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Baryogenesis from symmetry principle

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ABSTRACT

In this work, a formalism based on symmetry which allows one to express asymmetries of all the particles in terms of conserved charges is developed. The manifestation of symmetry allows one to easily determine the viability of a baryogenesis scenario and also to identify the different roles played by the symmetry. This formalism is then applied to the standard model and its supersymmetric extension, which constitute two important foundations for constructing models of baryogenesis.

1. Introduction

The evidences that we live in a matter-dominated Universe are very well-established [1]. While the amount of antimatter is negligible today, the amount of matter (i.e. baryon) of the Universe has been determined with great precision by two independent methods. From the measurement of deuterium abundance originated from Big Bang Nucleosynthesis (BBN) when the Universe was about a second old (with temperature $T_{\rm BBN} \sim$ MeV), Ref. [2] quotes the baryon density normalized to entropic density as $10^{11} Y_B^{\rm BBN} = 8.57 \pm 0.18$. From the measurement of temperature anisotropy in the cosmic microwave background radiation imprinted by acoustic oscillation of photon–baryon plasma when the Universe was about 380 000 years old ($T_{\rm CMB} \sim 0.3$ eV), Planck satellite gives $10^{11} Y_B^{\rm CMB} = 8.66 \pm 0.06$ [3]. The impressive agreement between the two measurements is a striking confirmation of the standard cosmological model.

In order to account for the cosmic baryon asymmetry, baryogenesis must be at work before the onset of BBN. Although the Standard Model (SM) of particle physics (and cosmology) contains all the three ingredients for baryogenesis: baryon number violation, C and CP violation, and the out-of-equilibrium condition [4], it eventually fails and new physics is called for [5]. Clearly these ingredients are necessary but not sufficient. Moreover, the early Universe is filled with particles of different types that interact with each other at various rates, rendering it a daunting task to analyze them. In this work, I would like to advocate the use of *symmetry* as an organizing principle to analyze such a system. In particular, I will show that by identifying the symmetries of a system, one can relate the asymmetries of all the particles to the corresponding conserved charges without having to take into account details of how those particles interact.[1] This should not come as a surprise since symmetry dictates physics: when we specify a symmetry and how particles transform under it, the interactions are automatically fixed. I will first review the formalism in Section 2. Then the roles of $U(1)$ symmetries are clarified in Section 3. In Sections 4 and 5 respectively, I will apply this formalism to the SM and its supersymmetric extension as they form important bases for constructing models of baryogenesis. Finally I conclude in Section 6.

2. Formalism

Here I will review the formalism that we will use in this work.[2] For a system with s number of symmetries labeled $U(1)_x$ and consisting of $r \geq s$ distinct types of complex particles labeled i (i.e. not self-conjugate like real scalar or Majorana fermion) with corresponding chemical potentials μ_i and charges q_i^x under $U(1)_x$, the most general solution is given by

$$\mu_i = \sum_x C_x q_i^x, \tag{1}$$

where C_x is some real constant corresponding to $U(1)_x$. It is apparent that Eq. (1) is the solution for chemical equilibrium conditions for any possible in-equilibrium interactions since by definition, the

[1] It should be stressed immediately that the symmetries do not have to be exact. If a symmetry is approximate, the corresponding charge will be quasi-conserved with its evolution described by nonequilibrium formalism like Boltzmann equation. In other words, the description of the system boils down to identifying *only* the interactions related to approximate symmetries.

[2] The formalism was first introduced by Ref. [6] to prove that the generation of hypercharge asymmetry in a preserved sector implies nonzero baryon asymmetry. See also the relevant discussion in Chapter 3.3 of Ref. [7].

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interactions necessarily preserve the symmetry. Note that symmetry discussed in this work always refers to $U(1)$ which characterizes the charge asymmetry between particles and antiparticles. The $U(1)_x$ can be exact (like gauge symmetry) or approximate (due to small couplings, and/or suppression by mass scale and/or temperature effects). The diagonal generators of a nonabelian group do not contribute as long as the group is not broken [6]. For instance one does not need to consider conservation of third component of weak isospin T_3 before electroweak (EW) phase transition.

Now for each $U(1)_x$, according to Noether's theorem there is a conserved current and the corresponding conserved charge density can be constructed as

$$n_{\Delta x} = \sum_i q_i^x n_{\Delta i}, \tag{2}$$

where $n_{\Delta i}$ is the number density asymmetry for particle i. To proceed we need two further assumptions. Firstly, particle i is assumed to participate in fast *elastic* scatterings such that its phase space distribution is either Fermi–Dirac $[\exp(E_i - \mu_i)/T + 1]^{-1}$ or Bose–Einstein $[\exp(E_i - \mu_i)/T - 1]^{-1}$ for fermion or boson respectively. Secondly, there are fast *inelastic* scatterings for particle i and its antiparticle $\bar{i}$ to gauge bosons (which have zero chemical potential) such that $\mu_{\bar{i}} = -\mu_i$. These two assumptions are justified for instance when the particles have gauge interactions. Now Eq. (2) can be related to its chemical potential for $\mu_i \ll T$ as follows[3]

$$n_{\Delta i} = n_i - n_{\bar{i}} = \frac{T^2}{6} g_i \zeta_i \mu_i. \tag{3}$$

In the above g_i specifies the number of gauge degrees of freedom and

$$\zeta_i \equiv \frac{6}{\pi^2} \int_{z_i}^{\infty} dx\, x \sqrt{x^2 - z_i^2} \frac{e^x}{(e^x \pm 1)^2}, \tag{4}$$

