Lecture # 10.

Main points of #9.

Considered idea of nucleosynthesis

Freezing temperature of reactions which transforms $p \Leftrightarrow n$ is $T^* \approx 0.8\,MeV \Rightarrow$

$$\frac{n_n}{n_p} = e^{-\frac{m_n - m_p}{T^*}} \approx \frac{1}{5}$$

Then this is somewhat decreased because of n-decays, down to $n_n/n_p \approx \frac{1}{7}$ at $T \approx 0.1\,MeV$

All n go to ^4He, as it has largest binding energy for light elements

so $$X_4 = \frac{4 \cdot n_{^4He}}{n_p + n_n} = 0.25$$

Today: Baryogenesis

– [illegible]

– [illegible] dark matter particles

$\Rightarrow$ ν_e, ν_μ, ν_τ

[illegible]

[illegible]

[illegible]

Baryogenesis

Questions: why $n_B - n_{\bar{B}} \neq 0$?

why $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$?

- What is needed (Sakharov)

(i) baryon number nonconservation

But consistent with stability of matter:

$$\tau_p \gtrsim 10^{31} \text{ years}$$

(ii) Deviations from thermal equilibrium:

In thermal equilibrium

$$n_p = n_{\bar{p}} = \frac{1}{e^{\epsilon/T} - 1}$$

(No chemical potential as baryon number is non-conserved

(iii) violation of C & CP parities

particles : $p \quad n \quad e \quad \nu \quad \gamma$

$\bar{p} \quad \bar{n} \quad e^+ \quad \bar{\nu} \quad \gamma$

truly neutral particle

CPT theorem : masses and total lifetimes are equal

(one of the reasons why in thermal equilibrium baryon number is zero

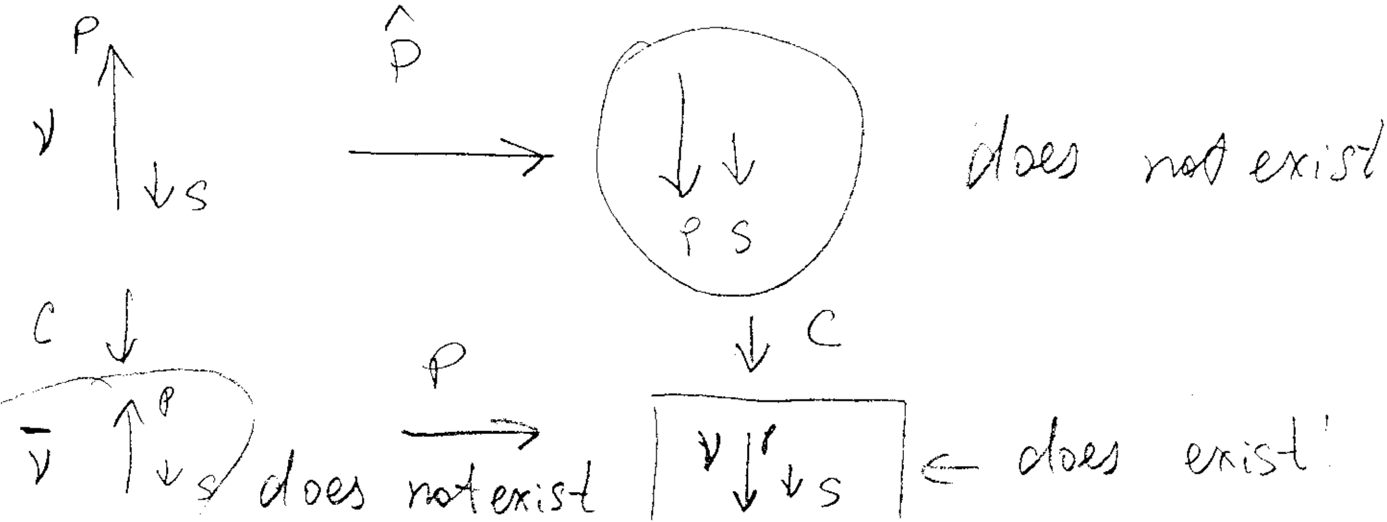
Before 1956 : people believed that P & C parities were exact

