DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 88-128
August 1988

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ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

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Electroweak Production of the Baryon Asymmetry†

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Abstract

We review a new proposed scenario of the baryon asymmetry generation in the framework of standard electroweak theory. We discuss cosmological predictions and upper bounds on the Higgs and top masses and consider recent lattice results on the structure of ground state of gauge theories.

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†Talk given at XXIV International Conference on High Energy Physics, Munich 4-10 August 1988, Fed.Rep.Germany

1 Introduction

The existence of the baryon asymmetry of the universe (BAU) is the unique observational argument in favour of baryon number non-conservation For the explanation of BAU people have invoked, till the present time, some exotic interactions which exist in the different types of grand unified, supersymmetric and superstring theories. In most of the models baryogenesis takes place in the early stages of the universe's expansion, at temperatures $T \sim 10^{12} - 10^{15}\ GeV$. However, recently it has been realized that anomalous electroweak baryon number non-conserving processes, which are exponentially suppresssed at zero temperatures [1], are in fact very fast at moderate temperatures of order weak scale [2]. This ensures that GUT scenario for BAU production has to be reconsidered. Moreover, BAU generation in the framework of standard electroweak theory seems to be possible.

The aim of this talk is to discuss physics and cosmological implications of anomalous electroweak fermion number non-conservation. First, we shall shortly describe the mechanism of B-violation at high temperatures and consequences of high rate of anomalous processes. Then we will turn to the scenario of electroweak production of baryon asymmetry and discuss cosmological bounds and predictions for the Higgs boson mass. The scenario is based on some dynamical assumptions on the structure of high temperature ground state of gauge-Higgs system. So finally we discuss recent Monte-Carlo lattice simulations of electroweak physics near the first order phase transition with the breaking of SU(2)xU(1) group.

2 Electroweak Baryon Number non-Conservation at High Temperatures

Non-trivial vacuum structure of non-abelian gauge theories with left-right asymmetric fermionic content leads to anomalous fermion number non-conservation [1]. In particular, baryonic (B) and leptonic (L) numbers are not conserved in standard electroweak theory. B and L violation is caused by the winding of the SU(2) gauge fields. The anomaly of the fermionic current links the winding of the gauge fields and the change in baryon (and lepton) number together by

$$B(t_2) - B(t_1) = L(t_2) - L(t_1) = \frac{N_f}{16\pi^2}\int_{t_1}^{t_2} dt \int d^3x\ TrF_{\mu\nu}\ F^*_{\mu\nu}\ , \qquad (1)$$

where N_f is the number of families of quarks and leptons. Nonzero winding of the gauge field appears for the transitions between the states which are excitations of vacua with different topological numbers, say

$$A_i = 0,\ \phi = (0\ \ v)\ \ and\ \ A_i = g\partial_i g^{-1}\ ,\phi = g\,(0\ \ v) \qquad (2)$$

with g being the matrix of large gauge transformation. Here A and ϕ are gauge and scalar fields respectively, v is vacuum expectation value. Topologically distinct vacua are separated by potential barrier [3,4] with the height $M_{sph} = 2M_W/\alpha_W B(\lambda/\alpha_W) = 8 - 14\ TeV$ for λ varying from 0 to infinity (λ is the scalar self-coupling constant). Index (sph) refers here to sphaleron, i.e. static unstable solution to the classic equations of motion [4]. In a sense, this configuration lies on the middle of the way from one vacuum to the nearby one.

The transitions between topological sectors can proceed by two different mechanisms. If the energy E of the system is small compared with M_{sph} then the only way is quantum tunneling. The amplitude for such process is exponentially suppressed as $exp(-2\pi/\alpha_W) \sim 10^{-86}$ [1]. In contrast if $E \geq M_{sph}$ the system could in principle pass over the barrier classically without any suppression [5,4,2]. This is indeed the case for high temperatures prevailing in early universe [2]. Here the rate of thermal fluctuations with changing of topological number is given by the Boltzman factor $exp(-M_{sph}/T)$, and this factor goes to one for high temperatures [2].

Now the theory of anomalous fermionic number non-conservation is well elaborated. The actual computation of the rate beyond the Gaussian (one loop) approximation is possible [6] (although even one loop calculations still absent due to complexity of the problem). Some information is available for the prefactor. Generally, the rate of topological transitions per unit time and unit volume has the form [7,8]

$$\Gamma = Z_0 exp(-M_{sph}(T)/T)\kappa, \tag{3}$$

where $M_{sph}(T)$ is temperature dependent sphaleron mass, κ is a numerical factor of order 1 coming from calculation of determinants in sphaleron background and Z_0 is zero mode normalization [7]:

$$Z_0 = \frac{(2M_W)^4}{2\pi}\left(\frac{M_W}{2\pi\alpha_W T}\right)^3 N_{tr}\ N_{rot}, \tag{4}$$

$N_{tr} = 26$, $N_{rot} = 5.3\ 10^3$ for $M_H = M_W$.

