Electroweak Baryogenesis and the Standard Model

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ABSTRACT

Electroweak baryogenesis is addressed within the context of the standard model of particle physics. Although the minimal standard model has the means of fulfilling the three Sakharov's conditions, it falls short to explaining the making of the baryon asymmetry of the universe. In particular, it is demonstrated that the phase of the CKM mixing matrix is an insufficient source of CP violation. The shortcomings of the standard model could be bypassed by enlarging the symmetry breaking sector and adding a new source of CP violation.

Introduction

The origin of the baryon asymmetry of our universe (BAU) is a fundamental question of modern physics. A. Sakharov[1] established on general ground that particle interactions might account for the production of the BAU at an early epoch of the universe provided that some of these interactions are B violating processes which operated in a C and CP violating environment during a period the universe was in non-thermal equilibrium.

The state of the art in particle physics is the standard model of the theory of the interactions between quarks and leptons. CP violation has been observed and might originate from the mass matrix of the quarks. B violation is believed to have taken place through non-perturbative processes of the theory of weak interactions in a high temperature plasma. Non-equilibrium in particle distributions in the plasma was generated at the electroweak phase transition. Although the three Sakharov's requirements are potentially fulfilled by the standard model the latter comes short to explaining the making of the BAU.

In what follows, I describe how each of the three Sakharov's conditions is addressed by the minimal standard model. I briefly discuss the obstacles to proving or disproving the making of the baryon asymmetry at the electroweak phase transition using known ingredients of particle physics.

I. Departure from Thermal equilibrium

The electroweak phase transition

$SU(2)$ gauge symmetry was unbroken in the early universe.[2] To argue so, one notes that the Higgs field was in contact with a thermal bath containing $M_W^{\pm}$, Z and t-quarks whose masses are important parameters of their equilibrium distributions. On one hand, the Higgs self-interaction energy, $V(\phi)$, was minimized for an Higgs expectation value ϕ_m of order $v \simeq 250$ GeV. On the other hand, the free energy of the plasma was minimized for $\phi_m = 0$, i.e., in the limit of massless particles. General arguments of thermodynamics imply that the Higgs expectation value was

then lying at an intermediate value, at the minimum of the sum of the effective potential and the free energy of the plasma, $V(\phi, T) = V(\phi) + F(M_W, M_t; \phi, T)$.

Calculation of the free energy is a central problem. It is usually attempted perturbatively, that is, a guess is made as to what a good approximation of the plasma might be and small corrections are subsequently added. A popular starting point is *a gas of free particles*; its free energy is

$$F^{\text{free}}(M_W, M_t; \phi, T) = \sum_{species} \int_0^{M^2} dM' M' \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{1}{E} \frac{1}{e^{E/T} - 1} \tag{1}$$

$$\simeq -\frac{103\pi^2}{90}T^4 + \frac{T^2\phi^2}{24}\left(\frac{9M_W^2 + 6M_t^2}{v^2}\right) - \frac{T\phi^3}{12\pi}\left(\frac{9M_W^3}{v^3}\right) + \ldots. \tag{2}$$

At high temperature, the first two terms in eq. (2) dominate any other term in $V(\phi, T)$, hence, $V(\phi, T)$ is minimal for zero Higgs expectation value, $\phi_m = 0$, and *electroweak symmetry is restored at high temperature*. At low temperature, F^{free} is negligible in respect to $V(\phi, T)$, in which case *electroweak symmetry is broken*. Inevitably, as the universe cooled down to an intermediate temperature of order $T_c \sim (M_H/M_W)v$ (~ 100 GeV), a phase transition occurred during which the Higgs field developed a non-zero expectation value which interpolates between 0 and v. The actual mechanism of transition is of crucial importance for establishing the time scale of non-equilibrium; its determination requires a complete knowledge of $F(\phi, T)$ beyond the free gas approximation. There are two ideal possibilities.[*]

A second order phase transition

If the Higgs expectation value evolves continuously from 0 to 250 GeV as the universe cools down from T_c to below, the transition is said to be second order. The time dependence of the Higgs expectation value induces a departure from equilibrium whose typical time scale τ_{nonequi} is of the order of the inverse of the

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[*] For attempts to interpolate between these two possibilities, see Ref. 3.

rate of expansion of the universe, $\tau_{\text{nonequi}} \sim H^{-1} \sim \frac{M_{\text{Planck}}}{T^2} \sim 10^{17}/T$. This is about 17 order of magnitude slower than a typical microscopic process in the plasma. The "baryon per photon" ratio produced cannot possibly be larger than $n_B/s \sim \tau_{\text{equi}}/\tau_{\text{nonequi}} \sim (\frac{1}{T})/(\frac{10^{17}}{T}) \sim 10^{-17}$, an amount which is too small to make a significant contribution to the asymmetry observed today, $(n_B/s)_{Obs.} \sim 10^{-10}$.

