Baryogenesis at the Electroweak Scale†

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ABSTRACT

The realisation that the electroweak anomaly can induce significant baryon number violation at high temperature and that the standard models of particle physics and cosmology contain all the ingredients needed for baryogenesis has led to vigourous search for viable models. The conclusions so far are that the Standard Model of particle physics cannot produce baryon asymmetry of required magnitude. It has too little CP violation and sphaleronic transitions wipe out any asymmetry produced if the Higgs is heavier than about 50 GeV, a range already excluded by accelerator experiments. We review the sphaleron solution, its connection to the high temperature anomalous rate and then summarise possibilities where phenomenologically testable extensions of the Standard Model may yet explain the baryon asymmetry of the Universe.

1 Introduction

An observed fact of nature is the asymmetry between the occurrence of matter and antimatter. This asymmetry is not of a local nature as evidenced by an almost continuous distribution of luminous bodies or hydrogen clouds in the Galaxy as also on the extragalactic scales. Violent annihilation processes that may be expected at the boundary of regions containing matter and antimatter are also not to be

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seen.[1] Since baryon number is a good symmetry of all observed processes, one has to assume the asymmetry to be of primordial nature and thus the problem passes into the domain of the early Universe.

The net baryon number is not an important conserved number from the point of view of elementary particle physics. It is not known to couple to any gauge bosons, which would have justified its conservation. Thus we may safely assume that some high energy processes yet undiscovered in fact violate baryon number[2]. Then in the fleeting moments of the early Universe, at ultra high temperatures, the number was not conserved and what we see is the residue left over after the annihilation of baryons and antibaryons. The above line of thinking suffers from a further, deeper problem when we compare the density of the net baryon number n_B with the entropy density n_γ of photons. Standard Big Bang cosmology tells us that above a certain temperature in the early Universe, baryon antibaryon pairs would be freely created by photons, and the approximate thermodynamic equilibrium would make the separate densities of the baryon number n_b and the antibaryon number $\bar{n}_b$ to be of the same order of magnitude as n_γ aside from the asymmetry induced by processes at an even higher energy scale. If the high energy processes violated baryon number freely, we would expect the asymmetry $n_B = n_b - \bar{n}_b$ to be of the same order of magnitude as n_b or $\bar{n}_b$. In that case, at lower energies, after the mutual annihilation, we expect $n_b = n_B \simeq n_\gamma$. Since both n_B and n_γ scale as S^{-3}, where S is the Friedmann scale factor, the ratio of the two should remain constant throughout the later history of the Universe. This wishful thinking is contradicted by the observed value of this ratio[1], which is in the range $10^{-10} - 10^{-12}$. This is obtained by direct estimate of the density of luminous matter and hydrogen clouds, compared to entropy density of the microwave background. There is a second method which confirms this value, as well as confirming the basic premise of the Big Bang cosmology. This is the n_B/n_γ ratio needed so that we have the nucleosynthesis data about He to H by weight at its correct value[1] of 25%. We are thus faced with the challenge of introducing particle physics interactions that violate baryon number, at the same time providing for the asymmetry, a fine tuned number in the range mentioned above.

In the following, in section 2, we recapitulate the subtle requirements for dynamical production of baryon number in the early Universe. In section 3, we introduce the sphaleron and the reasons for looking for baryogenesis at the electroweak scale. We also discuss here the bound placed on the Higgs boson mass by the requirement of electroweak baryogenesis. In section 4 we introduce a class of mechanisms fulfilling the requirements of electroweak baryogenesis. These will rely on the details of the electroweak phase transition, to be understood in terms of the temperature dependent effective potential. In section 5 we discuss the work done by our group related to previous section, viz. baryogenesis in electroweak phase transition induced by cosmic strings. Section 6 contains the conclusions. Due to limitations of space this review is rather brief and selective. The references cited contain more details. I hope however to convey the essentials and to share the excitement associated with making just enough baryons to ensure that we exist in the state we do.

