Baryogenesis: Cosmology Final Project

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From our understanding of the state of energy at very early times in our universe, one would expect high energies to be accompanied by many symmetries. We have learned in this course that many of these symmetries are intimately linked to that high-energy regime and break as the temperature and matter-energy density of the universe decreases with the scale factor. First, the universe is at high enough density to be considered in the Planck regime, cooling into an era of grand unification in which all forces other than gravity are unified: strong, weak, and electromagnetic. Possibly a decoupling of the strong force starts an era of inflation during which a great smoothing of the universe and it's contents occurs. At later times the electroweak force, a coupling of the weak nuclear and the electromagnetic forces, breaks and we go through no further major transitions of energy scale before we arrive at the present state of the universe in which we live and look up at the sky.

With the invention of the Dirac equation, formulated by Paul Dirac around 1928, the existence of antiparticles was proposed and later proven to be true in nature. The CPT theorem guarantees an antiparticle has the same mass and lifetime, but exactly opposite charge to it's corresponding particle. An example with which we're familiar is the electron-positron pair. Very important in our current understanding of possible dark matter annihilation signatures is putting precise constraints on another pair as well, the proton-antiproton particles.

As is already clear, fundamental symmetries of nature often break in lower-energy regimes. At high energy one would expect equal numbers of baryons and antibaryons. A reasonable assumption would be that at lower energies these particles simply combine and annihilate leaving photons, and indeed this is likely the key behind the fact that the ratio of photons to baryons is $\sim 10^{-9}$. But, why do any baryons remain at all? Even given some low abundance remaining un-annihilated from the freeze-out, we would expect to see equal numbers of baryons and antbaryons.

It is possible that there are galaxies floating around made entirely of antimatter, but this is unlikely because we would expect to see high annihilation rates at the boundaries in the (inter-galactic medium)IGM between them. Also, there are tight constraints on the possibility of antimatter galaxies set by observed antimatter cosmic ray abundances. Antimatter stars, for one, are expected to produce a significant number of cosmic ray antinuclei such as antihelium. The Balloon-borne Experiment with Superconducting Spectrometer (BESS) has found antiprotons, but these can also be made from collisions of cosmic rays with atoms in the upper atmosphere. As yet, no antihelium nuclei have been found, but as these cannot be made via the same process, their detection would be strong evidence of regions of the universe filled with antimatter.

Currently most evidence suggests that most of the universe really is comprised of matter, with any antimatter having been made by secondary processes. Since there is no real evidence yet for antimatter galaxies, we conclude that the universe began with a very slight asymmetry between matter and antimatter. Since it's difficult to imagine why the universe would be asymmetric from the moment of it's creation (apart from anthropic arguments), it is likely that this asymmetry arises during a phase transition of the matter/energy in the hot early universe before it cooled to the critical temperature of $\sim 10^{15}$ GeV.

In 1967, well before the construction of Grand Unified Theories (GUT), Andrei Sakharov proposed a set of three necessarily conditions necessary in order for a baryon generating process to produce matter and anti-matter at differing rates:

1. $\Delta B \neq 0$ reactions
2. CP violation
3. non-equilibrium conditions

It turns out that GUT's almost naturally satisfy some or all of these conditions. GUTs do not distinguish between baryons and leptons thereby allowing the possibility of reactions that generate a net baryon asymmetry. Gauge bosons of the GUT mediate the baryon-lepton exchanges and may decay asymmetrically. So this satisfies the first condition. The second condition is observed to be satisfied by at least the decay of neutral kaons. The third condition is necessary to prevent backreactions from erasing a baryon asymmetry and is met by the standard freeze-out picture we have learned.

However, inflation is predicted to wipe out the baryon asymmetry produced by GUTs. Theories of Leptogenesis, asymmetry from the electroweak transition, and Affleck-Dine baryogenesis, get around this inflation problem. However, the first is considered unlikely without supersymmetry and the remaining two are less well understood. Current neutrino experiments can, in principle, explore this parameter space, and constraints from the LHC on the Higgs boson will give insight into leptogenesis. Affleck-Dine baryogenesis is attractive because it provides a dark matter candidate and current studies of diffuse gamma-ray emission may put tight constraints on this in the near future.