10 Aspects of Baryogenesis

In the preceding section, we have applied the Boltzmann formalism to dark matter. Of course, we can also try to apply it to ordinary baryonic matter, e.g. to the annihilation channel

$$b + \bar{b} \leftrightarrow \gamma + \gamma \tag{10.1}$$

For a prediction, we need an estimate for the cross section $\langle \sigma v \rangle$. On an effective level, the interactions between baryons can be thought of as being mediated by pions with a mass $m_\pi \simeq 140$ MeV. Hence, a dimensional analysis suggests: $\langle \sigma v \rangle \sim \frac{1}{m_\pi^2}$.

Inserting this into (9.30), we would get

$$\Omega_b \simeq 10^{-11} \tag{10.2}$$

which is obviously way too small in order to match observation $\Omega_b \simeq 0.05$. In fact, the existence of such a large amount of baryons (and thus of us) in the universe is one of the least understood facts in present day cosmology.

One may assume that the baryon-antibaryon asymmetry has been an initial condition at the time of the big bang. However, it is not even clear whether such an initial condition would have survived the cosmic evolution, since the standard model features mechanisms to wash out such an asymmetry.

Current belief holds that the asymmetry between matter and anti-matter has been generated dynamically.

Any successful theory of baryogenesis must necessarily satisfy the Sakharov conditions (Sakharov '67):

1) Violation of baryon number.
2) Violation of C and CP. (10.3)
   (charge and charge-parity conjugation)
3) Departure from equilibrium.

Let us justify these conditions:

1) The necessity that baryon number B

must be violated, i.e. that B is <u>not</u> a conserved quantum number, is obvious: A universe with $B=0$ initially cannot evolve into one with $B \neq 0$ if B was conserved.

2) Charge conjugation must also be violated: if C was an exact symmetry then any process $i \to f$ would be equal to the corresponding process for the anti-particles $\bar{i} \to \bar{f}$.
If the first produced baryon number, the second would destroy it again, such that no net baryon number could be generated.
The reason for CP violation is similar though somewhat more subtle: Consider some state with momentum $\vec{p}$ and spin $\vec{s}$ and a corresponding process $i(\vec{p}, \vec{s}) \to f(\vec{p}, \vec{s})$.
Now, any relativistic quantum field theory must be invariant under CPT symmetry (CPT theorem). CP invariance would thus entail T invariance.
Under time reversal T, the process would

read $f(-\vec{p},-\vec{s}) \rightarrow i(-\vec{p},\vec{s})$.

If T reversal was a symmetry, then an integration over momenta and summation over spin, would again lead to a vanishing net baryon number.

3) The baryon asymmetry must be generated in processes that proceed out of equilibrium. Consider, e.g. the non-relativistic limit, where

$$n_p = 2g\,(mT)^{3/2}\, e^{-\frac{m}{T}}\, e^{\frac{\mu_p}{T}} \tag{10.4}$$

and $$n_{\bar{p}} = 2g\,(mT)^{3/2}\, e^{-\frac{m}{T}}\, e^{-\frac{\mu_p}{T}}$$

where we have used $\mu_{\bar{p}} = -\mu_p$

Baryon number (per volume) then is obtained from

$$B \sim n_p - n_{\bar{p}} \sim (mT)^{3/2}\, e^{-\frac{m}{T}} \sinh\frac{\mu_p}{T} \tag{10.5}$$

Baryon number violating process now effectively correspond to transitions

$$\bar{p} + \ldots \rightarrow p + \ldots \tag{10.6}$$

Replacing an anti-particle by a particle in equilibrium (i.e. without changing the energy) is only possible, if $\mu_p = 0$. From (10.5) it then follows that $B = 0$.

In fact, at a first glance, we seem to have all ingredients available for baryogenesis, because the standard model features B-violating processes on the quantum level through so-called anomaly-induced interactions.
The weak interactions are, in fact, C and CP violating (cf. Kaon decays).
And it is conceivable that the cosmological evolution provides for suitable non-equilibrium conditions.
However, the devil is in the details.

Models of baryogenesis are easy to write down. As a simple example let us

consider the following (unspecific) model:
All we need is to postulate the existence of a sufficiently massive but unstable particle that decays into lighter particles in a way that violates baryon number.
Decay parameters can be arranged such that the decay occurs out of equilibrium (think of a radioactive decay of a nucleus which is also not an equilibrium process).

For definiteness, let us assume that this heavy particle X has two decay channels a and b with baryon numbers B_a and B_b. The anti-particle $\bar{X}$ then has decay channels $\bar{a}$ and $\bar{b}$ with baryon number $-B_a$ and $-B_b$.

