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Baryogenesis and its Observable Consequences

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ABSTRACT

The origin of matter anti-matter asymmetry is one of the most important questions to answer in order to understand the present Universe. Although there were very interesting ideas regarding the generation of asymmetry for baryons (the dominant part of observable matter), it was hard to distinguish each model based on terrestrial experiments. However, recently, several attempts have been made to connect baryogenesis mechanisms and observable consequences, so that the true origin of asymmetry can be explored through new experiments. In this review, we explain why new physics beyond the Standard Model is necessary to understand the origin of matter anti-matter asymmetry, and discuss various old and new ideas of baryogenesis and their observable consequences.

INTRODUCTION

The key ingredient for the structure formation in our Universe is the matter anti-matter asymmetry at the beginning of the nucleosynthesis. If there are equal amounts of matter and anti-matter, all protons and neutrons are annihilated away with their anti-particles, and no light nuclei and atoms are formed in sizable amounts. By measuring abundances of light nuclei, the shape of the CMB (cosmic microwave background), and the matter power spectrum, we can determine how many *baryons*, composite particles made by quarks, should survive at the early Universe. Those observations predict the baryon asymmetry as [1]

$$\frac{n_B}{s} = 8.7^{+1}_{-1} \times 10^{-11},$$

where n_B is the number density of the baryons, and s is the entropy density of the Universe.

Since the inflation paradigm is very well accepted in cosmology, all pre-existing baryon asymmetry is diluted by inflation, which means that we need to explain why such a number is generated through cosmological evolution. The process to generate such an asymmetry is called as *baryogenesis*. After inflation and subsequent reheating period, the Universe was very hot and dense, and all kinds of interactions that would be neglected during the present Universe become important. This is important for baryogenesis, because in the present Universe we know that the proton is quite stable so that the baryon number violating interactions are negligible. But at high temperatures, there could be many sources for baryogenesis, depending on the laws of physics at very small scales. In this context, lots of interesting ideas in particle physics have been proposed.

In next section, we first describe conditions for baryogenesis and we explain why we need new physics models beyond the Standard Model (SM) of particle physics to realize such conditions. After introducing key ideas in early works, we focus on some recent approaches that attempt to predict more observable effects in terrestrial experiments.

CONDITIONS FOR BARYOGENESIS

In order to generate baryon asymmetry through cosmological evolutions, several conditions should be satisfied. For example, if the baryon number is conserved, no baryon asymmetry could be created from nothing. Therefore, the baryon number should be broken. There are also other conditions to be satisfied. Sakharov first suggested such conditions, summarized in three arguments, as:

1) The Baryon number (B) should be broken,
2) C and CP should be broken, and
3) B violating interactions should be out-of-equilibrium [2].

C corresponds to charge conjugation symmetry, and P is parity symmetry. If C and CP are not broken, the asymmetry generated by particle's interactions is the same size as that generated by anti-particle's interactions but the sign is opposite. Therefore, the asymmetries are canceled with each other after their production. The third condition is also needed, because even if there was a nonzero baryon asymmetry in the beginning, it would be washed out if the baryon number violating interactions are in equilibrium.

It would be necessary to check whether or not such conditions could be satisfied without any new physics beyond the SM, because the SM is a very well confirmed framework for fundamental particles and their interactions up to very small scales, $10^{-15}m$. First of all, in the SM, the baryon number is not absolutely conserved, but broken by a $SU(2)_W \times U(1)_Y$ anomaly. In the present Universe, its effect is very suppressed, so that proton is quite stable. However, its effect becomes important when the temperature of the Universe is larger than 100 GeV. Secondly, C and CP are explicitly broken. The left handed fermions act very differently from the right handed fermions. This seems to fulfill the Sakharov's second condition. However, the CP violating effect is quite suppressed by the small mixing angles through the Jalskog invariant,

$$J_{cp} = -\mathrm{Im}\,[V_{ud}V_{cs}V^*_{us}V^*_{cd}] \sim 10^{-5}$$

Finally, we could consider the electroweak phase transition as the possible source of an out-of-equilibrium process. At high temperatures, the SM Higgs gets thermal corrections so that the Higgs field is trapped at the origin. After the temperature becomes lower than the critical temperature, the Higgs can develop its vacuum value through the phase transition, and the gauge symmetry, $SU(2)_W \times U(1)_Y$ is spontaneously broken. If this phase transition is first order, then bubbles are produced, expand and collide with each other. All those processes are out-of-equilibrium process. Unfortunately, it turns out that the electroweak phase transition in the SM is not first order but a cross-over [3]. Therefore, it becomes clear that by using solely the SM, the Sakharov conditions cannot be satisfied, and that we need a new physics model to generate a correct amount of baryon asymmetry.