Some progress was achieved in understanding of topological transitions at temperatures higher than the critical one. The problem here is the absence of saddle point solution to expand about. Nevertheless, the dependence of the rate on the gauge coupling is known. It was proved [6] (see also [7]) that for $T > T_c$

$$\Gamma = A\ (\alpha_W T)^4, \tag{5}$$

where A is a numerical constant.

There were carried out the calculations of the rate in simple two dimensional theories (U(1) Higgs model [9] and 0(3) σ-model [10]). Sphaleron decay was tested numerically in U(1) Higgs model in 1+1 dimensions in [11]. In the same theory real time evolution of high temperature configurations was investigated on a computer in [12]; the results completely confirm qualitative as well as quantitative features of the theory of sphaleron transitions.

Now let us turn to the cosmological implications of the high rate. Baryon number non-conserving processes are in thermal equilibrium till sufficiently small temperature T^* determined by the equation

$$\Gamma\ /\ T^{*3} \simeq t_u^{-1} = T^{*2}\ /\ M_{Pl}, \tag{6}$$

where t_u is the age of the universe at the freezing moment. Typically $T^* < 200$ GeV. This implies washing out of preexisting baryon asymmetry (e.g. coming from GUTs) unless special conditions are satisfied [2,13,6,7]. One can find for standard model [13,6]:

$$\Delta = \frac{n_B}{n_\gamma}\Big|_{T=T^*} = \frac{4}{13}\Delta_{B-L} + O(10^{-6})\Delta_{GUT}, \tag{7}$$

where n_B and n_γ are densities of baryons and relic photons, Δ_{GUT} is GUT's BAU, Δ_{B-L} is B-L asymmetry. For GUTs with B-L conservation (like SU(5) and different types of SO(SO)) we expect $\Delta_{B-L} = 0$ so resulting asymmetry is small compared with initial one. Therefore, to save GUT scenario of baryon generation one should create a huge amount of baryons (like the model of Ref. [14]) or to construct theories with strong (B-L) non-conservation [15]. However, it is interesting to ask whether it is possible to produce BAU entirely in the framework of electroweak theory without any exotic interactions. The next section is devoted to this issue [16].

3 Electroweak Production of Baryon Asymmetry

In principle, in the early universe at temperatures of order 100 GeV all necessary conditions [17] for the BAU production are satisfied. First, anomalous fermion number non-conservation is strong enough. Second, there is CP non-conservation in the standard electroweak theory coming from Kobayashi-Maskawa mixing. At last, large deviations from thermal equilibrium during the first order phase transition (PT) with breaking of SU(2)xU(1) group are expected.

Let us compare the states of the universe just before and after the first order PT. At $T > T_c$ gauge symmetry is restored, $\phi = 0$ and gauge fields are nearly massless. This implies the power infrared divergences in the sector of SU(2) static magnetic fields and, presumably, the nontrivial structure of the ground state at distances$\sim (\alpha_W T)^{-1}$ [18,19]. In contrast, at $T < T_c$ vacuum expectation value of the Higgs field is nonzero and gauge fields are massive. Here the ground state consists of small fuctuations of gauge and Higgs fields near the vacuum configurations. Therefore during the PT equilibrium (at $T > T_c$) configuration $|A,\phi|$ will decay, producing, generally speaking, nonzero number of baryons given by anomaly equation (1). By power counting one can get [16] that the local density of baryons produced could be as large as

$$\Delta \sim \alpha_W{}^3 \tag{8}$$

in the region with size $\sim (\alpha_W T)^{-1}$. One expects that different ground state configurations produce different number of baryons and antibaryons. Hence, to find baryon asymmetry we must take into account all admissible configurations. For this aim it is convenient to introduce the effective potential for the density of created baryons

$$B \equiv n_{cs} \equiv \frac{1}{volume}\frac{N_f}{16\pi^2}\int_{t_c}^{\infty} d^4x\ Tr F_{\mu\nu}F^*_{\mu\nu}. \tag{9}$$

It is possible because B depends only on the initial state at the moment t_c. Three possible forms for $V(n_{cs})$ are shown in Fig.1. Unfortunately, a perturbative calculation of V(B) is impossible. We postpone the discussion of Monte-Carlo results [20] till the next section.