A first order phase transition

A first order phase transition is one in which the expectation value of the Higgs develops an instability. A thermal fluctuation triggers a local transition of ϕ from 0 to a non-zero value $\sim \phi_m$; this is the phenomenon of bubble nucleation. Some of these bubbles expand, their interface sweeps the plasma requiring a given species to becomes massive and to rapidly relax to a new thermal distribution. This produces a temporary non-equilibrium situation with a time scale τ_{nonequi} of the order of $\tau_{\text{nonequi}} \geq$ thickness/velocity $\sim 10^{(1-3)}/T$. As this time scale is comparable to the microscopic plasma scale, the production of a "baryon per photon" ratio is allowed in the neighborhood of the moving bubble wall, up to an amount $n_B/s \sim 10^{-(1-3)}$, far sufficient for the purpose of baryogenesis.

A first order phase transition allows electroweak baryogenesis to meet the first of Sakharov's criteria. The uncovering of this possibility resulted in an extensive study of the dynamics of expansion of an electroweak bubble.[5,7] The main properties of this dynamics reflect heavily the non-equilibrium structure of the plasma at the bubble interface, and are now fairly well understood. Bubbles grow to a macroscopic size of order $10^{12}/T$ until they fill up the universe. This size is far larger than the microscopic scale of baryogenesis, $\sim 1/\alpha_W T$, and complications due to the curvature of the wall can be ignored. The thickness of the interface is of the order $(vM_H^2/M_W^3)1/T \sim (10-100)/T$, while the terminal velocity of expansion v_W has been evaluated to be in a non-relativistic range and no smaller than ~ 0.02.[†] This lower value is the result of a saturation of the wall damping which is

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† More exactly, in this limit v_W is proportional to the amount supercooling in the plasma and is sensitive to the Higgs mass ($\sim 1/M_H^{3/2}$)and the top quark mass. The value quoted is

attained when the wall thickness is smaller than the plasma mean free paths of the relevant gauge bosons and t-quarks. Calculations in this limit are very reliable.[5,7] Furthermore, in this range of velocities, the growth has been shown to be stable[9]. The above considerations lead to a fairly simple and "user-friendly" picture of the electroweak phase transition.

Discussion

The current status of our understanding of the electroweak phase transition leads to the wide-spread belief that it was a first order transition provided that the Higgs mass not be too large.[7,14] However, unresolved calculational difficulties due to the non-abelian structure of the gauge sector prevents to establish reliably the order of the transition. The essence of these difficulties can be formulated in the following way.[10]

Computation of the free energy of a nearly massless plasma beyond the approximation of a gas of free particles (1) is needed. Difficulties arise because of large energy corrections from mutual particle interactions. More specifically, gauge bosons W's and Z's follow the Bose-Einstein distribution $(\exp E/T - 1)^{-1}$. The plasma contains a large fraction of small momenta $(|\vec{k}| < M)$ gauge bosons, which diverges as $\int d^3\vec{k}\, T/M$ in the massless limit. Multiple gauge interactions between these quanta contribute to the free energy an amount $(T/M)g_W^2(T/M)g_W^2\ldots$. The sum of these contributions, denoted ΔF, can be expressed as a series expansion in powers of $g_W^2 T/M$

$$\Delta F = \sum_n \left(\frac{g_W^2 T}{M} \right)^n f_n(M/T) \, . \tag{3}$$

These corrections are expected to affect the quality of the order of the transition as it has been understood that a first order transition occurs only as the result of the presence of this large number of low momenta gauge bosons in the plasma :[‡]

a reduction in their number implies a phase transition more weakly first order.

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for $M_H \sim 60$ GeV and $M_t \sim 180$ GeV.[7]

‡ More specifically, the term responsible for the first order structure is the cubic term in (2).