EARLY IDEAS FOR BARYONGENESIS

We first introduce representative ideas for baryogenesis before going to the recent discussions.

GUT Baryogenesis

The first nontrivial example for baryogenesis is based on the Grand Unified Theory (GUT) [4], in which all the SM gauge couplings are unified at a scale $M_{GUT} \sim 2\times 10^{16}$ GeV, and the SM gauge groups are embedded in a larger group, G, for $T > M_{GUT}$, All quarks and leptons are also unified in irreducible representations of G. The GUT group, G, is spontaneously broken at M_{GUT}, and some gauge bosons (X, Y) become heavy due to the Higgs mechanism. X, Y bosons can decay to quarks (q) and leptons (ℓ) through the baryon number violating interactions, and they can also decay to anti-quarks (q) and anti-leptons (ℓ). Then the asymmetry could be generated from out-of-equilibrium decays of X to quarks and anti-quarks with different decay rates as $\Gamma(X \to q\ell) \neq \Gamma(X \to \bar{q}\bar{\ell})$.

The model is very well motivated but there are several problems. First of all, in order to produce sizable amounts of X, Y bosons, the temperature of the Universe should be considerably higher than 10^{16} GeV during the early Universe. At these temperatures, the large number of magnetic monopoles could be generated, and they become disastrous at later time in the Universe. Secondly, although the asymmetry of baryons is generated, its abundance is canceled out by the lepton asymmetry generated from same decay channel of X, Y bosons. In the SM, there is a *sphaleron process* (the process built in the SM) which violates both baryon (B) and lepton (L) numbers, keeping B-L conserved. for temperatures with 10^2 GeV $< T < 10^{13}$ GeV, sphalerons are in equilibrium, so all baryon asymmetry would be washed out if the B-L number is vanishing as in the case of GUT baryogenesis. The idea was simple and elegant but it could not be realistic.

Thermal Leptogenesis

From the above example, the sphaleron process seems rather cumbersome, because it makes the baryon number violating interactions in equilibrium so that we cannot satisfy Sakharov's third condition. However, it turns out that sphalerons could play a more important role if we consider a generation of lepton asymmetry, *leptogenesis*, because sphalerons can transfer a part of asymmetry from the lepton number to the baryon number. Therefore, if Sakharov's third condition would be modified to 'B-L violating interactions are out-of-equilibrium.', baryogenesis would still work via leptogenesis.

The well-known example [5] for this class is thermal leptogenesis. The lepton number violating interactions are well motivated, because neutrinos are very light compared to the ordinary charged leptons and quarks but still massive with $m_\nu \sim 0.1$ eV. Such a small but finite neutrino mass can be explained by a see-saw mechanism. If we introduce the massive Majorana fermion, N with a mass M_N, the lepton number violating interactions can be introduced as $y_\nu \ell h N$ in the Lagrangian density. The low energy neutrino mass is given by $y_\nu^2 v^2/M_N$, where v is the Higgs vacuum value of 246 GeV. For a large value of M_N, the small value of the neutrino mass becomes natural. The bonus is that if the Universe was hotter than $T > M_N \sim 10^9$ GeV, the neutral fermion can out-of-equilibrium decay to the lepton, the Higgs (ℓh) and anti-lepton, the Higgs ($\bar{\ell} h$) with different decay rates. The baryon asymmetry generated in this way can be well matched with observations.

Spontaneous Baryogenesis

The last example that we introduce in this section is *spontaneous baryogenesis*, which provides an exception to Sakharov's third condition [6].

The idea is to attack the basic assumption of the third condition: CPT symmetry. Let us consider a motion of a scalar field, $\phi(t, x)$ at the early Universe. In an expanding Universe, the scalar field feels the additional frictions whose size is proportional to the expansion rate. Therefore it would not be quickly settled down at its true vacuum value, but could slowly roll with a nonzero velocity, $\dot{\phi} \neq 0$ toward its vacuum value. If such a rolling scalar field exists as the background of the Universe, then CPT would be spontaneously broken. If we consider interactions between the scalar field and the baryon current (J_B^μ) as

$$\mathcal{L} \ni (\partial_\mu \phi)\, J_B^\mu,$$

the nonzero $\dot{\phi}$ can play the role of the chemical potential, i.e. the energy of quarks and that of anti-quarks are different when B violating interactions are in equilibrium. Therefore, the equilibrium distributions for quarks and anti-quarks are different as

$$n_q - n_{\bar{q}} = c_q \dot{\phi}\, T,$$

where c_q is the constant, depending on the degrees of freedom, and T is the temperature of the Universe.

