Baryon asymmetry

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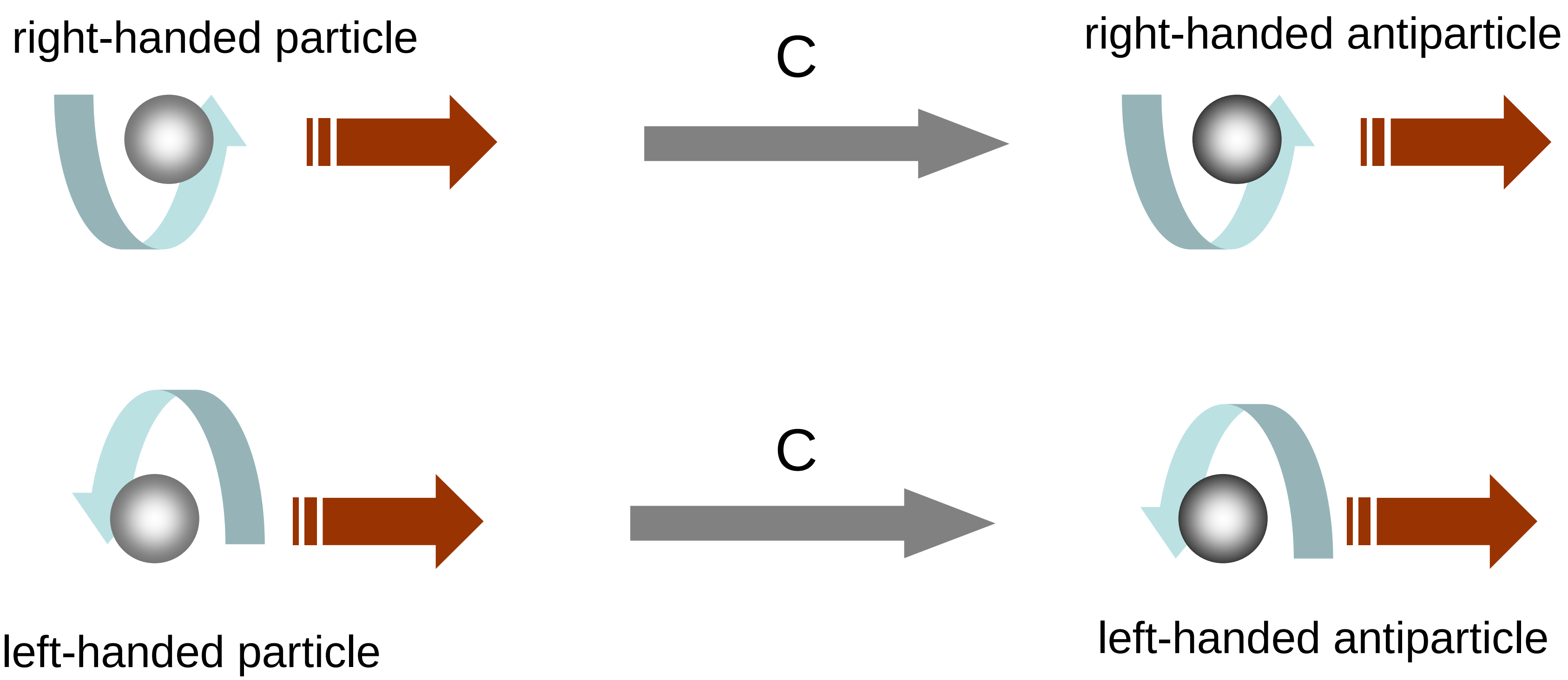
Outline (Part 1):

- Introduction
- Observations of baryon asymmetry
- Some basic thermodynamics
- Sakharov conditions
- The out-of-equilibrium decay scenario