Let us discuss cosmological consequences of all three types of the potential [16]. In the first case (Fig.1c) the physical degeneracy of the ground state is absent and universe is CP symmetric before the phase transition. The BAU arising during the phase transition must be proportional to the measure of CP-violation in the anomalous processes with fermion number non-conservation. CP effects reveal themselves only in 14th order on Yukawa coupling constants, the lowest order CP-violation trace on fermionic flavours is of order

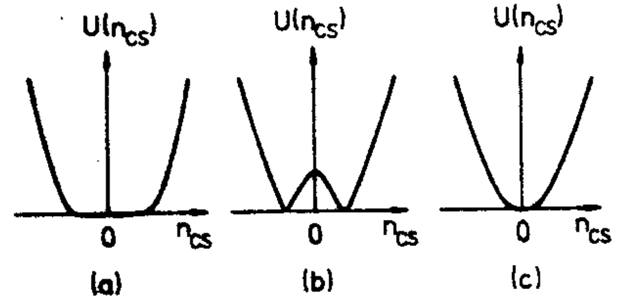

Fig. 1

$$D \ = \ (\frac{g_W^2}{2M_W})^7 \ S_1^2 S_2 S_3 \ sin\delta \ m_t^6 m_b^4 m_c^2 m_s^2 \ \sim \ 10^{-22}. \qquad (10)$$

Here $S_i \ = \ sin\theta_i$, θ_1 is the Cabibbo angle, δ is the CP violating phase. Inspite of the large number of diagrams contributing to B non-conservation (combinatorial factor is of order 10^4) and possible amplification of CP-violation due to temperature effects [16] the number 10^{-22} is too small for the explanation of the observed BAU $\Delta_{obs} \ = \ 10^{-8} \ - \ 10^{-10}$.

Effective potentials of the form shown in Fig.1a,b correspond to the spontaneous CP violation in hot electroweak plasma. The case 1b implies the existence of CP-domains in the early Universe. From the random character of the domains creation we expect that the average Chern-Simons charge $< n_{cs} >$ equal to zero initially. After the electroweak phase transition we shall have baryon asymmetry in the regions of space occupied by domains with $n_{cs} \ > \ 0$ and antibaryon asymmetry in other part of space. For the BAU explanantion we need an efficient mechanism for the growing of the domain size up to the scale of the visible universe. The domain structure of the universe could disappear if there is sufficiently strong CP-violation at high temperatures $T \ \sim \ 10^{15}$ GeV [16]. Here the pure state (in one of the potential V(n_{cs}) minima) might occur during the universe evolution. However, the baryon asymmetry generation entirely in the framework of standard electroweak theory seems to be impossible for Fig.1b too.

Let us turn now to the most interesting case shown in Fig.1a. Here the ground state of gauge theories at high temperatures has an infinite degeneracy with respect to the Chern-Simons number. In strong interacting (for $k \ < \ g^2T$) high temperature nonabelian gauge theory the degeneracy could be a consequence of the Bose-Einstein condensation of quasi-particles which were found in [20]. Let us stress, however, that the physical reason for the degeneracy is not essential from the cosmological point of view.

The key observation is that the universe expansion together with baryon number non-conservation and CP-violation breaks the degeneracy with respect to B. Using the results of [21,22] it may be shown that additional contribution to the effective action for static gauge fields is [16]:

$$\Delta F \ = \ \delta_{ms} \, n_{cs} \ T/M_0. \qquad (11)$$

Here $M_0 \ = \ M_{Pl}/1.66N^{\frac{1}{2}}$, N being the effective number of massless degrees of freedom, δ_{ms} is the microscopic asymmetry in the processes with $\Delta B \ \neq \ 0$, proportional to factor D in

Eq.(10). Note that the sign of δ_{ms} is connected with the sign of δ and therefore with the sign of CP violation in K^0 decays. This contribution bends the plateaux in Fig.1a. Therefore, if one starts from some point with, say. $n_{cs} = 0$ then after sufficient time the system finds itself in the state with maximal possible n_{cs}. This happens if [16]

$$\rho \ = \ 4(4\pi M_0 \alpha_W^2 \delta_{ms}/T_c)^{\frac{1}{2}} \ > \ 1. \qquad (12)$$

Note that if (12) is satisfied then the magnitude of n_{cs} does not depend on the value of CP violation and is determined only by infrared properties of high temperature gauge-Higgs system. The sign of n_{cs} is connected with the sign of CP-violation in K^0 decays. During the first order phase transition the asymmetric gauge-Higgs state decays, producing the baryon asymmetry

$$\Delta \ = \ \frac{n_B}{s} \ = \ \frac{45}{4\pi^2 N} \ \frac{n_{cs}(T_c)}{T_c^3} \ S(M_H) \ = \ \Delta_{max} \ S(M_H), \qquad (13)$$

where s is entropy density, S(M_H) is the macroscopic suppression factor of the BAU. It takes into account the reheating of the universe after the phase transition and dilution of the asymmetry by the (semiequilibrium) electroweak processes with $\Delta B \ \neq \ 0$.

