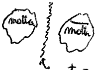
{Leptogenesis} Baryon Asymmetry of the Universe (BAU) Recap

Small step back:

* Today we see mostly particles and no antiparticles. We know that there are not many antiparticles around.
• Maybe one could have thought that antiparticles are somehow segregated from particles in ≠ region of space



$E_\gamma = 511\,\mathrm{keV}$ so we should expect a strong gamma ray signal from the interface region, which we don't see

$e^+ e^- \to \gamma\gamma$

• $\frac{\text{flux of antihelium}}{\text{flux of helium}}$ cosmic rays $< 5 \times 10^{-7}$ so we really don't have lots of antimatter around.

$\Rightarrow \underline{B \neq 0}$! The total baryon number of the Universe is non zero, we indeed have more particles than antiparticles.

/!\ From what we have measured, from the properties of the particles of the Standard Model of particle physics, from early U. dynamics, we get that this is unexpected! Microscopic physics clashes with macroscopic physics → Beyond the Standard Model (BSM) physics! → Interesting

• Today, $\frac{\#\text{density of relic antibaryons}}{n_\gamma} \simeq 10^{-10^5}$, so we really shouldn't expect to see any relic antibaryons!

⇒ All in all, we need a mechanism that allows us to generate a non-zero baryon number in the Universe / that prefers particles over antiparticles.

* **Sakharov's condition:**
(i) Out of equilibrium
(ii) C & CP violation
(iii) Baryon number violation

} Ingredients that our mechanism need to fulfill!

out of eq requirement:

(i) A formal derivation:

The baryon number of an in-equilibrium system can be computed

baryon # quantum operator; Thermal average; $\beta = 1/T$

$$\langle \hat{B} \rangle_T = \mathrm{Tr}\left[e^{-\beta \hat{H}} \hat{B} \right] = \mathrm{Tr}\left[(\hat{C}\hat{P}\hat{T})(\hat{C}\hat{P}\hat{T})^{-1} e^{-\beta \hat{H}} \hat{B} \right]$$

charge, parity, time reversal

$\hat{H}$ commutes with CPT and trace cyclicity.

$$= \mathrm{Tr}\left[e^{-\beta \hat{H}} \underbrace{(\hat{C}\hat{P}\hat{T})^{-1} \hat{B} (\hat{C}\hat{P}\hat{T})}_{= -\hat{B}} \right] = -\mathrm{Tr}\left[e^{-\beta \hat{H}} \hat{B} \right] = -\langle \hat{B} \rangle_T = 0!$$

(ii) C & CP violation: From a QM perspective, we want $|\mathcal{M}_{A\to B}|^2 - |\mathcal{M}_{\bar{B}\to\bar{A}}|^2 \neq 0$ (amplitude of transition)

$A \circledast B \xrightarrow[\text{transform}]{CP} \bar{B} \circledast \bar{A}$ because C transform $A \to \bar{A}$, $B \to \bar{B}$ and P reverses the momentum so the initial state becomes the final state and vice-versa.

We can always write $\mathcal{M}_{A\to B} = c_0 \mathcal{M}_0 + c_1 \mathcal{M}_1$ (classical piece; quantum corrections) and

$$\mathcal{M}_{\bar{B}\to\bar{A}} = c_0^* \mathcal{M}_0^* + c_1^* \mathcal{M}_1^*$$ because $\langle f|i\rangle = \langle i|f\rangle^*$ from Q.M.

$$\Rightarrow |\mathcal{M}_{A\to B}|^2 - |\mathcal{M}_{\bar{B}\to\bar{A}}|^2 = 2 \cdot \mathrm{Im}(c_0 c_1^*)\, \mathrm{Im}(\mathcal{M}_0 \mathcal{M}_1^*)$$ ⇒ C P violation is a quantum effect!

Complex couplings are required. Interference between tree-level and one-loop

(iii) B violation evident.

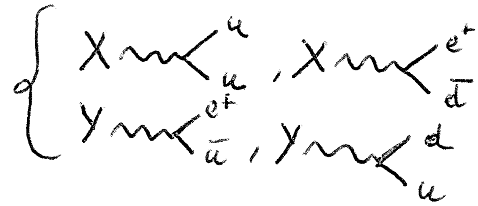
* GUT baryogenesis (Grand Unified Theory)

Let us put B-violat° in perspective.

Grand Unified Theories aim at making all forces {photon, W-Z boson, gluon} unify ⇒ all these vector bosons are different "avatars" of the same fundamental force.

But they provide more than that: They also say that matter (fermion, lepton, quarks) is unified → They are also ≠ "avatars" of same fundamental matter field.

So it's not so shocking to learn that they provide processes that {violate baryon number, transform quarks into leptons. (Not surprising, E.W. electric charge ν initial and not. in stacked)

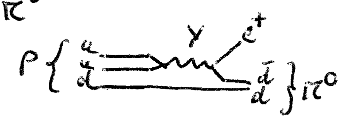


⇒ Processes that involve the X & Y bosons can provide the baryon-number violat° that is required in generating the Baryon Asymmetry of the Universe (BAU)

However...

