# Baryogenesis

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## 1 Introduction

It is an observational fact that the universe contains more baryons than antibaryons. This is true of our immediate environment in particular but, as we shall see, also on scales on the order of the Hubble length. The domination of baryons over antibaryons raises a number of questions. The first is: how large is the baryon density of the universe? For that, see Sec. 2. Could it be that this excess is only local, that the antimatter is hiding somewhere? Sec. 3 dispatches that question. Is there a "microphysical" mechanism for generating a baryon excess from symmetric initial conditions (a so-called *baryogenesis* mechanism)? We survey the possibilities in Sec. 4. Finally, in Sec. 5 we look at possible experimental confirmation for the proposed microphysical mechanisms.

## 2 Measuring the baryon excess

There are two independent ways to measure the baryon content of the universe. Both ways measure the ratio $\eta$ of the present-day number density of baryons, $n_B$, to the present-day number density of photons, $n_\gamma$. The results from the two experiments agree to remarkable accuracy. The agreement is not only between two experimental methods but also between two epochs in the development of the universe: neutrino decoupling and recombination.

### 2.1 Baryon number from BBN

In the big-bang model of the universe, production of light elements ("big-bang nucleosynthesis") occurs when the universe has cooled to the binding energy of the light nuclei, $T \sim 1$ MeV. The formation rates of the light elements are sensitive to the nucleon density, which to good approximation equals the baryon density. Fig. 1 shows how the primordial abundances of several light elements vary with $\eta_{10} = \eta \cdot 10^{10}$ [1]. The small boxes indicate the 1-$\sigma$ primordial concentrations extracted from experiment; the larger boxes indicate the "concordance" values. The blue-shaded background indicates the "concordant" region:

$$2.6 < \eta_{10} < 6.2.$$

As far as I can tell, "concordance" means that the values of $\eta$ derived from the various observables agree roughly, but that the uncertainties from experiment and theory are large enough that it does not make sense to quantify the agreement.

### 2.2 Baryon number from the CMB

The WMAP CMB anisotropy measurements provide the second experimental measurement of $n_B$. The position of the peaks and troughs as well as the relative amplitudes are sensitive to many cosmological