The calculation of the magnitude and sign of δ_{ms} is a very difficult task due to high order of perturbation theory. The rough estimates yield $\delta_{ms} \ \sim \ 10^{-16} - 10^{-22}$ and $\rho \ \sim \ 10 - 10^{-2}$ [16]. If we use for $n_{cs}(t_c)$ the estimate (8) we get

$$\Delta \ \sim \ (10^{-6} - 10^{-11}) \ S(M_H) \qquad (14)$$

which is not very far from reality $\Delta_{obs} \ \simeq \ 10^{-8} - 10^{-10}$. The dependence of the suppression factor S on M_H is presented in Fig.2. If $M_H \ > \ M_{crit} \ \simeq \ 45$ GeV, then the reactions with B non-conservation are in thermal equilibrium after the phase transition. They wash out all the BAU created during the decay of the ground state. For $M_H \ \simeq \ M_{CW}$ (M_{CW} is the Coleman-Weinberg [23] value of the Higgs mass) the electroweak phase transition takes

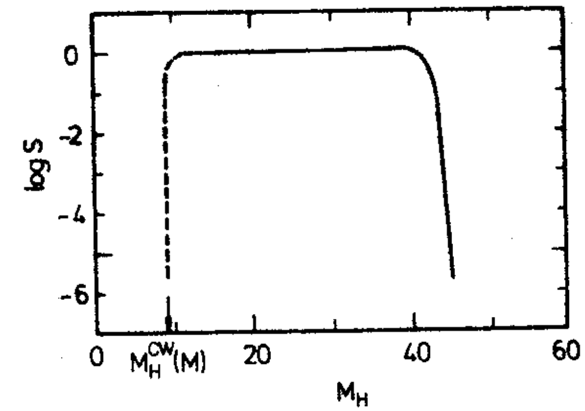

Fig.2 The dependence of BAU suppression factor on M_H. The position of the left fall of the curve coincides with the Coleman-Weinberg value of Higgs boson mass and depends on the t-quark mass.

place with strong supercooling which results in the entropy generation [24,25]. This implies the reduction of the ratio n_B/s. Hence, the production of BAU in the electroweak theory is possible only for [16]

$$M_{CW} < M_H < M_{crit} \simeq 45\ GeV. \qquad (15)$$

In Fig.3 we plot the different bounds on Higgs and top masses [8]. The curve 1 comes form the requirement that one loop effective potential must be bounded from below [26]. Curve 2 corresponds to the Coleman-Weinberg type of the potential. For the points below it the effective potential has additional minimum at $\phi = 0$ and the probability of the phase transition with the breaking SU(2)xU(1) is exponentially small [24]. Curve 3 gives the upper bound on the Higgs mass (15) which appears to be independent on t-quark mass. Let us stress that the bound on M_H also ensures the upper bound on the t-quark mass $M_t < 80$ GeV. Generally, the baryon asymmetry produced by the ground state decay is of order α_W^3 (see Eq.(8)). This number is larger than the observed asymmetry. The sufficient dilution of the BAU takes place very near to the two quoted values of M_H: M_{CW} and $M_{crit} \simeq 45$ GeV. This can be considered as an almost exact prediction of the Higgs boson mass from cosmology (if the ground state is indeed degenerate). In the *exact* Coleman-Weinberg type of theory it is possible to give a more or less unambiguous prediction of the values of the t-quark and Higgs boson simultaneously. The reason is that the only way to decrease the BAU is through entropy production during electroweak phase transition. In addition, the magnitude of entropy production is an unambiguous function of the Higgs boson mass. We find in this way [16]

$$M_H = \frac{\pi T_{chiral}^2}{\sigma}\left(\frac{8N}{15}\right)^{1/2}\left(\frac{\Delta_{max}}{\Delta_{obs}}\right)^{2/3}, \ \sigma = 250\ GeV. \qquad (16)$$

Here T_{chiral} is the temperature of the chiral phase transition in a world with 6 massless quarks coinciding in this case with T_c [25]. If we take for an estimate $\Delta_{obs} = 10^{-9}$, $\Delta_{max} = 10^{-6}$ (see (8)), we get $M_t \simeq 80 GeV$ and $M_H \simeq$ 0.8-1.5 GeV for $T_{chiral} \simeq$ 300-400 MeV.

