Baryogenesis

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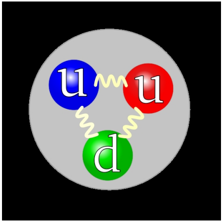
Student Seminar Theoretical Physics 2008-2009

December 20, 2008

Baryons and Baryon Number

Baryon: a particle consisting of three quarks, with a baryon number $B = 1$
Examples: proton, neutron



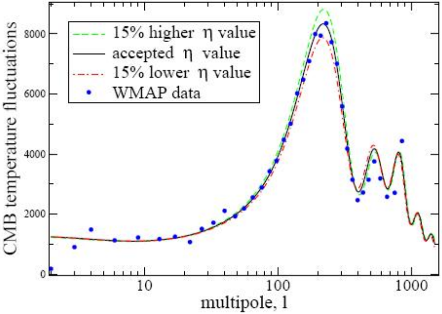
$$B = \frac{N_q - N_{\bar{q}}}{3}$$

for baryons $B = 1 \rightarrow$ triquarks, pentaquarks (?)

Baryon Number of the Universe $\simeq$ Number of Baryons in the Universe

Observational Evidence for Baryon Asymmetry

- More matter than antimatter
- Baryon-to-photon density ratio η obtained from BBN and CMB



$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10} \quad \text{(WMAP 2008)}$$

Better: Baryon-to-entropy density ratio $\frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s} \simeq \frac{1}{7.04}\eta$

Homogeneous Baryon Symmetric Universe

- $B = 0$
- Equal amount of particles and antiparticles
- Freeze out

$$\frac{n_b}{n_\gamma} = \frac{n_{\bar{b}}}{n\gamma} \simeq 10^{-20}$$

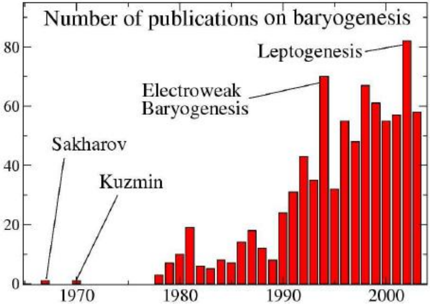
  Too small!
- Inflation excludes 'initial conditions'

How can the baryon asymmetry be created from an initially baryon symmetric universe?

Baryogenesis

Baryogenesis: dynamical generation of a non-zero baryon number from an initially baryon symmetric universe

- B (nearly) conserved in Standard Model
- Mid 1970's: B-violating GUT theories



Baryogenesis

Baryogenesis: dynamical generation of a non-zero baryon number from an initially baryon symmetric universe

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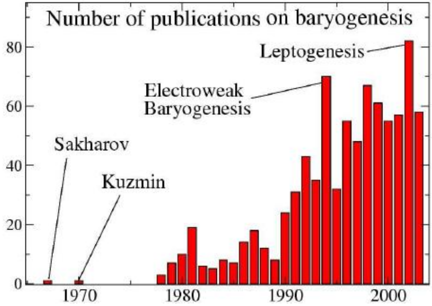


But: 1967(!) Sakharov realizes need for dynamically creating the baryon asymmetry $\rightarrow$ Baryogenesis

Sakharov's conditions

"According to our hypothesis, the occurence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot Universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions." [1]

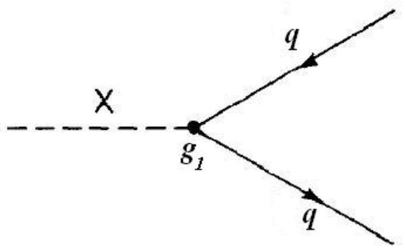
Three conditions:

- 1: Baryon number violation
- 2: C and CP violation
- 3: Departure from Thermal Equilibrium

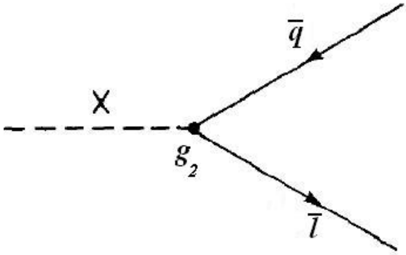
[1] A.D Sakharov, *JETP Lett.* **6**, 24 (1967)

1: Baryon Number Violation

Simple model: $\mathcal{L}_{int} = g_1 X q^\dagger q + g_2 X \bar{q}^\dagger \bar{l} + \text{h.c.}$