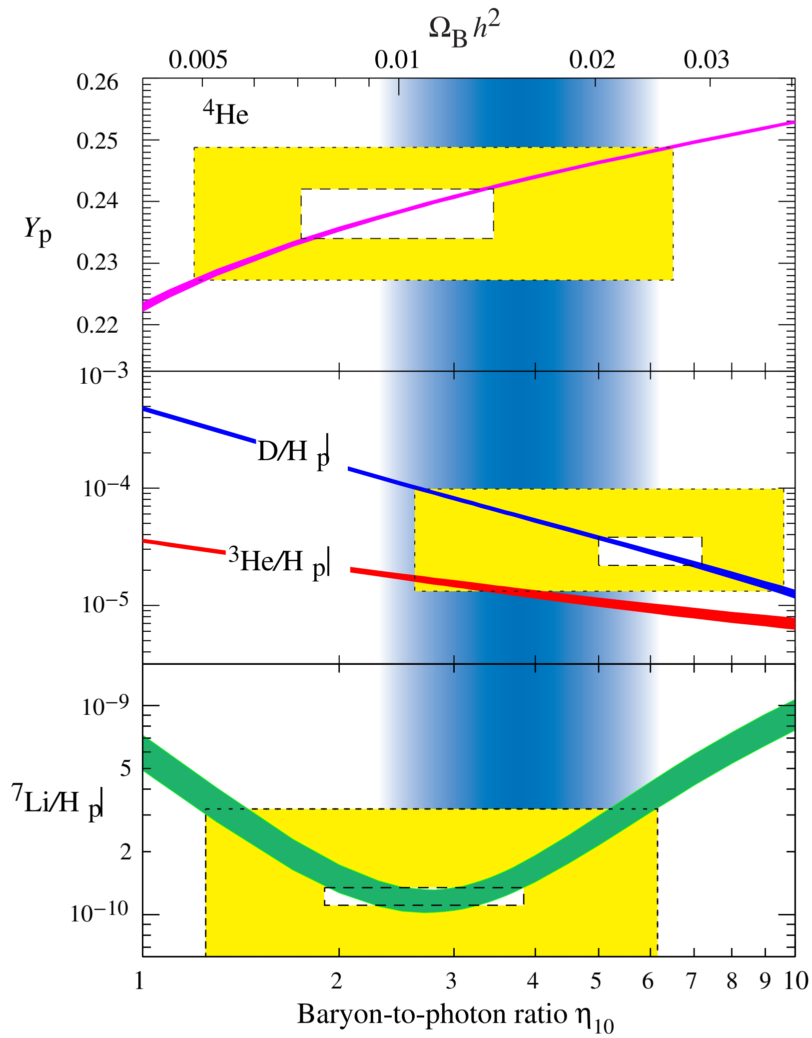


Figure 1: Dependence of the primordial light element abundances on $\eta_{10}(= \eta \cdot 10^{10})$

parameters, including $\Omega_{_B}h^2$. A fit to the WMAP sky maps extracts the age of the universe, decoupling time, $\Omega_m h^2$, $\Omega_{_B}h^2$ and $\Omega h^2$ simultaneously [2]. (For an interesting discussion of how $\Omega_{_B}h^2$ in particular affects the power spectrum, see [3].) The combined WMAP and BBN result yields

$$\eta = \left(6.1^{+0.3}_{-0.2}\right) \cdot 10^{-10}.$$

### 2.3 Implications

The experimental value of $n_{_B}$ raises two disturbing questions. "Why is the value so small?" and "Why is the value so big?" A variable that could, as far as we know, choose any value from zero to fifty times the measured value (when $\Omega_b h^2$ would be $\mathcal{O}(1)$) but chooses to be as small as it is must have a compelling reason to do so. The smallness of $\eta$ suggests that the "natural" value for $\eta$ is zero, but that through some mechanism it is made to deviate slightly from this natural value. $\eta = 0$ is indeed the most reasonable value to expect; it is the value that would arise if the universe were matter-antimatter-symmetric — every baryon would have an antibaryon partner, and the net number of baryons would be zero. The great puzzle is why this number is nonzero, as we will discuss in greater detail in Sec. 4.

## 3 Rationalizing the baryon excess away

Before we turn to the pressing matter of explaining whence the baryon excess arises, we need to discuss its robustness to arguments that the universe *can*, despite the experimental evidence, be brought into matter-antimatter balance. It turns out that the baryon excess is quite robust.

### 3.1 Cosmic diffuse gamma rays

Cohen, de Rujula and Glashow (CDG) have explored a model in which matter and antimatter segregate into domains during the evolution of the universe [4]. Such a model has been offered as explanation for the strong evidence that there are no sizeable nearby accumulations of antimatter — if the antimatter isn't nearby, then it must be far away. The CDG paper examines the observable effects of matter and antimatter domains of linear size $d_0$ and concludes that this size has to be approximately the Hubble radius to agree with observational evidence. Their argument is sketched in the following paragraphs.

If matter and antimatter domains indeed exist, then at some time since the last scattering of the CMB they must have been in contact. We can infer this from the isotropy of the CMB: if there had been voids between matter and antimatter domains, then these voids would be observable in the CMB.

If the domains have been in contact or are still in contact, then the nucleons in the matter domain should be annihilating the antinucleons in the antimatter domain. The main reaction is proton-antiproton annihilation to several pions, which further decay to photons or electrons:

$$\begin{aligned} p + \overline{p} \quad \rightarrow \quad & \pi^0(\rightarrow \gamma\gamma), \\ & \pi^{\pm}(\rightarrow e\nu_e\nu_\mu\overline{\nu}_\mu) \end{aligned}$$

The annihilation products should lead to an observable effect. The annihilation electrons will Compton-scatter off CMB photons; they will also heat the interstellar medium. By both these mechanisms they will alter the CMB spectrum. The annihilation photons will contribute to the cosmic diffuse gamma radiation (CDG) reaching the Earth. A quantitative analysis shows that the effects due to the annihilation electrons do not lead to a strengthening of existing limits on the size of the putative antimatter domains. The prediction for the CDG contribution, however, leads to a very strong limit. Fig. 3 shows the observed CDG spectrum