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A leading approximation to the free energy which better accounts for the contribution of the longitudinal components of the gauge bosons is the free energy of a *gas of quasiparticles*. These quasiparticles, or "plasmons",[6] are collective excitations in the plasma and arise from the "dressing" of the low momenta ($|\vec{k}| < M$) longitudinal modes with large momenta ($|\vec{k}| \sim T$) modes. The quasiparticle approximation is obtained by simply substituting the thermal distribution of a free boson with the one of a free quasiparticle

$$\frac{1}{e^{\sqrt{\vec{k}^2 + M^2}} - 1} \longrightarrow \frac{1}{e^{\sqrt{\vec{k}^2 + M^2 + M_D^2}} - 1}, \qquad (4)$$

M_D is the Debye mass $M_D \simeq g_W T$. According to (4), the fraction of the population of longitudinal (quasi-)gauge bosons with momentum $|\vec{k}| < M << T$ is reduced in respect to the corresponding free gauge boson population, as $T/M \to T/(M^2 + M_D^2)^{1/2} \sim 1/g_W$. It is finite (no infrared divergence!) and sufficiently small to convert the infrared expansion (3) of the corresponding interaction energy ΔF, into a computable series expansion in powers of g_W. Making the substitution (4) in expression (1) to obtain the leading contribution F_{quasi}^{free} from F^{free},[10] leads to a corresponding suppression of the contribution of the longitudinal modes to the strength of the first order transition.[§] Resummation methods have been successful to account for these effects.[8,7]

Interactions among the transverse components of the gauge fields and between them and other gauge fluctuations in the plasma are believed[15] to generate an effective "magnetic mass", $M_M = \# g_W^2 T$, which cuts off the distribution of low momenta modes in a way similar to substitution (4). There is no known method of computing this mass reliably. Furthermore, contributions to ΔF involving transverse gauge bosons cannot be accounted for with the "quasiparticle" method: making the analog substitution (4) in (3) leads to a finite but *non-perturbative* series unless $\#$ is shown to be sufficiently large, in which case, expression (2) yields a

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§ The cubic term in (2) becomes $\frac{9T}{12\pi}((\phi\frac{M_W}{v})^2 + M_D^2)^{3/2} \sim \frac{9T M_D^3}{12\pi} + \mathcal{O}(\phi^2/T^2)$, for $\phi \leq \phi_m$.

second order or a very weakly first order transition. This sort of analyses have been performed using resummation techniques and are fairly inconclusive. Expansion about a gas of free quasi-particles is not adequate. Other methods ought to be developed. Currently, no technique has turned to be successful to strictly establish the order of the electroweak phase transition.

II. Baryon number violating processes

An ideal setting for the baryon number violating processes is as follows. (a)B-violation occurs at an infinite rate ($\Gamma_B^u = \infty$) in the unbroken phase in order to produce an asymmetry in the region of the plasma disturbed by the moving interface of a bubble of broken phase. (b)B-violation is turned off in the broken phase ($\Gamma_B^u = 0$) in order to preserve inside the bubble, the BAU produced. In practice, this optimal situation is not realized.

Anomalous baryon number violation

The B violating processes of the standard model result from the conjunction of the non-trivial topological structure of an $SU(2)$ gauge theory and of the chiral $SU(2)$ anomaly. The former can be formulated in expressing the existence of an infinite number of distinct sectors in the configuration space which are mapped to each other by large gauge transformations. These distinct sectors are characterized by an integer N_{CS}, the Chern-Simons number. A physical process interpolates between two such sectors provided it has a space-time integrated value of $F\tilde{F}(x)$ proportional to the difference between the Chern-Simons numbers of the initial and final sectors $\int dx^4 F\tilde{F}(x) = 1/32\pi^2 \ \Delta N_{CS}$. These processes conspire with the anomalous baryon and lepton currents ($\partial j_\mu^{B,L}(x) = (3/32\pi^2)F\tilde{F}(x)$), to produce a net change of the baryon and lepton numbers $\Delta B = \Delta L = 3\Delta N_{CS}$. The above formal arguments do not guarantee the existence of these anomalous processes. However, such processes are believed to have taken place in the high temperature plasma of the early universe.

Finite temperature baryon number violation

In the broken phase,[11] adjacent topological sectors are separated by an energy barrier at the top of which sits the sphaleron configuration whose energy is proportional to the expectation value of the Higgs condensate, $E_{sph} \sim g_W \phi_m / \alpha_W$ and whose typical size is of order $1/g_W \phi_m$. At zero temperature, the barrier is too high $E_{sph} \simeq 10$ GeV and only instantons can achieve a transition at a negligible rate. At high temperature, relevant gauge-Higgs modes are thermally populated and sphalerons have a non-zero probability of being produced. Baryon number violation occurs but is Boltzmann suppressed,[4] $\Gamma_B^b \propto T^4 e^{-E_{sph}/T}$.

