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KEK Preprint 97-238
December 1997
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NAME	I.D. No.	M.S.

Talk given at the Pacific Particle Physics Phenomenology Workshop, November 1997, Seoul, Korea.

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Electroweak phase transitions

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Abstract

There are clear evidences that the world is made of exclusively matter, at least on the $10^{13} M_{\odot}$ scale. The observed baryon asymmetry of the universe has finally been determined at the finite temperature electroweak phase transition. Some features of this phase transition are summarized. Particular interest is paid to the analytical and lattice estimates on the sphaleron transition and to the nature of the electroweak phase transition in the standard model and in the minimal supersymmetric standard model. In the standard model the electroweak baryogenesis scenario can be excluded; hoverer, there is a small region in the parameter space of the minimal supersymmetric standard model, which might explain the observed baryon asymmetry.

1 Introduction

At high temperatures (e.g. in the early universe) the electroweak gauge symmetry is restored. As the universe expands and supercools there is a phase transition between the high temperature "symmetric" and low temperature "broken" phases. The characteristics of this phase transition (critical temperature: T_c, surface tension: σ, etc.) are clearly of interest. An attractive proposal is to understand the observed baryon asymmetry as produced at the finite temperature electroweak phase transition [1]. In order to provide the observed baryon asymmetry three conditions must be satisfied.

a. existence of baryon number violating processes (in the standard model

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this can be ensured by sphaleron transitions)

b. C and CP violation

c. departude from the thermal equilibrium (the basic question is the strength of the phase transition).

Section 2 will discuss the first (a) Section 3 the last (c) condition. Section 4 contains the conclusion.

2 Sphaleron rate at finite temperature

The basic source of the baryon number violating processes in the standard model is the electroweak anomaly for baryon number, which demands that

$$\Delta B \sim g^2 \int dt d^3x \mathrm{tr} F \tilde{F}, \tag{1}$$

where g is the weak coupling and F is the field strength of the weak gauge field. This anomaly equation relates the produced baryon number to topological transitions of the weak gauge fields. The vacua with different topological numbers (N_{CS}) are separated by a potential barrier. Note, that the anomaly equation holds not only for baryons but for leptons, too. Thus, baryon and lepton numbers are violated simultaneously ($B+L$ violation).

At zero temperature the transition between the vacua is a tunneling event with an unobservably small probability: $\approx 10^{-170}$. The transition at high temperatures, but below T_c is a thermal jump. The system jumps up to the top of the barrier (a saddle point: sphaleron) and rolls down to the neighbouring vacuum. In the meantime baryon and lepton numbers are violated. The jump to the barrier, therefore the transition rate is suppressed by the Boltzmann factor

$$\Gamma \propto \exp\left[-E_{sph}/T\right], \tag{2}$$

where the sphaleron energy is proportional [2] to the mass of the W-boson $E_{sph} \propto m_W/\alpha_W$. Rapid baryon violation processes in the broken phase can wash out the asymmetry generated before. Therefore a "minimal" condition for a successful baryogenesis is that these processes should be slower than the expansion rate of the universe. Comparing 2 with the Hubble constant the minimal condition can be written as $\varphi_b/T_b > 1$, where φ_b is the value of the Higgs field at the transition temperature T_b.

Above T_c the exponential suppression of the transition rate is absent. Naive power counting suggest

$$\Gamma = \kappa \cdot (\alpha_w T)^4, \tag{3}$$

where the constant κ is of order 1. Recently it has been argued [3] that the assumptions used to derive 3 are not valid. The real dependence on

α_w is a different one

$$\Gamma = \kappa' \cdot \alpha_w^5 T^4. \tag{4}$$

The reason is a damping effect for the gauge field. The origin of this damping is the fact that nearly static magnetic fields can be absorbed by the system, which results in a loss of energy for the magnetic fields of interest.