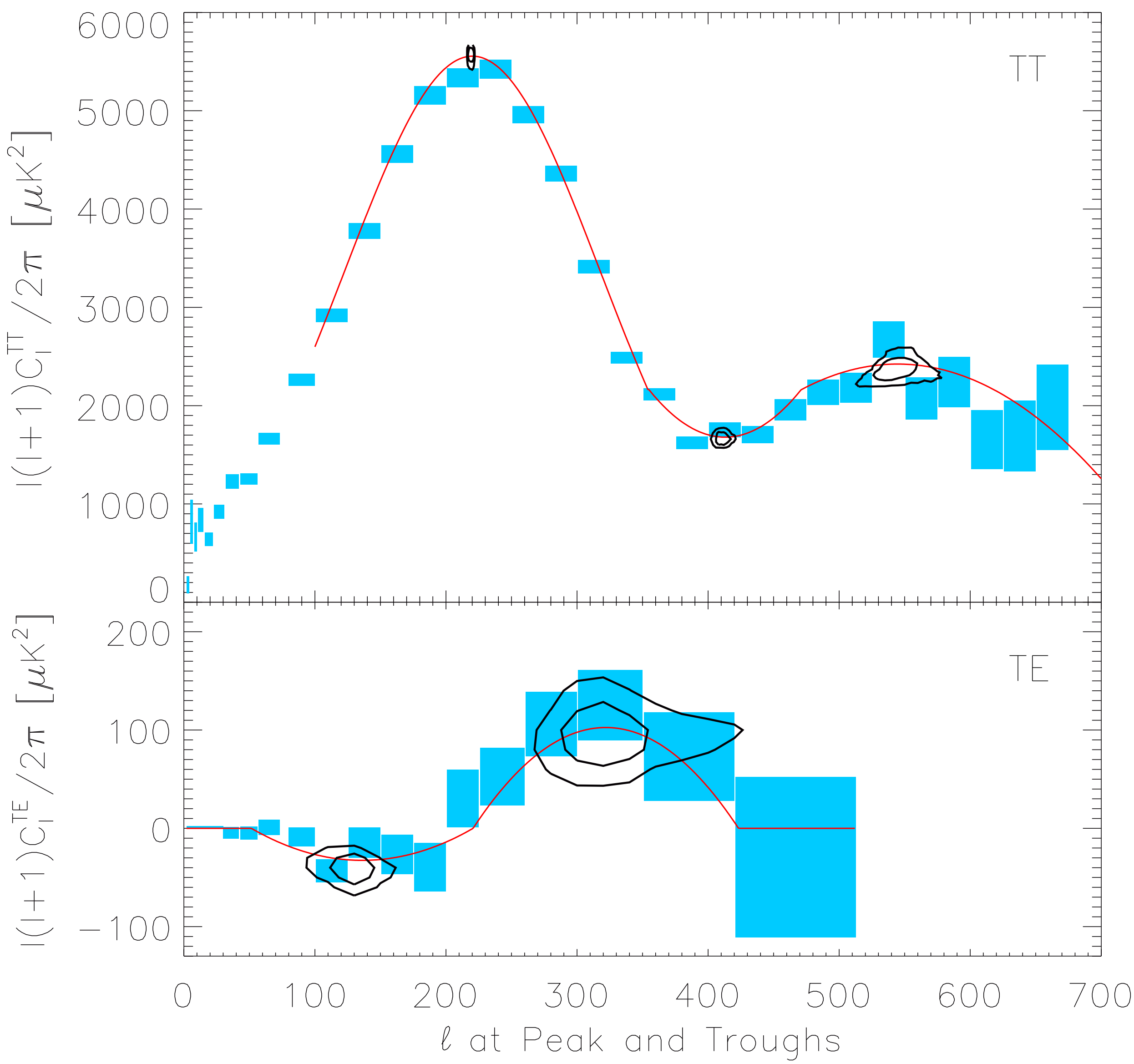


Figure 2: WMAP acoustic peaks in the temperature angular power spectrum (TT) and temperature-polarization cross-power spectrum (TE). The value of $n_B$ is determined mostly by the ratio of the amplitudes of the first and second TT peaks.