Introduction

The charge operator transforms matter into antimatter and vice versa

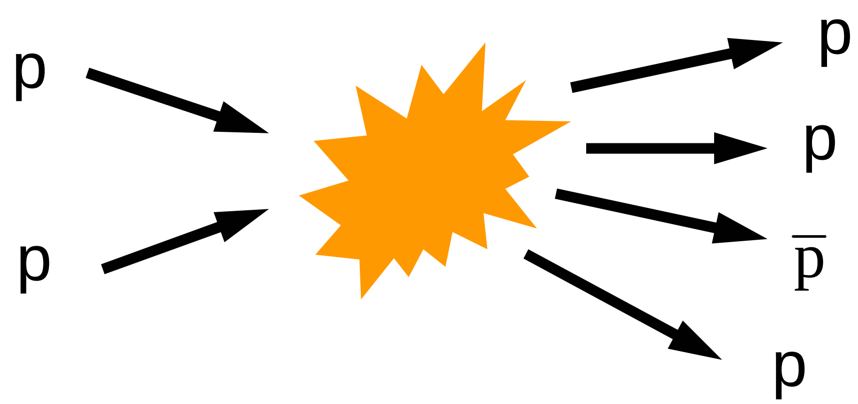


Introduction

- Matter is what we are made of
- Direct contact of matter and antimatter leads to annihilation
- Einstein: $E=mc^2$
- 1kg matter + 1kg antimatter releases as much energy as 300 000 000 000kg of coal
- Unfortunately: no antimatter in the neighbourhood

Introduction

- Thus we need a lot of energy to produce antimatter



- In accelarators: 0.000 000 01g of antimatter produced in history, including < 100 antohydrogen atoms
- by Cosmic rays: in the upper layers of the atmosphere

Observations of baryon asymmetry

- No antimatter in our solar system
- Detected ratio $\frac{\text{antiprotons}}{\text{protons}} \approx 10^{-4}$ consistent with reaction $pp \rightarrow 3p + \overline{p}$
- no strong X-rays from cluster gas
- Matter/antimatter island $>> 10^{14} M_{\odot}$

  -> problems with causal contact
- Statistical fluctuations? NO!
- Baryon number $B = \frac{n_b}{s} \approx 6 \ldots 10^{-11}$ small, but noticeable
- i.e. quark-antiquark asymmetry in the early universe

Observations of baryon asymmetry

Theory of Baryogenesis:

tries to explain the origin of asymmetry,

while assuming an initially symmetric universe

Some basic thermodynamics

- Early times: universe was approx. in **thermal equilibrium**
- Number density n and energy density ρ in T.E. given by occupation function $f(\mathbf{p})$ or $f(E)$ respectively

$$n = \frac{g}{(2\pi)^3} \int f(\mathbf{p}) d^3 p \qquad \rho = \frac{g}{(2\pi)^3} \int E(\mathbf{p}) f(\mathbf{p}) d^3 p \qquad p = \frac{g}{(2\pi)^3} \int \frac{|\mathbf{p}|^2}{3E(\mathbf{p})} f(\mathbf{p}) d^3 p$$

$$f(E) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

The probability that a certain state in the energy interval E..E+dE is occupied

- Approximations for limit cases are useful

Some basic thermodynamics

Relativistic Limit T>>m

$$n = \frac{\xi(3)}{\pi^2} g T^3 \begin{cases} 1 & B \\ \frac{3}{4} & F \end{cases} \qquad \rho = \frac{\pi^2}{30} g T^4 \begin{cases} 1 & \mathrm{B} \\ \frac{7}{8} & \mathrm{F} \end{cases} \qquad p = \rho/3$$

Non-relativistic limit

$$n = g \left(\frac{mT}{2\pi} \right)^{3/2} \exp[-(m-\mu)/T] \qquad \rho = mn \qquad p = nT << \rho$$

$$\text{since } \rho_{rel} >> \rho_{non-rel} \Rightarrow \rho_{tot} \approx \rho_{rel} = \frac{\pi^2}{30} g_* T^4 \text{ with } g_* = \sum_{i=boson} g_i \left(\frac{T_i}{T} \right)^4 + \frac{7}{8} \sum_{i=fermi} g_i \left(\frac{T_i}{T} \right)^4$$

The Einstein equation and assuming isotropy and homogenity leads to the Friedmann equation and the first law of thermodynamics