P : $x \to -x$, $t \to +t$, $\underbrace{v \to -v}_{\text{velocity}}$

spin $\to$ spin ($s \sim \vec{x} \times \vec{v}$)

C : particle to antiparticle

Discovery of P & C non-conservation associated with neutrinos



So, P and C are broken, but CP may be exact

If CP is exact – no difference between particles and antiparticles $\Rightarrow$ baryon asymmetry cannot arise

1964 – discovory of CP-breaking in decays of K^0 mesons
(K_1 & K_2 , K_S & K_L)

$K^0 \to \pi^- e^+ \nu$ asymmetry in K^0 decays

$\bar{K}_1^0 \to \pi^+ e^- \bar{\nu}$ $\dfrac{\# e^+ - \# e^-}{\# e^+ + \# e^-} \sim O(10^{-3})$

"Absolute definition" of matter
- take equal number of K^0 & $\bar{K}^0$
- call "positron" a charged lepton which appears more often in decays
- call proton the baryon of the same sign of charge

$\Downarrow$

If CP is broken then baryon asymmetry can arise.

Grand Unified baryogenesis

Grand unified theories – (GUT)
unification of strong, weak &
electromagnetic interactions

Information on GUT's important
for us (for explanation of BAU)

fundumental particles – baryons –
are quarks rather than protons
or neutrons

$$q: \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{matrix} q = 2/3, & b = \frac{1}{3} \\ \underbrace{q = -1/3}_{\text{electric charge}}, & \underbrace{b = 1/3}_{\text{baryon number}} \end{matrix}$$

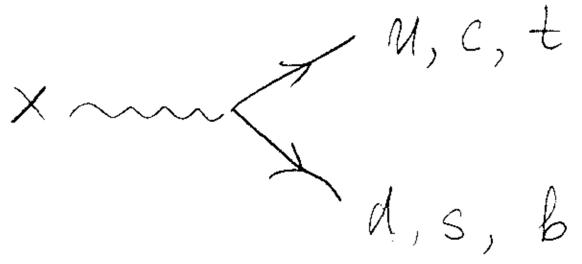
nucleons consist of 3 quarks:

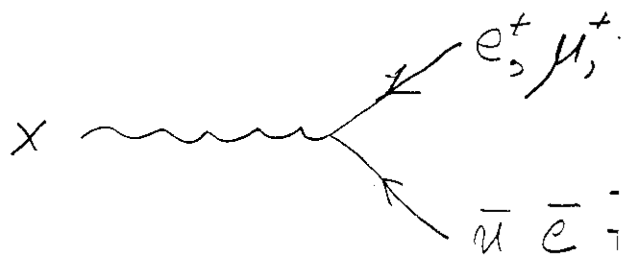
$p = uud$
$n = udd$

$\boxed{\text{mesons are contructed from quarks \& antiquarks, } q\bar{q}}$

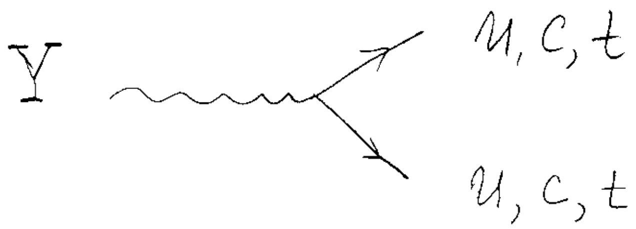
In ordinary conditions (small temperatures & densities) quarks do not
exist in free state (confinement of
quarks)