Branching ratio r



Branching ratio $1 - r$

$$r = \frac{\Gamma(X \to qq)}{\Gamma(X \to qq) + \Gamma(X \to \bar{q}\bar{l})}$$

1: Baryon Number Violation

Particle	Final state	Branching ratio	B	L
X	qq	r	$B_1 = \frac{2}{3}$	0
X	$\bar{q}\bar{l}$	$1-r$	$B_2 = -\frac{1}{3}$	-1
$\bar{X}$	$\bar{q}\bar{q}$	$\bar{r}$	$-B_1 = -\frac{2}{3}$	0
$\bar{X}$	ql	$1-\bar{r}$	$-B_2 = \frac{1}{3}$	1

$$\begin{aligned}\Delta B &= rB_1 + (1-r)B_2 - \bar{r}B_1 - (1-\bar{r})B_2 \\ &= (r-\bar{r})(B_1 - B_2) \\ &= r - \bar{r}\end{aligned}$$

$\longrightarrow$ Non-zero only when both C and CP are violated

2: C Violation

Consider reaction

$$X \to Y + B$$

C conserved:

$$\Gamma(X \to Y + B) = \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$

thus

$$r - \bar{r} \equiv \frac{\Gamma(X \to Y + B) - \Gamma(\bar{X} \to \bar{Y} + \bar{B})}{\Gamma_X} = 0$$

$$\to \Delta B = 0 \quad !$$

C violation is necessary for baryogenesis!

2: CP Violation

Consider example

$$X \to q_L q_L, \quad X \to q_R q_R$$

C violation:

$$\Gamma(X \to q_L q_L) \neq \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$$

CP conservation:

$$\Gamma(X \to q_L q_L) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R)$$

then

$$\begin{aligned} r - \bar{r} &\equiv \frac{\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_X} \\ &= \frac{1}{\Gamma_X}\Big[\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) \\ &\quad -\Gamma(\bar{X} \to \bar{q_L}\bar{q_L}) - \Gamma(\bar{X} \to \bar{q_R}\bar{q_R})\Big] = 0 \\ &\quad \to \Delta B = 0 \quad ! \end{aligned}$$

C **and** CP violation are necessary for baryogenesis!

3: Departure from Thermal Equilibrium

In equilibrium

$$n_b = n_{\bar{b}}$$

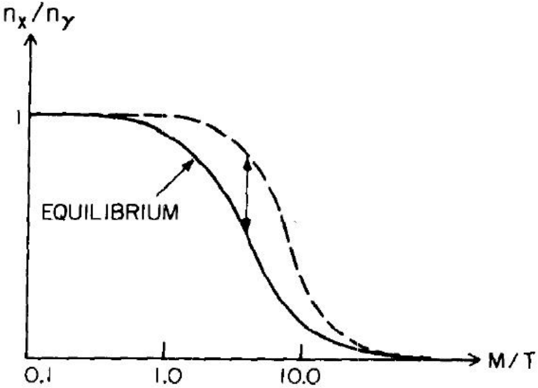
How to depart from equilibrium?

- For $T \gg M_X$, $n_X = n_{\bar{X}} \simeq n_\gamma$
- For $T < M_X$, equilibrium abundance of X is

$$\left(\frac{n_X}{n_\gamma}\right)_{EQ} \simeq (M_X/T)^{3/2} \exp(-M_X/T)$$

- As long as $\Gamma_D > H$, equilibrium abundance is maintained
- When $\Gamma_D < H$, X bosons are overabundant
  $\rightarrow$ departure from equilibrium

3: Departure from Thermal Equilibrium



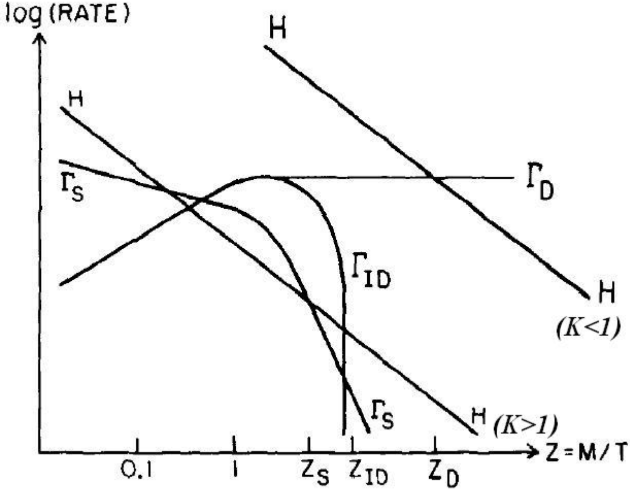
When $\Gamma_D < H$, the abundance of n_X/n_γ does not track the equilibrium value: reactions are too slow