Some basic thermodynamics

- Temperature dependence of H

$d\left(\rho a^3\right) + pd\left(a^3\right) = TdS \Rightarrow \text{if } dS = 0, \text{so } \rho \approx a^{-3(1+w)} \text{ where } p = w\rho.$

Thus assuming g_*=*const* :

$\text{In radiation dominated case}: w = \tfrac{1}{3} \Rightarrow \rho \propto a^{-4} \propto T^4$

$$a \propto T^{-1} \quad \text{and since } H = \left(\frac{8\pi}{3m_{pl}}\rho\right)^{1/2} \Rightarrow H = 1.66 g_*^{1/2} \frac{T^2}{m_{pl}}$$

- Entropy in T.E.

Entropy per comoving volume remains constant i.e $dS = 0$

$$s = \frac{S}{V} = \frac{p+\rho}{T} \quad , s \text{ is the entropy density} \Rightarrow s = \frac{2\pi^2}{45} g_{*s} T^3 \quad \text{and since } s \propto a^{-3} \Rightarrow n \propto s$$

Some basic thermodynamics

- Definition of the baryon number

  $B \equiv \frac{n_B}{s}$ is the number of baryons in some comoving volume
- However, $\eta \equiv \frac{n_B}{n_\gamma}$ is not, if g_{*s} or n_γ is changing
- Decoupling:

  relativistic species becomes nonrelativistic

  -> entropy transfer

  -> plasma temp. dropping is slowed $T \propto g_{*s}^{-1/3} a^{-1}$

  -> species cools as $T \propto a^{-2}$

  relativistic species decouples from heat bath

  -> no entropy transfer

Some basic thermodynamics

-> temperature drops for decoupled species and plasma as $T \propto a^{-1}$

- So, since $T \propto a^{-1} \Rightarrow \frac{\dot{T}}{T} = -H$
- interaction rate keeping pace with H -> T.E.
- Rough Criterion for staying in T.E.

$$\Gamma > H$$

- valid if,

  -particles are coupled to plasma

  -crucial rate for maintaining T.E is involved

Some basic thermodynamics

- η has not changed since nucleosynthesis without much entropy producing processes
- So $n_B = \eta n_\gamma$ should give us todays baryon number density
- From nucleosynthesis we know $4 \times 10^{-10} \leq \eta \leq 7 \times 10^{-10}$
- Calculations using CMB gives us $n_\gamma = 415 cm^{-1}$
- Thus: $1.66 \times 10^{-7} cm^{-1} \leq n_B \leq 2.90 \times 10^{-7} cm^{-1}$
- Or equivalently $n_B = \frac{\rho_B}{m_B} = \frac{\Omega_B}{m_B} \rho_C$, with $\rho_c = \frac{3H^2}{8\pi G} = 1.88 \times 10^{-29} h^2 g\, cm^{-1}$

  gives:

$$0.015 \leq \Omega_B h^2 \leq 0.026$$

Sakharov conditions

- Max. asymmetry today
- Tiny asymmetry at early times,but it is not appealing to impose an asymmetry as initial condition
- 1967 Sakharov postulated 3 conditions which should allow for a developing asymmetry from a baryon-antibaryon symmetric universe
- Condition 1: Baryon number violation
- Condition 2: C & CP violation
- Condition 3: Departure from T.E.

Sakharov conditions

- We want now understand the conditions in the context of the out-of-equilibrium decay of heavy particles
- Let's see how it works on probably the simplest model possible
- Given an heavy boson, which can decay in two different ways (2 decay channels)

Reaction	Branch ratio	Baryon number
$X \to qq$	r	B_1=2/3
$X \to \bar{q}\bar{l}$	1-r	B_2=-1/3
$\bar{X} \to \bar{q}\bar{q}$	r'	$-B_1$=-2/3
$\bar{X} \to ql$	1-r'	$-B_2$=1/3

Branching ratio

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

Sakharov conditions

- Initial symmetric conditions i.e $n_X = n_{\bar{X}}$
- Net baryon number produced by decay of all X and $\bar{\mathrm{X}}$ particles

$$\Delta B = rB_1 + (1-r)B_2 - r'B_1 - (1-r')B_2$$

$$= \underbrace{(r - r')}_{\text{vanishes if C or CP is conserved}} \underbrace{(B_1 - B_2)}_{\text{vanishes if B is conserved}}$$

