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Baryogenesis in the early Universe

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Abstract. We review various attempts to create the observed baryon asymmetry of the Universe. In particular, we consider models of GUT baryogenesis, baryogenesis via leptogenesis, the Affleck–Dine mechanism, electroweak baryogenesis and baryogenesis via topological defects and primordial black holes.

Keywords. Baryogenesis; baryon asymmetry.

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1. Introduction

Understanding the matter-antimatter asymmetry of the Universe is one of the most interesting issues at the interface of particle physics and cosmology. We believe that at very early times there was an equal amount of matter and antimatter in the Universe. However if you look around us today there is not much evidence of that. Clearly there is a matter-antimatter asymmetry in the solar system. Furthermore, the antimatter seen in cosmic rays is well explained by secondary interactions with the interstellar medium indicating that our galaxy too is made up of only matter. If one goes to larger scales and considers a matter symmetric Universe with clusters containing both matter and antimatter then one would expect to see a gamma ray excess coming from the intracluster gas of X-ray emitting clusters. So let us go to even larger scales and consider a Universe with superclusters containing clusters of matter and antimatter. Surprisingly there is no observational evidence that rules out such a scenario, i.e., domains of cluster size (~ 20 Mpc) are the largest regions for which we can rule out the presence of both matter and antimatter co-existing [1]. In fact, a device called the Alpha Matter Spectrometer or AMS which can detect antimatter up to a distance of 300 Mpc made a test flight in May 1998 and is scheduled to be installed on the International Space Station in the year 2000 (it will run for 3 years). However, it has also been argued that unless matter and antimatter domains are separated on a scale of at least about 1000 Mpc (the horizon distance today is 6000 Mpc) the photons from annihilations taking place between $z = 1100$ and $z = 20$ would have shown up in the diffuse cosmic gamma ray spectrum [2].

There have been attempts to create a Universe with large matter and antimatter domains. However we shall only consider below models that create a baryon asymmetry of $\sim 10^{-10}$ compatible with primordial nucleosynthesis in the entire observable Universe.

2. GUT baryogenesis

The oldest models of baryogenesis are the GUT baryogenesis models which have also been attempted in the context of SUSY GUTS [3]. If you start with a Universe that is baryon number symmetric and you want to end up with a baryon asymmetry in the Universe then you need to have baryon number violation. In GUTS there are heavy gauge and Higgs bosons whose interactions violate baryon number. Consider such a heavy boson X which has two decay channels $X \rightarrow q\bar{l}, q\bar{q}$ respectively with decay rates r_1 and r_2. Let $\bar{X}$ be its antiparticle with analogous decay channels with decay rates r'_1 and r'_2. Let q and l be quarks and leptons which carry baryon number 1/3 and 0 respectively. If one assigns X a baryon number based on one decay mode then the other decay mode violates baryon number. Thus one has baryon number, or B, violation. One further requires CP violation so that the decay rate r_1 of X to quarks, is not equal to the decay rate r'_1 of $\bar{X}$ to antiquarks. Finally one also needs B violating interactions to be out of thermal equilibrium to create a baryon asymmetry because, in equilibrium, the interactions of the particles will drive the baryon number to 0. These three conditions, namely, B violation, CP violation and the out-of-equilibrium requirement are referred to as Sakharov's conditions.

There are some problems with GUT baryogenesis models.

1. Typically the mass of the X particle is about 10^{16} GeV. But in an inflationary Universe the mass of the inflaton is of the order of 10^{13} GeV(from measurements of the CMBR anisotropy) and it is difficult to create X particles during reheating either via direct inflaton decays or in the thermal bath.
2. If one chooses the X mass to be less than 10^{13} GeV then one has problems with proton decay, which gets worse for supersymmetric GUTs.
3. In supergravity and superstring theories there are a number of massive scalars which decay after the GUT phase transition releasing a large amount of energy into the Universe. This dilutes the baryon-to-entropy ratio.

In recent years the understanding of reheating in the Universe after inflation has gone through a sea change. If one studies the equations for the inflaton decay then for certain values of the momenta of the daughter particles one hits a resonance. The inflaton can then decay very quickly and explosively via 'parametric resonance'. In this case it is possible for the inflaton field to create X particles during reheating even if they are heavier than the inflaton and to obtain a baryon asymmetry through their decays [4].

