Sakharov Conditions for Baryogenesis

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1. THE MATTER-DOMINATED UNIVERSE

The experimental evidence is that we live in a matter dominated universe. Our manned and unmanned exploration of the solar system tell us that it is made up of the same stuff as the Earth. Observational evidence from radioastronomy and cosmic ray detection indicate that the Milky Way, as well as interstellar space and distant galaxies, are also made of matter. We conclude that the *baryon number* B for the observable universe is greater than 0. Another way to describe the baryon asymmetry is to quote the experimental baryon to photon ratio η, which the latest WMAP data places in the vicinity of

$$\eta = \frac{n_B - n_{\bar{B}}}{\gamma} = 6 \times 10^{-10} \ \frac{\text{excess baryons}}{\text{photon}} \qquad (1)$$

In our experience, antimatter is an exotic substance which is created in colliders or arrives from deep space and matter dominates our day to day existence. Considering the parallels between the two, the value of η seems remarkably large. Explaining this asymmetry is an important area of current research.

There are a few possibilities for how things got this way.

1. The universe has always been baryon-asymmetric. After the big bang, $B > 0$ and nothing has happened to change this. Although this has been the prevailing theory in the past, it has fallen out of favor for a few reasons. A universe with $B = 0$ at creation which evolves according to Nature into the state we observe today is more theoretically appealing. In addition, it's very likely that any initial asymmetry would be quickly eliminated due to thermodynamic considerations. We will discuss this last point in more detail later.

2. The universe actually is baryon-symmetric. In this model, $B = 0$ at the big bang and has been zero forever. The universe expanded quickly enough that not all of the matter and antimatter pair-annihilated before random fluctuations in the matter/antimatter density separated. These isolated pockets in which one or the other dominated, would form local clumps of matter or antimatter galaxies and clusters. If this were the case, there should be a number of experimentally observed phenomena. We should detect annihilation radiation from interstellar space where matter and antimatter should mingle. High-energy cosmic rays should be made up of matter and anti-matter with roughly equal probability, since they can be expected to fairly sample the universe. All experimental evidence is to the contrary: we don't see this an isotropic annihilation radiation, and in cosmic rays, protons outnumber antiprotons on the scale of 10^4 to 1. Additionally, calculations show that this "freeze-out abundance" would only produce a value of $\eta = 10^{-20}$ in matter-dominated regions[1].

3. The universe started out baryon-symmetric but now isn't. In this formulation, $B = 0$ in the beginning and Nature has since then generated a baryon excess (at some point, $\frac{dB}{dt} > 0$). This idea is called *baryogenesis* since the matter excess is *generated* after the Big Bang by some process. Clearly, baryogenesis must precede *nucleosynthesis*, the creation of nucleons and light nuclei, and so must have happened within the first 10^{-12} seconds, since the quark epoch begins shortly after that.

Finding a hypothetical process that implements baryogenesis and explains the observed matter-asymmetry is an important open question in physical cosmology.

2. SAKHAROV CONDITIONS

In 1967, Andrei Sakharov described three minimum properties of Nature which are required for any baryogenesis to occur, regardless of the exact mechanism. In his paper "CP Symmetry Violation, C-Asymmetry, and Baryon Asymmetry of the Universe", Sakharov did not list the conditions explicitly. Instead, he described the evolution of a universe which goes from a B-excess while contracting in a big crunch to an $\bar{B}$-excess after the resultant big bang. His three key assumptions are now known as they Sakharov conditions:

1. At least one B-number violating process.
2. C- and CP-violation
3. Interactions outside of thermal equilibrium.

These conditions must be met by any explanation in which $B = 0$ during the Big Bang but is very high in the present day. They are necessary but not sufficient - scientists must describe the specific mechanism through which baryogenesis happens. Much theoretical work in this cosmology and high-energy physics revolves around

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[1] This, as well as the consistent failure of cosmic anti-matter searches was called the "annihilation catastrophe"

finding physical processes which fit the three above properties and correctly predict the observed baryon density η. We'll discuss a number of possible processes later.

3. B-NUMBER VIOLATION

If every fundamental interaction conserves B-number individually, then it will always be conserved globally. Thus, there must exist a process of the form

$$X \to Y + B \tag{2}$$

Above, X and Y have a baryon number of zero, and B is excess baryons ($B > 0$). Clearly, the existence of this kind of process is a minimum starting point.

