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Can the Observed Baryon Asymmetry be Produced at the Electroweak Phase Transition?

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Abstract

I investigate the possibility that the observed baryon number of the universe might have been generated at the electroweak phase transition. To get such baryon number generation, I assume that the Higgs structure of the electroweak theory may be more complicated than in the standard model, resulting in a heavy Higgs without a vacuum expectation value, and that there is a first order electroweak phase transition which allows for supercooling to temperatures $T_{SC} \geq 1\ Gev$, and for which the reheat temperature is less than the temperature for which baryon number changing processes shut off in electroweak theory $T_{\Delta B} \leq T_{EW}$, where T_{EW} is the electroweak transition temperature. I also assume there is strong CP violation at the electroweak temperature, most possibly induced by an inflationary cosmology, and radiated away at $T \sim 1\ Gev$ by an invisible axion. I use the fact that sphaleron processes generate baryon number change and strong CP violation. With a plausible assumption about Higgs couplings, I make a speculative estimate of the baryon asymmetry to be $\mu/T \sim 10^{-8} - 10^{-14}$.

1 Introduction

It has been suggested recently that the baryon number of the universe might be generated at the electroweak phase transition,[1], by dynamics accessible at a Tev scale rather than at a GUT scale.[2] This scenario has as one of its attractive consequences, in parallel with the scenario of Dimopoulos and coworkers[3] that the physics underlying the dynamical models may be tested experimentally in the not too distant future.

The scenario suggested by Shaposhnikov makes use of the recent observation that baryon number is violated at a substantial rate down to temperatures of the order of 100 Gev in the electroweak theory.[4]–[8] This baryon number violation takes place through field configurations called sphalerons.

In this paper, I shall use a physical picture of the sphaleron as collection of resonances which decay into of order $1/\alpha_W$ number of particles. I shall further assume that this baryon number violation takes place at temperatures large compared to that where one can reliably do weak coupling computations, and that the decays take place through sphalerons which are not solutions of the classical equations of motion. This assumption is no doubt controversial, but can be argued by scaling arguments in electroweak theory[8], and can be more convincingly argued to be true in model field theories such as the O(3) sigma model in 1+1 dimensions.[9]. There is now convincing Monte-Carlo simulations of 1+1 dimensional models which support this picture.[10]

The picture of the sphaleron as a collection of a set of resonances is consistent with what is known of the sphaleron when it may be treated as a solution of the classical equations of motion. In this circumstance, the width of the sphaleron, M_w, is much less than the typical sphaleron mass M_w/α_w. This collection of resonances has a typical spacing of less than or of order M_w, which is comparable to the width. This collection of resonances is therefore analogous to doorway states in nuclei.

It should also be carefully noted that in the symmetric phase of a gauge theory, these resonances are densely packed and strongly interacting. The dilute gas approximation is certainly not a valid approximation. The sphalerons have a size and lifetime of order

$$R \sim (g_W^2 T)^{-1} \sim (4\pi\alpha_W T)^{-1} \sim (\frac{1}{3}T)^{-1} \tag{1}$$

and estimates of the density of sphalerons give[8],[11]

$$\rho_{Sp} \sim (g_W^2 T)^3 \sim \frac{1}{30}T^3 \tag{2}$$

Oftentimes in this paper I will draw perturbative diagrams to infer orders of magnitudes of various processes, but the reader should be warned that such diagrams cannot be taken seriously for precise quantitative estimates.

A corollary of these assumptions is that in strongly interacting SU(3) Yang-Mills theories, there should be strongly interacting axial vector nonconserving sphalerons. This follows since the sphaleron of the electroweak theory at high temperature is essentially the sphaleron of a strongly interacting SU(2) Yang-Mills theory. The Higgs decouples at high temperature. Therefore we expect that there should also be sphalerons of SU(3) Yang-Mills theory, or QCD. Such sphalerons have been found in various attempts to construct low energy Lagrangians for confining theories.[12]–[13]. We should also note that with respect to violation of symmetries and emission of zero modes of fermions, these sphalerons are in all respects similar to instantons, except that the sphaleron is a real time excitation.