with $z_i \equiv m_i/T$. In the relativistic limit ($T \gg m_i$), we have $\zeta_i = 1(2)$ for i a fermion (boson) while in the nonrelativistic limit ($T \ll m_i$), we obtain $\zeta_i = \frac{6}{\pi^2} z_i^2 \mathcal{K}_2(z_i)$ with $\mathcal{K}_2(x)$ the modified Bessel function of type two of order two. Using Eqs. (1) and (3), Eq. (2) can be written as

$$n_{\Delta x} = \frac{T^2}{6} \sum_y J_{xy} C_y, \tag{5}$$

where we have defined the symmetric matrix J as follows

$$J_{xy} \equiv \sum_i g_i \zeta_i q_i^x q_i^y. \tag{6}$$

We can invert Eq. (5) to solve for C_y in terms of $n_{\Delta x}$ and substituting it into Eq. (1) and then making use of Eq. (3), we obtain[4]

$$n_{\Delta i} = g_i \zeta_i \sum_{y,x} q_i^y \left(J^{-1}\right)_{yx} n_{\Delta x}. \tag{7}$$

[3] The expansion in $\mu_i/T \ll 1$ is justified as long as the number asymmetry density is much smaller than its equilibrium number density. For instance with $n_{\Delta i}$ the order of the observed baryon asymmetry, the expansion holds when the corresponding particle mass over temperature $m_i/T \lesssim 20$.

[4] As long as $r \geq s$ and there are no redundant symmetries, in the sense that all the symmetries are linearly independent and there is no rotation in the s-dimensional symmetry space that can make all the r distinct particles uncharged under some $U(1)$, J always has an inverse.

Eventually one would like to relate this to baryon asymmetry i.e. the baryon charge density. By substituting Eq. (7) into Eq. (2) for baryon charge density, we have

$$n_{\Delta B} = \sum_{y,x} J_{By} \left(J^{-1}\right)_{yx} n_{\Delta x}. \tag{8}$$

Eqs. (7) and (8) make the symmetries of the system manifest: the solutions are expressed in term of conserved charges $n_{\Delta x}$, one for each $U(1)_x$ symmetry. In fact $\{n_{\Delta x}\}$ forms the *appropriate* basis to describe the system. While q_i^x comprises the charges of particle i under $U(1)_x$, J matrix embodies full information of the system (all possible interactions consistent with the symmetry are implicitly taken into account). Notice that calculating J is particularly *simple* and circumventing the traditional approach of having to count the number of chemical potentials and determine the chemical equilibrium conditions. It is now apparent that baryogenesis fails ($n_{\Delta B} = 0$) if: (I) the system does not possess any symmetry in which case $C_x = 0$ for all x in Eq. (1) or; (II) the system possesses only $U(1)_x$'s which always remain exact such that none develops an asymmetry in which case $n_{\Delta x} = 0$ for all x.

For instance, the baryogenesis scenario proposed in Ref. [8] fails due to the following reasons. In that work, there are initially four effective symmetries: $U(1)_{B/3-L_\alpha}$ ($\alpha = \{1, 2, 3\}$) and $U(1)_{\tilde{\psi}}$. During baryogenesis, $U(1)_{B/3-L_\alpha}$ is always conserved i.e. $n_{\Delta(B/3-L_\alpha)} = 0$ while a large enough *CP* asymmetry at the TeV scale requires fast $U(1)_{\tilde{\psi}}$ violation i.e. $C_{\tilde{\psi}} = 0$. As a result, $n_{\Delta B} = 0$.

3. The roles of $U(1)$ symmetries

In general, the reaction rate of a process γ in the early Universe is temperature-dependent $\Gamma_\gamma(T)$. At each range of temperature T^*, by comparing $\Gamma_\gamma(T^*)$ to the expansion rate of the Universe $H(T^*)$, we can categorize the reactions into three types [9,10]: (i) $\Gamma_\gamma(T^*) \gg H(T^*)$; (ii) $\Gamma_\gamma(T^*) \ll H$; (iii) $\Gamma_\gamma(T^*) \sim H(T^*)$. The reactions of type (i) are fast enough to establish chemical equilibrium and are implicitly 'resummed' in the J matrix in Eq. (6). The reactions of type (ii) either do not occur or proceed slow enough. The former is due to exact symmetry like gauge symmetry while the latter is due to small couplings, and/or suppression by mass scale and/or temperature effects. Finally the reactions of type (iii) should be described by nonequilibrium formalism like Boltzmann equation in order to obtain quantitative prediction. In this work, the effective symmetries concern both reactions of types (ii) and (iii). In particular gauge symmetry always belongs to type (ii) and can play an interesting role as '*messenger*'. If an approximate symmetry belongs to type (ii), it can acquire a role as a '*messenger*' or '*preserver*' while if it is of type (iii), it can act as '*creator/destroyer*'.

To understand the roles of $U(1)$ alluded to above, it is illuminating to group the charges as follows. Among all the charges $U = \{n_{\Delta x}\}$, there is a subset $U_0 = \{n_{\Delta a}\}$ where the net charges vanish $n_{\Delta a} = 0$. In this case, we can remove them from the beginning and left with $\tilde{U} = U - U_0 = \{n_{\Delta m}\}$ to describe the system. From Eq. (5), we have a set of linear equations $n_{\Delta a} = \sum_b J_{ab} C_b + \sum_m J_{am} C_m = 0$, which allows us to solve for C_a in terms of C_m.[5] After eliminating C_a, the number density asymmetry for particle i can be expressed as

$$n_{\Delta i} = g_i \zeta_i \sum_{m,n} \tilde{q}_i^m \left(\tilde{J}^{-1}\right)_{mn} n_{\Delta n}, \tag{9}$$

[5] We use $a, b, \ldots$ to label the charges in U_0 and $m, n, \ldots$ to label the charges in $\tilde{U}$.