Title: 13/14 PSI - Explorations in Particle Theory - Lecture 14

Date: Apr 25, 2014 09:00 AM

URL: http://pirsa.org/14040071

Abstract:

Final presentations:

Wed, May 7, morning

Yesterday: SM

1) $\cancel{B}$ ✓ $\quad \cancel{B}, \cancel{L}$, $B-L$ conserved.

2) $\cancel{CP}$ → CKM phase, too small ✗

3) Departure from eq → electroweak phase transition ✗

XIV Leptogenesis

Sphalerons violate B, L

conserve $B-L$

sphalerons tend to make $B \simeq$

So if I create a

asymmetry at

this $L_{tt} \longrightarrow$

XIV Leptogenesis

Sphalerons violate B, L
conserve $B-L$

sphalerons tend to make $B \approx L$

So if I create a lepton asymmetry at $T \gtrsim V$,
this $L_{tot} \longrightarrow B_{tot}$

Want to break $U(1)_{B-L}$

All SM fields charged under $U(1)_B$ are also charged under $SU(3)_c$

$\longrightarrow$ it can happen, the models are a little complicated.

Leptons: We have leptons in the broken phase are neutral, ν

$\rightarrow$ natural framework for breaking global symmetries

X

Roadmap

① Neutrino masses

② Sakharov conditions in leptogenesis

③ Asymmetry generation

① Neutrino masses

In the SM, neutrinos are massless.

$$Y_\ell \overline{l}_R H^\dagger l_L \longrightarrow \frac{y_\ell v}{\sqrt{2}} l_R^+ l_L^-$$

mass for e, μ, τ.

It turns out $m_\nu \neq 0$

$$m_{\nu\,\text{heaviest}} \sim 0.05 \text{ eV}$$
$$m_e \sim 500 \text{ keV}$$

Mass for neutrinos = new RH neutrinos.

$$Y_u \overline{Q}_L H u_R + Y_d \overline{Q}_L H^\dagger d_R$$

$\Delta Y = 1$

$$Y_\ell \overline{l}_L H^\dagger l_R + Y_\nu \overline{l}_L H \nu_R \qquad Y = 0.$$

$\nu_R \rightarrow SU(2)$ singlet, $SU(3)$ singlet, $Y = 0$

Write down all gauge-inv. interactions

$$\mathcal{L} = y_\nu \bar{\ell}_L H \nu_R + \frac{1}{2} m_N \bar{\nu}_R^c \nu_R$$

this term breaks $U(1)_L$

$\nu\nu + \nu^\dagger \nu^\dagger$

$m_N \to 0$

This action explicitly breaks $U(1)_L$

$\nu_R \to e^{i\alpha} \nu_R$

$\bar{\nu}_R^c \to e^{i\alpha} \bar{\nu}_R^c$

After electroweak symmetry breaking:

$$\frac{y_\nu v}{\sqrt{2}} \bar{\nu}_L \nu_R + \frac{m_N}{2} \bar{\nu}_R^c \nu_R$$

$\frac{1}{2} m_N \bar{\nu}_R^c \nu_R^c$

$\longrightarrow \frac{1}{2} m_N e^{2i\alpha} \bar{\nu}_R^c \nu_R$

Physical masses:

$$m_{light} = \frac{y_\nu^2 v^2}{2 m_N}$$ SM neutrino

$m_{heavy} \simeq m_N$ new RH neutrino

$m_{light} \sim (\text{Dirac mass}) \left(\frac{v}{m_N}\right)$

$\boxed{m_N \gg v}$, m_{light} very tiny

Call... mo...

We ... expl... ma...

(2) Sak...

i) B...

Called the see-saw mechanism

We see that ν_R can explain observed ν_L masses

② Sakharov conditions

i) $\not{B} \rightarrow \checkmark$

combination of $\not{L}$ + sphalerons (provided $m_N > v$)

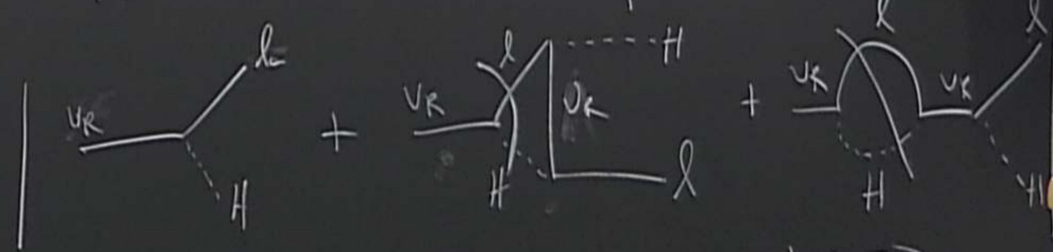
③ $\not{CP}$: ✓ We have new Yukawa coupling Y_ν → 3×3.