3: Departure from Thermal Equilibrium

Simple model for: Decay rate Γ_D, inverse decay rate Γ_{ID}, Hubble rate H

$$\begin{aligned}
\Gamma_D &\simeq \alpha M_X \begin{cases} M_X/T & T \geq M_X \\ 1 & T \leq M_X \end{cases} \qquad , \alpha \sim g^2/4\pi \\
\Gamma_{ID} &\simeq \Gamma_D \begin{cases} 1 & T \geq M_X \\ (M_X/T)^{3/2} \exp(-M_X/T) & T \leq M_X \end{cases} \\
H &\simeq g_*^{1/2} T^2/m_{pl}
\end{aligned}$$

3: Departure from Thermal Equilibrium



$$K = \left(\frac{\Gamma_D}{H}\right)_{T=M_X}$$

For $K < 1$, departure from equilibrium!

3: Departure from Thermal Equilibrium

Calculation of n_B/s is now very simple:

- For $T \gg M_X$, $n_X = n_{\bar{X}} \sim n_\gamma$
- Each decay creates a net baryon number $\Delta B = r - \bar{r}$
- $s = g_* n_\gamma$, $g_* \simeq 10^2$
- $$\frac{n_B}{s} \simeq \frac{\Delta B n_\gamma}{g_* n_\gamma} = \frac{\Delta B}{g_*}$$

For $n_B/s \simeq 10^{-10}$, we only need a tiny C,CP violation of $\sim 10^{-8}$!

GUT Baryogenesis

- Renormalized couplings as function of energy do not meet at a point
- Include supersymmetry $\rightarrow$ couplings equal at $M_{GUT} \simeq 2 \times 10^{16}$GeV

"Grand Unifying Theories[1]"

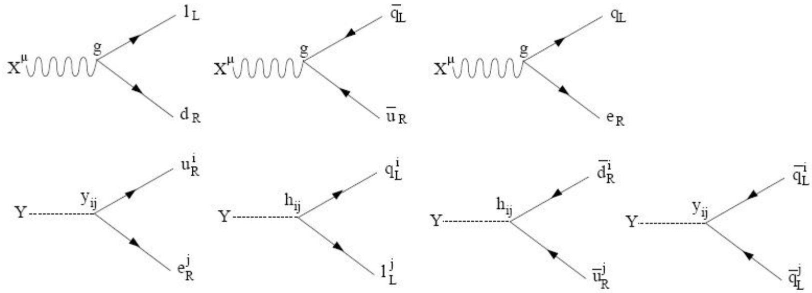
- Standard Model $SU(3) \times SU(2) \times U(1)$ is effective theory
- Unifying gauge theories: $SU(5)$, $SO(10)$, ...

Important: B violating interactions are generic feature of GUTs!
(For example: proton decay, not yet observed)

[1] Buras, Ellis, Gaillard and Nanopoulos, Nucl. Phys. B **135** (1978) 66.
According to John Ellis, at first they didn't have the 'guts' to use the name GUT.

Simplest GUT model: $SU(5)$

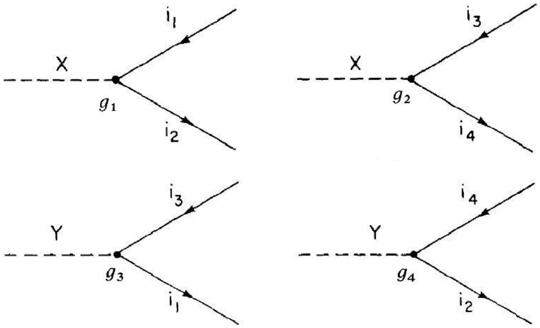
- Heavy gauge bosons X^μ
- Heavy Higgs bosons Y
- B-violating decays of X^μ and Y



- Yukawa couplings h_{ij} and y_{ij} complex $\rightarrow$ CP-violation

Simplified $SU(5)$ GUT

$$\mathcal{L}_{int} = g_1 X i_2^\dagger i_1 + g_2 X i_4^\dagger i_3 + g_3 Y i_1^\dagger i_3 + g_4 Y i_2^\dagger i_4 + \text{h.c.}$$