3. Baryogenesis via leptogenesis

In models of baryogenesis via leptogenesis one first creates a lepton number (L) asymmetry in a manner similar to that in GUT baryogenesis by the out-of-equilibrium decays of heavy right-handed Majorana neutrinos [5,6]. Then one uses B+L violating sphaleron processes to convert the lepton asymmetry into a baryon asymmetry. (We shall discuss sphaleron processes in greater detail later in the context of electroweak baryogenesis.) One can see how this works by supposing that we create a lepton asymmetry of 10 from heavy neutrino decays. Rewriting this in terms of $B + L$ and $B - L$ one sees that we have $B + L = 10$ and $B - L = -10$, assuming no initial net baryon number in the Universe. Now if we have $B + L$ violating processes in thermal equilibrium they will reduce the $B + L$ to 0 while keeping $B - L$ constant. Therefore one ends up with $B = -5$ and $L = 5$. Thus a lepton asymmetry in the Universe has been converted into a baryon asymmetry. (Actually $B \sim 1/3$ $(B - L)$ rather than 1/2 $(B - L)$ as above because the sphaleron processes couple only to left-handed particles.)

Models of baryogenesis via leptogenesis are attractive for two reasons. These models do not require much modification of the standard model. One only has to introduce right-handed Majorana neutrinos and not consider a more complicated GUT model. Furthermore, one solution of the solar neutrino problem involves neutrino oscillations which requires the light neutrinos to have mass. Models with heavy right-handed Majorana neutrinos are often invoked to provide mass to the light neutrinos via the seesaw mechanism. So one sees that models with right-handed Majorana neutrinos are well motivated. However the low reheat temperature after inflation constrains many of these models [7].

Similar mechanisms of baryogenesis via leptogenesis have been studied in which one creates the lepton asymmetry by decays of sneutrinos and by R-parity violating decays of sfermions and neutralinos.

4. The Affleck–Dine mechanism

This is realised in the context of supersymmetric GUTS. When supersymmetry breaks certain combinations of squark and slepton fields get a mass. Furthermore in supersymmetric GUTS these fields have effective quartic couplings that violate baryon number. The Affleck–Dine mechanism makes use of this B violation [8].

One can understand the Affleck–Dine mechanism in the context of a toy model. Consider a potential for a complex scalar field ϕ given by

$$V(\phi) = m^2 \phi^* \phi + \frac{1}{2} i \lambda (\phi^4 - \phi^{*4}) \, . \tag{1}$$

Assign ϕ a baryon number of 1 based on its interactions with standard model particles. For example, if ϕ is like a squark then a squark decays to a quark and a photoion and so you can assign the baryon number of the quark to the squark (photoions carry no baryon number). Then the last term above violates baryon number. It also violates CP.

In this model one has inflation after supersymmetry breaks. Due to quantum fluctuations in the ϕ field during inflation (note that the ϕ field is not the inflaton) the ϕ field is displaced from the minimum of its potential by the end of inflation. Now after inflation one would expect the ϕ field to oscillate about the minimum of its potential. But a scalar field can only oscillate if the period of its oscillation is less than the age of the Universe. It turns out that the end of inflation is less than the period of oscillations. So instead of oscillating the field rolls slowly. However, instead of going straight down its potential the field picks up some angular momentum in ϕ space because of the quartic couplings. Later when the Universe becomes old enough ϕ oscillates in its potential.

As we mentioned earlier ϕ carries baryon number. Therefore there is a baryon current associated with

$$j_\mu^B = -i \phi^* \overleftrightarrow{\partial_\mu} \phi = \frac{1}{2} (\phi_1 \partial_\mu \phi_2 - \phi_2 \partial_\mu \phi_1) \, , \tag{2}$$

where we have used $\phi = 1/\sqrt{2}(\phi_1 + i\phi_2)$ for the second equality. Now recall that $\int j_0^B \mathrm{d}^3x = B$. Ignoring spatial variations in ϕ, which is a good assumption after inflation, $j_0^B = B/\mathrm{Volume} = n_B$, where n_B is the baryon number density. Therefore

$$n_B = \frac{1}{2}(\phi_1\dot{\phi}_2 - \phi_2\dot{\phi}_1)\,. \tag{3}$$

As the field ϕ rolls down its potential this quantity increases. Solving the equations of motion for ϕ_1 and ϕ_2 one finds out the value of n_B. When the field rolls sufficiently down and ϕ becomes small the quartic B violating couplings become ineffective. Subsequently, as the field oscillates, the baryon number density only changes because of the expansion of the Universe.