4. C- AND CP-VIOLATION

Simple baryon number violation is not enough explain matter-antimatter asymmetry if C is a symmetry of the universe. If C is conserved, then every B-number violating reaction $X \to Y + B$ has the same width as the C-conjugate reaction:

$$\Gamma(X \to Y + B) = \Gamma(\bar{X} \to \bar{Y} + \bar{B}) \tag{3}$$

Since both processes proceed at the same rate, B-number is conserved over long periods of time. So C-violation is a Sakharov condition.

However, this is not quite enough. Consider a hypothetical B-number violating process $X \to q_L q_L$ which creates left-handed baryons. If CP is a symmetry of Nature, then this process proceeds at the same rate as the CP-conjugate process $\bar{X} \to q_R q_R$, and thus

$$\begin{aligned}\Gamma(X \to q_L q_L) + \ \Gamma(X \ &\to q_R q_R) = \\ \Gamma(\bar{X} \ &\to \bar{q_L}\bar{q_L}) + \Gamma(\bar{X} \to \bar{q_R}\bar{q_R})\end{aligned} \tag{4}$$

The C-conjugate reactions have a different width, but the sum of the two will still preserve baryon number (although this kind of reaction would generate excess *handedness*). Thus, CP needs to be violated as well, so that the rate of baryogenesis exceeds that of anti-baryogenesis. With C- and CP-violation, the rate of B-production can exceed that of $\bar{B}$-production.

5. INTERACTIONS OUTSIDE OF THERMAL EQUILIBRIUM

Even with CP-violation working in favor of baryon generation, there are thermodynamic considerations. The energy difference between a particle and its corresponding antiparticle is

$$\Delta E = m_{matter} - m_{antimatter} = 0 \tag{5}$$

At thermal equilibrium, the Boltzmann distribution dictates that there should be equal amounts of matter and antimatter. Other processes will turn any baryon-asymmetry back into even numbers of baryons and antibaryons. Thus, any baryogenesis must happen under conditions outside of thermal equilibrium. As noted earlier, this argument is the reason that any initial B-asymmetry after the big bang might be quickly eliminated.

Additionally, after baryogenesis takes place and the universe returns to thermal equilibrium, the conditions must have changed such that the generated asymmetry cannot be reversed.

6. CONDITIONS IN THE STANDARD MODEL

All of these ingredients are compatible the Standard Model. Whether or not a single mechanism can combine all of them to provide the baryon-dominated universe we see today is an open question. An example of each of the conditions in Nature is given below.

6.1. B-number violation

The Standard Model Lagrangian conserves B classically, but there is a global anomalies under which B-conservation could be violated. Though they have never been observed experimentally, baryon-number violating processes are plausible in the standard model. The canonical example is the *sphaleron process*, which we'll describe here. In electroweak gauge theory, the vacuum state is infinitely degenerate, and the different substates are separated by energy barriers. Through a quantum tunneling process, the system can move to a different vacuum substate which has nonzero baryon number. This process is heavily-suppressed at low energies (below the so-called *sphaleron mass* of ~ 10 TeV), so it is not expected to occur in Nature today, but is feasible at earlier points in the universe's history. The sphaleron process is non-perturbative, so a true Feynman diagram can't be drawn for it, but an example of it is shown in Figure 1.

This process trades three leptons, one from each generation, for nine quarks, three within each generation, and one of each color per generation. L and B are not conserved separately (in the example below, $\Delta L = \Delta B = \pm 3$, $\Delta B - \Delta L = 0$), though the quantum number $B - L$ is. In a sense, this process generates a baryon excess out of a lepton excess, an idea we will return to when talking about leptogenesis. Unfortunately, testing this hypothetical process in the laboratory is out of reach of technology for the foreseeable future.

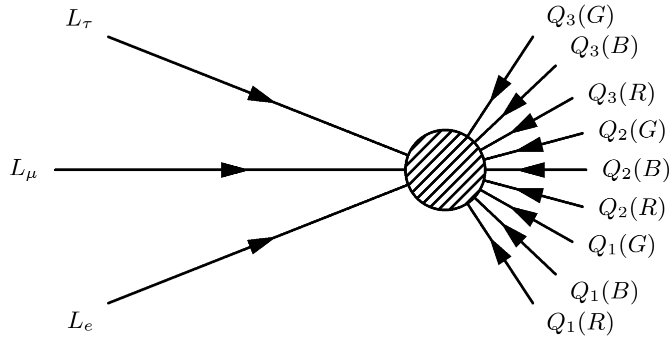

FIG. 1: Sphaleron process. The incoming quantum numbers are $L = 3$ and $B = 0$. The outgoing quantum numbers are $L = 0$ and $B = -3$.