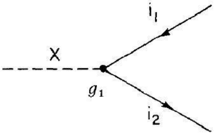


Want to calculate

$$\Delta B = r - \bar{r} = \sum_f B_f \frac{\Gamma(X \to f) - \Gamma(\bar{X} \to \bar{f})}{\Gamma_X}$$

Tree diagram amplitudes and decay rate

- For $X \to \bar{i}_1 i_2$, $\mathcal{M} = g_1 F_X$, and



$$\Gamma(X \to \bar{i}_1 i_2) = |\mathcal{M}_X|^2 = |g_1|^2 |F_X|^2 = |g_1|^2 I_X$$

- Similarly, for $\bar{X} \to i_1 \bar{i}_2$

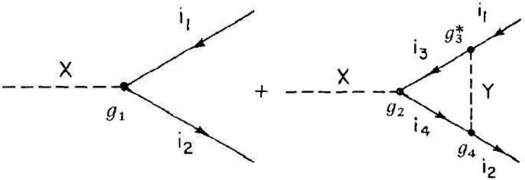
$$\Gamma(\bar{X} \to i_1 \bar{i}_2) = |\mathcal{M}_{\bar{X}}|^2 = |g_1^*|^2 |F_{\bar{X}}|^2 = |g_1^*|^2 I_{\bar{X}}$$

- Since $M_X = M_{\bar{X}} \to I_X = I_{\bar{X}}$,

$$\Delta B = B_{12} \Gamma_X^{-1} \left[\Gamma(X \to \bar{i}_1 i_2) - \Gamma(\bar{X} \to i_1 \bar{i}_2) \right] = 0$$

- At tree level, there is no B violation!

One-loop correction (1)



Now

$$\mathcal{M}_X = g_1 F_X + g_2 g_3^* g_4 F_Y$$

and

$$\begin{aligned}
\Gamma(X \to \bar{i}_1 i_2) &= \mathcal{M}_X^* \mathcal{M}_X \\
&= (g_1^* F_X^* + g_2^* g_3 g_4^* F_Y^*)(g_1 F_X + g_2 g_3^* g_4 F_Y) \\
&= |g_1|^2 |F_X|^2 + |g_2|^2 |g_3|^2 |g_4|^2 |F_Y|^2 \\
&\quad + g_1 g_2^* g_3 g_4^* F_X^* F_Y + (g_1 g_2^* g_3 g_4^* F_X^* F_Y)^* \\
&= |g_1|^2 I_X + |g_2|^2 |g_3|^2 |g_4|^2 I_Y \\
&\quad + g_1 g_2^* g_3 g_4^* I_{XY} + (g_1 g_2^* g_3 g_4^* I_{XY})^*
\end{aligned}$$

One-loop correction (2)

Similarly

$$\Gamma(\bar{X} \to i_1 \bar{i}_2) = |g_1^*|^2 I_X + |g_2^*|^2 |g_3^*|^2 |g_4^*|^2 I_Y + g_1^* g_2 g_3^* g_4 I_{XY} + (g_1^* g_2 g_3^* g_4 I_{XY})^*$$

Thus

$$\begin{aligned} \Gamma(X \to \bar{i}_1 i_2) - \Gamma(\bar{X} \to i_1 \bar{i}_2) &= g_1 g_2^* g_3 g_4^* I_{XY} + (g_1 g_2^* g_3 g_4^* I_{XY})^* \\ &\quad - g_1^* g_2 g_3^* g_4 I_{XY} - (g_1^* g_2 g_3^* g_4 I_{XY})^* \\ &= 2 I_{XY} \mathrm{Im}(g_1 g_2^* g_3 g_4^*) - 2 I_{XY}^* \mathrm{Im}(g_1 g_2^* g_3 g_4^*) \\ &= 4 \mathrm{Im} I_{XY} \mathrm{Im}(g_1 g_2^* g_3 g_4^*) \end{aligned}$$

So

$$\Delta B_{12} = \frac{4 \mathrm{Im} I_{XY} \mathrm{Im}(g_1 g_2^* g_3 g_4^*)}{\Gamma_X} (B_{i_1} - B_{i_2})$$

One-loop correction (3)