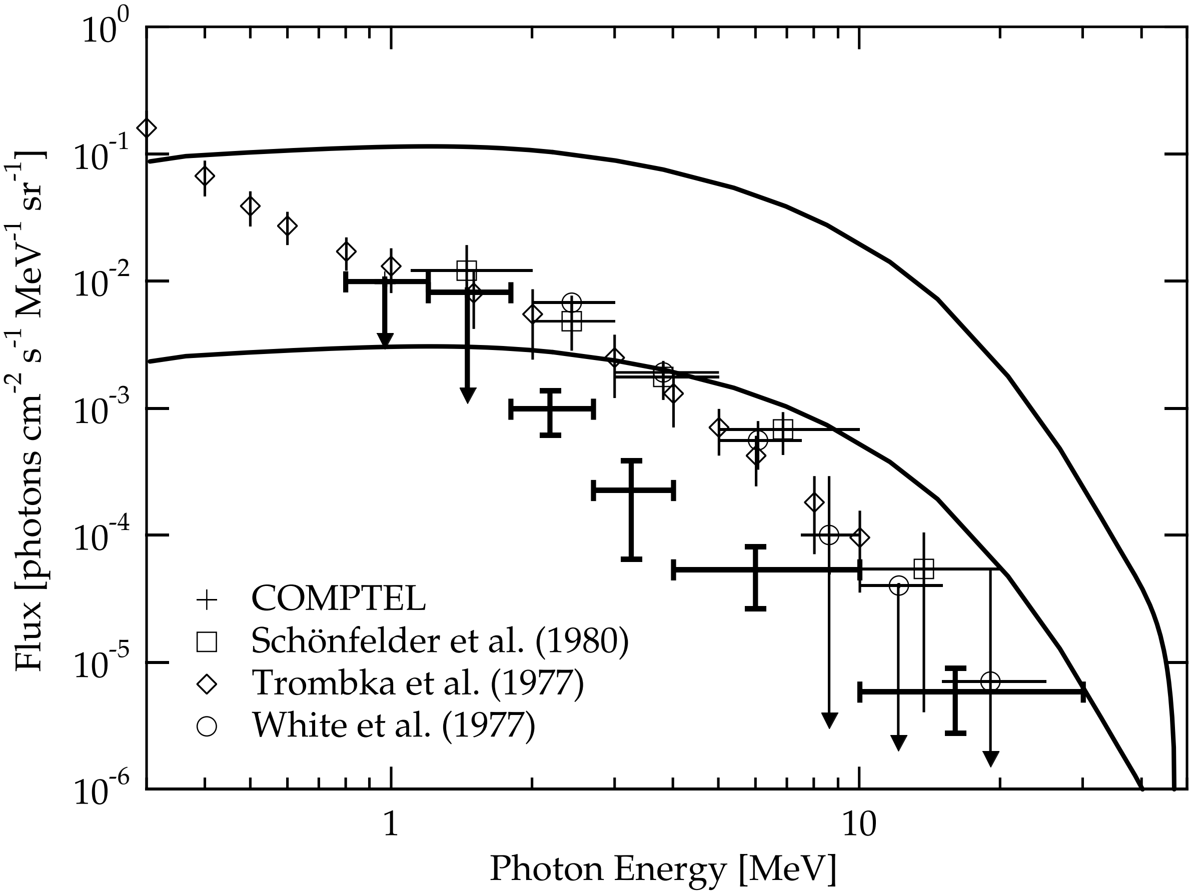


Figure 3: CDG data and expected photon spectra from proton-antiproton annihilation. The top curve results from 20 Mpc domains, the bottom curve from 1 Gpc domains. The annihilation photons peak near the energy one would expect if all pions from the $p\overline{p}$ annihilation are produced at rest ($\sim$ 70 MeV); from that energy they are redshifted by a factor up to $\sim 1000$, leading to an energy cutoff of a few MeV.

superimposed on the expected contribution from annihilation photons produced by 20 Mpc domains (top curve) and 1 Gpc domains (bottom curve). The data rules out domain sizes smaller than a Gpc. In effect, there is no space in our universe for even one of these antimatter domains.

### 3.2 Experimental search for antimatter

Despite the bleak CDG predictions for finding sizable antimatter accumulations, there are nevertheless experiments looking for antinuclei. These experiments need to be conducted outside the atmosphere because antimatter is copiously produced when cosmic rays collide with atmospheric nuclei; they are balloon-, satellite- or spacecraft-borne.