Let Γ_X be the total decay rate of the particle. The lifetime of the particle then is $t = \Gamma_X^{-1}$, most of the decays occur when the age of the universe is of the order of the particle's lifetime, $t \sim H^{-1}$.

The branching ratios for the decay into the two channels is related to the corresponding channel decay rate,

$$r = \frac{\Gamma(X \to a)}{\Gamma_X} , \qquad \bar{r} = \frac{\Gamma(\bar{X} \to \bar{a})}{\Gamma_X} \qquad (10.7)$$

$$1 - r = \frac{\Gamma(X \to b)}{\Gamma_X} , \qquad 1 - \bar{r} = \frac{\Gamma(\bar{X} \to \bar{b})}{\Gamma_X} .$$

According to CPT symmetry of relativistic quantum field theories, Γ_X and $\Gamma_{\bar{X}}$ must be equal. The net baryon number produced by the decays is

$$\begin{aligned} \Delta B &= B_X + B_{\bar{X}} \\ &= (r B_a + (1 - r) B_b) + (- \bar{r} B_a - (1 - \bar{r}) B_b) \\ &= (r - \bar{r}) (B_a - B_b) \qquad (10.8) \end{aligned}$$

If the individual decays do not violate baryon number, we have $B_a = B_b = 0$ and thus $\Delta B = 0$. This illustrates Sakharov's first condition. Similarly, if C and CP were preserved, then $r = \bar{r}$ would hold and ΔB would vanish. Eq. (10.9) hence also reflects the 2nd Sakharov condition.

The net baryon density produced by the X decays is related to the density of the X particles:

$$n_B = \Delta B \, n_X \qquad (10.9)$$

If n_X was originally in equilibrium with the primordial plasma, we have approximately $n_X \sim n_\gamma$. With this, we get

$$\eta = \frac{n_B}{n_\gamma} = \frac{\Delta B \, n_X}{n_\gamma} \sim \Delta B. \qquad (10.10)$$

In such models, the amount of baryon number violation is related to the baryon-to-photon ratio. This means that not much ΔB is needed per particle decay, as $\eta = 6 \cdot 10^{-10}$.

This model (presented rather unspecificly here) is rather simple, but requires a new particle with specific properties which has not been observed so far. Still, the model is paradigmatic for more concrete scenarios where such out-of-equilibrium decays of heavy particles are encoded.

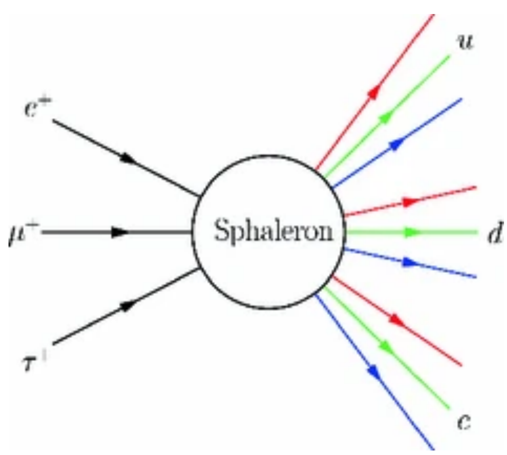
A popular class of models are grand-unified-theories (GUT). Here, all spinor matter fields (quarks and leptons) are embedded into a suitable representation of a large gauge group (e.g. $SU(5)$, $SO(10)$, ...) and interactions can correspondingly mediate between the quark and lepton sector, thus introducing baryon number violation. Many viable scenarios are, in principle, available. However, GUT's also predict that the protons have a finite lifetime as they can typically decay into positrons and a neutral pion.

Such decays have been intensely searched for but not discovered so far, which puts a lower bound on the life-time of a proton ($> 1.67 \cdot 10^{34}$ s, Super-Kamiokande 2016).

This bound rules out a number of the more "natural" models of GUT's and correspondingly also their validity as a model for baryogenesis.

As mentioned above, also the electroweak sector of the standard model, in principle, satisfies the Sakharov criteria. Models based on these ingredients are summarized under electroweak baryogenesis.

The baryon-number violating process is a quantum effect (visible in a semi-classical approach to the quantum theory) that induces effective interactions among the matter particles. This process, called sphaleron, can violate baryon number by converting leptons into quarks, e.g.