In recent years there has been considerable activity in order to determine the sphaleron transition rate at both sides of the phase transition. No successful numerical method is known for a full Minkowskian theory; however, important results have been obtained by real time simulations in the classical approximation for the finite temperature theory. The used procedure contains several steps. The classical theory is formulated in terms of fields and their conjugate momenta on a spatial lattice. The phase-space of the system is then sampled with the statistical weight $\exp(-H/T)$. Starting with some initial configuration from the thermal sample the classical canonical equations give the real-time evolution of the fields. As a function of time one can determine different observables and their averages (such as changes of the topological charge). There are fewer physical degrees of freedom in the theory than the number of the phase space variables used to formulate it. It is a highly non-trivial task to find effective thermalization algorithms for constrained systems. At present there are two good solutions to this problem [4].

In the broken phase last year numerical simulations [5] indicated an extreme difference between the lattice results and 2. The observed sphaleron transition rate was a bit smaller than in the symmetric phase; however, no Boltzmann suppression has been seen. Going down into the broken phase the difference between the analytical and lattice results is several orders of magnitude. It is argued [3] that the reason is the problematic definition of the topological charge on a lattice, which give a systematic error in the rate.

A large scale numerical study for the sphaleron rate in the symmetric phase [6] favoured the naive $\Gamma = \kappa(\alpha_w T)^4$ law. The classical motion of the Chern-Simons number consists of two pieces. The thermal fluctuation, which linearly diverges with the lattice cutoff, and a random walk between different vacua. A detailed finite size and finite scaling analysis suggested that the above naive formula is correct with a coefficient of $\kappa = 1.09 \pm 0.05$. According to [3] the observed rate might be only a lattice artifact. The authors reanalysed their data with an improved technique (cooling of lattice field configurations to determine the time evolution of the topological charge) [7]. The new results has shown some deviation from the older one; however, the $\Gamma = \kappa' \alpha_w^5 T^4$ law of the symmetric phase can not be confirmed. A definitely positive outcome of this cooling technique is the new simulation in the broken phase. With the cooling

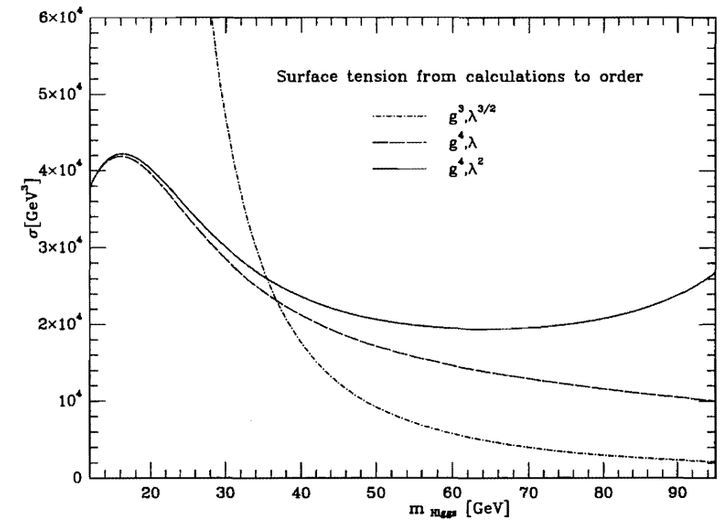

Figure 1: Surface tension from the different potentials as a function of m_H.

technique no transition between the different vacua has been observed. This result resolves the discrepancy between [5] and eq. (2).

3 The nature of the phase transition

Perturbative studies show that in the realistic Higgs mass range ($m_H > 77\ GeV$) the perturbative approach breaks down [9], it predicts $\mathcal{O}(100\%)$ corrections [8] for the relevant quantities (e.g. interface tension, latent heat or correction to the course of the phase transition). A nice illustration (c.f. Figure 1) for that is the interface tension as a function of the Higgs-boson mass in different orders of the perturbation theory.