In the unbroken phase, computation of the rate is a difficult task because of the difficulty of taking into account interactions between the very large low momenta modes of the massless gauge bosons, as briefly discussed in the previous section. However, general principles provide a fair understanding.[15] There is a natural length scale ξ in the plasma, expected to be of order $1/g_W^2 T$. On dimensional ground, a non-trivial configuration of spatial size ρ, has energy $E \sim 1/\alpha_W \rho$. The lowest energy configuration has the smallest spatial extension which cannot be smaller than ξ. Hence, the least energy configuration is expected to have energy $1/\alpha_W \xi \sim T$. We conclude that transitions between the different sectors *might* occur at an unsuppressed rate, that is $\Gamma_B^u = \kappa (\alpha_W T)^4$. No reliable analytic method of computation currently exists. Numerical simulations have been performed.[16] Such studies are difficult and currently suggest the range $\kappa = 0.1 - 1$.

Discussion

Let us compare the actual situation with the ideal one we promoted earlier: $\Gamma_B^u = \infty$, $\Gamma_B^b = 0$.

In the unbroken phase, $B + L$ violating processes[*] occur at an unsuppressed rate $\Gamma_B^u \sim (\alpha_W T)^4$. During a long period prior the phase transition, as the temperature decreased from about 10^{13} GeV to 100 GeV, these processes were in thermal

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[*] These processes are $B - L$ conserving.

equilibrium, $\Gamma_B^b \gg HT^3$, and capable to wipe-out any pre-existing $B + L$ asymmetry.[4] This is a major constraint on models of early baryogenesis and has been the main motivation for contemplating electroweak baryogenesis.

In the broken phase, $\Gamma_B^b \propto T^4 e^{-E_{sph}/T}$. Not to loose the BAU produced, requires to tune this rate to no more than one baryon violating process per unit volume in a lifetime of the universe, $\Gamma_B^b \ll HT^3$. The structure of Γ_B^b and of $E_{sph} \sim g_W \phi_m / \alpha_W$ transform this condition into a restriction on the magnitude of the Higgs expectation value: $\phi_m \geq T$. In the minimal standard model, ϕ_m is inversely proportional to the square of the Higgs mass so that the above condition translates into an upper bound on the Higgs mass.[12] The latest estimates of this bound[13,7] yield $M_H < 45$ GeV, a value ruled out experimentally. This bound is a direct challenge to implementing electroweak baryogenesis in the minimal standard model. However, in almost any extension of the standard model, the relation between the Higgs expectation value and the Higgs mass involves additional parameters, which, in some cases,[14] may result in a less constraining bound compatible with current experimental data.

III. CP violation

In this last section, I confront the third of Sakharov's conditions to the standard model. More specifically, I establish the impossibility of implementing the complex phase of the CKM matrix as the source of CP violation for baryogenesis. This discussion follows closely a recent work done in collaboration with E. Sather.[21]

A possible mechanism

The standard model possesses a natural source of CP violation contained in the phase of the CKM matrix. Whether the latter participated to the making of the BAU is a fundamental question which was addressed for the first time in a proper physical context by Farrar and Shaposhnikov.[19] These authors proposed a simple mechanism of baryogenesis based on the observation that as the wall sweeps through the plasma, it encounters equal numbers of quarks and antiquarks which reflect asymmetrically as a result of the presence of CP-violation. This mechanism

leads to an excess of baryons inside the bubble and an equal excess of antibaryons outside the bubble. Ideally, the excess of baryons outside is eliminated by baryon violating processes while the excess inside is left intact, leading to a net BAU. Assuming ideal conditions, an upper bound for the "baryon-per-photon" ratio can be derived:[19,21] $n_B/s \leq 10^{-2} \times \alpha_W \times v_W \times \langle \Delta(\omega) \rangle_T$. The whole calculation of the baryon asymmetry now reduces to the determination of a suitable thermal average of the left-right reflection asymmetry $\Delta(\omega) = \text{Tr}(|R_{LR}|^2 - |\bar{R}_{RL}|^2)$, that is, the probability of a L-handed quark reflecting as a R-handed quark minus the probability for the CP conjugate process, summed over all quarks.

The non-trivial structure of the phase space is contained in the velocity factor v_W which reflects the departure from thermal equilibrium and the factor of α_W which reflects the vanishing of any asymmetry unless interactions with the W and Z bosons in the plasma are taken into account in the propagation of the quarks. In addition, the CP-odd quantity $\Delta(\omega)$ vanishes unless flavor mixing interactions occur in the process of scattering. This requires to taking into account interactions with the charged W and Higgs bosons. Furthermore, gluon interactions ought to be included for they strongly affect the kinematics of the quarks. At first, this might appear an insurmountable task. However, Farrar and Shaposhnikov suggested that all the relevant plasma effects can consistently be taken into account by describing the process as a scattering of suitably-defined[*] *quasiparticles*.[6,17]