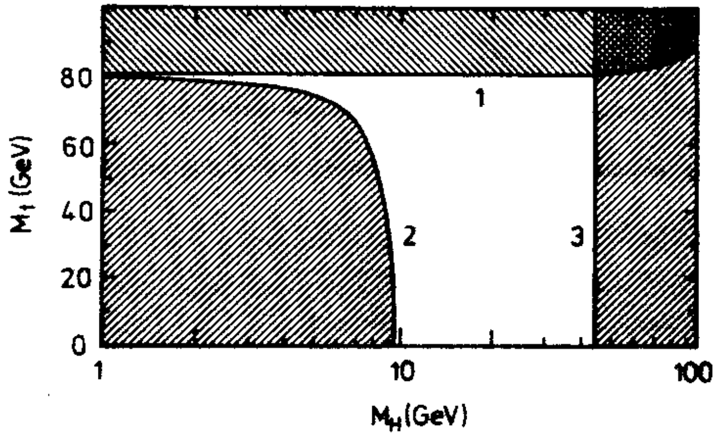

Fig.3 Survey of different bounds on the Higgs and top masses in standard electroweak theory. See the discussion of the curves 1 and 2 in [24].

4 Monte-Carlo Simulations of Baryon Asymmetry

It is possible to reconstruct on the lattice the sequence of events happened in universe during the first order electroweak PT [20]. Omitting all the details of numerical calculations (see [20]) the procedure is as follows. (i) Prepare hot equilibrium configuration A,ϕ of gauge and Higgs field in the unbroken phase with scalar potential $m^2\phi^2$. The set of these configurations corresponds to a moment just before 1st order phase transition. (ii) Use this set of configurations as initial conditions for evolution of the system in the broken phase with scalar potential $\lambda(\phi^2 - v^2)^2$. The change of the scalar potential immitates the physics of 1st order PT. (iii) Follow evolution of the system and calculate $Q = 1/16\pi^2 \int d^4x TrFF^*$ for every initial configuration. (iv) Construct effective potential V(Q) using the probability distribution

$$P(Q) = exp(-V(Q)/T). \qquad (17)$$

Here P(Q) is the probability to have Q in the interval Q, Q+ dQ.

Typical picture for P(Q) is shown in Fig.4. The peculiar feature of the distribution is the existence of additional peeks centered near integer Q $\neq$ 0. Different checks (including variation of the volume of the lattice and change of coupling constants) confirm the suggestion [20] that high temperature plasma is populated by gauge-Higgs fluctuations - quasi-particles, which decay during the electroweak phase transition, producing a topological change equal to one, thereby creating 12 fermions due to electroweak anomaly. The rough estimate of the concentration of quasiparticles is $n_{qp} \simeq 0.1(\pi\alpha_W T)^3$. However, the question on the form of V(Q) has not been answered, and any of the cases in Fig.1 seems to be admitted. Clarifying of this point desires the study of the collective properties of quasiparticles and, therefore, the consideration of big lattices [20]. Note, that the existence of quasiparticles can provide the mechanism for the potential degeneracy. In particular, the formation of Bose-Einstein condensate ensures the nontrivial potential like Fig.1a,b.

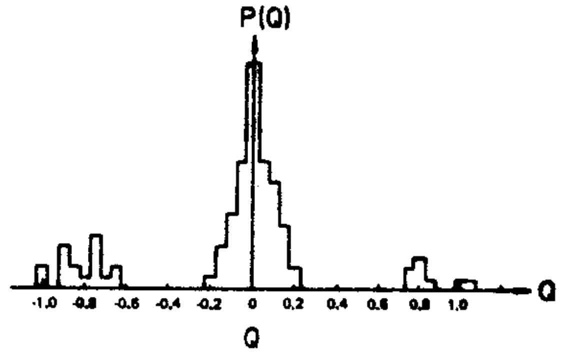

Fig.4

5 Conclusion

A lot of work remains to be done in order to clarify whether the scenario of BAU production is indeed realized in nature. First, complete lattice investigation of the ground state of gauge theories at high temperatures is necessary. Secondly, more accurate estimates of the effects of CP-violation (including the calculation of sign of δ_{m_s}) are highly desirable. At last, LEP e^+e^- mashine has to reject or to confirm in near future the BAU insisted cosmological predictions of the Higgs boson mass.

I am gratefull to DESY , where this paper was written, for kind hospitality.

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