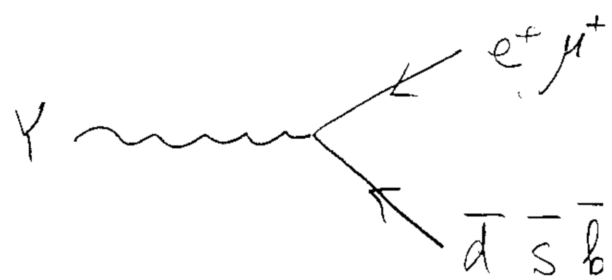
In GUTs there are particles – leptoquarks – which can decay on quarks and leptons with baryon number non-conservation:



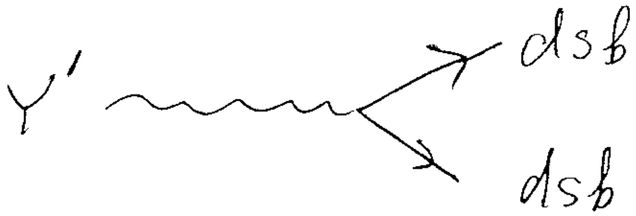


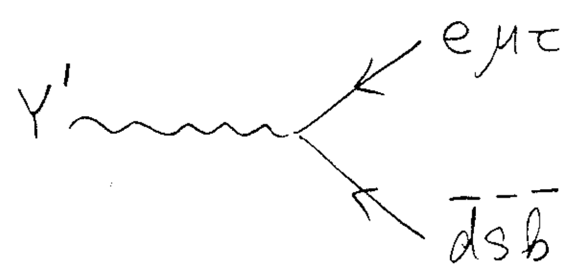
$$Q_X = \frac{1}{3}$$





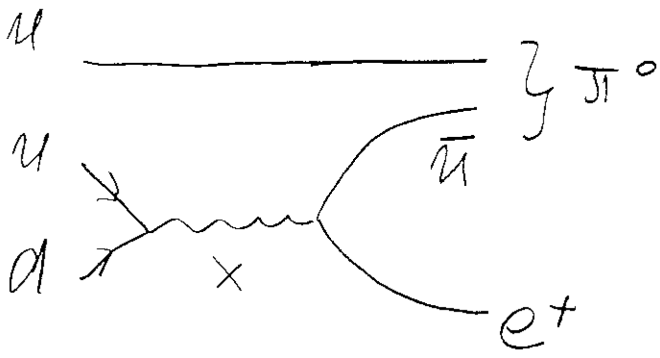
$$Q_Y = \frac{4}{3}$$





$$Q_{Y'} = -\frac{2}{3}$$

proton is unstable:



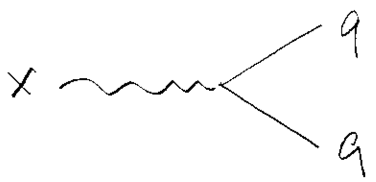
$p \to \pi^0 e^+$
$\quad \hookrightarrow \gamma\gamma$

proton width:

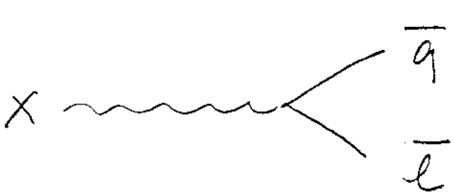
$$\Gamma = \frac{g^4}{M_X^4} \cdot m_p^5 \approx \frac{\alpha^2 m_p^5}{M_X^4}$$

Home work: find constraint on M_X from $\tau_p \gtrsim 10^{31}$ years.