↳ 3 new CP phases GOOD

· CP-odd phase

we also needed a CP-even phase

$|M|^2 \sim |$



$m_N > v \ (m_\ell, m_H)$ on-shell in loop $\Rightarrow$ Im (loop)

We get $\Gamma(\nu_R \to \ell H) - \Gamma(\nu_R \to \bar{\ell} H^*) \neq 0$

$$\varepsilon \equiv \frac{\Gamma(\nu_R \to \ell H) - \Gamma(\nu_R \to \bar{\ell} H^*)}{\Gamma(\nu_R \to \ell H) + \Gamma(\nu_R \to \bar{\ell} H^*)}$$

$\longrightarrow$ # of excess ℓ vs $\bar{\ell}$ PER ν_R decay

Assume ν_{R_1} is the most important

$$\boxed{\varepsilon = \frac{1}{8\pi} \frac{1}{(Y_\nu Y_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(Y_\nu Y_\nu^\dagger)^2\right]_{1i} f\left(\frac{M_{N_i}^2}{M_{N_1}^2}\right)}$$

$\neq 0$

$$f(x) = \sqrt{x}\left[1 + (1+x)\log\left(\frac{1+x}{x}\right)\right] + \frac{\sqrt{x}}{1-x}$$

③ Departure from equilibrium

New couplings (can be small) $\rightarrow \Gamma/H < 1$

New mass thresholds $\rightarrow e^{-m_N/T}$

Have some scales at which you can go out of eq. $\rightsquigarrow \Gamma/H < 1$

$\rightarrow$ Details $\rightarrow$ compute the Boltzmann eq.

$$\left(\frac{M_{N_i}^2}{M_{N_1}^2}\right)$$

Boltz

A fe

Boltzmann eq: Most is similar to DM

$$\dot{n}_\ell + 3H n_\ell = -\tilde{C}[\ell, \cdots]$$

A few differences:

a) cannot assume CP symmetry.

$$\int d\Pi \cdots [|M|^2_{\rightarrow} f_i - |M|^2_{\leftarrow} f_f]$$

$$|M|^2_{\rightarrow} = (1 + \tfrac{\varepsilon}{2})|M_0|^2$$

$$|M|^2_{\leftarrow} = (1 - \tfrac{\varepsilon}{2})|M_0|^2 \quad \rightarrow \text{keep leading order in } \varepsilon$$

b) cannot assume $\mu_\ell = 0$

$$f = e^{-(E+\mu)/T}$$

$$\frac{\mu_\ell}{T} \propto \frac{n_\ell - n_{\bar{\ell}}}{T^3}$$

$\mu_H = \mu_{\nu_R} = 0$

its own antiparticle

c) Multiple processes + fields.

ν_R, $\ell - \bar{\ell}$

$\nu_R \to \ell H$

$\nu_R \to \bar{\ell} H^*$

$\ell H \to \bar{\ell} H^*$

$T \sim \nu_R$

· subtraction

Some things stay the same

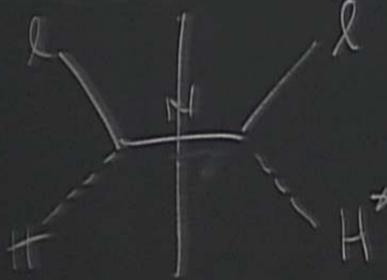
- assume kinetic eq.
- assume SM fields are in full thermal eq.

$$\frac{dY_{\nu_R}}{dx} = -\frac{x}{H(m_{\nu_R})}\langle\Gamma_{\nu_R}\rangle\left(Y_{\nu_R} -\right.$$

$\nu_R \to \ell H$

$\nu_R \to \bar{\ell} H^*$

$\ell H \to \bar{\ell} H^*$



$T \sim \nu_R$

· subtraction

Some things stay the same

◦ assume kinetic eq.

