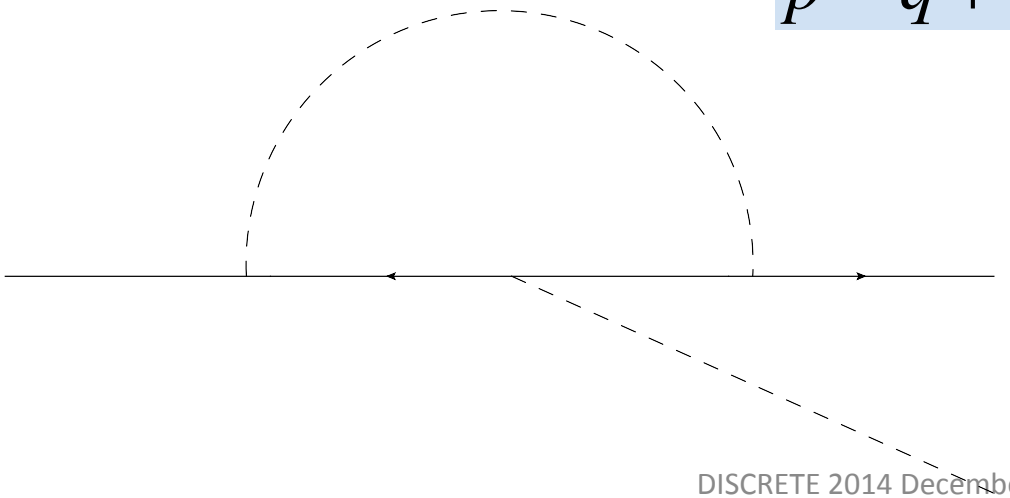
$$N^c = N$$

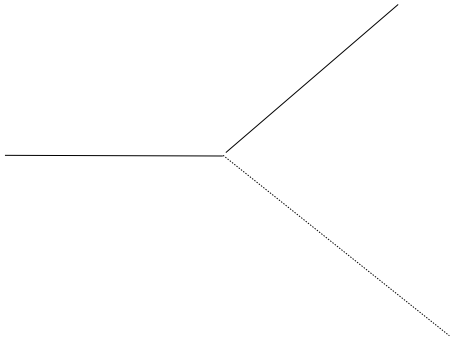
Majorana condition

Γ_1 : $N \to \bar{\phi} + L$ Γ_2 : $N \to \phi + \bar{L}$

$$E_{p,r} = E_{q,s} + E_k$$

$$\vec{p} = \vec{q} + \vec{k}$$





$$\Gamma_1 = \sum_k \frac{|Y_k|^2}{32\pi^2} \frac{m^2}{\Omega} \frac{\Omega + B_0}{\Omega - B_0}$$

$$\Gamma_2 = \sum_k \frac{|Y_k|^2}{32\pi^2} \frac{m^2}{\Omega} \frac{\Omega - B_0}{\Omega + B_0}$$

$$\Gamma = \Gamma_1 + \Gamma_2 \qquad \Omega \equiv \sqrt{B_0^2 + m^2} \qquad r \equiv \frac{\Gamma_1}{\Gamma}$$

Decay of a single N produces on average

$$\Delta L = r - (1 - r) = 2r - 1 = \frac{2\Omega B_0}{\Omega^2 + B_0^2}$$

Decay out of equilibrium

$$\Rightarrow \quad \Gamma \simeq H \qquad \textit{Hubble rate}$$

$$H = 1.66\, T^2 N^{1/2} M_P{}^{-1}$$

$$T_D \simeq 6.2\, 10^{-2}\, \frac{|Y|}{N^{1/4}} \sqrt{\frac{m_P \left(\Omega^2 + B_0{}^2\right)}{\Omega}}$$

Also require that $k_B T < \Omega$

$$n_N = \sum_{\lambda} \frac{1}{(2\pi)^3} \int d^3 p \, f(p,\lambda)$$

At high temperatures

$$f(p,\lambda) = \exp\left(-\beta\sqrt{m^2 + (p + \lambda B_0)^2}\right)$$

$$\Delta L^{Total} = \frac{2\Omega B_0}{\Omega^2 + {B_0}^2} n_N$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10} \Rightarrow \frac{B_0}{m} \sim 10^{-7}$$

$B_0 \sim 0.1 Gev$

CPT and non-equilibrium

T is the time reversal operator; write CPT $\equiv\Theta$

CPT theorem: a local, Lorentz-invariant unitary

QFT is invariant under Θ (Schwinger, Pauli, Luders, Jost, Bell; more recently Greenberg, Chaichian,Dolgov,Novikov)

Criterion (3) assumes the validity of the CPT invariance ($[H,\Theta]=0$), *H* being the Hamiltonian.

Equilibrium average of *B* (= $\langle B\rangle$)

$$\langle B\rangle = Tr\left(e^{-\beta H}B\right) = Tr\left(\Theta\Theta^{-1}e^{-\beta H}B\right) = Tr\left(e^{-\beta H}\Theta^{-1}B\Theta\right)$$

However $\{\Theta,B\}=0$ and so $\langle B\rangle = 0 \Longrightarrow$ Requirement for nonequilibrium