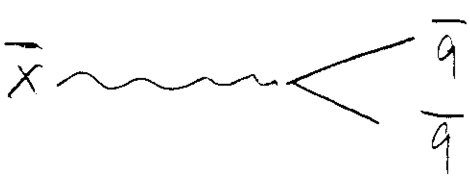
CP - violation in leptoquark decays



: $\Gamma(X \to qq)$



: $\Gamma(X \to \bar{q}\bar{\ell})$



: $\Gamma(\bar{X} \to \bar{q}\bar{q})$

: $\Gamma(\bar{X} \to q\ell)$

CPT :

$$\Gamma(X \to qq) + \Gamma(X \to \bar{q}\bar{\ell}) = \Gamma_{tot} =$$

$$= \Gamma(\bar{X} \to \bar{q}\bar{q}) + \Gamma(\bar{X} \to q\ell)$$

or: $\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q}) = \Gamma(\bar{X} \to q\ell) - \Gamma(X \to \bar{q}\bar{\ell})$

CP - violation :

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

Suppose we have one X and one $\bar{X}$

How many baryons we will get after their decay?

$$X : \quad B = \frac{2}{3} \frac{\Gamma(X \to qq)}{\Gamma_{tot}} - \frac{1}{3} \frac{\Gamma(X \to \bar{q}\bar{\ell})}{\Gamma_{tot}}$$

$$\bar{X} : \quad B = -\frac{2}{3} \frac{\Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_{tot}} + \frac{1}{3} \frac{\Gamma(\bar{X} \to q\ell)}{\Gamma_{tot}}$$

$$\text{total } B : \quad \frac{2}{3} \frac{\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_{tot}} - \frac{1}{3} \frac{\Gamma(X \to \bar{q}\bar{\ell}) - \Gamma(\bar{X} \to}{\Gamma_{tot}}$$

$$= \frac{\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_{tot}}$$

Baryon asymmetry

concentration of leptoquarks

$$\Delta = \frac{n_B}{S} \sim \frac{\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_{tot}} \cdot \frac{n_X}{S}$$

entropy density

Kinetics & thermodynamics of leptoquark decay
(or, how to find n_X / S).

Thermal equilibrium:

$$\frac{n_X}{n_\gamma} \approx \begin{cases} \frac{T^3}{T^3} \simeq 1 & , \text{ if } T \gg m_X \\ \left(\frac{m}{T}\right)^{3/2} \exp\left(-\frac{m_X}{T}\right), & \text{if } T \ll m_X \end{cases}$$

processes in which leptoquarks take part:

$X \to qq$; $X \to \bar{q}\bar{l}$

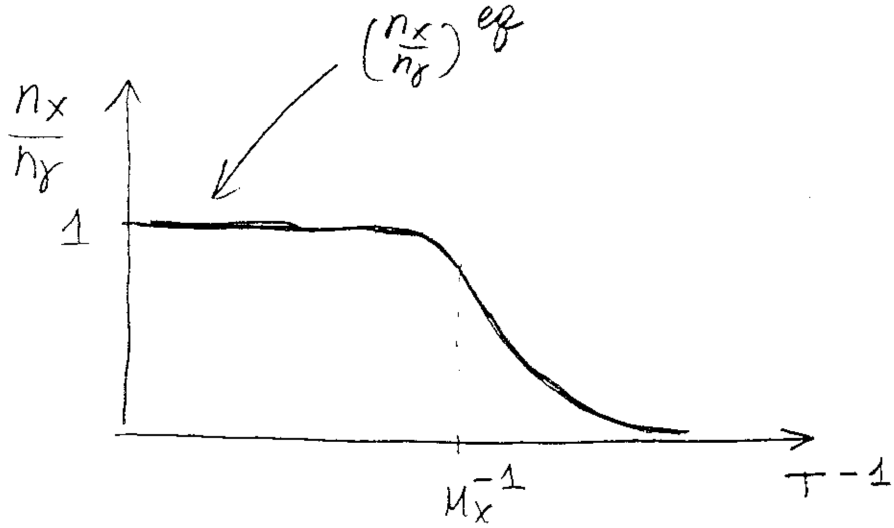
and (very important) inverse processes

$qq \to X$; $\bar{q}\bar{l} \to X$

in thermal equilibrium rates of direct and inverse processes are the same

rate of direct processes

$$\Gamma_{tot} \approx \begin{cases} \Gamma_{tot} \dfrac{m_X}{T}, & \text{if } T \gg m_X \quad \dfrac{T}{m_X} \text{ - Lorents factor} \\ \Gamma_{tot}, & \text{if } T \lesssim m_X \end{cases}$$