In this mechanism, one can get a baryon asymmetry as large as 10^{-2} which is quite large. These models are also popular in the context of superstring theories.

Sphalerons can destroy the asymmetry created in these scenarios but one can work with a GUT that violates $B-L$ or suppress the decay of the ϕ field before the sphaleron processes shut off at a temperature ~ 100 GeV to get around this problem [9].

5. Electroweak baryogenesis

In the last ten years there has been a lot of interest in models of electroweak baryogensis in which the baryon asymmetry is created during the electroweak phase transition [10]. Baryon number violation in the electroweak sector is related to the structure of the vacuum in non-abelian gauge theories. In non-abelian gauge theories such as $SU(2)_L$ one has degenerate vacua which are topologically distinct. What distinguishes them is the winding number of the gauge field configuration or the Chern–Simons number. When one makes a transition from one vacuum to another 3 quarks and a lepton are created. This baryon number violating transition violates $B+L$ but not $B-L$.

t'Hooft calculated the transition rate from one vacuum to another at zero temperature and found it was negligible. But in the mid-80's Kuzmin, Rubakov and Shaposhnikov showed that at high temperatures above 100 GeV, when the electroweak symmetry is restored, one can have thermal processes called sphaleron processes that cause transitions from one vacuum to another. In the unbroken phase, the rate for baryon number violation is

$$\Gamma \sim \alpha_W^4 T^4 \tag{4}$$

where α_W is the weak coupling and T is the temperature, and in the broken phase it is

$$\Gamma \sim \exp(-\frac{a\langle\phi\rangle}{T}) \tag{5}$$

where a is a parameter and $\langle\phi\rangle$ is the expectation value of the Higgs field. The standard model (and its extensions) has CP violation which can bias the baryon number violating interactions to create more baryons than antibaryons. These models assume that the electroweak phase transition is first order and proceeds via bubble nucleation. The sphaleron processes are in equilibrium outside the bubble wall and in the outer part of the wall with the rate of B violation given by eq. (4) while they are out of equilibrium inside the bubble and in the inner part of the wall as $\langle\phi\rangle$ in eq. (5) is large.

What is appealing about electroweak baryogenesis is that one has the possibility of creating the baryon asymmetry at the electroweak scale which is experimentally accessible. As we shall see, this has allowed one to put stringent constraints on these models.

We shall consider two models of electroweak baryogenesis – the charge transport mechanism and spontaneous baryogenesis.

Charge transport mechanism: This mechanism is valid when the electroweak bubble wall is thin, where thick and thin walls are defined by whether the mean free path of the particles in the plasma is less than or greater than the wall thickness. In the earliest version of this mechanism one considers fourth generation neutrinos bouncing off the bubble wall. Because of CP violation the reflection and transmission rates for neutrinos with respect to the wall is different from that for antineutrinos. Therefore one gets a lepton asymmetry outside the wall and inside it. The asymmetry outside the wall is then converted to a baryon asymmetry via sphaleron processes. Then the bubble expands and engulfs the asymmetry. Once the plasma is in the bubble there are no B violating interactions to destroy the asymmetry that has been created. This method has also been used with top quarks and tau leptons bouncing off the electroweak bubble wall.

A similar mechanism exists in left-right symmetric models where fermions scattering off bubbles in a first order left-right symmetry breaking phase transition create a lepton asymmetry which is converted to a baryon asymmetry by sphalerons.

Spontaneous baryogenesis: Spontaneous baryogensis models work when one has thick bubble walls. In these models one has a term in the lagrangian like $\mathcal{L} \subset \partial^\mu \theta j_\mu^B$ where θ is a phase associated with the Higgs sector. For example, in the two Higgs doublet model it is the relative phase between the two Higgs doublets. Ignoring spatial variations in θ and j_μ^B we get

$$\mathcal{L} \subset \dot{\theta} j_0^B = \dot{\theta} n_B = \dot{\theta}(n_b - n_{\bar{b}}) \,, \tag{6}$$

where $n_{b,\bar{b}}$ are baryon and antibaryon number densities respectively. This then looks like a term that contributes differently to the energy of baryons and antibaryons and so one claims that it behaves like an effective chemical potential for baryon number in the bubble wall where $\dot{\theta}$ is non-zero. In that case one has B violating processes in thermal equilibrium and a non-zero chemical potential for baryon number in the outer regions of the wall. Then by thermodynamic arguments the baryon number density is driven to $n_B \sim (\text{chemical potential})\, T^2 = \dot{\theta} T^2$ as the plasma passes through the wall.