A popular way to study the problem is to perform a dimensional reduction in perturbation theory. One starts with the original theory (e.g. Standard Model) and integrates out the heavy degrees of freedom perturbatively. The obtained theory is a three-dimensional bosonic one. The temperature dependent parameters of this theory are determined by the matching conditions between the full theory and the reduced one. Static thermodynamical properties, mass spectrum and other related features have been studied both analytically and numerically for these three-dimensional models (a recent summary is [10] and see references therein). According to these results the electroweak phase transition is

of first order for small Higgs-boson masses; however, it turns out to be an analytic cross-over above $m_H \approx 67$ GeV (critical Higgs-boson mass value for the SU(2)-Higgs model) [11]. Due to the large mass of the top-quark the phase transition can not fulfil the φ_b/T_b condition for any choice of the Higgs-boson mass.

Another possibility is to study the full four-dimensional theory by lattice simulations. Since fermions always have nonzero Matsubara frequencies, the perturbative treatment of these, at high temperatures very massive, modes could be satisfactory. Thus, the starting point of the lattice analyses is the $SU(2)$-Higgs model, which contains the essential features of the standard model of electroweak interactions. In the last three years our group (DESY-Electroweak collaboration) presented a series of papers (see e.g. [12]) in order to clarify the details of the phase transition on four-dimensional lattices. Our work has been done on computers at HLRZ Jülich (CRAY-T90) and DESY-Ifh, Zeuthen (APE-Quadrics). The simulations have been performed for four set of parameters ($m_W = 80$ GeV): $m_H \approx 18\ GeV$, $35\ GeV$, $49\ GeV$, $80\ GeV$. For the first three cases the usual lattice formulation can be applied, thus identical lattice spacings in the spacial and temporal directions. In these cases a fairly good agreement is found between the lattice results and perturbation theory [14]. The $m_H \approx 80\ GeV$ case is much more difficult. The phase transition gets weaker, the lowest excitations have masses small compared to the temperature, T. From this feature one expects that a finite temperature simulation on isotropic lattice would need several hundred lattice points in the spatial directions even for $L_t = 2$ temporal extension. In order to solve this problem we have used the simple idea that finite temperature field theory can be conveniently studied on asymmetric lattices, i.e. lattices with different spacings in temporal and spacial directions [13]. The resulting action contains anisotropies in the couplings. This action has been studied in perturbation theory and on the lattice. The values of the thermodynamical quantities (σ/T_c^3 and $\Delta\epsilon/T_c^4$) for $m_H \approx 80$ GeV are substantially smaller than their perturbative values. They are even consistent with a no first order phase transition scenario on the approximately 1-σ level. These results can be interpreted as a sign for the endpoint for the finite temperature electroweak phase transition.

Similarly to the standard model case we have now perturbative two-loop results for the minimal supersymmetric standard model phase transition [15]. An interesting feature of the result that it opens the baryogenesis window for light stop. Setting sun QCD diagrams (stop-gluon) can give large logarithmic contributions which increase the strength of the phase transition. Nevertheless the allowed parameter space is very constrained. In particular $m_H < 85$ GeV will be soon tested at LEP. Since the setting-sun diagrams have bad infrared behaviour a lattice Monte-Carlo approach is probably needed in order to answer the question in

this case, too.

4 Conclusions

Analytical and real time numerical result for sphaleron processes are still not in complete agreement. Above T_c new analytical estimates suggest a $\Gamma \propto \alpha_w^5 T^4$ behaviour for the transition rate, which is not seen in numerical studies. The present numerical techniques are not sensitive enough to determine the sphaleron transition rate below T_c. Perturbative studies show, that the electroweak phase transition can not be described above $m_H = 70$ GeV by perturbative methods. Lattice results exclude successful baryogenesis in the minimal standard model. The present bounds on the Higgs-boson mass most probably results in a cross-over (no phase transition scenario). The minimal supersymmetric standard model still has some constrained parameter region, which perturbatively predicts a phase transition, strong enough for baryogenesis.

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