$(t \approx M_0/T^2)$

decoupling temperature:

(*) $\Gamma_{tot} \approx \dfrac{T^2}{M_0}$; $T^* \approx \sqrt{\Gamma_{tot} M_0}$ (if $T^* \lesssim m_X$)

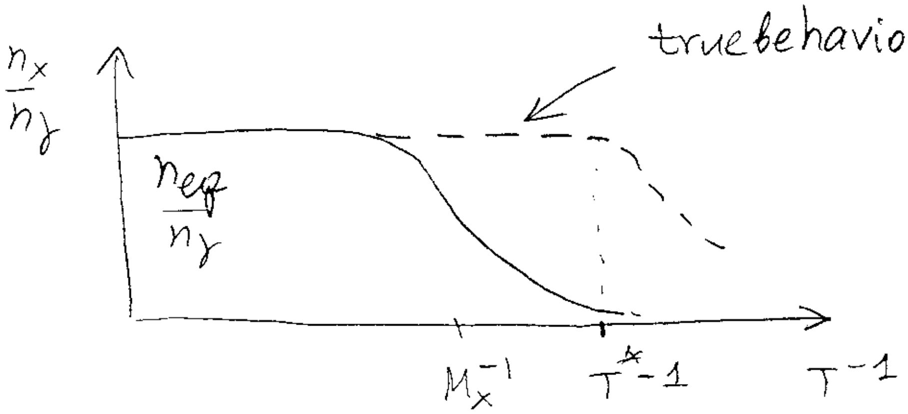
(**) or $\Gamma_{tot} \dfrac{m_X}{T} \approx \dfrac{T^2}{M_0}$, $T^* \approx \left(\Gamma_{tot} m_X M_0\right)^{1/3}$ (if $T^* \gtrsim m_X$)

(*) 1st case: $\Gamma_{tot} M_0 \lesssim m_X^2$; $\dfrac{m_X^2}{\Gamma_{tot} M_0} \gtrsim 1$

(**) 2nd case: $\dfrac{m_X^2}{\Gamma_{tot} M_0} \lesssim 1$

$\boxed{\text{Let } T^* \lesssim M_X}$ $\Rightarrow$

$\frac{n_X}{n_\gamma} = 1$ till T^*, because particles do not decay at all at $T \gtrsim T^*$



in this case $\frac{n_X}{n_\gamma} \approx 1$ at the moment of decay $\Rightarrow$

$$\Delta = \frac{n_B}{s} \approx \frac{\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_{tot}} \cdot \frac{1}{N_{eff}}$$

N_{eff} – number of degrees of freedom,

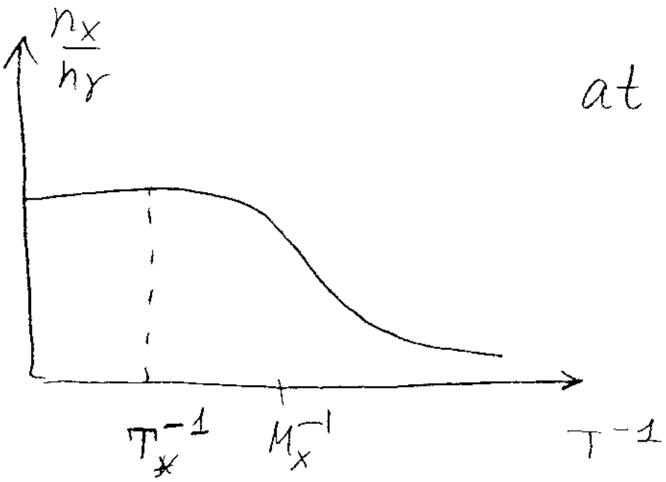
$N_{eff} \sim 100$

(counting all quarks, leptons, vector boson

Denote $\delta_{micro} \equiv \frac{\Gamma(X - qq) - \Gamma(X \to \bar{q}\bar{q})}{\Gamma_{tot}} \frac{1}{N_{eff}}$