In any model of baryogenesis in cosmology, the Sakharov conditions require both that the system be out of equilibrium and that CP be violated.[14] The first condition is easily achieved by having a first order electroweak phase transition, a feature which under some conditions may exit in the standard model, and is a feature of many generalizations of the standard model. The second condition is more difficult to achieve. In the KM model of CP violation, the magnitude of CP violation is orders of magnitude too small, $\delta \sim 10^{-21}$.[1]

In Shaposhnikov's scenario, the CP violation is generated by dynamical symmetry breaking. It is assumed that at high temperatures there is a condensation of Chern-Symons density, which at the electroweak phase transition is converted into baryon number through the weak anomaly. The density of baryon number which results is

$$\rho_B \sim (g_W^2 T)^3 (T_{SC}/T_{RH})^3 \tag{3}$$

where T_{RH} is the reheating temperature in the electroweak theory, and T_{SC} is the supercooling temperature at which the phase transition is initiated. In Coleman-Weinberg models,[15]-[16] the entropy generation from reheating is of order $10^{-4}-10^{-6}$. The matter density is of order $\rho_{mat} \sim 10\ T^3$ at the electroweak scale so that we find naturally the baryon to photon ratio is of order

$$\rho_B/\rho \sim 10^{-6} - 10^{-10} \tag{4}$$

which is in the range of allowed values.

Although the Shaposhnikov scenario naturally gives a baryon asymmetry in the allowed range it suffers from some theoretical difficulties. It is difficult although possible to make sense of the gauge dependent Chern-Symons density. This involves introducing an order parameter which is non-local in time and is the difference of Chern-Symons charge at some arbitrary time and the time of interest. The spontaneous breakdown of CP in the high temperature phase is also a bit unnatural. Recall that the high temperature phase of electroweak theory is 3 dimensional SU(2) pure Yang-Mills theory at zero temperature. This is true because at high temperatures in electroweak theory both the scalar degrees of freedom and the longitudinal vector bosons acquire a mass of order gT and decouple (Fermions decouple because their Matsubara frequency begins at $q^o = 2\pi T/2$) There is no compelling theoretical evidence that this confining strong coupling theory should break CP, and strong coupling arguments would favor the symmetric phase.

2 A New Way to Generate the Baryon Asymmetry

In this paper, I present an alternative mechanism for generating a baryon asymmetry from the physics present at the Tev scale. In this model I assume there is a large strong CP violation at the Tev scale. The simplest way this can occur and not destroy conventional particle physics phenomenology is by the existence of a generic invisible axion. [17]-[21] By generic I shall mean that we shall only use its existence together with what is conventionally postulated about strong interactions to derive our results. This hypothesis is experimentally testable if the axion is detected and studied.

In the standard invisible axion cosmology, at temperatures larger than a Gev, the axion potential is taken to be flat, and the axion field may have an expectation value which is uniform $\Theta \sim 1$ throughout the universe. At a temperature of order a Gev, the axion field begins to oscillate around zero, because at this scale instanton effects generate a non-flat axion potential.[22] We have therefore a natural mechanism for disposable CP violation at temperatures above a Gev. This mechanism for generating disposable CP violation has been explored by Yoshimura.[23]

In order to make use of the above strong CP violation, I must assume that the relevant physics takes place before on the average the axion field has zero expectation value. In order to get out of equilibrium, there must be a first order phase transition, which clearly must be assumed to supercool to a temperature

$$T_{SC} \geq 1 \ Gev \tag{5}$$

In order to generate a baryon asymmetry, I assume that in the false high temperature phase baryon number violation is turned on, and in the low temperature phase it is shut off. It must therefore be

$$T_{RH} \leq T_{\Delta B} \tag{6}$$

In direct computations, $T_{\Delta B} \sim T_{EW}$,[24], that is the temperature at which baryon asymmetry generating processes shut off is of the order of the temperature when the false phase is first unstable with respect to decay into the true phase. In many circumstances, these temperatures are only a few percent different, and not a large range in temperature must be jumped over in the process of the transition. Whether or not such limitations are possible and natural depend on details of the Higgs potential, and in some cases on the strong interaction dynamics in the symmetric phase at a temperature near a Gev.