- Provide X massive enough: interactions that decrease number of the heavy bosons are ineffective for $T < M_X$

→overabundance

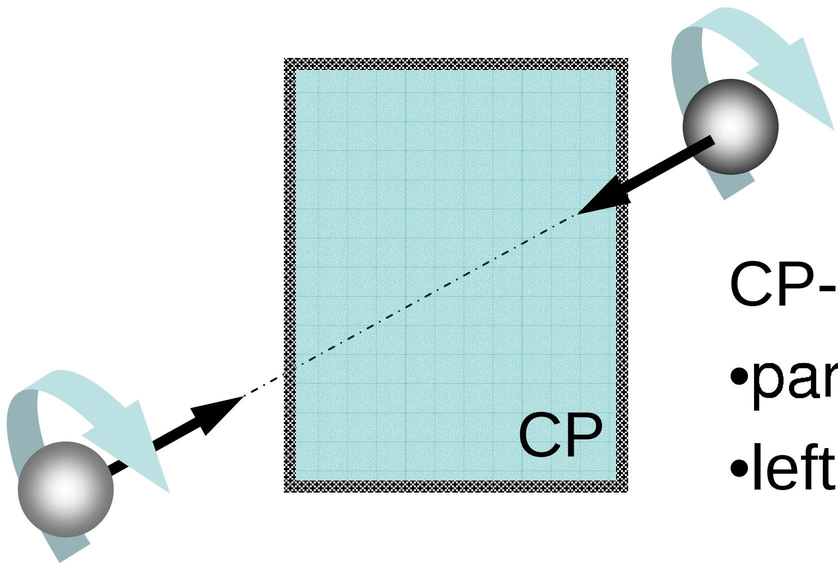
- At $T << M_X$ bosons decay without back reactions

→ net baryon number produced

But why are both violations, C **and** CP-violation, necessary?

Sakharov conditions

CP-transformation as a ‘magic mirror’