Baryon number produced by the decay of X is

$$\Delta B_X = \frac{4\,\mathrm{Im} I_{XY}\,\mathrm{Im}(g_1 g_2^* g_3 g_4^*)}{\Gamma_X}[(B_{i_1} - B_{i_2}) - (B_{i_3} - B_{i_4})]$$

and by Y

$$\Delta B_Y = -\frac{4\,\mathrm{Im} I_{YX}\,\mathrm{Im}(g_1 g_2^* g_3 g_4^*)}{\Gamma_Y}[(B_{i_1} - B_{i_2}) - (B_{i_3} - B_{i_4})]$$

so in total

$$\Delta B = 4\left\{\frac{\mathrm{Im} I_{XY}}{\Gamma_X} - \frac{\mathrm{Im} I_{YX}}{\Gamma_Y}\right\}\mathrm{Im}(g_1 g_2^* g_3 g_4^*)[(B_{i_1} - B_{i_2}) - (B_{i_3} - B_{i_4})]$$

Is GUT Baryogenesis the origin of the baryon asymmetry?

- Inflation dilutes pre-existing baryon number
- Reheating temperature $\sim 10^{16}$ GeV needed to create X bosons
- In most inflationary models $T_{REH} \ll 10^{16}$ GeV
- Also: $T_{REH} > 10^{9}$ GeV leads to production of magnetic monopoles and gravitinos

Are there other mechanisms to understand the baryon asymmetry?

Electroweak Baryogenesis

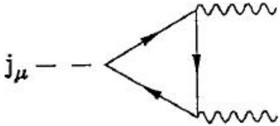
The Standard Model satisfies all of Sakharov's conditions!

- C-violation discovered in 1957, CP violation in 1964
- Out-of-equilibrium conditions in the expanding Universe
  $\rightarrow$ Phase transitions (Example: Electroweak)

What about B violation in the Standard Model?

B violation in the Standard Model

B is violated by the triangle/chiral anomaly



$$\partial_\mu j_B^\mu = \frac{1}{32\pi^2}\mathrm{Tr}(F^{\mu\nu}\tilde{F}_{\mu\nu}) = \frac{1}{32\pi^2}\mathrm{Tr}(F^{\mu\nu}F^{\rho\sigma}\epsilon_{\mu\nu\rho\sigma})$$

But

$$\frac{1}{32\pi^2}\mathrm{Tr}(F^{\mu\nu}\tilde{F}_{\mu\nu}) = \partial_\mu K^\mu$$

with

$$K^\mu = \epsilon^{\mu\nu\lambda\rho}\mathrm{Tr}(F_{\nu\lambda}A_\rho - \frac{2}{3}A_\nu A_\lambda A_\rho)$$

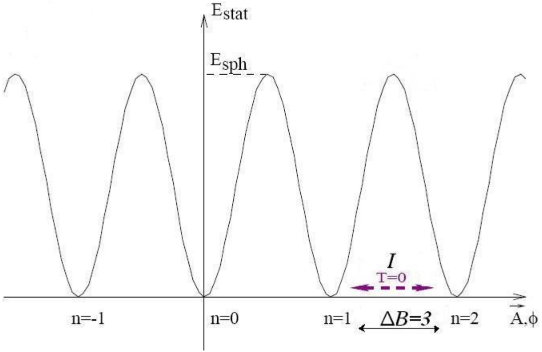
Make a shift:

$$j_B^\mu \to j_B^\mu - K_\mu$$

Perturbatively conserved, but non-pertubative effects!

Instantons

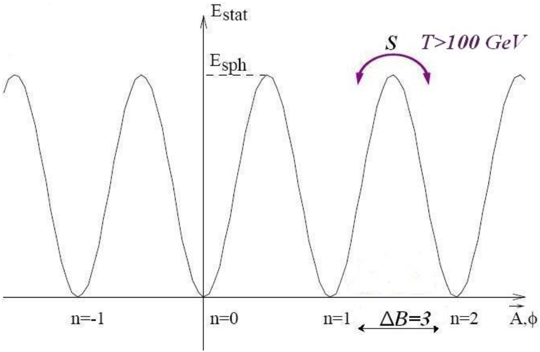
- Yang-Mills vacuum structure



- At $T = 0$, B violation through non-perturbative effects $\rightarrow$ instantons[1]
- Tunneling amplitude $\propto \exp(-4\pi/\alpha_W) \simeq 10^{-162}$
- Too small to have ever happened!