In fact, what I am really assuming here is that during the conversion of one phase into another, the system is strongly out of equilibrium. The first temperature at which equilibrium is restored is taken to be the reheat temperature.

I can now estimate the baryon number produced in such a phase transition. The density of sphalerons is taken to be $\rho \sim (g_W^2 T)^3$ which is consistent with detailed estimates. The entropy density of matter at the electroweak scale should be of order $\rho_{mat} \sim (4\pi^2/90) N_{dof} T^3 \sim 40 \ T^3$. Let the asymmetry in the decay of sphalerons into baryons and into anti-baryons at the transition temperature be defined to be ϵ We shall later estimate this parameter. Finally, the entropy generation at the transition is T_{SC}^3/T_{RH}^3 which must be in the range $1 - 10^{-6}$ by our dynamical assumptions.

In fact, we expect that the reheat and supercooling temperatures should be close together and of order of the electroweak scale. At the confinement scale, instantons have turned on and the axion field is oscillating. It is hard to imagine the supercooling temperature being naturally above but close to the confinement scale.

Putting together the factors for the rate of baryon number violation and the factors for entropy generation,

$$\rho_B/\rho_{mat} \sim \epsilon \left(10^{-3} - 10^{-9}\right) \tag{7}$$

What is the magnitude of ϵ? It must come from the interference of a sphaleron induced baryon number changing process and a strong CP violating process. At high temperatures in the strong interactions, instanton induced rates are very small. We however expect strong CP violation due to strong sphaleron transitions. Recall that if there are sphaleron transitions in the electroweak theory in the high temperature phase then there surely should be such transitions in QCD. In QCD the sphaleron transitions violate parity and CP for non-zero theta angle. Notice that the size of the QCD sphaleron is $R \sim 1/g_s^2 T \sim 1/T$ which is about three times smaller than the electroweak sphaleron. The sizes and lifetimes are therefore comparable.

I can generate and interference by the type of diagrams shown in Fig. 1a-c. These diagrams are entirely analogous to instanton diagrams. The difference in interpretation is that the sphaleron exists in real time. In Fig. 1a the sphaleron decays into $3N_f$ quarks and N_f leptons where N_f is the number of fermion generations. In the decay on the average $1/\alpha_W$ Higgs particles, W's and Z's are produced. In combination with the quarks, I also expect a fair amount of induced soft gluon radiation.

In Fig. 1b is the interfering diagram where both an electroweak and a strong sphaleron decay. Here the strong CP violating sphaleron absorbs one quark of each flavor and flips its helicity. To undo the helicity flip and put the quarks in a state where interference is possible, I assume that a Higgs is emitted from each flavor of quarks. This is shown in Fig. 1c.

Technically, in order to get a baryon excess from such a process, the strong sphaleron must interact with a baryon number non-conserving sphaleron during the helicity flip, and this process is not shown in the diagram.[2] This is easy to accomplish due to the strongly interacting nature of the dense sphaleron soup.

I naively expect the rate for the diagram of Fig. 1b to be of the order of the rate for making an electroweak sphaleron. The strong sphaleron is made quite often and there should be enough present to tie the quark lines onto to make a connected diagram shown in Fig 1b. This expectation is of course speculative, and I know of no existing theoretical framework in which to compute the interference.

Of course to get the interference, the quark lines must have the same quantum numbers in the final state, and this is accomplished by scalar particle emission. Unfortunately, the quarks connected to the strong sphaleron in Fig 1b have the opposite helicity to those in Fig. 1a. The helicity must be flipped. This is done by inserting helicity flip interactions with scalars as shown in Fig. 1c. There must clearly be one Yukawa coupling angle for each species of quark (in the limit where weak mixing angles are zero). We therefore estimate ϵ to be

$$\epsilon = (4\pi)^{-3}\, \Pi_i(K_i)\, (10^{-3} - 10^{-9}) \tag{8}$$

where K_i is the Yukawa coupling to the quark flavor i. We have included a factor of 4π which results from the phase space integral over final states. We have ignored any possible enhancements of the emission rate arising from the coherent field of the sphaleron. Recall that the sphaleron itself has a coherent field associated with the Higgs field, and might also contain a component associated with an extra doublet.