One of these experiments, the Anti-Matter Spectrometer (AMS), is scheduled to be installed on the International Space Station. Its principle of operation is as follows. A charged particle in a magnetic field will have a curved trajectory. By measuring the radius of the trajectory, the momentum $p = \gamma\beta m$ can be inferred. If the detector also records the energy loss of the particle (which is a well-understood function of

$\beta$) or the time the particle takes to traverse the detector ("Time of flight", TOF), which is proportional to $\beta^{-1}$, we can determine the mass of the particle. The direction in which the track bends in the magnetic field tells us the charge. If we find a particle with negative charge and mass $4m_p$ or greater, we have detected an antinucleus. Whether this antinucleus indicates that there are enough other antinuclei to balance the observed asymmetry is not clear, although observing for example an anticarbon nucleus would indicate the existence of antistars. Fig. 4 shows the results of the search for antihelium in an AMS test flight aboard the Space Shuttle; so far there is no evidence for antinuclei.

# 4 Microphysical mechanisms for producing the baryon excess — baryogenesis

We are faced with compelling observational evidence that the universe contains more matter than antimatter. Unless we are willing to make the unappealing assumption that the initial condition of the universe was matter-antimatter-asymmetric, we have to find a mechanism to generate the asymmetry from symmetric initial conditions. This process of generating the asymmetry is called "baryogenesis". It was Sakharov who first proposed that the universe might have started out symmetric, and who determined the conditions that any baryogenesis mechanism must fulfill [6]. These conditions are called the "Sakharov conditions" in his honor. We summarize them in the following section; then we discuss the various asymmetry generation mechanisms that have been proposed.

## 4.1 Sakharov conditions

To produce a matter-antimatter asymmetry from equal initial abundances of matter and antimatter, the baryogenetic mechanism must satisfy the following conditions:

$B$ **violation** The net baryon number $B$ (*i.e.* the number of baryons minus the number of antibaryons in the universe) must be violated. This is a rather obvious condition, but quite difficult to fulfill — no process observed terrestrially has violated $B$ so far.

*CP* **violation** The combined operation of charge conjugation ($C$) and parity inversion ($P$) transforms a particle into its antiparticle. "*CP* violation" describes the phenomenon of observing a process involving particles (say a generic inhabitant $X$ of the very early universe decaying through some intermediate particles into protons), then observing the same process with all particles replaced by their antiparticles ($\overline{X} \to \cdots \to \overline{p}$), and finding that the particle process differs from the antiparticle process, for example in the decay rate: $\Gamma(X \to \cdots \to p) \neq \Gamma(\overline{X} \to \cdots \to \overline{p})$. Recall that we are trying to make a particle excess out of initially equal abundances of particles and antiparticles ($X$ and $\overline{X}$); to accomplish this, we need a higher decay rate to particles than to antiparticles — and thus *CP* violation.

**Departure from thermal equilibrium** As long as the universe is in thermal equilibrium, statistical mechanics will take care of keeping particle and antiparticle abundances equal. This is so because the only intrinsic property of the particles on which the equilibrium distributions depend is the particle mass. We have no experimental evidence to believe that particle and antiparticle masses differ, and compelling theoretical reasons to believe particle and antiparticle masses are exactly the same. To make particles more abundant than antiparticles, then a departure from thermal equilibrium is required.

## 4.2 Electroweak baryogenesis

The Standard Model of particle physics contains all the ingredients necessary to satisfy the Sakharov conditions. *CP* violation is described by the Kobayashi-Maskawa mechanism [7]. $B$ violation is implemented in