CP-transformation changes

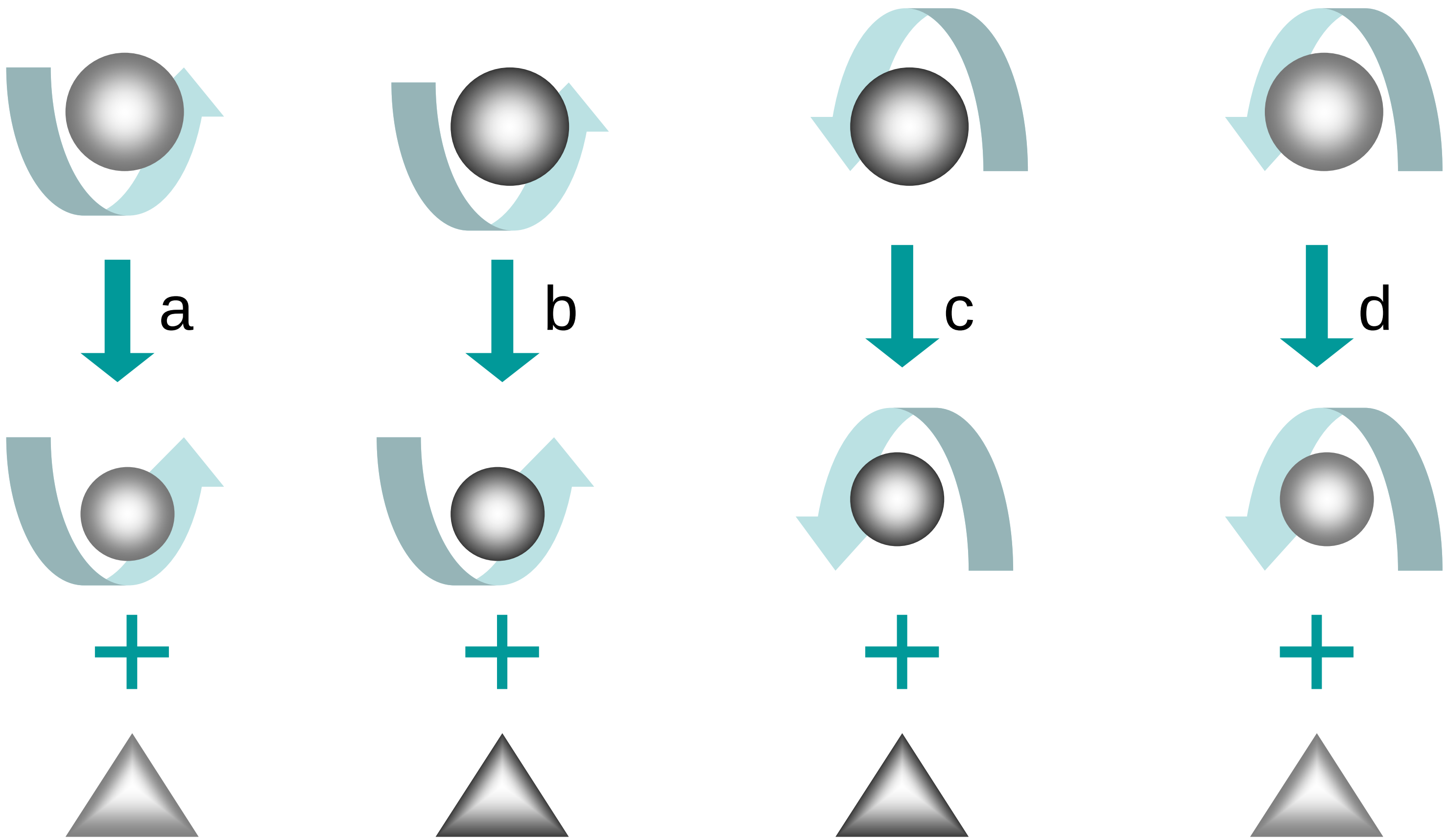
- particle ←→ antiparticle
- left-handed ←→ right-handed

Weak interactions are not C and P symmetric!

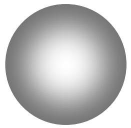
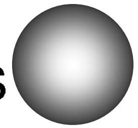
However, CP is **almost** conserved!

Sakharov conditions

Example: Decay of particle



Sakharov conditions

- In T.E particles  and antiparticles  occur in equal number independent of their handed-ness
- Without C-violation a=b and c=d (i.e. interaction rates equal), thus a+d=b+c →no net baryon number created
- Without CP-violation a=c and b=d. Again, a+d=b+c and the produced excesses cancel

Sakharov conditions

- *B violating reactions:*

  Somehow obvious since the universe develops from a baryon symmetric state B=0 to a state B<>0
- *C violation:* without this violation the baryon/antibaryon excesses of the reactions $a \to b$ and $\bar{a} \to \bar{b}$ cancel
- *CP violation:* due to the CPT-Theorem, CP invariance is identical with T invariance. Thus without the CP violations the reactions $a(x_i, p_i, s_i) \to b(x_j, p_j, s_j)$ and $b(x_j, -p_j, -s_j) \to a(x_j, -p_j, -s_j)$ cancel if we integrate over the momentum space (in order to obtain number densities)

Sakharov conditions

- This is the basic picture, but is it realistic?
- B violation:
  - generic feature of GUTs
  - stability of proton -> very massive boson
  - large mass leads to suppression at ‘usual’ temperatures
- C,CP violations:
  - C maximally violated in weak decays
  - CP violation in Kaon system observed, but not well understood

Sakharov conditions

- How can C, CP violation be achieved? → **Let's think of a toy model**
- 2 Bosons X,Y
- The generalisation of the above derived formula for the produced baryon number is:

$$\Delta B_X = \sum_f B_f \frac{\Gamma(X \to f) - \Gamma(\overline{X} \to \bar{f})}{\Gamma_X} \quad \text{for } \Delta B_Y \text{ similar}$$