Let $\overset{*}{T} \gtrsim M_X$

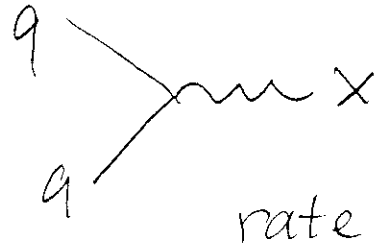
$$\frac{n_X}{n_\gamma} \approx \frac{n_{eq}}{n_\gamma} \quad \text{till } \overset{*}{T}$$



at $T \lesssim T^*$ rate of decay is larger than the rate of Universe expantion

Computation is more complicated

Consider inverse process



rate of inverse process :

$$\Gamma_{invers} \sim \Gamma_{tot} \underbrace{\exp\left(-\frac{m_X}{T}\right)}\left(\frac{m_X}{T}\right)^{3/2}$$

this factor comes from concentratio of quarks, $n_q(1) \cdot n_q(2) \sim \exp\left(-\frac{E_{tot}}{T}\right)$,

$E_{tot} = m_X$ in order to create X

Compare it with the rate of universe expansion:

$$\left(\frac{m_X}{T}\right)^{3/2} \Gamma_{tot} \exp\left(-\frac{m_X}{T}\right) \approx \frac{T^2}{M_0} \Rightarrow$$

$$\left(\frac{m_X}{T}\right) = x; \qquad x^{7/2} e^{-x} = \frac{m_X^2}{M_0 \Gamma_{tot}}$$

$$\frac{7}{2} \log x - x = \log \frac{m_X^2}{M_0 \Gamma_{tot}};$$

$$x \approx \log \frac{M_0 \Gamma_{tot}}{M_X^2} + \frac{7}{2} \log \log \frac{M_0 \Gamma_{tot}}{M_X^2} \Rightarrow$$

$$\frac{n_X}{n_\gamma} \approx x^{3/2} e^{-x} \approx$$

$$\approx \left[\log \frac{M_0 \Gamma_{tot}}{M_X^2}\right]^{3/2} \frac{m_X^2}{M_0 \Gamma_{tot}} \left[\log \frac{M_0 \Gamma_{tot}}{M_X^2}\right]^{-7/2} =$$

$$= \frac{m_X^2}{M_0 \Gamma_{tot}} \frac{1}{\left(\log \frac{M_0 \Gamma_{tot}}{M_X^2}\right)^2}$$

Note: Solution to Boltzmann equation gives log in the 1st power.

So :

$$\Delta \approx \begin{cases} \delta_{micro} \quad ; & \dfrac{m_X^2}{\Gamma_{tot} M_0} \gtrsim 1 \\[2ex] \delta_{micro} \cdot \dfrac{m_X^2}{\Gamma_{tot} M_0} \quad ; & \dfrac{m_X^2}{\Gamma_{tot} M_0} \lesssim 1 \end{cases}$$

Usually : $m_X \approx \alpha \cdot m_X$, $\alpha \approx \alpha_{EM} \simeq O\left(\frac{1}{100}\right)$

δ_{micro} : at most $O\left(\frac{1}{N_{eff}}\right) \sim \frac{1}{100}$
if CP- violation is 100%

$$\Rightarrow \quad \frac{m_X^2}{\Gamma_{tot} M_0} \gtrsim 10^{-8} \; ;$$

$$m_X \gtrsim 10^{-8} \alpha M_0 \approx 10^{8} \text{ GeV}$$

if CP- violation is small,
$\delta_{micro} \sim 10^{-10}$, then one
requires $m_X \gtrsim \alpha M_0 \approx 10^{16}$ GeV