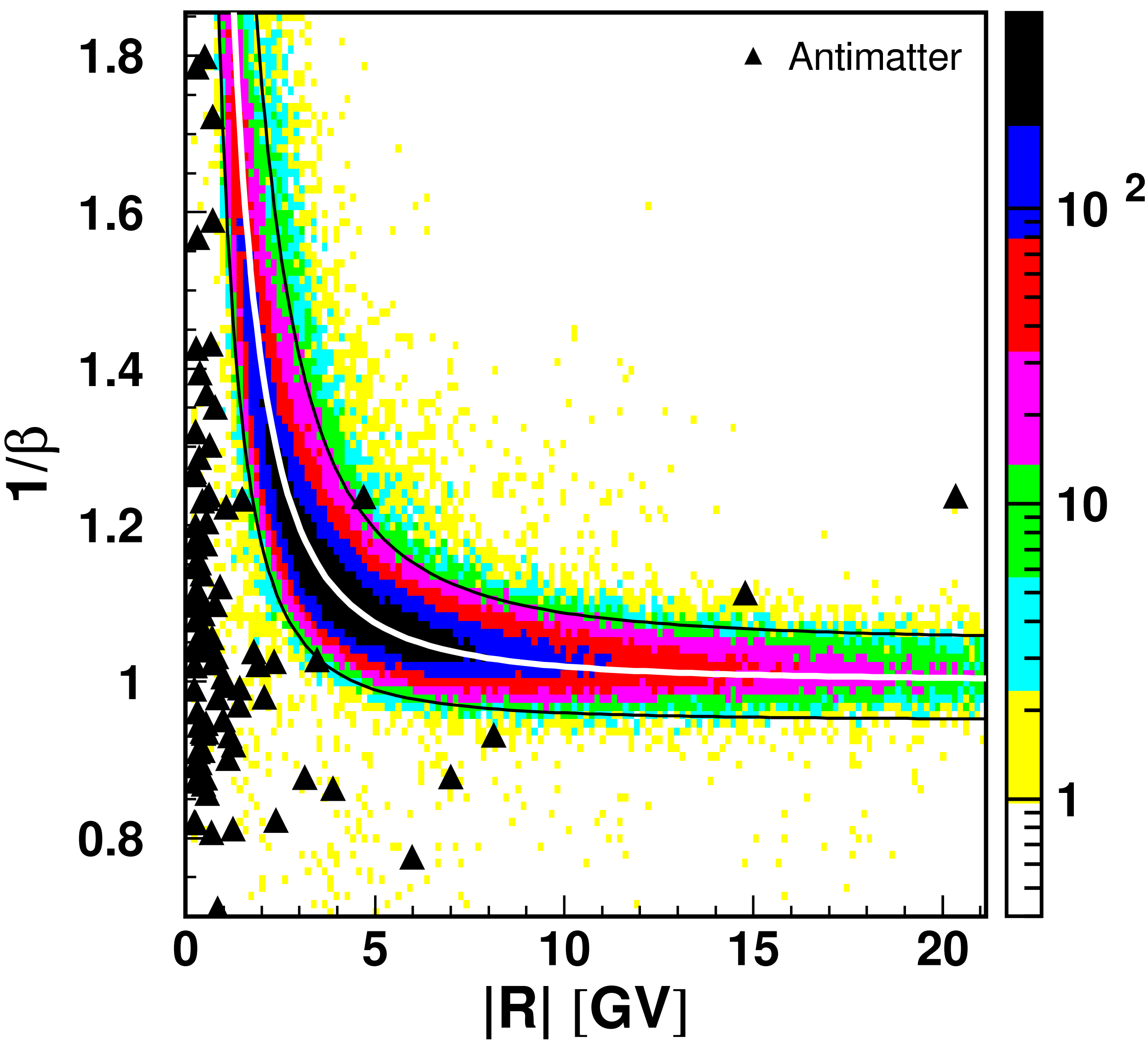


Figure 4: Results of an antihelium search in the AMS during a test flight aboard the Space Shuttle [5]. $|R|$ is the rigidity, $R = p/q$. Particles of mass $4m_p$ lie along the white band. Particles with $q < 0$ are indicated as black triangles. There are no antihelium candidates in this data set.