2 General Requirements

The possibility of cosmological explanation of baryon asymmetry relying on particle physics was proposed by Sakharov[3] in the early days of CP violation as well as Microwave Background. Suppose there exist reactions in which baryon number (B) is violated. However if there is charge conjugation symmetry (C), such reactions cannot give rise to net baryon number, since both particles as well as antiparticles would be equally created or destroyed. Let us also suppose that C is violated in such reactions. However, as the reaction products begin to build up , the reverse reactions would also become viable, returning the products to the B symmetric state. We must therefore also suppose existence of different rates for the forward and the reverse reactions, a possibility realisable in particle physics theories with violation of time reversal symmetry T, or equivalently, CP assuming CPT invariance, P being parity. However, in thermal equilibrium, *CPT invariance still implies equality of n_b and $\bar{n}_b$.* Therefore one also needs out-of-equilibrium conditions. In the early Universe, these could be provided by the decay or decoupling of particles as certain temperature thresholds are crossed, or by the occurance of a phase transition due to formation of condensates. Then with the state of the Universe not time symmetric, the time irreversible processes could leave their distinct mark.

It is clear that several factors have to conspire rather delicately to produce the required results. Our hope is that we make hypotheses that are generic and yet lead to this rather fine tuned number n_B/n_γ. Ideally we would like to allow for maximal possible B violation as well as maximal possible CP violation and have the small number come out compulsively as the result of a distinct, preferably unique mechanism. Proposals of this nature were made in the context of grand unified theories, where out-of-equilibrium decays of superheavy bosons led naturally to the number needed. At present we have no compelling model of grand unified interactions, but that is not the reason why we shall turn to electroweak baryogenesis. It is in fact deeper understanding of rather intricate facts of the Standard Model itself that lead us to look at this energy scale in greater detail.

3 The anomaly and the sphaleron

In Quantum Mechanics we usually expect the symmetries of the classical system to be reflected as linear invariances of the Hibert space, and a conserved quantity is expected to be represented by a hermitian operator commuting with the Hamiltonian. This however is not always true and a variety of other possibilities is now known to occur for the case of Relativistic Field Theory. In the phenomenon known as anomaly,[4] a classically conserved axial vector current associated with fermions may turn out to be not conserved in the Quantum Theory. Specifically, one finds that

$$\partial_\mu j^\mu_A = \frac{g^2}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} \tag{1}$$

where g is the gauge coupling. This anomaly of the fermionic current is associated with another interesting fact of gauge field theory. It was shown by Jackiw and Rebbi that the ground state of a nonabelian gauge thoery consists of many configurations of gauge fields which although not permitting any nonzero physical field strengths, can not be continuously gauge transformed into each other, *i.e.*, the gauge transformation connecting them cannot be deformed to the identity transformation. Such pure gauge vacuum configurations can be distiguished from each other by a topological charge called the Chern-Simons number

$$N_{C-S} = -\frac{2}{3}\frac{g^3}{32\pi^2}\int d^3x \epsilon^{\mathrm{ijk}}\epsilon^{\mathrm{abc}} A_\nu^a A_\rho^b A_\sigma^c \tag{2}$$

The existence of gauge equivalent sectors labelled by the Chern-Simons number is related to the fermionic anomaly because one can show that the RHS of eqn.(1) is equal to a total divergence $\partial_\mu K^\mu$ where

$$K^\mu = \epsilon^{\mu\nu\rho\sigma}\left(F_{\nu\rho}^a A_\sigma^a \quad - \quad \tfrac{2}{3} \quad g \quad \epsilon^{\mathrm{abc}} A_\nu^a A_\rho^b A_\sigma^c \right) \tag{3}$$

so that with $F^{\mu\nu} = 0$,

$$\Delta Q_A \equiv \Delta \int j_A^0 d^3x = -\Delta\left(\frac{g^2}{32\pi^2}\int K^0 d^3x\right) \equiv -\Delta N_{C-S} \tag{4}$$

Thus the violation of the axial charge by unit occurs because of a quantum transition from one pure gauge configuration to another. The standard model sphaleron[5] is supposed to be a time independent configuration of gauge and Higgs fields which has maximum energy along a minimal path joining sectors differing by unit Chern-Simons number. See figure 1.

