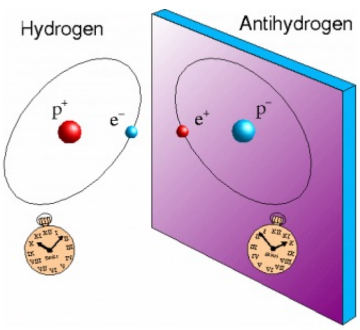
VII. Baryogenesis

7.1. Baryogenesis and baryon asymmetry

Observational evidences

Antimatter was predicted by Dirac (1928) and found (positrons) in cosmic Rays by Anderson (1932). Since then, we know that all particles have their antiparticles, with the same mass and opposite charge (CPT invariance).



However, we do not observe any antimatter in the Universe, there is an asymmetry. The ratio of antiproton-proton flux in cosmic rays is $\sim 10^{4}$ over a large range of energies. The anti-Helium to Helium flux is constrained to be less than $\sim 10^{-6}$. There is no evidence for antinuclei in the Universe, but anti-hydrogen has been generated in the lab.

Today, we think all antimatter annihilated in the early Universe with matter to produce photons:

$$p + \bar{p} \Longleftrightarrow \gamma + \gamma$$

We need to figure out why there is a small remnant of matter left and why didn't it all annihilate into photons.

Baryon to photon ratio.

We can parametrize this asymmetry using η, relating the remnant density of baryons and antibaryons to the density of photons.

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

which is constant since $n_B \sim a^{-3}$ and $n_\gamma \sim a^{-3}$

$$n_\gamma = \frac{1}{\pi^2}\left(\frac{k_B T}{\hbar c}\right)^3 \int_0^\infty \frac{x^2}{e^x - 1}\,dx = \frac{2\zeta(3)}{\pi^2}\left(\frac{k_B T}{\hbar c}\right)^3 \approx 20.3\left(\frac{T}{1k}\right)^3 cm^{-3}$$

This constancy is true at least at late times, but at early times and high temperatures many heavy particles were in thermal equilibrium, which later annihilated to produce more photons but not baryons.

It is better to use the entropy:

$$s \equiv \frac{\text{entropy } S}{\text{volume } V} = \frac{p+\rho}{T} = \frac{2\pi^2}{45} g_* T^3 = 7.04\left(\frac{g_{*s}}{3.91}\right) n_\gamma$$

$$\rightarrow \boxed{\eta \equiv \frac{n_B - n_{\bar{B}}}{s} = 1.80\, g_{*s} \frac{n_B - n_{\bar{B}}}{s} \approx \text{const}}$$

It is common to use η_{10} instead of η:

$\eta_{10} = 10^{10}\eta = 273.7\,\Omega_B h^2$

$$\left.\begin{array}{ll} \text{BBN (2014)} & \eta_{10} = 6.2 \pm 0.5 \\ \text{Planck (2018)} & \eta_{10} = 6.103 \pm 0.038 \end{array}\right\} \text{Constrains}$$

Origin of baryons

Even in a homogeneous baryon-symmetric universe, there would still be a few baryons and anti-baryons left since annihilation is not perfectly efficient.

At freeze-out there is a small remnant:

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \sim 10^{-20}$$

Which is too small to account for BBN or CMB.

Hot Big Bang theory

In the old HBB theory, baryon asymmetry was considered as an initial condition. However, in the context of inflation this is not possible since inflation would dilute any primordial asymmetry, and we would start again in a baryon-symmetric Universe after reheating. (Universe grows by $e^{60} \sim 10^{27}$: $1\,m \rightarrow 12\,Gly$).

Therefore, the baryon asymmetry of the universe must be generated after inflation.

7.2. Sakharov conditions

Baryon number violation

We require more baryons than antibaryons.

At tree level, the SM Lagrangian is invariant under Baryon number phase transformations. B-violating interactions today are extreamly weak, otherwise we would have observed them (e.g. via the decay of the proton).

Current limits to the proton lifetime are from SuperKamiokande (2014):

$$\tau_p > 1.29 \times 10^{34} \text{ years} \quad (95\% \text{ c.l.}).$$

The lowest-dimension (6) operators mediating proton decay are of the form:

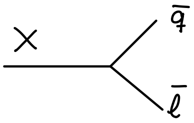
$$\frac{qqql}{\Lambda^2}, \quad \frac{d^c u^c u^c e^c}{\Lambda^2} \qquad \Delta B = \Delta L = 1 \qquad \Delta(B-L) = 0$$

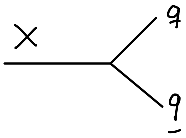
with typical decay process: $p^+ \longrightarrow e^+ + \pi^0 \longrightarrow e^+ + 2\gamma$

GUT theories

In GUT theories it is postulated that quarks ($B = 1/3$) and leptons ($L = 1$) are members of the same multiplet of a larger group $G = SU(5)$ or $SO(10)$. The breaking of G generates the difference between quarks and leptons. The gauge bosons X and Y are the mediator of GUT interactions.

B-violating GUT interactions go via operators Xqq, $X\bar{q}\bar{l}$





In GUT theories, the proton decay is via X gauge bosons:

$$\tau_p \sim \alpha_{GUT}^{-2} M_X^4 m_p^{-5} > 1.29 \times 10^{34}\,\text{years} \quad \Rightarrow \quad M_X > 10^{16}\,\text{GeV}$$

But the Universe never reheated above such high energies after inflation. Present bounds (from absence of B-modes in CMB polarization) suggest that inflation reheated well below GUT energies, and thus thermal GUT baryogenesis is not viable.