- Let's assume a Lagrangian $L = g_1 X i_1^* i_2 + g_2 X i_4^* i_3 + g_3 Y i_1^* i_3 + g_4 Y i_2^* i_4 + \text{h.c.}$
- If we just look at the tree level the interactions rates $\Gamma(X \to \bar{i}_1 i_2)$ and $\Gamma(\overline{X} \to i_1 \bar{i}_2)$ cancel
- We need the interference terms from the first-loop corrections to obtain the following

$$\Delta B_X + \Delta B_Y = 4\left[\frac{\mathrm{Im}(I_{XY})}{\Gamma_X} - \frac{\mathrm{Im}(I_{YX})}{\Gamma_Y}\right]\mathrm{Im}(g_1^* g_2 g_3^* g_4)[(B_4 - B_3) - (B_2 - B_1)]$$

Sakharov conditions

- B-conservation → $\left(B_4 - B_3\right) = \left(B_2 - B_1\right)$ → no net baryon number produced
- Need 2 B-violating bosons
- Need complex coupling constants
- Masses of the bosons must be higher than the sum of the masses of the loop particle in order to obtain a complex kinematic factor
- C, CP violation arise from interference with loop diagrams → $\Delta B \propto g^N \Rightarrow \text{small}$

Sakharov conditions

Departure from T.E. (1 - Example):

- Assuming a non-rel. massive species X in T.E., in addition to *kinetic equilibrium*, the species is also in the *chemical equilibrium*,i.e. the sum of the chemical potentials of the source and final products of reactions are equal: $\mathrm{a}+\mathrm{b} \to \mathrm{c}+\mathrm{d} \xrightarrow{Ch.E.} \mu_a + \mu_b = \mu_c + \mu_d$
- Since we allow for the annihilation $X + \overline{X} \to 2\gamma \xrightarrow{Ch.E.} \mu_X = -\mu_{\overline{X}} = \mu$ we obtain a baryon number excess depending on μ
  $B \propto n_X - n_{\overline{X}} \propto \sinh(\mu/T)$
- If the particles can undergo B violation reactions (condition 1) $XX \to \overline{XX} \xrightarrow{Ch.E.} \mu_X = \mu_{\overline{X}} = 0$, -> B=0 (wash out)

Sakharov conditions

Departure from T.E. (2 - Motivation):

- Let’s see why in T.E. the number density of X and $\overline{X}$ is the same if there exist B-violating reactions, i.e. any initial or produced asymmetry is washed out.
- This is done by a “derivation” of the Boltzmann equation which describes the evolution of the number density of a given particle species
- Due to the wash-out-effect no baryon asymmetry can be created in T.E.

Sakharov conditions

Departure from T.E. (3 – Boltzmann Equation):

Imagine a group of people attending the same high school. These people are very busy and their meetings are short and not more than 2 persons meet at a time. When you meet your colleague, there exist two possibilities:

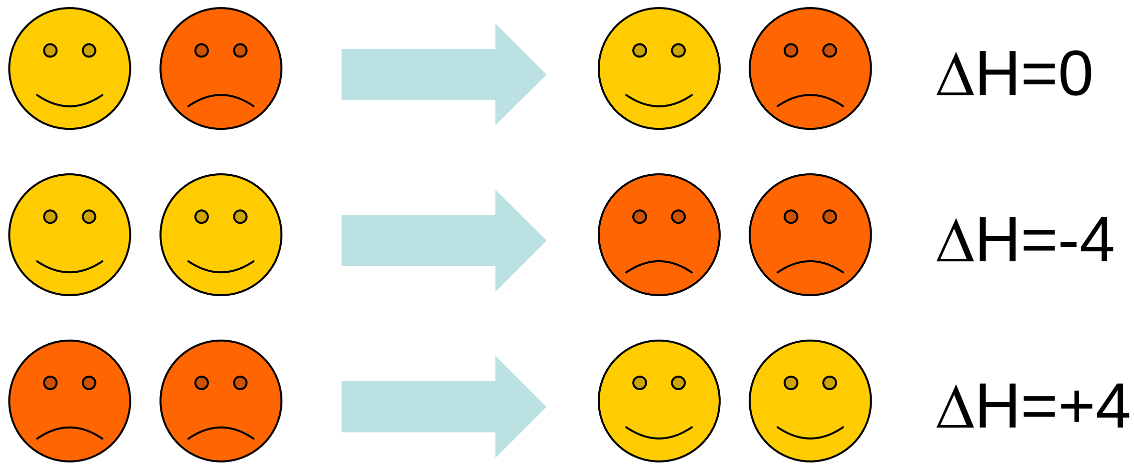
- You see your colleague happy. Being jealous of it, you become unhappy.
- You see your colleague unhappy. ‘Schadenfreude’ means you become happy due to it.