In the standard model, of course, the product over Yukawa couplings is orders of magnitude too small, $\epsilon \sim 10^{-20}$. However there are generalizations of the standard model involving heavy scalars with masses of order $M_S \sim M_Z$. If in such a model, the scalars couple primarily to quarks, then the limits on the Yukawa couplings are very weak. In some models, the flavor changing neutral currents may be eliminated at tree level. The only real constraint in these models comes from the one loop strangeness changing neutral currents, requires only that the light fermions Yukawa coupling be of order $K_{light} \sim .3g_w$.[25] In such models it is easy to imagine

$$\epsilon \sim \alpha_w^3 \sim 10^{-5} \tag{9}$$

A weak part of this argument is that in order to get an interference, there must also be an equal number of gluons in the final state of both the diagram with and without the sphaleron. Since there are at least 9 quarks emitted from the electroweak sphaleron, and since $\alpha_s \sim .2$, we expect a multiplicity of several gluons in the final state of the process represented by the first diagram. Also, the multiplicity of the strong sphaleron is expected to be on the order of $1/\alpha_s$, so that its multiplicity is of the order of several. The overlap might be substantial in this circumstance. I cannot rule out however that this overlap might be tiny because of near orthogonality of the gluons radiated from the quarks and those radiated from the strong sphaleron, or that there may be a significant missmatch in multiplicity. Also, the picture of perturbative gluons propagating as quasi-free excitations at the wavelengths appropriate for sphaleron processes may be misleading, and the strong coherent nature of interactions may be important. In any case, this missmatch may be expected to reduce the rate somewhat.

In fact, an order of magnitude estimate of the amplitude for strong instanton processes suggests that the rate for processes with even zero gluon prongs might not be so small. I estimate that the probability of an instanton event within the space-time volume of a sphaleron is of the order of $10^{-1} - 10^{-2}$. If this is interpreted as the order of magnitude probability for zero prong strong sphaleron events, these processes alone make a significant contribution to the rate. Since the effect we seek comes from an interference and involves amplitudes, not squares of amplitudes, the rate arising from this process may be even larger.

To summarize, the diagram estimates are heuristic and at best semi-quantitative. They automatically build in the factors of Yukawa couplings expected for strong CP violation. They are not capable of resolving dynamical factors, such as an unknown function of α_s which may arise from a missmatch of the number of gluons in the final states of the interfering diagrams.

Finally, when we make these naive estimates, we are assuming there is no cancellation from summing over the various contributions to the CP violating process.

3 Conclusions

To conclude, I have argued the baryon asymmetry is of order

$$\rho_B/\rho \sim \epsilon\,(10^{-3} - 10^{-9}) \tag{10}$$

and in some generalizations of the standard model, this may be naturally in the range of

$$\rho_B/\rho \sim 10^{-8} - 10^{-14} \tag{11}$$

In the above computation, the a large uncertainty arises from the degree of supercooling. To get an acceptable ratio, $\sim 10^{-9} - 10^{-10}$, the supercooling cannot be too extreme. This can be the case if the supercooling temperature is of the order of the electroweak phase transition scale, as is natural to expect.

Also, a large amount of uncertainty must be ascribed to the computation of ϵ. I have estimated the powers of coupling involved, but my estimate of this complicated interference diagram involving classical excitations could be wrong in principle. My estimate of ϵ is certainly heuristic and hand waving, and computational method should be developed to test its truth.

Finally, assuming that the above result is true, it remains to present a class of models with the required degree of entropy generation and the correct magnitude of scalar couplings. It seems plausible that there should exist such models with a natural first order phase transition and a minimal amount of entropy generation, but a concrete model is lacking.