Although the baryon asymmetry exists while B violating interactions are in equilibrium, they should be decoupled from thermal bath before ϕ stops rolling. Otherwise, the final asymmetry would be zero. For a given time t_{dec} when B violating interactions become out-of-equilibrium, the final baryon asymmetry is given as $n_B/s \propto (\dot{\phi}/T)_{t=t_{dec}}$.

BARYOGENESIS WITH OBSERVABLE PREDICTIONS

The previous examples of baryogenesis are simple and elegant. However, the baryon asymmetry in those models is usually generated at very high temperatures, $T \gg 100$ GeV, compared to the weak scale. The problem with these very high temperatures is that it would be very difficult to prove its the underlying mechanisms of baryogenesis based on terrestrial experiments such as collider or beam dump experiments. In this section we will provide several examples that allow baryogenesis to give interesting observable signatures in terrestrial experiments.

Wimpy Baryogenesis

One of these directions is based on the simple observation that the energy density of dark matter (ρ_{DM}) and that of baryons (ρ_B) are similar

$$\rho_{DM} \simeq 5\rho_B$$

It could be just a coincidence. Or there could be a deeper reason for such a relation that can give a hint regarding the nature of dark matter and the origin of baryon asymmetry.

Wimpy baryogenesis is a kind of class where a baryon asymmetry originates from the abundance of Weakly Interacting Massive Particles (WIMPs) at the early Universe [7]. WIMPs are the best candidate for dark matter because its freeze-out relic density naturally accounts for the observed value. If the baryon asymmetry is generated by late time decays or annihilations of WIMPs, we could understand why the amount of baryons is similar to the amount of dark matter.

In order to realize this mechanism, several neutral and SM charged TeV or weak scale particles are necessary. Therefore, it is directly related with collider searches. One might worry that in these low scale baryogenesis models, in which an asymmetry is generated at around $T \leq M_{wimp}/\,20 \sim 10$ GeV, the proton could be unstable and decay quickly because of sizable baryon number violating operators. However, protons still can be stable even though the baryon number is violated, because proton decay channels such as $p \to e^+ \pi^0$ (K^0) also violate the lepton number, and if the lepton number is unbroken, the decay channels are forbidden. That is the reason why we can use sizable baryon number violating operators at low temperatures.

Cogenesis

The other class of models is cogenesis for both baryon and dark matter asymmetries. In this class, dark matters are not WIMP-like particles but are more strongly interacting particles, so that most of them are annihilated and only the asymmetric part remains at low temperatures. These candidates are called *asymmetric dark matter*.

The idea of asymmetric dark matter is also introduced to understand the coincidence of $\rho_{DM} \simeq 5\rho_B$. If M_{DM} is five times bigger than the proton mass ($M_{DM} \simeq 5$ GeV), the asymmetries of baryons and dark matters are the same. Therefore, it naturally leads to considering a co-generation mechanism for both baryon and dark matter asymmetries. Although the original idea was introduced quite some time ago, recently this idea has received new attention because of experimental hints for the existence of light dark matter whose mass is around 5 GeV [8].

On one hand, in these models, it is necessary to explain why the mass of dark matter is similar to that of the proton. There could be some mirror symmetry between the SM and the dark sector so that composite particles such as twin baryons could exist. The twin baryons get their masses mostly from twin confining mechanisms like protons and neutrons. Interestingly, in the context of solving a little hierarchy problem in the SM, a twin Higgs scenario has been suggested, in which stable (long lived) twin baryons are naturally obtained.

One can suggest a cogenesis model to generate both baryon and twin baryon asymmetries from the decay of TeV scale particles [9]. The model has a $U(1)_B+U(1)_{\tilde{B}}$ symmetry, where B is a baryon and $\tilde{B}$ is a twin baryon number. The neutral particle can both decay to (anti-) quarks $qqq(\bar{q}\bar{q}\bar{q})$ and also to (anti-)twin quarks, $\tilde{q}\tilde{q}\tilde{q}(\bar{\tilde{q}}\bar{\tilde{q}}\bar{\tilde{q}})$, whose asymmetries are exactly the same size with their opposite signs. An interesting aspect of this model is that the dark matter is not absolutely stable, and can decay to SM particles mediated by colored scalar particles. Depending on the life-time of a colored scalar, we can find meaningful signatures at collider experiments or gamma-ray signals from dark matter decay measured by satellites [9]. The cosmological and collider signatures are tightly related with each other. Such observations can give new hints about baryogenesis and also about dark matter.