[1] G. 't Hooft, *Phys. Rev. Let.* **37**, 8 (1976)

Sphalerons



- At $T > 100$ GeV, transitions between vacua are unsurpressed[1]
- Finite T-transitions $\rightarrow$ sphaleron[2]-processes

[1] Kuzmin, Rubakov, Shaposhnikov, *Phys. Lett.* **155B**, 36 (1985)
[2] Klinkhamer, Manton, *Phys. Rev. D* **30**, 2212 (1984)
From the Greek sphaleros, meaning 'ready to fall'

Sphaleron transition rate

- For $T < E_{sph} \simeq 100$ GeV (EWPT = Electroweak Phase Transition),

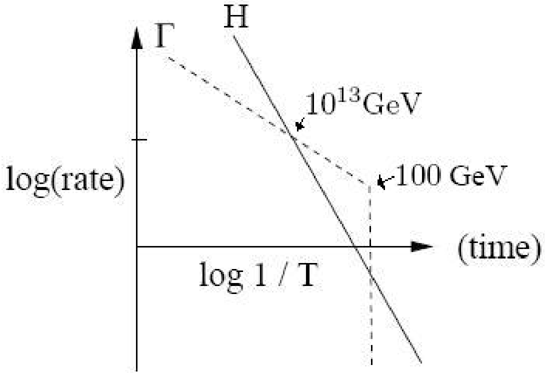
$$\frac{\Gamma_{sph}}{V} \propto T^4 e^{-\frac{E_{sph}}{T}}$$

- For $T > E_{sph} \simeq 100$ GeV,

$$\frac{\Gamma_{sph}}{V} = (25.4 \pm 2.0)\alpha_W^5 T^4 = (1.06 \pm 0.08) \times 10^{-6} T^4$$

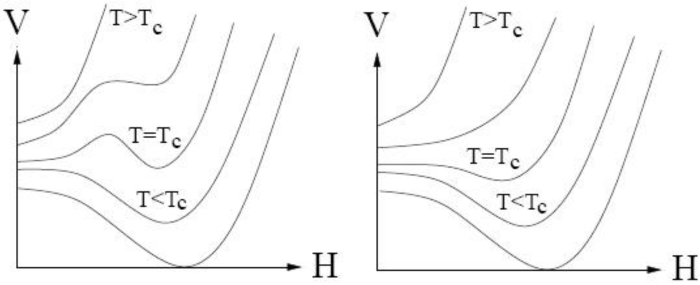
- Take thermal volume $V = \frac{1}{T^3}$
- compare to Hubble rate $H \sim g_*^{1/2} T^2 / m_p$

Sphaleron transition rate



Sphalerons are out of equilibrium for $T > 10^{13}$ GeV and $T < 100$ GeV
Freeze-in of baryon asymmetry below EWPT

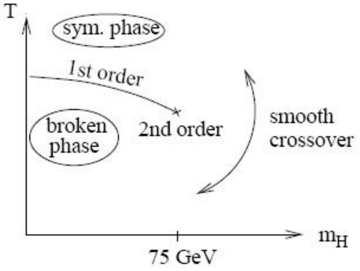
Electroweak Phase Transition (EWPT)



A first order EWPT leads to out-of-equilibrium conditions

Is EW Baryogenesis the origin of the baryon asymmetry?

- Higgs mass < 80 GeV leads to first order EWPT
- Too light!



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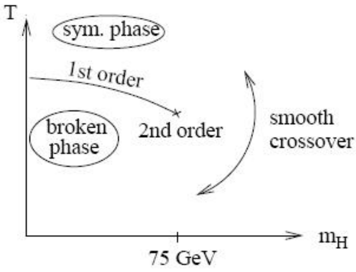

- C,CP in the SM exists in the CKM-matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Amount of C, CP violation $\sim 10^{-20}$
- Far too small to explain the baryon asymmetry $\sim 10^{-10}$!

Beyond the Standard Model

Extensions of SM:

- 2HDM: two Higgs doublets
- MSSM: supersymmetry

Can solve the problems:

- Higgs mass < 250 GeV for first order EWPT
- More particles, more couplings, more C and CP violation

Does supersymmetry exist in nature?

Summary

- Baryon asymmetry $\eta \simeq 6 \times 10^{-10}$, small but significant
- The Sakharov conditions need to be satisfied for baryogenesis
- GUT baryogenesis satisfies all conditions, but inflation makes this scenario not plausible
- The SM provides a source for B-violation, but produced B is too small
- Extensions of the SM can explain the observed η, but need to be tested (LHC)
- Other mechanisms could explain the baryon asymmetry (ex. leptogenesis)

The future will tell us more!

Questions?[1]

[1] Thanks to T. Prokopec and J. Koksma for answering many and thank you for listening!