Baryogenesis and leptogenesis

What is it about?

The dark matter that we discussed before has an influence only through its energy density; it doesn't matter if the energy is carried by particles or antiparticles (e.g. hydrogen or antihydrogen). In other words: „dark matter = particles + antiparticles". At the same time, all visible universe is made of particles (antiparticles can be produced when cosmic rays collide with atmosphere, but only in tiny amounts). So we have: „matter asymmetry = particles − antiparticles". Given that most of the mass is in protons, we frequently refer to „baryon asymmetry". Its quantitative measure is $\frac{n_B}{n_\gamma} \approx 6\times10^{-10}$ (p.12). The question is, could such an asymmetry be produced from nothing?

Sakharov conditions:

*A.D. Sakharov, „Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe", JETP Lett. 5 (1967) 24

The criteria that need to be satisfied to generate a baryon asymmetry are encoded in the three Sakharov conditions:

(i) there must be baryon number violation
[otherwise any reaction generates as many antibaryons as baryons]

(ii) there must be C and CP violation
[otherwise the total number densities of particles and antiparticles coincide]

(iii) the system must depart from thermal equilibrium
[in equilibrium any reaction and inverse reaction proceed equally fast]

In principle these conditions could be satisfied by the Standard Model:

*G. 't Hooft, „Symmetry breaking through Bell-Jackiw anomalies", Phys. Rev. Lett. 37 (1976) 8

(i) baryon number is violated by the chiral anomaly*:

$$\partial_\mu \sum_{k=1}^{N_g} \{ \underbrace{\bar{Q}_k \gamma^\mu Q_k}_{\text{„B"}} + \underbrace{\bar{\ell}_k \gamma^\mu \ell_k}_{\text{„L"}} \} = \frac{N_g}{32\pi^2} \varepsilon^{\mu\nu\rho\sigma} \{ \underset{\underset{\boxed{SU_L(2)}}{\uparrow}}{g_w^2 G^a_{\mu\nu} G^a_{\rho\sigma}} - \underset{\underset{\boxed{U_Y(1)}}{\uparrow}}{g_Y^2 F_{\mu\nu} F_{\rho\sigma}} \}$$

(ii) C is violated by weak interactions,
CP by a phase in the CKM matrix.

(iii) a thermal phase transition could provide for a deviation from thermal equilibrium.

But this does <u>not</u> work in practice, as for the physical value of m_H there is only a smooth crossover (cf. p. 29).

Apart from the existence of dark matter, the existence of a baryon asymmetry shows that there must be physics „Beyond the Standard Model".

Notation:

$$Y_B := \frac{n_B - n_{\bar{B}}}{s} \quad ; \quad n_{\bar{B}} = \text{antibaryon density} \ll n_B .$$

$$Y_L := \frac{n_L - n_{\bar{L}}}{s} \quad ; \quad n_{\bar{L}} = \text{antilepton density}.$$

The value of Y_L is not known, as we do not know if the cosmological neutrino background carries an asymmetry. We also denote $Y_{B\pm L} := Y_B \pm Y_L$.

Leptogenesis:

Perhaps the simplest idea for generating $Y_B \neq 0$ is called leptogenesis*: one first generates $Y_L \neq 0$, a part of which is reprocessed into $Y_B \neq 0$ through the mechanism discussed on p.43.

We recall that the introduction of right-handed neutrino fields (p.25) leads to two important predictions:

(i) there are heavy eigenstates, „sterile neutrinos", with yield Y_R

(ii) lepton number is violated:

$$\mathcal{L} \supset -h_\nu \left(\bar{\nu}_R \tilde{\phi}^\dagger \ell_L + \bar{\ell}_L \tilde{\phi} \nu_R \right) - \frac{M_M}{2} \left(\bar{\nu}_R^c \nu_R + \bar{\nu}_R \nu_R^c \right)$$

phase transformation of ℓ_L could be compensated for by that of ν_R

but these terms are not invariant

In this situation our rate equations take the form**

$$\begin{cases} Y'_{L-B} = -\hat{\Gamma}_L \, Y_{L-B} - \hat{\Gamma}_{L,R} \left(Y_R - Y_R^{eq} \right) + \mathcal{O}\left(Y - Y^{eq} \right)^2 \\ Y'_R = -\hat{\Gamma}_R \left(Y_R - Y_R^{eq} \right) - \hat{\Gamma}_{R,L} \, Y_{L-B} + \mathcal{O}\left(Y - Y^{eq} \right)^2 \end{cases}$$

Here $\hat{\Gamma}_R$ is a rate like on p.25-26, but this time we do not need to be stable, i.e. $\hat{\Gamma}_R \gg 1$ is allowed at low temperatures, which significantly enlarges the parameter space.