◦ assume SM fields are in full thermal eq.

$$\frac{dY_{\nu_R}}{dx} = -\frac{x}{H(m_{\nu_R})}\langle \Gamma_{\nu_R}\rangle \left(Y_{\nu_R} - Y_{\nu_R}^{eq}\right)$$

$\nu_R \to \ell H \qquad \langle \Gamma \rangle \simeq \Gamma_{\nu_R}$

for $T \lesssim \nu_R$

$$x = \frac{m_{\nu_R}}{T}, \quad Y = \frac{n_{\nu_R}}{s}$$

$$\frac{d}{dx}$$

$$\frac{d}{dx}(Y_\ell - Y_{\bar\ell}) = \varepsilon \frac{x}{H(m_{\nu_R})} \langle \Gamma_{\nu_R} \rangle \left(Y_{\nu_R} - Y_{\nu_R}^{eq} \right)$$

creating an asymmetry in ℓ vs $\bar\ell$

$$- \frac{x}{H(m_{\nu_R})} \, s \langle \sigma(\ell H \to \bar\ell H^*) v \rangle (Y_\ell^{eq})^2 \, Y_{\ell - \bar\ell}$$

washout (destruction of asymmetry)

For out of eq → turn off washout, but asymmetry gen stay on

$\langle \Gamma_{\nu_R} \rangle \left(Y_{\nu_R} - Y_{\nu_R}^{eq} \right)$

$\to \ell H \quad \langle \Gamma \rangle \approx \Gamma_{\nu_R}$

for $T \lesssim \nu_R$

$Y = \frac{n_R}{s}$

Solution:

I	II
washout is fast	washout is slow
$n_\ell\langle\sigma v\rangle > H$	$n_\ell\langle\sigma v\rangle < H$

$$\longrightarrow x = \frac{m_{\nu_R}}{T}$$

I

$$\frac{dY_{\ell-\bar\ell}}{dx} = -\frac{x}{H(m_{\nu_R})}\, s\langle\sigma v\rangle \left(Y_\ell^{eq}\right)^2 Y_{\ell-\bar\ell}$$

$$= -C(x)\, Y_{\ell-\bar\ell} \longrightarrow Y_{\ell-\bar\ell} \sim Y_{\ell-\bar\ell}(0)\, e^{-\int C(x)dx} \approx 0$$

(II) $$\frac{dY_{\ell-\bar{\ell}}}{dx} = \frac{\varepsilon\, x}{H(m_{\nu R})} \langle \Gamma_{\nu R} \rangle \left(Y_{\nu R} - Y_{\nu R}^{eq} \right)$$

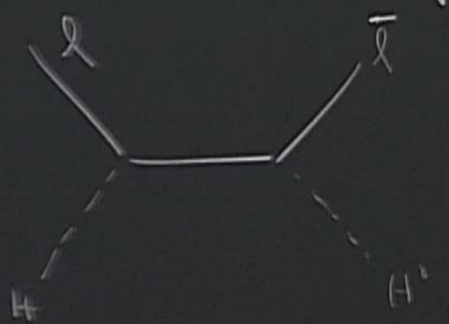
$$= -\varepsilon \frac{dY_{\nu R}}{dx}$$

$$\boxed{Y_{\ell-\bar{\ell}}(\infty) = \varepsilon\, Y_{\nu R}(x_{fo})}$$

* ALL DECAYS of ν_R AFTER

FREEZE-OUT GENERATE L-Σ

of washout $\ell H \to \bar{\ell} H^*$



$$\langle \sigma v \rangle \sim \frac{y^4}{8\pi} \frac{m_N^2}{m_N^4} \sim \frac{y^4}{8\pi} \frac{1}{m_N^2}$$

$$m_N \sim M_{P1} \longrightarrow Y_{\nu_R}(x_{fo}) = Y^{eq}_{\nu_R}(x_{fo})$$

If $\Gamma_{\nu_R} < H$

$$\tau_{\nu_R} > t^{-1} \longrightarrow Y_{\nu_R}(x_f) \gg Y^{eq}_{\nu_R}(x_f)$$

$$Y_l - Y_{\bar{l}} \sim 10^{-10} \Rightarrow \boxed{m_{\nu_R} > 10^{9}\,\mathrm{GeV}}$$