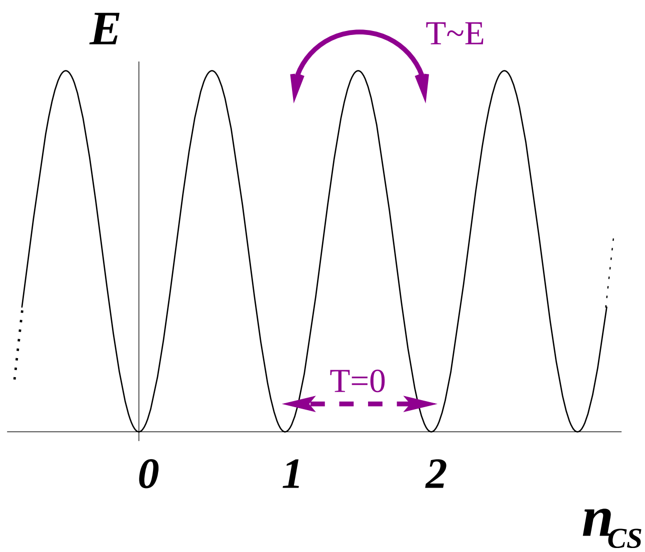


Figure 5: The sphaleron process takes the vacuum from one ground state to another. In the process $B$ and $L$ are violated (but $B-L$ is conserved). The process involves tunneling through a barrier; it is a rare process at zero temperature, but it can be efficient at high temperature.

"sphaleron" interactions. These interactions are in some ways like quantum tunneling. The vacuum has a degenerate ground state, but the ground states are separated by an energy barrier. (See the sketch in Fig. 5.) In making the transition from one ground state to the other, $B$ and the lepton number $L$ are violated. At low temperature these transitions are rare because of the height of the barrier; at higher temperature they can occur much more frequently and lead to large $B$ and $L$ violation. The sphaleron mechanism violates $B$ and $L$ but conserves $B - L$; this will be important in a few sections when we discuss leptogenesis. Finally, a departure from equilibrium may occur when the electroweak symmetry is broken; whether this is the case depends on the mass of Higgs boson.

The current limit on the Higgs mass ($m_H > 114$ GeV) almost rules out the electroweak phase transition as a source of disequilibrium. The large mass of the Higgs combined with the smallness of the observed $CP$ violation almost entirely excludes the parameter space in which the standard model can account for the observed baryon asymmetry. Supersymmetric extensions to the standard model expand the parameter space; we will know a great deal more about the feasibility of electroweak baryogenesis once supersymmetry is explored experimentally at the next generation of colliders.

## 4.3 Planck-scale baryogenesis

At the Planck scale we expect quantum gravity to become the dominant interaction. In quantum-gravitational interactions, we should not expect any quantum numbers to be conserved. An intuitive way to see this is to note that black holes are fully described by their mass, their angular momentum and their entropy; quantum-gravitational interactions involving the exchange of virtual black holes therefore have no knowledge of the interacting particles' other quantum numbers and can violate all of them.

If quantum gravity is the mechanism for baryogenesis, then we are in an unfortunate position; the relevant energy scale is $10^{19}$ GeV, which will remain inaccessible to colliders for the foreseeable future. We'll be left with a mechanism untestable by experiment. We can draw comfort from the following argument. The Planck scale is in all likelihood higher than the energy scale at the end of inflation; whatever baryon excess was generated by quantum gravity is washed out by inflation; and so the present-day baryon excess is probably not generated by quantum gravity. That clears the way for a more testable mechanism.

## 4.4 GUT-scale baryogenesis

The strong, weak and electromagnetic couplings, when extrapolated from the energies that are currently experimentally accessible to us, are approximately equal to each other at $\sim 10^{16}$ GeV. This observation has motivated theorists to propose that the strong and electroweak interactions "unify" at that energy. Theories that accomplish this unification are called "grand unified theories" (GUT).

These theories involve heavy bosons ($m \sim 10^{16}$ GeV) that couple quarks to leptons. $B$ violation is in effect built into GUTs from the start. $CP$ violation can come from KM mechanism as in the standard model or from the newly introduced couplings to the heavy bosons. Thus, it is possible that baryogenesis occurred at the GUT energy scale.

GUT-scale baryogenesis poses a similar problem to Planck-scale baryogenesis. It occurs at energies so high that it eludes testing in terrestrial experiments. Once again we can take heart in the fact that inflationary scenarios disfavor this mechanism. If the reheating of the universe at the end of inflation exceeds a certain temperature, more WIMPs are produced than is consistent with the observed $\Omega_m$. In many circles the reheating temperature limit is believed to lie below the GUT scale, ruling out GUT baryogenesis after the inflationary era.

## 4.5 Leptogenesis

Leptogenesis [8] is currently the favored mechanism for baryogenesis. In this mechanism the universe first acquires a lepton excess, which is then converted into a baryon excess by a process that violates $B$ and $L$ but conserves $B - L$ — for example the standard-model sphaleron mechanism.