C, CP violation

C, CP and CPT symmetries

1. Scalars

$C: \ \phi \longrightarrow \phi^* \qquad P: \ \phi(t,\vec{x}) \longrightarrow \pm\phi(t,-\vec{x}) \qquad CP: \ \phi(t,\vec{x}) \longrightarrow \pm\phi^*(t,-\vec{x})$

2. Fermions

$C: \ \psi_L \longrightarrow i\sigma_2 \psi_L^* \qquad \psi_R \longrightarrow -i\sigma_2 \psi_L^* \qquad \psi \rightarrow i\gamma_2 \psi^*$

$P: \ \psi_L \longrightarrow \psi_R(t,-\vec{x}) \qquad \psi_R \rightarrow \psi_L(t,-\vec{x}) \qquad \psi \rightarrow \gamma^0 \psi(t,-\vec{x})$

$CP: \ \psi_L \longrightarrow i\sigma_2 \psi_R^*(t,-\vec{x}) \qquad \psi_R \rightarrow -i\sigma_2 \psi_L^*(t,-\vec{x}) \qquad \psi \rightarrow i\gamma^2\gamma^0 \psi^*(t,-\vec{x})$

3. Vectors

$C: \ A^\mu \longrightarrow -A^\mu$

$P: \ A^\mu \longrightarrow (A^0, -\vec{A})(t, -\vec{x})$

$CP: \ A^\mu(t,\vec{x}) \longrightarrow (-A^0, \vec{A})(t, -\vec{x})$

C, CP violationing interactions

Sakharov realized that it is not enough to have B-violating interactions out of equilibrium, one also needs C and CP violating interactions:

C violation: excess of $b > \bar{b}$ must not be balanced by $\bar{b} > b$

CP violation: $b_L > \bar{b}_R$ different from $\bar{b}_L > b_R$

Consider the decay $X \to Y + B$ and the (Charge) C conjugate process $\bar{X} \to \bar{Y} + \bar{B}$. If C is a symmetry of the Lagrangian, then the rates are the same:

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

If there are equal number of $B = 0$ states X and C-conjugate $\bar{X}$, then the net baryon production grows like:

$$\frac{dB}{dt} \propto \Gamma(X \to Y + B) - \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$

and thus vanishes in the case of C-conserving interactions.

$$\frac{dB}{dt} \sim 0$$

Shakharov also realized that one needed CP violating interactions. Let us consider the decay $X \to q_L + q_L$ and $X \to q_R + q_R$.

$$\left.\begin{array}{ll} \text{Under CP:} & q_L \to \bar{q}_R \\ \text{Under C:} & q_L \to \bar{q}_R \end{array}\right\}$$ L, R Keeps track of fermion in SU(2) doublet

Even though CP-violation implies $\Gamma(X \to q_L + q_L) \neq \Gamma(\bar{X} \to \bar{q}_L + \bar{q}_L)$

CP-conservation would imply:

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

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

and therefore:

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

Thus, as long as the initial state has equal numbers of X and $\bar{X}$, we end up with no net baryon asymmetry.

Out of equilibrium interactions and SM

Most of the history of the Universe has occurred via adiabatic expansion, with fundamental interactions Keeping particles in thermal and chemical equilibrium.

In order for baryogenesis to occur, it is necessary that the B-violating interactions occur out of equilibrium, since otherwise all the produced baryons will be washed out. Suppose a process such as $X \to Y + B$ with initial $B=0$ state decaying into a state Y also with $B=0$, plus a state B with non-zero baryon number. If the process occurs in thermal equilibrium, then the rate in one direction is identical to the rate in the opposite direction:

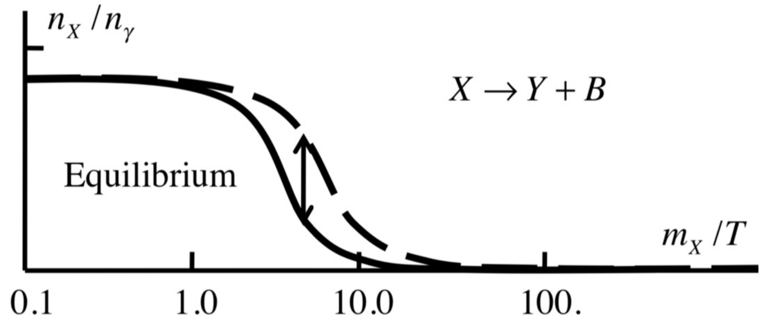
$$\Gamma(X \to Y+B) \rightleftharpoons \Gamma(Y+B \to X)$$

So that no net baryon number is produced, since the inverse process destroys B as fast as the direct process generates it.

Out of equilibrium decay of massive particles

A classic example is the decay of a massive particle X out of equilibrium, when $m_X > T$ at the time of X decay, $\tau \sim 1/\Gamma(X \to all)$

In this case, the energy of the final state $Y+B$ is of the order of the temperature T, and there is no phase space available for the inverse decay $Y+B \to X$ since $m_X > T$ and the rate is Boltzmann-suppressed:



$$\Gamma(Y+B \to X) \sim e^{-M_X/T} << 1$$

Thus, we generate an extra abundance of B.