fig. 1 Energy profile of gauge fields

It is convenient to obtain this time independent solution in the approximation that the Weinberg angle is zero. Thus, the sphaleron of an $SU(2)$ theory spontaneously broken by a complex isospinor Higgs is given by[5][6] (in the gauge $A_0^a = 0$)

$$\sigma^a A_i^a = -\frac{2i}{g} f(r) \frac{\partial}{\partial x^i} U^\infty(\vec{r})(U^\infty(\vec{r}))^{-1} \tag{5}$$

and

$$\phi(\vec{r}) = h(r) U^{\infty}(\vec{r}) \begin{pmatrix} 0 \\ \mu \end{pmatrix} \tag{6}$$

with

$$U^{\infty}(\vec{r}) = \frac{1}{r} \begin{pmatrix} z & x + iy \\ -x + iy & z \end{pmatrix} \tag{7}$$

The energy of such configurations can be estimated to be $M_W/\alpha_W \simeq 10$ TeV. Detailed study[7][24] of the sphaleron with correct value of the Weinberg angle does not change the conclusions to be elaborated below. The small mixing with the $U(1)_Y$ gives rise to a small magnetic dipole moment to the sphaleron, with accompanying modification in the energy.

In the Standard Model, Q_A turns out to be the combination of the baryon and lepton numbers, $B + L$. If we assume the physical vacuum to be a state characterised by a definite value of N_{C-S}, for instance the valley at $N_{C-S} = 0$ in fig. 1, a spontaneous quantum transition to another state of $\Delta N_{C-S} = \pm 1$ can occur only by passing under an energy barrier of height at least as much as set by the sphaleron energy $E_{\mathrm{sph}} \simeq 10$ TeV.

Kuzmin, Rubakov and Shaposhnikov[8] conjectured that at high temperatures, the sphaleron occurs freely as a fluctuation, and that the system makes transitions to neighbouring valleys by going *over* the barrier. This would establish a chemical equilibrium between baryons and antibaryons (as well as leptons and antileptons). Any preexisting asymmetry in the $B + L$ number would therefore be wiped out at the Weinberg-Salam phase transition scale.

Subsequent analysis has substantiated this conjecture in two different temperature ranges: i)$0 << T << E_{\mathrm{sph}}$ and ii)$T \geq E_{\mathrm{sph}}$ using different techniques. Case i) is amenable to reliable approximation techniques.[9] Accordingly, the thermal rate for unit change in Chern-Simons number is

$$\frac{\Gamma}{V} = \frac{T^4 \omega}{M_W(T)} \left(\tfrac{\alpha_W}{4\pi} \right)^4 N_{tr} N_{\mathrm{rot}} \left(\tfrac{2 M_W(T)}{\alpha_W T} \right)^7 \exp\{ \frac{-E_{\mathrm{sph}}(T)}{kT} \} \kappa \tag{8}$$

Here $\omega = \partial^2 V_{\mathrm{eff}} / \partial \phi^2 \mid_{\phi=0}$; N_{tr} and N_{rot} are counts of sphaleron zero modes estimated to be $N_{tr} \times N_{\mathrm{rot}} \cong 1.3 \times 10^5$ and $\kappa\tilde{}1$ is a determinant. For case ii), no approximation techniques exist. Sphaleron does not exist because $\langle\phi\rangle^T = 0$ in the high temperature regime. But heuristic arguments suggest[10]

$$\Gamma = A(\alpha_W T)^4 \tag{9}$$

where A is a dimensionless constant which should be close to unity. We shall refer to this as the *high temperature* mechanism. In order to establish this mechanism simulations have been carried out on a lattice[11]. Gauge fields are set up on a lattice in contact with a heat bath and allowed to evolve in fixed time steps, keeping track of the integral number Q_{C-S} at every stage. The one such calculation carried out[11] indeed detects occasional rapid jumps signalling $\Delta Q_{C-S} = \pm 1$, and an empirical value of A between 0.1 and 1.0. See fig. 2.