6.2. C- and CP-violation

C-violation in the weak interaction was first demonstrated in 1957 by physicists studying the decay of muons and antimuons. Indirect violation of CP-symmetry in the Standard Model was first seen in the decay of neutral K-mesons in 1964. Since then, CP-violation in the weak interaction has been well-established.

This Sakharov condition clearly exists in Nature, but there are complicating questions. Theorists believe there may not be enough CP-violation in the weak interaction to generate enough baryons fast enough. If CP is a symmetry of the strong interaction (the "strong CP problem"), then does the mechanism behind baryogenesis necessarily involve the weak interaction? Even if there is CP-violation built into the QCD Lagrangian, theorists believe that it would be many orders of magnitude too *large* to explain the universe.

6.3. Interactions outside of equilibrium

There is a natural setting for interactions outside of thermal equilibrium in the Standard Model. Consider the spontaneous electroweak symmetry breaking that happens during the electroweak phase transition (EWPT), which takes place around the temperature $T \sim 100$ GeV or so. An illustrative analogy for this phase transition is like bubbles of steam forming inside boiling water. The inside of the "bubbles" where the symmetry has broken is at thermal equilibrium with its surroundings, as are the outside of the bubbles. The boundary is a different story. On the interphase between the two phases, all interactions occur outside of equilibrium. As the bubbles expand to cover all space and the universe cools, the results of whatever happened on the boundaries become "frozen in", as the processes that would undo the results become suppressed in the new regime.

7. BARYOGENESIS MECHANISMS

The following are a few proposed baryogenesis mechanisms, which vary in their likelihood and popularity among theorists.

Electroweak phase transition. This mechanism involves the three examples of the Sakharov conditions in the Standard Model above. During the electroweak phase transition, baryon-generating processes (such as the sphaleron process) took place at the interphase. Due to CP-violation, baryon generation dominated over the conjugate process. After the transition ended, the temperature fell below the sphaleron mass. The baryon excess was therefore "frozen in" and has been with us ever since. Unfortunately, current theoretical calculations result in a much lower value of η than experiment. In particular, CP-violation in the quark sector may not be enough to explain the large asymmetry.

Leptogenesis. In this model, a large lepton excess is generated through some unknown mechanism, and then $B - L$ conserving processes turn this into a baryon excess directly. CP-violation in leptogenesis becomes effective CP-violation in baryogenesis. This mechanism is more attractive because CP-violation in the lepton sector is not nearly as constrained (largely because measuring it is much more experimentally challenging). This mechanism turns the puzzle of *baryo*genesis into the complementary one of *lepto*genesis. Experimental constraints on lepton CP-violation could be consistent with this mechanism, and it is a popular possibility.

GUT-scale physics. Baryogenesis could have occurred just after the Big Bang, before the unified-scale regime decoupled into the familiar strong and electroweak interactions. In unified theories, quarks couple to leptons and so B-number violation is automatic. Testing this mechanism is made more difficult by the fact that conditions which duplicate the GUT-scale environment are not experimentally feasible to recreate in the laboratory ($\sim 10^{16}$ GeV).

Planck-scale physics. There are many other possibilities that theorists can come up with. At the Planck scale, where quantum gravity effects dominate, no quantum numbers are expected to be conserved, and a baryon excess can be generated in any number of ways. Just like the GUT-scale possibility, the energy scales are inaccessible in the laboratory ($\sim 10^{19}$ GeV).

There are other possibilities, such as exotic supersymmetry theories in which the partner scalar fields of standard-model fermions engage in B-violating processes which explain baryogenesis as well as serve as a mechanism for dark matter creation.

The open problem of baryogenesis integrates other key questions in high-energy physics and cosmology, such as the evolution of the universe, symmetry violation and unification at high temperatures. Our continued inability to present a coherent and convincing baryogenesis mechanism is one of the strongest indicators that the Standard Model is incomplete as is.