The number of assumptions which go into this computation are large, but perhaps not larger than those of GUT models. Unlike the case for GUT models, all of these assumptions can be either experimentally tested or checked by better theoretical computations. The estimate of the rate can in principle be computed with precision . The invisible axion is a low mass particle which may in principle be detected. The structure of the Higgs potential can be probed in experiments at the Tev scale.

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References

[1] M. E. Shaposhnikov, Nuc. Phys. B287, 757 (1987); Nuc. Phys. B299, 797 (1988)

[2] E. W. Kolb and M. S. Turner, Ann. Rev. of Nuc. and Particle Science, 33, 645 (1983)

[3] S. Dimopoulos and L. Hall, Phys. Lett. 196B, 135 (1987).

[4] N. Manton, Phys. Rev. D28, 2019 (1983).

[5] F. Klinkhamer and N. Manton, Phys. Rev. D30, 2212 (1984)

[6] V. Kuzmin, V. Rubakov and M. Shaposhnikov, Phys. Lett. 155B, 36 (1985)

[7] P. Arnold and L. McLerran, Phys. Rev. D36, 581 (1987).

[8] P. Arnold and L. McLerran, Phys. Rev. D37, 1020 (1985)

[9] E. Mottola and A. Wipf, Los Alamos Preprint (1988)

[10] V. Rubakov, private communication

[11] J. Ambjorn, M. L. Laursen and M. E. Shaposhnikov, Niels Bohr Institute Preprint, NBI-HE-88-38 (1988)

[12] J. M. Cornwall and G. Tiktouplos, Phys. Lett. 181B, 353 (1986)

[13] M. Baker, J. Ball, and F. Zachariasen, private communication.

[14] A. D. Sakharov, Pisma ZhETF, 5, 32 (1967)

[15] S. Coleman and E. Weinberg, Phys. Rev. D7, 1888 (1973)

[16] E. Witten, Nucl. Phys. B177, 477 (1988)

[17] R. D. Peccei and H. Quinn, Phys. Rev. Lett. 38, 1440 (1977).

[18] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).

[19] F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

[20] J. E. Kim, Phys. Rev. Lett. 43, 103 (1979)

[21] M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. 104B, 199 (1981)

[22] J. Preskill, M. B. Wise, and F. Wilczek, Phys. Lett. 120B. 127 (1983).

[23] M. Yoshimura, Phys. Rev. Lett. 51, 439 (1983)

[24] H. Aoyama, H. Goldberg and Z. Ryzak, Phys. Rev. Lett. 60, 1902 (1988)

[25] H. Haber and G. L. Kane, Nuc. Phys. B161, 493 (1979)

Figure Captions:

1. Fig. 1a: An electroweak sphaleron decaying into three quarks of one generation and a lepton. (In a theory with more than one generation, all generations of quarks and leptons are emitted.) The emission of Higgs, Zs, Ws and gluons is not indicated on this or the following diagrams.
2. Fig. 1b: An electroweak sphaleron as above interacting via quark exchange with a strong sphaleron.
3. Fig. 1c: The quarks in the final state of Fig. 1b having their helicity flipped by scalar emission.