fig. 2 N_{C-S} evolution in a thermal bath

Γ is the anomalous transition rate ignoring the presence of fermions, and is equal for $\Delta Q_{C-S} = +1$ and $\Delta Q_{C-S} = -1$. The rate for B-number violation is then obtained from the difference between the forward and reverse rates, which depend upon the chemical potentials of the baryons and the antibaryons. Then the final result is

$$\frac{\partial(B+L)}{\partial t} = -\frac{13}{2} n_f \frac{\Gamma}{T^3}(B+L) \tag{10}$$

where n_f is the number of fermion generations. The general conclusion is therefore, that the anomaly is unsuppressed at high temperatures and no net $B+L$ can remain. This gives rise to two broad options for explaining the baryon asymmetry: A) The $B-L$ number of the Universe is non-zero for some reason, so that with

$B + L = 0$, $n_B = n_L \neq 0$ survives. For this to be a satisfactory explanation, one needs a natural mechanism for non-zero n_{B-L}. B) Net $B + L$ is generated at a scale not much larger than the electroweak scale, and is neutralised incompletely by high temperature electroweak processes. We shall not take up a discussion of these possibilities but persue the possibility of baryogenesis *at* the electroweak scale. Hopefully, the latter approach has fewer free parameters and will be easy to check against phenomenology.

There is at least one important consequence of the above analysis which we can derive within known phenomenology. Suppose the net B-number just after the electroweak phase transition is B_{in}. Since the rate in eq. (8) is known, we may integrate eq. (10) to calculate how much B-number survives the menace of the sphaleron. We note that the rate Γ depends on the temperature dependent expectation value $\langle\phi\rangle^T \equiv v$, which in turn is determined by the parameters of the Higgs potential, and hence in turn by the Higgs mass m_H. If the rate Γ is slow enogh to become comparable to the expansion rate of the Universe, the sphalerons will not succeed in neutralising the $B + L$ number. Following Shaposhnikov[12], we integrate eq. (10) and obtain for suppression factor $S \equiv B_0/B_{in}$,

$$S \;=\; \exp\left(-\Gamma/H\right) \tag{11}$$

where B_0 is the net baryon number left over, and H is the Hubble parameter just after the electroweak scale. S has an implicit dependence on m_H, which is plotted in fig. 3.

fig. 3 Suppression factor vs. Higgs mass

We see that for large m_H such as $m_H>$ 70GeV, $B+L$ would have to be zero *regardless of the physics beyond the electroweak scale.* A light Higgs mass $m_H\sim$ 20 to 35 GeV allows all the asymmetry before the electroweak phase transition to survive. Assuming a modest value $B_{in}=10^{-5}$, we are led to the conclusion $m_H<$ 45GeV since B_0 must be 10^{-10}. Sinc eaccelerator experiments have already ruled out m_H lighter than 57GeV, this raises serious doubts about the completeness of the Standard Model with one Higgs. This is indeed the most significant result implied by the anomaly structure of the Standard Model.

4 Models of Electroweak Baryogenesis

It is clear from the preceeding section that the Standard Model needs to be modified, firstly to generate baryon asymmetry and secondly, to prevent the wash out of the asymmetry. We shall consider here some modifications to the Standard Model that are minimal and satisfy the above requirements. In particular, we dshall examine models in which the asymmetry is generated *at* the electroweak phase transition.

As was explained in sec 2, time irreversible processes are an essential ingredient of any recipe for baryogenesis. Kuzmin et al[8] pointed out that this requirement could be met neturaly if the electroweak phase transition was dirst order. Here by first order we mean one in which the order parameter changes discontinuously at the phase transition. The free energy of the Higgs field is given in the field theoretic formalism by the finite temperature effective potential. The high temperature expansion for the same is given correct to $O(\hbar)$ by

$$V^T_{eff} \;=\; -(2\lambda\sigma^2+M_1^2-(M_2/\sigma)^2T^2)\phi^2-\frac{T}{4\pi}(\frac{M_3}{\sigma})^3\phi^3+\lambda\phi^4+(\frac{M}{\sigma})^2\phi^4\ln(\frac{\phi}{\sigma})^2 \quad (12)$$

where M_1, M_2 and M_3 are mass dimension parameters depending on physical masses M_W, M_Z, M_t; σ is the zero temperature expectation vallue of the Higgs field, $\sigma=246$GeV; λ determines the Higgs self-coupling. The opposite signs between T^2 and the zero-temperature coefficient in the ϕ^2 term signals that for large enough temperature, the effective mass-squared of the Higgs is positive and the symmetry no longer appears broken[13]. The form of the quartic potential leads to a variation in its shape with change in the parameter T as shown in fig. 4.

