Baryogenesis: Some handpicked concepts

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Abstract

In this article we describe the process of Baryogenesis and explore certain related concepts. We explore handpicked proposed mechanisms of baryogenesis such as EW transitions and gravitational baryogenesis to understand the process which has made possible the existene of the observable universe as we know it, as well as ponder upon the possible qualtities of said processes. The article is almost fully qualitative in nature to intrigue the readers interest.

1 Baryogenesis and Sakharov conditions

We're all familiar with widely accepted theory of how the universe began with a big bang some 13.8 billion years ago followed by an inflationary phase followed by a nuch of other phases, during which a lot of weird stuff happened (radiation dominated universe to matter dominated universe, deconfinement to confinement of the quark-gluon plasma, etc) that eventually got us to the stage we are in today. Using today's accelerator technology when we smash nuclei at very high energies, we're able to create new particles and antiparticles. By the laws of conservation of baryon number B (baryons are basically bound states of three quarks such as protons and neutrons which make up all nuclei), an equal number of new baryons and anti baryons are produced so that difference between number of baryons and anti-baryons remains the same no matter what process of production or technology we use.

We assume that at the time of the creation of the universe, at the point of matter production the physics we see today allowed only equal amounts of baryons and anti-baryons to be produced back then. However the observable universe contains an overabundance of matter over antimatter and therefore there must have been a process somewhere early on in the cosmological timescale when there was an imbalance of matter over anti-matter. The process which caused said imbalance and allowed matter to numerically dominate over-antimatter so vastly that led to present day conditions is known as Baryogenesis.

One might be wondering why we call it Baryogenesis when it only involves baryons and not other forms of matter like electrons, pions, photons etc. Well

baryons being the heaviest of particles consist of the majority of the mass of the universe after dark matter and dark energy (cameo appearance), but particles like electrons, muons, and their anti-particles and associated neutrinos are known as leptons (each with its own lepton number L) and are formed by a similar process known as leptogenesis.
These were all fermions (those which have half integer spin). Bosonic particles such as mesons (pions, kaons etc) are bound states of quarks and anti-quarks and as such they have no baryon number as quarks and anti quarks have baryon numbers equal in magnitude ($\frac{1}{3}$) and opposite in sign. So any process that forms mesons doesn't violate baryon number conservation or even lepton number conservation (quarks have zero lepton number). Infact, since photons and gluons are their own anti-particles, there need not be any particle-over-atniparticle favoring process for them.
So the big question is how did such an imbalance come about. Several well thought hypothetical mechanisms for the process had been proposed since the posing of this problem. Over-time, as were more and more theoretical developments in cosmology, newer constraints were placed upon the subsequent proposed mechanism. This brings us to the Sakharov conditions. Andrei Sakharov, a nuclear weapons scientist, proposed in a landmark (and rather short) paper that there are three conditions necessary any baryon synthesizing process should satisfy. These are as follows [1]

- Baryon number B must be violated
- C and CP invariance must be violated
- Process occurs out of thermal equilibrium

Clearly B has to be violated in any scenario where we expect to gain a net number of baryons. As for the second condition, let's first understand what C and CP invariance are. C stands for charge conjugation and it is a transformation in which we swap all particles with anti-particles and vice-versa (hence reversing the sign on all of the charges associated with the particles such as electric charge, color charge etc). P stands for Parity and it transforms all particles and anti-particles into their mirror images (reflection about an axis). Any physical process that remains invariant under charge conjugation or parity transformation or simultanously both is C symmetric, P symmetric or CP symmetric respectively.

C symmetry violation is necessary so that interactions which produce more anti-baryons that baryons are suppressed and there is a bias towards positive net baryon number production. To understand the necessity of CP invariance, one must understand handedness (helicity) of particles. If a particle/antiparticle's spin is along the same direction as its momentum then it's right handed and if opposite then it's left handed; they're both mirror images of each other so a parity transformation flips the handedness. To make sure there more left handed baryons than right handed anti-baryons and more right handed baryons than left handed anti-baryons we need CP-symmetry violation in any baryogenetic process.