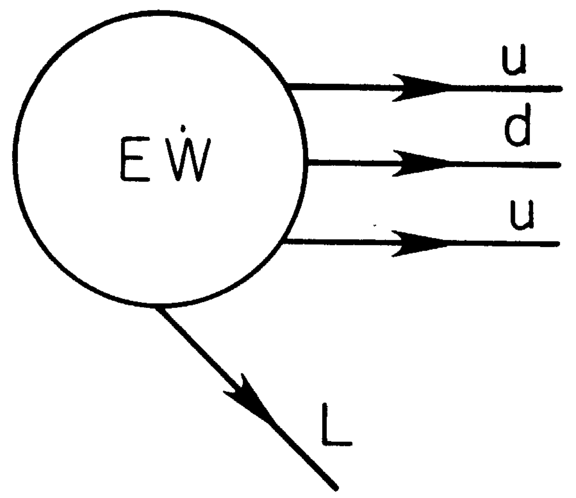

FIGURE 1

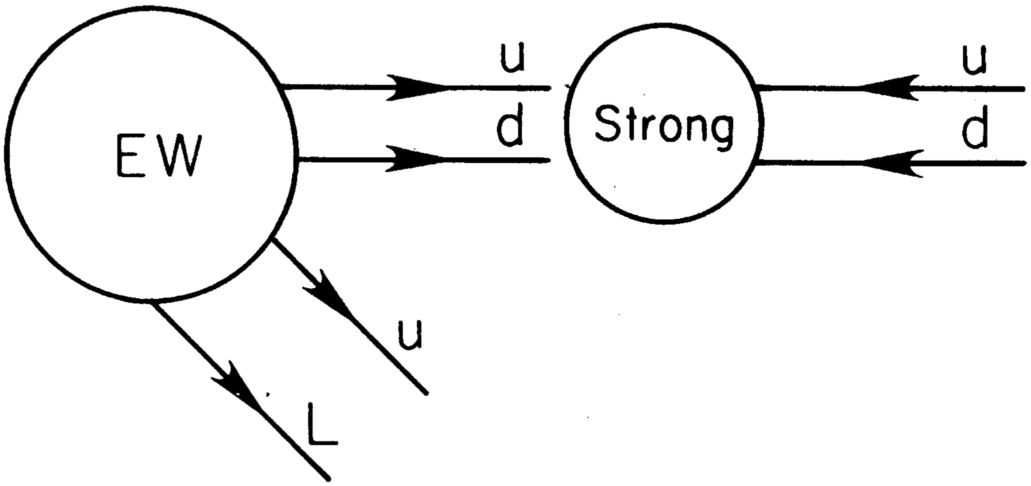

FIGURE 2

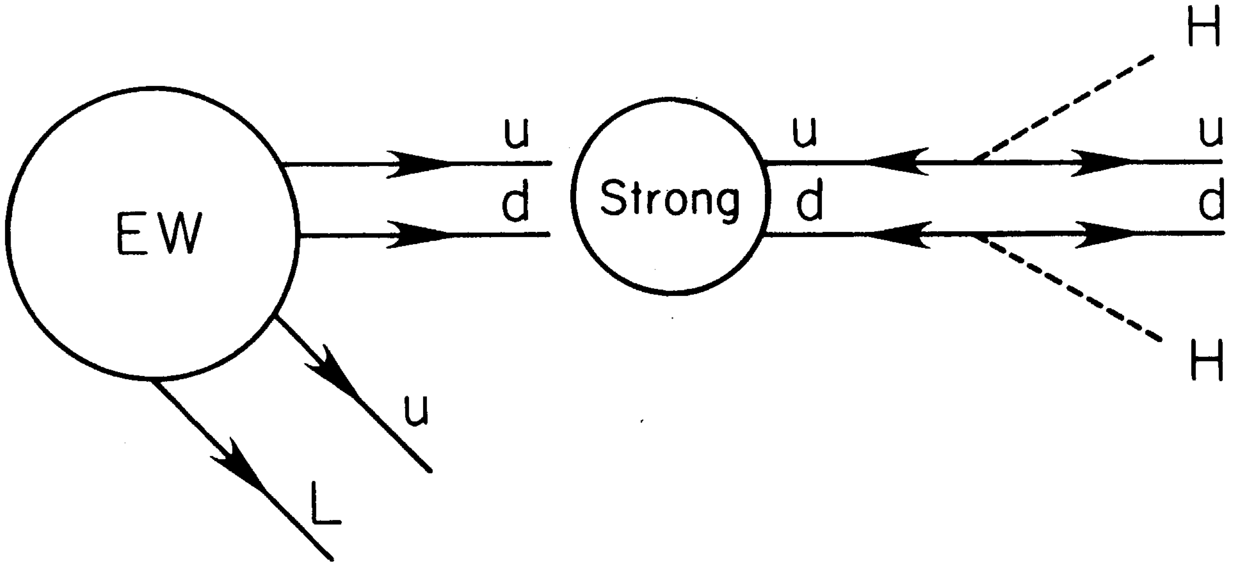

FIGURE 3