Neutron Anti-neutron Oscillation with Effective Baryogenesis

Although baryon number violating interactions do not make protons unstable, interesting phenomena could happen to neutrons, because there could be oscillation between a neutron (B=1) and an anti-neutron (B=−1) without breaking lepton number. If the neutron in the nuclei is oscillated to an anti-neutron, it could be quickly annihilated, so that observable signals are generated. The current bound on the oscillation time ($\tau_{n-\bar{n}}$) is [10]

$$\tau_{n-\bar{n}} > 2.7\times10^{8}\ \text{sec}$$

The possibility to connect neutron anti-neutron oscillations and baryogenesis can be studied in more detail through an effective operator approach.

The simplest example for baryogenesis is given as [11]

$$\mathcal{L} \ni \frac{1}{2}M\chi^2 + \frac{\chi(qqq)}{\Lambda_1^2} + \frac{(qqq)(qqq)}{\Lambda_2^5} + h.c.$$

where χ is the singlet Majorana fermion, and q is the SM quark. The out-of-equilibrium decay of χ to qqq and their anti-particles with different decay rates, due to the dimension nine operator $(qqq)^2$, generates the baryon asymmetry. Interestingly, this dimension nine operator is also the source of neutron anti-neutron oscillation. Therefore, we could directly correlate the origin of baryon asymmetry and neutron anti-neutron oscillations.

On one hand, the higher dimensional operators, $(qqq)^2/\Lambda_2^5$, could be obtained by integrating out colored scalar particles with masses of the order of Λ_5. We could also predict the observable consequence of such colored scalars at collider experiments. Such triangular relations would be a special feature of this kind of model. Future experiments for neutron anti-neutron oscillation, and collider experiments could reveal the origin of matter anti-matter asymmetry in the Universe.

New Approaches with Electroweak Baryogenesis

The idea of electroweak baryogenesis is to utilize a first order electroweak phase transition, if it is realized, as the source of baryogenesis. After the temperature becomes lower than the critical temperature (T~100 GeV), the phase transition happens at each uncorrelated local space point. Therefore, bubbles will form at each point, and expand. Inside the bubble the Higgs field gets a finite value, and $SU(2)_W\times U(1)_Y$ is broken so that all baryon number violating interactions are out-of-equilibrium. On one hand, outside the bubbles, the Higgs field is still at the origin: it is the symmetric phase. In this phase, the sphaleron process is active so that B and L number violations are in equilibrium. The out-of-equilibrium process happens as the bubble walls scatter off the background plasma composed of quarks and anti-quarks. The reflection and transmission coefficients by the bubble walls are different for quarks and anti-quarks if C and CP are broken. After the CP asymmetric plasma diffuses to the symmetric phase, the baryon asymmetry is generated through the sphaleron process.

After the Higgs particle was discovered with a mass of m_h = 125 GeV at the LHC, it became much clearer that the electroweak phase transition for the Standard Model is a cross-over. Therefore, we need an extension of the SM to achieve a first order phase transition. There are many works proposing an extension of the SM including new light colored scalars, real singlets or Higgs doublets [3]. The mass of all those particles should be around the weak scale, 100 GeV, so there are several constraints from the electric dipole moments of baryons and leptons and collider searches.

The extension of the Higgs potential with the axion like particle (ALP) could give a new interesting example of electroweak baryogenesis [12]. The potential has the form

$$V = V(h, \sin\theta, \cos\theta),$$

where h is the Higgs field, $\theta = a/f$, and a is the axion field with a period, $2\pi f$. For a relatively large value of f, we could still obtain the sizable first order phase transition with the correct amount of baryon asymmetry. As we can take a large f, the axion mass is suppressed by f, which becomes lighter than the proton. It is exactly the target of beam dump experiments for light scalar particles [13]. This is the first work to relate the search of axion like particles to baryogenesis.

CONCLUSIONS

Although modern science is very successful in explaining the nature of the Universe, we still do not have any concrete evidence about how matter and anti-matter asymmetry were generated in the early Universe. However, there are many interesting ideas regarding how matter and anti-matter asymmetry were generated, and recent progress has focused more on observable consequences in order to confirm or rule out models through various experiments such as collider searches, neutron anti-neutron oscillations, and light scalar searches. We hope that within a few years, we will be able to discover more clues on the origin of the Universe.

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