Finally there is T-symmetry. Any process which remains invariant with time reversal (if the process were to run backwards in time), i.e. it shows no no particular bias to move in either directions in time flow then it is T-symmetric. Due to the second law of thermodynamics, processes out of equilibrium must move forward in time so as to increase entropy. The CPT theorem states that all physical phenomena in the universe must be symmetric under a simultaneous CPT transformation. To make sure the theorem is not violated, baryogenetic mechanisms must happen out-of-equilibirum so that there is no T-symmetric version of this mechanism which also favors the reverse process, i.e. anti-baryon production at the same rate.

2 Gravitational Baryogenesis

Let us discuss one of the proposed mechanisms known as gravitational baryogenesis. But first let's familiarize ourselves with certain we will use later. In general relativity an important quantity one uses is the Ricci scalar R which gives scalar curvature of space-time (scalar because it assigns a number not vector to each point). The other types of curvature encoding quantities are the Ricci tensor $R_{\mu\nu}$(whose trace is the Ricci scalar) and Riemann tensor $R_{\mu\nu\rho\sigma}$but we will not be needing those. The other quantity we need is baryon number current J^{μ} which is exactly what it sounds like- a current of baryon number B given by $J^{\mu} = \partial_{\mu}B$ giving a net B or B-L in the equilibirum.
A gravitational interaction between the Ricci scalar and the baryon number current having a lagrangian term of the form [2]

$$\frac{1}{M^2}\int d^4x\sqrt{-g}(\partial^{\mu}R)J^{\mu} \tag{1}$$

where the derivative scalar curvature (similar to $\partial_{\mu}\phi$ terms in Lagrangians) couples J^{μ} can lead to net baryon number, essentially known as gravitational baryogenesis. M is just the cutoff scale (basically a range of energy within which are calculations are relevent) which is of the order of 10^{18} GeV. In vacuo this interaction breaks CP symmetry and conserves CPT symmetry. Here we take a bit of a departure from what we know because out of vacuo, as the universe expands it violates CPT symmetry and makes baryon-antibaryon anti-symmetric processes energetically favorable.
We consider a certain temperature T_{BG} above which such processes are possible in thermal equilibirum. As long as such temperatures remain, the term in (1) gives opposite sign energy contributions of different magnitudes for baryons and anti-baryons and hence violate CPT in any non-vacuo state. To satify the CPT theorem, thermal equilibirum favors redistribution of matter to have a net B going forwards in time. Once the universe cools below T_{BG} no new production

occurs but the already produced asymmetry remains.

3 Role of Primodial Black Holes

The mechanism described above generates a chemical potential μ_B so as to have an associated energy cost for each baryon produced or anti-baryon removed from the system. Such gravitational interactions can arise during the expansion of the universe. Another interesting way such a chemical potential can be generated is from black hole evaporation through hawking radiation [3].
We all have the notion of 'nothing escapes the event horizon' ingrained into our heads. However following Bekenstein's work, Hawking showed that black holes too can emit radiation when virtual particles are produced at the event horizon and the antiparticle falls into the black hole while the particle is emit. This description is an oversimplification but it'll do for the scope of this article. In this way, the time evolution of a black hole causes it to 'evaporate'.
Due to the No Hair theorem the only information one can have about a black hole are its mass M, charge Q and angular momentum L. So when matter falls into a black hole, all of its quantum numbers (except M,Q,L) are lost and the quantum numbers of the particles emitted in black hole evaporation are unrelated to the original information about the infalling matter.
Thus in theory baryons can be emitted from a black hole. But again we can ask the question that if black holes were formed from mostly baryonic matter, as seen in the modern universe, then how can such a process produce a sufficiently large number of baryons than there originally was. Here is where primordial black holes come in. In the early universe's, when it was radiation dominated, the black holes that were formed due to collapse of dense nuclear matter were known as primordial black holes. The collapsing matter should have had near equal amounts of baryonic and anti-baryonic parts. And when such black holes radiate, a net baryon number is produced. This gives us a chemical potential μ_B dynamically generated at the horizon [4].
Infact due to black hole evaporation, the universe takes a random walk in B-space. For clarification, a random walk is a set of random number of steps along different axes that transports a system (or a drunk person) from one point to the other. Even though rate of black hole evaporation depends upon the mass of the black hole, when and how many baryons are evaporated is random. So it is akin to taking a random walk in one dimensional B-space, starting from one B value and ending up in another.

4 References

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