fig. 4 Variation in V_{eff}^T with T

There exists a temperature T_1 at which the system has two equienergetic minima separated by a barrier. This barrier persists till $T_c < T_1$, at which the second derivative of V at $\phi = 0$ changes sign from positive to negative so that $\phi = 0$ no longer remains a minimum. Between the temperatures T_1 and T_c, the system is normally at $\phi = 0$ since that is the condition persisting from $T > T_1$. However since $\phi_2 \equiv \phi \neq 0$ is favorable, thermal fluctuations and quantum tunelling across the barrier is possible. Whenever tunelling to the true vacuum occurs in any region of space, it results in a "bubble", the inside of which consists of the true vacuum ϕ_2 and outside is still the unconverted false vacuum. According to a well developed formalism[14][15], the tunelling probability per unit volume per unit time is given by

$$\gamma = CT^4 e^{-S_{bubble}} \tag{13}$$

where S_{bubble} is value of

$$S = 4\pi \int r^2 dr \{ \frac{1}{2} \phi'^2 + V_{eff}^T[\phi] \} \tag{14}$$

extremised over ϕ configurations which satisfy the "bubble" boundary conditions $\phi(r = 0) = \phi_2$, $\phi \to 0$ as $r \to \infty$. Once a bubble forms, energetics dictates that it keeps expanding, converting more of the medium to the true vacuum. The expansion is irreversible and provides one of the requisite conditions for producing baryon asymmetry. The important question is whether the phase transition in the electroweak theory is first order or second order. Detailed calculations support the view that the form of the potential is indeed as given above giving rise to a temperature $T_1 > T_c$, so that the phase transition is first order. We thus have a B-number violating mechanism, an irreversible process as well as the well known CP violating effects right within the Standard Model, thus giving rise to the hopes of explaining the Baryon asymmetry at the electroweak scale.

Before proceeding with this discussion we should note that first order phase transition with bubble formation is not the only way time asymmetric conditions can arise. It has been pointed out by Brandenberger and collaborators that even with a second order phase transition, cosmic strings can play an important role in catalising baryon asymmetry production if other favorable conditions exist.[16] We can not include this interesting possibility for want of space.

The hope expressed above of explaining B asymmetry within the Standard Model is quickly belied by the fact that the extent of known CP violation is too small. A model independent dimensionless parameter characterising the scale of this effect has the value[17] $\delta_{CP} \sim 10^{-20}$. Since such a factor is expected to appear multiplicatively in the final answer, the resulting asymmetry would be too small. Additianally, we saw that the Standard Model Higgs seems to erase any B asymmetry generated prior to the electroweak scale. This leads us to make the minimal extension to the Standard Model, viz., to include one more complex Higgs doublet. The possibility of such has been extensively considered in other contexts as well[18]. For our purpose, this is a good extension to consider for two reasons 1) a phase transition with two Higgs doublets has the possibility of not wiping out the produced baryon asymmetry and still allowing the lightest Higgs to be heavier than 60 GeV[19]. 2) it is a source of additional CP violation which does not conflict with any known phenomenon.[18]

In the following we shall review one of the proposed scenarios for electroweak baryogenesis in some detail, and refer to reader to detailed reviews[20] for other possibilities. One class of possibilities we are unable to take up is that due to Cohen Kaplan and Nelson[21].

There are several proposals along these lines[20]. Unfortunately we cannot include any details of most. One class of proposals by Cohen Kaplan and Nelson involves scattering of neutrinos from the walls of expanding bubbles. If the neutrino is massive and has majorana mass, lepton number violation can occur in such a scattering, biasing the L number density in front of the wall, after CP violation has been taken into account. Outside the wall, the high temperature anomalous process would be going full swing, setting the $B+L$ number to zero, thereby creating $B=-L$, i.e., negative of the L generated by wall reflections. On this basic scheme several phenomenologically viable models have been proposed[21].