One must point out that the above is a somewhat older description of electroweak baryogenesis. More current descriptions take into account particle transport, diffusion, the fact that a thin wall may appear thick to a particle incident on the bubble at a close to grazing angle, etc.

There are problems with electroweak baryogenesis models in the context of the standard model. First of all there is insufficient CP violation in the standard model. Secondly experimental data from CERN indicates that the standard model Higgs mass is greater than 95 GeV. But in that case the electroweak phase transition appears to be second order or weakly first order. If it is second order then none of the above mechanisms work. If it is weakly first order, the separation between the two vacua is small and one has phase mixing. This makes it difficult to create an asymmetry. Thirdly, if the Higgs mass is greater than

45 GeV then the Higgs vacuum expectation value inside the bubble is too small to shut off sphaleron processes. Therefore any asymmetry created in or outside the wall is destroyed inside the bubble. Of course, as T decreases sphaleron processes will ultimately stop but by that time it is too late.

To get around the above problems one considers extensions of the standard model. In supersymmetric extensions one has extra phases that can enhance the CP violation in the theory. To get a first order phase transition one considers two Higgs doublet models as in the minimal supersymmetric standard model.

6. Topological defects

Topological defects have also been used to create a baryon asymmetry [11]. Monopole annihilation can give heavy GUT bosons whose decays can give a baryon asymmetry. With cosmic strings there are three ways of producing a baryon asymmetry. Cosmic strings networks contain loops. These loops oscillate giving out gravitational radiation but when their size becomes comparable to their width they collapse producing heavy GUT bosons whose decays can give an asymmetry. Secondly, cusps on strings or string loops, which are pieces of the string moving at the speed of light, can annihilate producing heavy GUT bosons. Finally when strings intersect and loops are formed quanta of GUT bosons can be released.

Recently an interesting model has also been proposed that can simultaneously explain the baryon asymmetry of the Universe by the decays of GUT bosons produced by topological defects at early times as well as the extra high energy cosmic rays seen today $(E > 10^{11}\,\mathrm{GeV})$ by decays of GUT bosons released in recent epochs by defects relatively close by ($d \lesssim 100\,\mathrm{Mpc}$) [12].

7. Primordial black holes

There exist three kinds of baryogenesis models that involve primordial black holes [11].

1. If the black hole is hot enough to radiate GUT gauge and Higgs bosons then a baryon asymmetry can be obtained in the asymmetric decay of these heavy particles.
2. In a B violating theory if the coupling of matter to gravity contains CP violating terms then because of grey body effects, i.e., because of different transmission coefficients for baryons and antibaryons in the gravitational field of the black hole, the Hawking radiation can contain more baryons than antibaryons.
3. Finally even in a B conserving theory the final Hawking radiation can contain more baryons than antibaryons. Let the black hole be hot enough to radiate some heavy particle A which decays via CP violating couplings to $L\bar{H}$ and $\bar{L}H$, where L is a light baryon and H is a heavy baryon. Because of CP violation let us assume that the first channel is preferred and say that one gets 10 L and $\bar{H}$ pairs and 5 $\bar{L}$ and H pairs. Since H and $\bar{H}$ are heavy they are more likely to be recaptured by the black hole. In that case one is ultimately left with 10 L and 5 $\bar{L}$ particles, which implies a net baryon asymmetry in the radiated particles. The black hole itself absorbs the opposite baryon number but this can not be measured or seen in subsequent radiation as black holes have no baryonic hair.

The problem with all these models is that it is difficult to estimate the mass distribution and number density of black holes in the early Universe.

8. Conclusion

I hope I have given you a flavour of the large variety of approaches people have adopted to create a matter-antimatter asymmetry. More technical details can be obtained from the sources listed in the references.

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