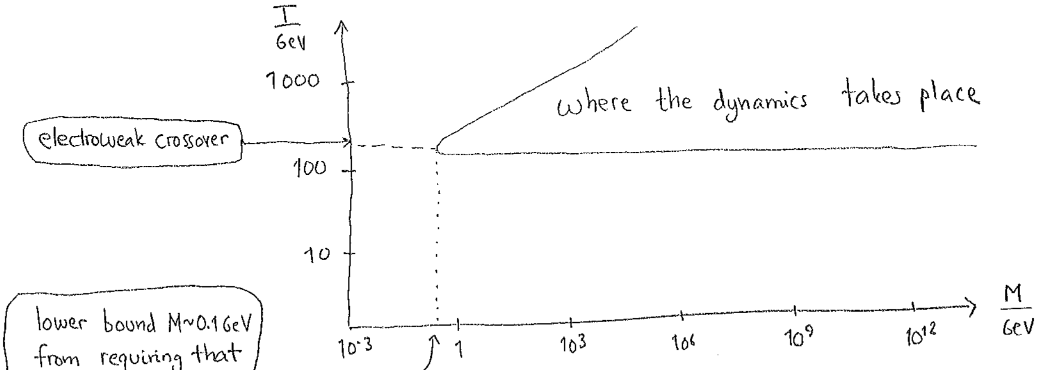
As Y_{L-B} is CP-odd (asymmetry) and Y_R is CP-even (energy density), the coefficients $\hat{\Gamma}_{L,R}$ and $\hat{\Gamma}_{R,L}$ are CP-odd and thus small.

The idea: * suppose $\hat{\Gamma}_R$ is not too large ⇒ Y_R out of equilibrium [cf. Sakharov (iii).]

* suppose $\hat{\Gamma}_{L,R}$ is non-zero ⇒ „source" for Y_{L-B} [cf. Sakharov (ii).]

* suppose $\hat{\Gamma}_L$ is not too large ⇒ Y_{L-B} is not „washed out" [cf. Sakharov (iii).].

A precise investigation requires lots of work, but in the end it can be made to function:



lower bound M~0.1GeV from requiring that ν_h decays fast enough in order not to spoil BBN and Neff (p.7-8)

⇒ The experimental search for M > 0.1GeV sterile neutrinos is an important contemporary challenge.

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* M. Fukugita and T. Yanagida, „Baryogenesis without Grand Unification", Phys. Lett. B 174 (1986) 45

** It is best to use Y_{L-B} rather than Y_L as a variable, given that it is not affected by the anomaly equation (cf. p.41)

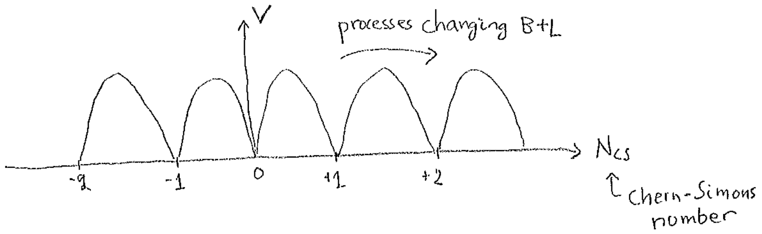
Sphalerons:

Let us now turn to the anomalous processes violating B+L (p.41). In this case the rate equation is best written as

$$Y_B' = -\hat{\Gamma}_{B+L}\left(Y_B - Y_B^{eq}\right),$$

where Y_B^{eq} can be non-zero if Y_{L-B} is non-zero. This equation should be solved simultaneously with those on p.42. (One could also write an equation for Y_{B+L} and then extract $Y_B = (Y_{B+L} - Y_{L-B})/2$.)

The crux of the problem is the determination of the anomalous rate Γ_{B+L}. This is closely related to the determination of the nucleation rate on p. 37, as the „vacuum structure" of Yang-Mills theory is non-trivial:



The rate can be estimated in various limits:

(i) $T=0 \Rightarrow$ quantum tunnelling*

$$\Rightarrow \Gamma_{B+L} \propto e^{-\frac{8\pi^2}{g_w^2}} \sim \text{very small (never observed)}$$

(ii) $T>0 \Rightarrow$ thermal fluctuation.

In this case the process takes place through a „static" (τ-independent) configuration, called a „sphaleron"**, and the rate takes the form

$$\Gamma_{B+L} \propto e^{-\frac{8\pi m_W}{g_w^2 T}}\,\phi\!\left(\frac{m_H}{m_W}\right),$$

where $\phi \sim 1$ is a slowly varying function.