Now, three different kinds of interactions happen:

- Happiness conserving interaction (happy person meets unhappy one)
- Happiness decreasing interactions (two happy persons meet)
- Happiness increasing interactions (two unhappy persons meet)

Sakharov conditions

Departure from T.E. (4 – Boltzmann Equation):



Happiness H = Number of happy people – Number of unhappy people

In T.E. the happiness increasing process and the decreasing process are equal probable.

Let us now estimate the change in happiness per unit time.

Sakharov conditions

Departure from T.E. (5 – Boltzmann Equation):

$\Delta H \sim$ 4(probability that an unhappy person meets another unhappy one – probability that happy person meets another happy one)

- The probability of being unhappy is just proportional to NU (the number of unhappy persons) relative to the total number of persons.
- While the probability of meeting another unhappy person is proportional to NU per unit area (or volume).
- Dropping some constant we obtain the following proportionality:

$\Delta H \sim (NU^2 - NH^2) \sim NU - NH \sim -H$ (const total number assumed)

If we make the transition from total numbers to number densities and the density of happiness changes, we get the following relation

$$\Delta n_H \sim -n_H$$

Thus, net happiness decays away exponentially.

Sakharov conditions

- How can departure from T.E. be achieved?
- 2 main categories models fall in:

  - $\Gamma \leq H$ + decay of particles

  - departure during phase transition which lead to symmetry breaking

The out-of-equilibrium decay scenerio

- QFT tells us:
  - decay rate of superheavy bosons $\Gamma_X \approx \alpha_X M_X$
  - decay rate of a (gauge singlet) scalar boson $\Gamma_X \approx \frac{M_X{}^3}{m_{pl}{}^2}$
- At high Temperature all particles assumed to be in T.E with roughly equal number density -> B=0
- At T ≤ M the equilibrium abundance decreases exponentially

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} \exp[-(m-\mu)/T]$$

- Thus, in order to stay in T.E. the species has to reduce their density rapidely

The out-of-equilibrium decay scenerio

- What are the possible reactions?

  - decay

  - inverse decay

  - annihilation

  - scattering

- Most important at $T \leq M$ is the **decay process**, since the inverse decay drops exponentially (Boltzmann-factor).

The out-of-equilibrium decay scenerio

- If $\Gamma_X >> H|_{T=M_X}$ the species can adjust their abundance by decay -> out-of-equilibrium condition not satisfied
- If $\Gamma_X \leq H|_{T=M_X}$ particles cannot decay on timescale H^{-1}
  - remain as abundant as photons
  - They decouple at $T > H|_{T=M_X}$ while still relativistic (hot relics)
  - At $T \approx M_X$ the particles $X, \overline{X}$ are overbundant
  - -> condition 3 is satisfied

  Using $H = 1.66 g_*^{1/2} \frac{T^2}{m_{pl}}$ this is equivalent to:

$M_X \geq g_*^{-1/2} m_{pl} \alpha_X \approx (10^{10} - 10^{16}) GeV$ for gauge bosons

$M_X \leq g_*^{1/2} m_{pl}$ for only gravitational interacting particles

Summary of Part 1

- Baryon asymmetry is observed in the universe
- In order to allow for the development of an baryon-antibaryon asymmetric universe from symmetric initial conditions a theory has to obey the Sakharov conditions

  - Baryon number violation
  - C and CP violation
  - Departure from thermal equilibrium

- In the context of a GUT the first two conditions could be satisfied
- The departure from T.E. may arise due to overabundance of heavy decaying particles