(10.11)

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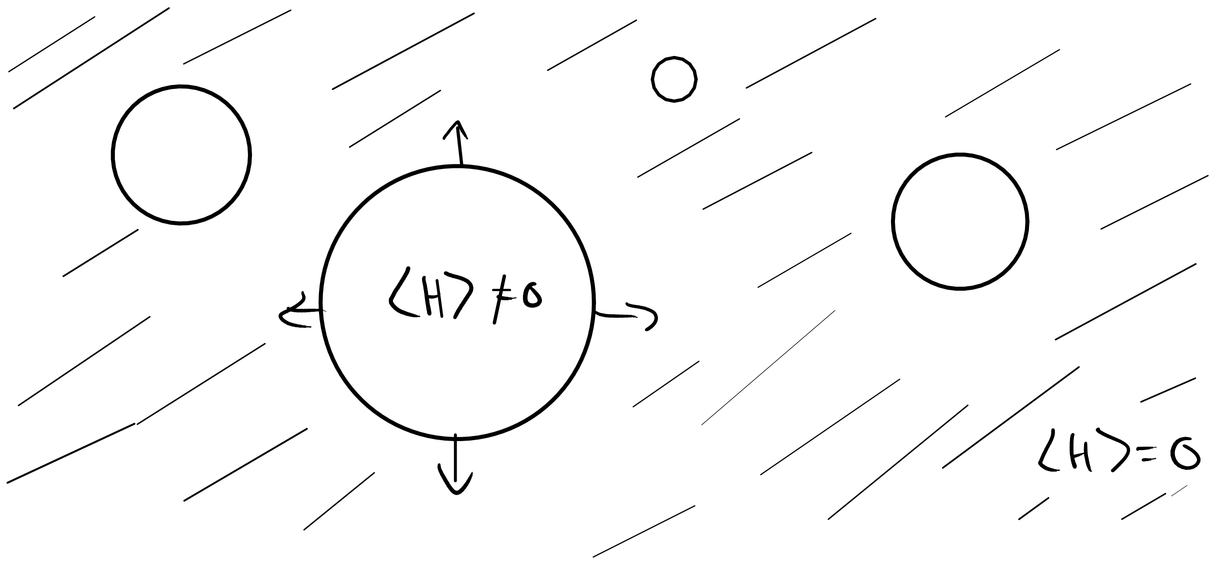
The second Sakharov criterion is satisfied in the standard model by the presence of a CP violating term, which is parametrized by a complex phase of the CKM mass matrix describing quark mixing. The third Sakharov criterion can be satisfied by the electroweak phase transition which is (presumably) a first order phase transition, similar to a liquid-gas transition (boiling water). During a first-order transition, the different phases can coexist providing for a non-equilibrium situation. The order parameter for the phase transition is the expectation value of the Higgs field. At high temperature, we have $\langle H \rangle = 0$ such that all fermions as well as the EW gauge bosons ($W^\pm, Z$) are massless. Similar to bubbles gas forming in boiling water, bubbles of the Higgs phase with $\langle H \rangle \neq 0$ form at the phase transition. This Higgs phase corresponds to the phase that we are living in (massive fermions and EW gauge bosons). As in

boiling water, the bubble walls expand rapidly an coalesce until only the Higgs phase remains



The actual $\Delta B \neq 0$ forming processes are rather involved. Loosely specking the CP asymmetry is active in and near the bubble walls accumulating quarks on the inside and antiquarks on the outside. The sphalerons, however, are much more efficient on the outside, as they occur more frequently in the $\langle H \rangle = 0$ vacuum, where they wash out the anti-baryon abundance outside and thus preserve the baryon abundance inside the bubbles also after coalescence.

The problem of EW baryogenesis is that the amount of CP violation in the standard model is rather small. Even worse, the EW phase transition is presumably only weakly first order and such that the system is rather close to equilibrium. However, the details depend on the details of the Higgs self-interactions which have not yet been measured, but are planned to be measured at the upcoming run at the LHC. If they are as predicted by the Standard model, EW baryogenesis may not be able to explain the existence of this large amount of matter as observed in our universe.

The currently maybe most popular model for baryogenesis is through <u>leptogenesis</u>.

This relies on the observation that the sphaleons an in (10.11) actually conserve $B-L$ (bayon minus lepton number). Eg. in (10.11) there are 3 antileptons in the initial state, i.e. $L_i = -3$ and $B_i = 0$, but 9 quarks (each with bayon number $\frac{1}{3}$) in the final state, i.e. $L_f = 0$, $B_f = 9 \cdot \frac{1}{3} = 3$

$$\Rightarrow \quad 3 = B_i - L_i = B_f - L_f \,. \qquad (10.12)$$

Therefore any model that creates a finite lepton number in the $\langle H \rangle = 0$ phase can transmute L into B by sphalerons.

Popular models postulate heavy right-handed (non standard model) neutrinos which decay out-of-equilibrium and produce a finite primordial L.

A reason for the popularity of such models is that they can be combined with a mechanism that explains the smallness of the neutrino masses (see saw mechanism).