(iii) $T > T_c \Rightarrow v \simeq 0 \Rightarrow m_W \simeq 0 \Rightarrow$ no barrier!

In this case Γ_{B+L} becomes fast***:

$$\Gamma_{B+L} \sim \alpha_w^5\, T, \qquad \alpha_w := \frac{g_w^2}{4\pi}.$$

In fact this far exceeds the Hubble rate at T~200GeV:

$$\hat{\Gamma}_{B+L} \sim \frac{\alpha_w^5\, T}{T^2/m_{Pl}} \sim \frac{\alpha_w^5\, m_{Pl}}{T} \overset{\alpha_w \sim \frac{1}{100}}{\sim} \frac{10^9\,\text{GeV}}{T}.$$

Summary: $\hat{\Gamma}_{B+L} \gg 1$ (so that $Y_B \approx Y_B^{eq}$) in the early Universe, until temperatures below the electroweak crossover, so that the Higgs mechanism sets in and the rate becomes exponentially suppressed. In the Standard Model this happens at $T \approx 130$ GeV. Any lepton asymmetries produced until then can be partly converted into a baryon asymmetry.

* G. 't Hooft, „Computation of quantum effects due to a four-dimensional pseudoparticle", Phys. Rev. D 14 (1976) 3432

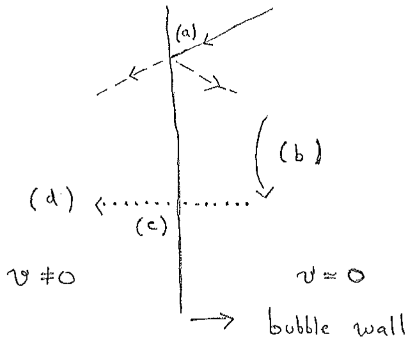
** F.R. Klinkhamer, N.S. Manton, „A saddle point solution in the Weinberg-Salam theory", Phys. Rev. D 30 (1984) 2212

*** V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, „On the anomalous electroweak baryon number non-conservation in the Early Universe", Phys. Lett. B 155 (1985) 36; P. Arnold, D. Son, L.G. Yaffe, „The hot baryon violation rate is $O(\alpha_w^5 T^4)$", hep-ph/9609481

Electroweak baryogenesis: In extensions of the Standard Model, there could be a first order cosmological phase transition (cf. p. 35-36). The rich dynamics associated with such a transition (cf. p. 39) leads to a departure from thermal equilibrium [Sakharov (iii)]. It may then be asked whether a baryon asymmetry could be produced by this dynamics,* even without having first produced Y_{L-B} like we did on p. 42.

* A review:
D. E. Morrissey,
M. J. Ramsey-Musolf,
„Electroweak baryogenesis",
arXiv: 1206.2942

To generate a baryon asymmetry requires a complicated four-step process which is often illustrated as follows:



(a) when particles cross to the Higgs phase, their mass and thereby dispersion relation changes. This leads to a partial reflection (like with light). In the presence of CP-violation [Sakharov (ii)], it may happen that more particles [e.g. top quarks] get reflected than antiparticles.

(b) the reflected particles participate in fast sphaleron processes in front of the wall, whereby B+L gets violated [Sakharov (i)].

(c) the re-processed particles are eventually overtaken by the advancing bubble wall.

(d) we now have a non-zero B+L in the broken phase. If sphalerons were still active, they could wash this out when making use of the originally transmitted antiparticles. So they need to be out of equilibrium [Sakharov (iii)].

The simplest quantitative consideration concerns point (d): to avoid wash-out, it is necessary that $\hat{\Gamma}_{B+L} < 1$, i.e.

$$\alpha_w^5 T \, e^{-\frac{2m_W}{\alpha_w T}\phi} < \frac{T^2}{m_{Pl}}$$

$$\Leftrightarrow \quad \frac{2m_W}{\alpha_w T}\phi > \ln\left(\frac{\alpha_w^5 m_{Pl}}{T}\right) \sim \ln\left(\frac{10^{9}\,\text{GeV}}{10^{2}\,\text{GeV}}\right) \sim 16$$

$$\boxed{m_W = \frac{g_w v}{2}}$$

$$\Leftrightarrow \quad \frac{v}{T} > 16 \cdot \frac{g_w}{4\pi} \cdot \frac{1}{\phi} \sim \frac{4}{\pi} \cdot \frac{2}{3} \cdot \frac{1}{\phi} \sim 1 .$$

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