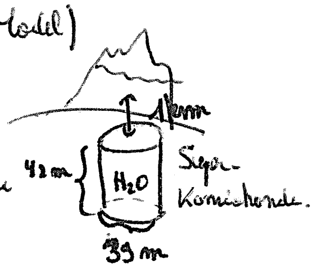
The unificat° of the forces forces the masses of the X & Y bosons to be fixed at $\sim 10^{14}$ GeV. It turns out that this has experimental ~~applicat~~ implicat°.

→ Proton decay! $p^+ \to e^+ + \pi^0$



(Impossible in the Standard Model)

$\tau_{p^+}^{GUT} \simeq 10^{30} - 10^{31}$ years (prediction from GUTs) but $\tau_{p^+} \gtrsim 1.67 \times 10^{34}$ years $\approx 10^{24} \times$ age of the Universe (experimental constraints)



⇒ GUTs are experimentally disfavoured and therefore they probably didn't generate the baryon asymmetry of the Universe...

* Baryogenesis via leptogenesis

It turns out that new physics related to neutrinos can help us generate the non-zero BAU.

"Sterile neutrinos", "Right-handed Neutrinos", "Heavy Neutral leptons"

neutrinos are massless in the S.M. → New particles are required to explain them ⇒ What if they can help us? (ex right-handed neutrinos; $N \sim \nu$ & they are like a heavy version of neutrino. $N \to \nu qq, \ldots$)

ii) But neutrinos are leptons, maybe they can violate L but it's going to be difficult to violate B from this...

But there's a phenomenon in the S.M. that can transfer $L \neq 0$ into $B \neq 0$ at high temperature ($T > 130$ GeV): Sphalerons!

→ 3 leptons into 9 quarks.

What about the other condit°?

(i) Right-handed neutrinos can be out-of-equilibrium in the Early Universe.

decay rate → $\Gamma_N \simeq \frac{y_\nu^2 m_N}{16} \underset{\uparrow}{\simeq} \frac{m_\nu \, m_N^2}{8\pi v^2}$ (To reproduce neutrino masses; v: Higgs vev = 246 GeV)

$$\Rightarrow \frac{\Gamma_N}{H} = \left(\frac{2\times10^{10}\,\text{GeV}}{T}\right)^2 \left(\frac{m_\nu}{0.01\,\text{eV}}\right)\left(\frac{m_N}{10^{10}\,\text{GeV}}\right)^2$$

and so at $T > 2\times10^{10}$ GeV, N's were decaying out of equilibrium! First condit° fulfilled if we have a bunch of N's at very high temperature.

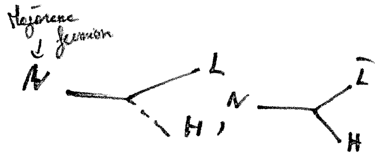
(iii) This is the most subtle point $\mathcal{L} \supset y_{ij}^\nu \bar{L}_i \nu_{R_j} H$

$|\mathcal{M}_{N\to LH}|^2 = |c_0 \mathcal{M}_0 + c_1 \mathcal{M}_1 + \ldots|^2$ but whatever

* The equations of leptogenesis

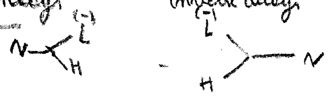
It would be nice to have a set of equat° that tracks how much L we generate in the early Universe. Like that we know if the underlying (microphysics / particle physics model) can reproduce the observed B.A.U.

Integrated Boltzmann equat° for the abundance of sterile neutrinos



$$\boxed{\frac{dn_N}{dt} + 3Hn_N \simeq -\Gamma_N^{Tot}\, n_N + \Gamma_N^{Tot}\, n_N^{eq}}$$

decays   inverse decays



where $\Gamma_N^{Tot} = \Gamma_{N\to LH} + \Gamma_{N\to \bar{L}H}$

and we know that $\Gamma_{N\to LH} - \Gamma_{N\to \bar{L}H} \neq 0$

$$\equiv \varepsilon_{cp}\, \Gamma_N^{Tot}$$

But if we look at the leptons

$$\frac{dn_\ell}{dt} + 3Hn_\ell = (\text{SM processes}) + \Gamma_N\, n_N - \Gamma_N\, n_N^{eq}$$

$$\frac{dn_{\bar{\ell}}}{dt} + 3Hn_{\bar{\ell}} = (\text{SM processes}) + \Gamma_{\bar{N}}\, n_N - \Gamma_{\bar{N}}\, n_N^{eq}$$

and we write $n_{\ell-\bar{\ell}} \hat{=} n_{\ell-\bar{\ell}}$

$$\Rightarrow \frac{dn_{\ell-\bar{\ell}}}{dt} + 3H\, n_{\ell-\bar{\ell}} \approx (\Gamma_N - \Gamma_{\bar{N}})(n_N - n_N^{eq})$$

$$\Rightarrow \boxed{\frac{dn_{\ell-\bar{\ell}}}{dt} + 3H\, n_{\ell-\bar{\ell}} \simeq \varepsilon_{cp}\, \Gamma_N^{Tot}(n_N - n_N^{eq})}$$

if $n_N > n_N^{eq}$ then $n_{\ell-\bar{\ell}} \nearrow$ and an asymmetry is generated!

$n_N > n_N^{eq}$ is easy if N decouples relativistically and takes a long time to decay!

$\Rightarrow$ Sphaleron $\Rightarrow$ BAU!