BARYOGENESIS WITHOUT GRAND UNIFICATION

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A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures

The current view ascribes the origin of cosmological baryon excess to the microscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle interactions is regarded as the standard candidate to account for this baryon number violation: The theory can give the correct order of magnitude for baryon to entropy ratio. If the Universe undergoes the inflation epoch after the baryogenesis, however, generated baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to raise the temperature above the GUT energy scale. A more irritating problem is that no evidences are given so far experimentally for the baryon number violation, which might cast some doubt on the GUT idea.

Some time ago 't Hooft suggested that the instanton-like effect violates baryon number in the Weinberg–Salam theory through the anomaly term, although the effect is suppressed by a large factor [3]. It has been pointed out, however, that this effect is not suppressed and can be efficient at high temperatures above the Weinberg–Salam energy scale [4]. This baryon number violating process conserves $B-L$, but it erases rapidly the baryon asymmetry which would have been generated at the early Universe with $B-L$ conserving baryon number violation processes as in the standard SU(5) GUT. (Baryon numbers would remain, if the baryon production takes place at low temperatures $T \lesssim O(100\ \mathrm{GeV})$, e.g., after reheating [5,6].) The process itself can not produce the baryon asymmetry, since it is unlikely to suppose a particular mechanism leading to departures from equilibrium [4].

In this letter, we point out that this electroweak baryon number violation process, if it is supplemented by a lepton number generation at an earlier epoch, can generate the cosmological baryon asymmetry without resorting to the GUT scenario: The lepton number excess in the earlier stage can efficiently be transformed into the baryon number excess. It is rather easy to find an agent leading to the lepton number generation. A candidate is the decay process involving Majorana mass terms.

Let us present a specific model which gives lepton number generation. We assume the presence of a right-handed Majorana neutrino N_R^i ($i = 1 - n$) in addition to the conventional leptons. We take the lagrangian to be

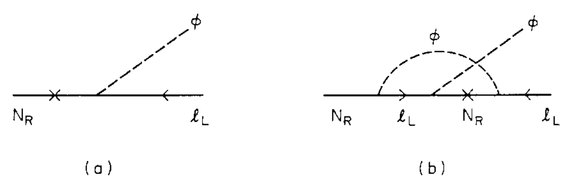

Fig 1 The simplest diagram giving rise to a net lepton number production The cross denotes the Majorana mass insertion.

$$\mathcal{L} = \mathcal{L}_{\rm WS} + \bar{\rm N}^i_{\rm R} \not\partial {\rm N}^i_{\rm R} + M_i \bar{\rm N}^{ic}_{\rm R} {\rm N}_{\rm R} + {\rm h.c.} + h_{ij} \bar{\rm N}^i_{\rm R} \ell^j_{\rm L} \phi^\dagger + {\rm h.c.}\,, \tag{1}$$

where $\mathcal{L}_{\rm WS}$ is the standard Weinberg–Salam lagrangian, and ϕ the standard Higgs doublet. For simplicity we assume three generations of flavours and the mass hierarchy $M_1 < M_2 < M_3$ In the decay of $\rm N_R$,

$$\rm N_R \to \ell_L + \bar\phi\,, \tag{2a}$$

$$\to \bar\ell_L + \phi\,, \tag{2b}$$

there appears a difference between the branching ratios for (2a) and (2b), if *CP* is violated, through the one-loop radiative correction by a Higgs particle. The net lepton number production due to the decay of a lightest right-handed neutrino $\rm N^1_R$ arises from the interference of the two diagrams in fig. 1, and its magnitude is calculated as [7]

$$\epsilon = (9/4\pi)\,{\rm Im}\,(h_{li} h^\dagger_{ij} h^\dagger_{jk} h_{kl}) I(M_j^2/M_i^2)/(hh^\dagger)_{11}\,, \tag{3}$$

with

$$I(x) = x^{1/2}\{1 + (1+x)\ln[x/(1+x)]\}\,.$$

If we assume h_{33} to be the largest entry of the Yukawa coupling matrix and $M_3 \gg M_1$, (3) reduces to

$$\epsilon \approx (9/8\pi)|h_{33}|^2 (M_1/M_3)\delta\,, \tag{4}$$

with δ the phase causing *CP* violation.

We apply the delayed delay mechanism [8] to generate the baryon asymmetry in the Universe. The out-of-equilibrium condition is satisfied, if the temperature T is smaller than the mass M_1 so that the inverse decay is blocked at the time when the decay rate $\Gamma = (hh^\dagger)_{11}/16\pi$ is equal to the expansion rate of the Universe $\dot a/a \sim 1.7\sqrt{g}T^2/m_{\rm Pl}$ (g = numbers of degrees of freedom), i.e.,

$$(\Gamma m_{\rm Pl} g^{-1/2})^{1/2} < M_1\,. \tag{5}$$

To obtain numerical factors for this condition, one has to solve the Boltzmann equation. Let us borrow the results of ref. [9] to obtain a rough number The lepton number to entropy ratio is given as