In the present review we shall treat in some detail only one class of models proposed by McLerran, Shaposhnikov, Turok and Voloshin[22]. Consider the model with two Higgs doublets. In the course of the phase transition, both of these acquire nonzero vacuum expectation value. Being complex, their expectation values would generically differ in their phase, thus allowing CP violation in their nontrivial ground state. The bias towards creation of baryons as against antibaryons would be signalled by the presence of terms in the effective action which are linear in the Chern-Simmons number. Net baryon production can result only if CP violating effects are coupled to this biasing term. A term with appropriate properties is contributed by the triangle diagram shown in fig. 5.

fig. 5 A nontrivial contribution to the S_{eff}

The presence of two Higgs raises the danger of flavour changing neutral currents, which is usually circumvented by coupling only one of the Higgs to the fermions or coupling up type fermions to one and down type to the other[23]. In either case, we get the dominant contribution to above kind of diagram only from a top quark loop with both scalar external legs coupled to the same Higgs. The $T \neq 0$ correction from this diagram can be calculated to be

$$\begin{aligned}\Delta S &= \frac{-7}{4}\zeta(3)\left(\frac{m_t}{\pi T}\right)^2 \frac{g}{16\pi^2}\frac{1}{{v_1}^2} \\ &\times \int (\mathcal{D}_i\phi_1^\dagger\sigma^a\mathcal{D}_0\phi_1 - \mathcal{D}_0\phi_1^\dagger\sigma^a\mathcal{D}_i\phi_1)\epsilon^{ijk}F^a_{jk}d^4x\end{aligned} \tag{15}$$

where m_t is the top quark mass, ζ is the Riemann zeta function, and the σ^a are the Pauli matrices. For homogeneous but time varying configurations of the Higgs fields, in the gauge ${A_0}^a = 0$, we can rewrite this in the form

$$\begin{aligned}\Delta S &= \frac{-i7}{4}\zeta(3)\left(\frac{m_t}{\pi T}\right)^2 \frac{2}{{v_1}^2} \\ &\int dt[{\phi_1}^\dagger\mathcal{D}_0\phi_1 - (\mathcal{D}_0\phi_1)^\dagger\phi_1]N_{CS} \\ &\equiv \mathcal{O}N_{CS}\end{aligned} \tag{16}$$

which has the linear dependence on the N_{CS} as required. The expectation value of the operator $\mathcal{O}$, the imaginary part of ${\phi_1}^\dagger\mathcal{D}_0\phi_1$, acts as the chemical potential for this number. $\langle\mathcal{O}\rangle$ is nonzero only in the walls of bubbles, which is what we need. However, to lowest adiabatic order $\mathrm{Im}\phi_1$ can be made zero by choice of gauge, and this persists when first derivatives are taken. In the next adiabatic order, one finds

$$\begin{aligned}\mathcal{D}_\mu\mathcal{D}^\mu\mathrm{Im}\phi_1 &= \frac{1}{2}R^3\cos\gamma(\lambda_5\cos\gamma\sin\gamma\sin\xi \\ &\qquad - \lambda_6\sin^2\gamma\sin 2\xi)\end{aligned} \tag{17}$$

where $\langle\phi_1\rangle \sim \langle\phi_2\rangle \sim R$ in the translation invariant ground state, γ and $\xi$are angles specifying relative phases of $\langle\phi_1\rangle$ and $\langle\phi\rangle_2$; λ_5, λ_6 are dimensionless quartic couplings in the two-Higgs doblet theory[18]. ξ characterises the CP violation which will show up only in the scalar sector. To arrive at a numerical estimate, we take $\mathcal{D}_\mu\mathcal{D}^\mu \sim M_H^2(T)$, the temperature dependent Higgs mass-squared, which also sets the scale for the bubble wall thickness. This leads to[22] $n_B/n_\gamma \sim 10^{-3}\alpha_W^4\sin 2\xi(T_c)$. If the quartic couplings as well as $\sin 2\xi(T_c)$ are all $O(1)$, this leads to an answer in the correct range of values.

