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Brief Reports

Brief Reports are accounts of completed research which do not warrant regular articles or the priority handling given to Rapid Communications; however, the same standards of scientific quality apply. (Addenda are included in Brief Reports.) A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.

Sphaleron-induced baryon-number nonconservation and a constraint on Majorana neutrino masses

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We point out that the baryon-number asymmetry in the Universe is erased by the sphaleron effect just below the electroweak phase transition irrespective of the primordial baryon- and lepton-number asymmetry, if there exists a Majorana-type interaction. The requirement to avoid this happening leads to the condition that m_ν (Majorana) < 50 keV for all species of neutrinos, regardless of whether or not neutrinos are stable.

It has been known that the baryon (B) and lepton (L) numbers might not be conserved in the presence of a number of topologically distinct vacua in the standard Weinberg-Salam electroweak model. 't Hooft[1] pointed out in 1976 that this B- and L-number nonconservation, in fact, is caused by quantum tunneling transitions between the topologically inequivalent vacua by instantons. The transition amplitude, however, is exponentially suppressed by the WKB factor $\exp(-8\pi^2/g_2^2)$ at zero temperature [g_2 is the weak SU(2) coupling], and the instanton processes are practically negligible.

The observation of Klinkhamer and Manton[2] has shed new light on the issue. They found a static, but unstable solution (called a sphaleron) of the classical field equation in the electroweak model, which corresponds to a saddle-point field configuration connecting the neighboring vacua. Kuzmin, Rubakov, and Shaposhnikov[3] then suggested that the sphaleron may induce an effect more important than the instanton at a high temperature in communicating two vacua; thermal fluctuations generate classical transitions from one vacuum to another passing over the sphaleron configuration. The rate for the thermal transition was recently calculated by several authors[4] with the aid of the Langer-Affleck theory[5] with the conclusion that the inclusive rate of B- and L-violating processes exceeds the Hubble expansion rate Γ_{exp} of the Universe at high temperatures 100 GeV $\lesssim T < T_c$, with T_c the critical temperature for the electroweak phase transition.

This causes important consequences for evolution of the baryon asymmetry of the Universe. If the Universe started with $B-L=0$, the primordial baryon asymmetry is washed out at the time slightly after the electroweak phase transition (recall that the vacuum transition processes conserve $B-L$). At this low temperature it is not easy to find an efficient out-of-equilibrium scenario that leads to an excess net baryon asymmetry. Possibilities[6] are discussed to generate baryon numbers using fluctuations at the time of the electroweak phase transition. This scenario may work only when the transition is first order. However, the recent experiment at LEP has given the constraint on the Higgs-boson mass m_φ that it be larger than 24 GeV.[7] We have now only a narrow window 24 GeV $\leq m_\varphi \leq 45$ GeV for this possibility to work, since for a Higgs-boson mass higher than this value the electroweak phase transition necessarily becomes second order. In any case whether this scenario survives will be tested in the near future. An alternative possibility to explain the baryon asymmetry in the present Universe is to postulate $B-L$ violating interactions[8] which have taken place at some stages in the very early Universe of $T \gg O(100)$ GeV.

In this Brief Report we point out that the baryon asymmetry is washed out in the general context, irrespective of any initial conditions, if there exist sizable Majorana-type interactions, which are often assumed to explain small Majorana masses for neutrinos. The survival condition of the baryon asymmetry of the Universe gives a constraint on such interactions, and hence on the neutrino masses that $m_\nu < 50$ keV for the heaviest of Majorana neutrinos.

In the standard electroweak model the lowestdimensional operator that violates $B-L$ is[9]

$$L=\frac{2}{M}l_L l_L \phi\phi + \text{H.c.} \tag{1}$$

where

$$l_L = \begin{bmatrix} \nu_e \\ e \end{bmatrix}_L, \begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L, \begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L \tag{2}$$

and ϕ is the Higgs scalar. The effective interaction of this form is induced as a consequence of some lepton-number-violating interactions at high energies. This represents a typical term that gives rise to the seesaw mechanism[10] in unified theories. With Eq. (1) neutrino masses are given by

$$m_\nu = v^2/M \ . \tag{3}$$

Here we take

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v \end{bmatrix}, \quad v=248 \text{ GeV} \ . \tag{4}$$

In the broken phase of electroweak symmetry the neutrino has the $(B-L)$-violating interaction with the physical Higgs boson φ as

$$L_{\text{int}} = \frac{1}{M}\nu_L \nu_L \varphi\varphi \ . \tag{5}$$

If the interaction (5) is strong enough to make thermal equilibrium of ν_L and φ, it erases the lepton asymmetry, and hence the baryon asymmetry under the action of the sphaleron-induced $B+L$ violation, whatever primordial B and L asymmetries there were. From Eq. (5) we have

$$\sigma(\nu_L + \varphi \rightarrow \overline{\nu_L} + \overline{\varphi}) \simeq \frac{1}{\pi}\left[\frac{1}{M}\right]^2 , \tag{6}$$

where we have neglected m_φ as well as m_ν, since the critical temperature T_c is much higher than the Higgs-boson mass ($m_\varphi^2/T_c^2 \simeq 0.2$, for example see Ref. 6) in the case of the second-order phase transition. Thus the rate of the L-number-violating process is roughly

$$\Gamma_{L\neq 0} \simeq \langle \sigma n_\varphi \rangle \tag{7}$$

$$\approx 0.122 \times \frac{1}{\pi}\frac{T^3}{M^2} \ . \tag{8}$$

The survival condition for baryon asymmetry of the Universe,

$$\Gamma_{L\neq 0}(T_c) < \Gamma_{\text{exp}} \simeq 17 T_c^2/m_{\text{PL}} \ , \tag{9}$$

leads to

$$M > 10^9 (T_c/100 \text{ GeV})^{1/2} \text{ GeV} \ . \tag{10}$$

(Above the critical temperature T_c the electroweak symmetry is restored and there are no sphaleron solutions at all. We assume here that B- and L-violating processes are suppressed in the unbroken phase as in the case of QCD.[11]) Inserting Eq. (9) into Eq. (3) we obtain

$$m_\nu < 50 \text{ keV} \left[\frac{100 \text{ GeV}}{T_c}\right]^{1/2} . \tag{11}$$

It is clear from Eq. (3) that the condition applies to the heaviest mass of neutrinos. We also note that, while this constraint is weaker than the one obtained from the mass density of the Universe ($m_\nu < 100$ eV h^2), it is applicable not only to stable neutrinos but also to any unstable neutrinos irrespective of their lifetime. This condition would place a significant constraint on the unified model beyond the Weinberg-Salam theory.

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