$$k(\Delta L)_i/s \sim 10^{-3}\,\epsilon K^{-1.2}\,, \tag{6}$$

with $K = \frac{1}{2}\Gamma/(\dot a/a)$ for $K \gg 1$. The parameters in (4) and in the expression of Γ are not directly constrained by low-energy experiments. One may have an idea, however, on the mass scale M_1 as follows: With the parameter in a reasonable range, one may obtain $\epsilon \lesssim 10^{-6}$. Then to obtain our required number for $k(\Delta L)_i/s \sim 10^{-10.5}$ (see below), $K \lesssim 30$ is necessary, which gives $M_1 \gtrsim 2.4 \times 10^{14}\ {\rm GeV}(hh^\dagger)_{11}$. If we assume $|h_{12}|^2, |h_{13}|^2 \lesssim |h_{11}|^2$ and take $(hh^\dagger)_{11} \approx |h_{11}|^2 \sim (10^{-5})^2$, then we are led to $M_1 \gtrsim 2 \times 10^4$ GeV. This constraint can also be expressed in terms of the left-handed Majorana neutrino mass [‡1] as $m_{\nu_e} \approx h^2_{11}\langle\phi\rangle^2/M_1 \lesssim 0.1$ eV. If the lightest left-handed neutrino has a Majorana mass smaller than this value, the required asymmetry can be generated.

Now let us discuss the generation of the baryon asymmetry. In the presence of an instanton-like electroweak effect the baryon asymmetry changes as [4]

$$\Delta B(t) = \tfrac{1}{2}\Delta(B-L)_i + \tfrac{1}{2}\Delta(B+L)_i \exp(-\gamma t)\,, \tag{7}$$

with $\gamma \sim T$. At the time of the Weinberg–Salam epoch the exponent is $m_{\rm Pl}/T\sqrt{g} \sim 10^{16}$ and the second term practically vanishes. Therefore we obtain

$$\Delta B = -(\Delta L)_i/2\,, \tag{8}$$

which survives up to the present epoch, and should give $k\Delta B/s \sim 10^{-10.8}$.

[‡1] Here we assumed the dominance of the diagonal matrix element. More precisely speaking, the matrix element constrained by our condition differs from that which appears in the observable neutrino mass: The left-handed neutrino mass matrix is given by $[m_\nu]_{ij} = \Sigma_k (h^{\rm T})_{ik} h_{kj}\langle\phi\rangle^2/M_k$ [10]. The double beta decay experiment measures the matrix element $[m_\nu]_{11} = (h^2_{11}/M_1 + h^2_{21}/M_2 + h^2_{31}/M_3)\langle\phi\rangle^2$, while eq (5) refers to $(|h_{11}|^2 + |h_{12}|^2 + |h_{13}|^2)\langle\phi\rangle^2/M_1$ and $h_{ij} \neq h_{ji}$ in general. (Here we took the basis where the charged-lepton mass matrix is diagonal.) Therefore, the double beta decay experiment does not constrain directly the parameters in eq (5). The tritium beta decay experiment measures the eigenvalue of the mass matrix $\|m_\nu\|$ (see ref. [11]).

A primordial lepton number excess existed before the epoch of the right-handed neutrino mass scale should have been washed out by the equilibrium of process (2) and its inverse process, if the Yukawa coupling $(hh^\dagger)_{22}$ or $(hh^\dagger)_{33}$ is large enough. The equilibrium condition $\Gamma_i \exp(-M_i/T) \gtrsim 1.7\sqrt{g}T^2/m_{\mathrm{Pl}}$ ($i = 2$ or 3) leads to a constraint similar to (5) but with the inequality reversed. The net baryon number destruction factor behaves as $\sim\exp(-\alpha k)$ ($\alpha \sim O(1)$) [9]. For $K \gtrsim 20$–30, the equilibrium practically erases the whole pre-existing lepton number excess. This condition is expressed as $(m_\nu)_{ii} > 0.1$ eV for the largest entry of the Majorana mass matrix.

In the presence of unsuppressed instanton-like electroweak effects, the lepton number equilibrium implies that the baryon excess which existed at this epoch should also be washed out, even if it was produced in the process with $B - L \neq 0$ Namely, if there are neutrinos with the Majorana mass heavier than $\sim$0.1 eV both baryon and lepton numbers which existed before this epoch are washed out irrespective of their $B - L$ properties.

In summary, we have the following possible scenarios for the cosmological baryon number excess:

(1) At a temperature above the mass scale M (= scale of right-handed Majorana neutrino), we started with $\Delta B = \Delta L = 0$ (The inflationary universe would give this initial condition). Then the lepton number is generated through the Majorana mass term, and is transformed into the baryon number due to the unsuppressed instanton-like electroweak effect.

(2) At the scale $>M$, baryon and lepton numbers are generated by the grand unification, or alternatively we start with a $\Delta B \neq 0$, $\Delta L \neq 0$ Universe. The equilibrium of $N_R \rightleftarrows \bar{\phi} + \nu_L$, $\phi + \bar{\nu}_L$, together with the electroweak process washes out both baryon and lepton numbers. Then the lepton number is newly generated by the out-of-equilibrium scenario, and it turns into the baryon number

(3) The baryon number with $B - L \neq 0$ is generated by the grand unification (e.g., the SO(10) model [12]). IF the scale M is too large to establish the equilibrium of N_R and $\phi + \nu_L$, then the initial $\Delta(B - L)$ will not be erased The electroweak process does not affect $B - L$, and hence the initial baryon number remains. This case is the original GUT baryon number generation scenario To achieve this, however, all neutrino mass matrix elements (Majorana mass) should be smaller than $\sim$0.1 eV If the double beta experiment would observe a Majorana mass greater than this value, this scenario fails.

In conclusion we have suggested a mechanism of cosmological baryon number generation without resorting to grand unification. In our scenario the cosmological baryon number can be generated, even if proton decay does not happen at all

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