The initial lepton excess that is required in this mechanism can come from, for example, heavy Majorana neutrinos ($N$). A Majorana neutrino is its own antiparticle. If the Majorana neutrino decays, for example, to a Higgs boson and a light lepton, $N \to \cdots \to \ell + \overline{\phi}$, then the $CP$-conjugate decay is $N \to \cdots \to \overline{\ell} + \phi$. If $CP$ is violated, then the decay rates of the $N$ into $\ell$ and $\overline{\ell}$ can differ, and the universe can end up containing more leptons than antileptons:

$$\Gamma(N \to \cdots \to \ell + \overline{\phi}) \neq \Gamma(N \to \cdots \to \overline{\ell} + \phi).$$

The reason the leptogenesis mechanism is popular is that the parameter space in which it is viable has not yet been constrained almost to death, as is the case for standard-model electroweak baryogenesis. At the same time, a major test of its viability is not too far in the future: within the decade, experiments should tell us the magnitude of $CP$ violation in the neutrino sector.

## 4.6 Affleck-Dine baryogenesis

The Affleck-Dine scenario for baryogenesis notes that in supersymmetric theories, where each of the ordinary fermion fields from standard-model physics has a scalar partner, the early universe contained baryon- and lepton-number-carrying scalar fields. Through interactions with the inflaton field $CP$-violating and $B$-violating effects can be introduced. As the scalar particles decay to fermions, the net baryon number the scalars carry can be converted into an ordinary baryon excess [9]. ([9] is a recent and very thorough review not only of Affleck-Dine baryogenesis but of baryogenesis in general.)

The Affleck-Dine mechanism is also a mechanism for dark-matter creation. Fluctuations in the scalar quark fields ("Q-balls") are a dark-matter candidate if they are stable. If they are unstable, they can still decay into dark matter. If the Affleck-Dine mechanism is indeed played out in nature, then its dual role of producing baryons and producing dark matter opens up the possibility of explaining the ratio between $\Omega_m$ and $\Omega_B$ from first principles.

# 5 Experimental tests

A theory that cannot be tested experimentally is a very unsatisfying theory. The most interesting baryogenesis mechanisms are those that can be tested in terrestrial experiments.

In the next generation of collider experiments, at the Large Hadron Collider, the parameter space for standard-model electroweak baryogenesis will be fully explored; either it will be found that SM baryogenesis can account for the observed baryon asymmetry, or SM baryogenesis will be ruled out. As for the supersymmetric extensions to the SM electroweak mechanism, we will certainly know a great deal more than we currently do, perhaps enough to say whether it can account for the asymmetry. The detailed knowledge about the scalar quark fields that we hope to gain at the LHC will also be useful in fleshing out the Affleck-Dine mechanism.

The near future also looks promising in the neutrino sector, where experiments currently being planned will measure the magnitude of neutrino *CP* violation. This measurement could tell us that the neutrino sector provides the required amount of *CP* violation for leptogenesis.

# 6 Conclusion

Baryogenesis is a field in which we know some things very well but can only speculate about others. It is a field that still has room for growth.

We can be almost certain that there is a matter excess in the universe. This puzzling excess, which is quite resistant to efforts to argue it out of existence, compels us to search for a mechanism that brought the excess into existence. The matter excess is a nagging questing demanding an answer.

We know what conditions proposed baryogenesis mechanisms have to fulfill; a number of these mechanisms have been proposed. It seems unlikely that standard-model physics can explain the matter excess, although we don't know for sure. There is probably new particle physics behind baryogenesis. This makes it an interesting field not only for cosmologists but also for particle physicists.

Aspects of some of the proposed mechanisms can be experimentally tested in the near future. Baryogenesis mechanisms could thus be elevated from speculation to theory. If that is the case, then baryogenesis is just around the corner from becoming an extremely exciting field — one that begins with a puzzling question with no answer and ends up with a conclusive answer to a fundamental question. That is the optimistic scenario for baryogenesis. The pessimistic scenario is that the relevant physics occurs at some extremely high energy scale, that the proposed mechanisms all solve the problem they were designed to solve but resist attempts at experimental verification. In the coming decade we will find out which scenario applies.

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