The bubble profile can be computed by making reasonable ansatz and the above calculation can be done numerically. In a particular case of bubble formation[24][28], one finds wall thickness $\sim 40T^{-1}$ and n_B/n_γ indeed $\sim 10^{-9}$.

5 String induced phase transition

For all mechanisms relying on the first order nature of the phase transition, the thickness and speed of the bubble walls are crucial parameters. Some of the mechanisms would work only in thin fast walls and others only for thick walls[20][25]. It is possible that the elecroweak phase transition was induced by cosmic strings present from an earlier symmetry breaking transition. That this is possible for a generic unified theory with several stages of symetry breakdown was shown in ref. [26]. This was investigated in detail for the electroweak effective potential in [27], where it is shown that the thickness of bubble walls in this case is

$$\Delta r \; = \; s(m_H)T^{-1} \tag{18}$$

where $s(m_h)$ is a scaling factor which varies in the range $0.7 - 0.5 \times (m_H/GeV)$ as m_H varies from 60 to 120 GeV. For the wall velocity we find $v \sim 0.5$ for the same range of Higgs mass. A multiple time snapshot of the progressing bubble wall is shown in fig. 6.

fig. 6 The induced bubble solution

This mechanism invokes the existence of new gauge forces at higher energies. However, the wall parameters givem above are determined entirely by the standard model physics, viz., m_H. These results show that the walls of string induced bubbles provide adiabatic conditions for a B-asymmetry generating mechanism, in particular conditions quite suited for the operation of the McLerran-Shaposhnikov-Turok-Voloshin (MSTV)[22] mechanism.

MSTV mechanism suffers from the drawback that to first adiabatic order in the spatial variation of the Higgs fields, it does not produce B-asymmetry. This happens because CP violation comes into play only if both the Higgs are involved whereas the FCNC constraint forces coupling of the top quark on ly to one of the two. Recently it has been shown[29] that the Glashow-Weinberg criterion is sufficient but too strong, and that the possibility of a fermion coupling to a small extent to another Higgs is open. Accodingly we investigated[30] the MSTV mechanism with this extension in the yukawa couplings. In this case two additonal diagrams similar to the one in fig. 5 contribute to S_{eff}. The value of the operator $\mathcal{O}$ was comuted in string induced bubble walls. The results are numerically in the same range; this is to be expected since the FCNC constraint still keeps the contribution of additional diagrams small but the effect is in the first adiabatic order, hence more robust.

6 Conclusion

For baryogenesis to occur in the early universe, three conditions of Sakharov are necessary. In the Standard Model, anomalous nature of the $B+L$ current allows for the violation of this number. Further, the understanding of the sphaleron solution permits the calculation of the rate of violation of this number at high temperature, indicating that the rate of violation becomes significant near the phase transition scale. Numerical simulations also suggest that the vilation is completely unsupressed above electroweak symmetry breaking scale. Secondly, CP violating interactions are possible in simple extensions of the Standard Model, although the CP violation is too small to produce the observed B-asymmetry. Finally, upon investigating the electroweak effective potential at high temperature, it is found to suggest a first order phase transition, thus providing the out-of-equilibrium conditions required by Sakharov's criteria. This raises the possibility that all the observed baryon excess in the Universe was manufactured at the electroweak scales and mostly involving known physics. We have reviewed the MSTV[22] mechanism involving two $SU(2)$ doublet scalars working as Higgs particles. We find several variations of this mechanism that would also be effective, in particular the one with less stringent restriction on Yukawa couplings enhances this effect.

The highly effective baryon-number violation suggested by the sphaleron and by numerical simulations above the electroweak phase transition raise the spectre of a universe without baryons if some mechanism for guarding them against the sphaleron menace does not exist. Shaposnikov's work duely extended shows that this implies that the Higgs mass in the Weinberg-Salam theory must be less than about 50 GeV, a range already excluded by accelerator experiments. This strongly suggests that the Standard Model needs an extension. This is very valuable information one derives about the fundamental forces at the microscopic scale by studying the early Universe.

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