CP violating observable

$\Delta(\omega)$ is a CP violating observable. It is known that a CP-violating observable is obtained by interfering various amplitudes with different CP properties. Farrar and Shaposhnikov proposed to describe the scattering of quasiparticles as completely quantum mechanical, that is, by solving the Dirac equation in the presence of a space-dependent mass term. In particular, they identified the source of the phase separation of baryon number as resulting from the interference between a path

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[*] These quasiparticles are the fermionic equivalent of the quasiparticles considered in section 1.

where, say, an s-quark (quasiparticle) is totally reflected by the bubble with a path where the s-quark first passes through a sequence of flavor mixings before leaving the bubble as an s-quark. The CP-odd phase from the CKM mixing matrix encountered along the second path interferes with the CP-even phase from the total reflection along the first path. Total reflection occurs only in a small range of energy of width m_s corresponding to the mass gap for strange quarks in the broken phase. This leads to a phase space suppression of order m_s/T, in which case, the "baryon-per-photon" ratio becomes $n_B/s \simeq 10^{-3}\alpha_W(m_s/T)\bar{\Delta} \simeq 10^{-7} \times \bar{\Delta}$. This estimate requires $\bar{\Delta}$, the energy-averaged value of the reflection asymmetry, to be at least of order 10^{-4} in order to account for the baryon asymmetry of the universe, a value claimed to be attained in Ref. 19.

In Ref. 20, it was pointed out that the above analysis ignores the quasiparticle width, or damping rate, embodied by the imaginary part of the thermal self-energy γ. The width has been computed at zero momentum as $\gamma \simeq 0.15g_s^2T \simeq 20$ GeV.[18]These authors made the important observation that this spread in energy is much larger than the mass gap $\sim m_s$ in the broken phase, and as a result largely suppresses the reflection process. A detail of their calculations is to appear soon.

What follows contains a summary of a recent and alternative analysis[21]which *fully* takes into account all relevant properties of a (quasi-)quark, as it propagates through the bubble wall.

Quantum coherence

A Dirac equation describes the relativistic evolution of the fundamental quarks and leptons. Its applicability to a quasiparticle is reliable for extracting on-shell kinematic information, but one should be cautious in using it to extract information on its off-shell properties. A quasiparticle is a convenient bookkeeping device for keeping track of the dominant properties of the interactions between a fundamental particle and the plasma. For a quark, these interactions are dominated by tree-level exchange of gluons with the plasma. It is clear that these processes affect the coherence of the wave function of a propagating quark. To illustrate this point,

let us consider two extreme situations.

• *The gluon interactions are infinitely fast.* In this case, the phase of the propagating state is lost from point to point. A correct description of the time evolution can be made in terms of a totally incoherent density matrix. In particular, no interference between different paths is possible because each of them is physically identified by the plasma. As a result, no CP-violating observable can be generated and $\Delta(\omega) = 0$.

• *The gluon interactions are extremely slow.* The quasiparticle is just the quark itself and is adequately described by a wavefunction solution of the Dirac equation, which corresponds to a pure density matrix. In particular, distinct paths cannot be identified by the plasma, as the latter is decoupled from the fermion. This situation was implicitly assumed in the FS mechanism. This assumption, however, is in conflict with the role the plasma plays in the mechanism, which is to provide a left-right asymmetry as well as the necessary mixing processes. In addition, this assumption is in conflict with the use of gluon interactions to describe the kinematical properties of the incoming (quasi-)quark.

The actual situation is of course in between the two limits above. The quasiparticle retains a certain coherence while acquiring some of its properties from the plasma. Whether this coherence is sufficient for quantum mechanics to play its part in the making of a CP-violating observable at the interface of the bubble is the subject of the remaining discussion.

The damping rate γ characterizes the degree of coherence of the quasiparticle. It is a measure of the spread in energy, $\Delta E \sim 2\gamma$, which results from the "disturbance" induced by the gluon exchanged between the quark and the plasma. From the energy-time uncertainty relation, $1/(2\gamma)$ is the maximum duration of a quantum mechanical process before the quasiparticle is scattered by the plasma. During this time, the quasiparticle propagates over a distance $\ell = v_g/2\gamma \simeq 1/6\gamma \simeq (100$ GeV$)^{-1}$, where v_g is the group velocity of the quasiparticle ($\sim 1/3$). The distance ℓ was introduced in Ref. 21 as the *coherence length*. The concept of coherence length leads to a straightforward description of the decoherence that occurs during

the scattering off a bubble.

Limited coherence and bubble reflection

To understand the impact of the limited coherence of the quasiparticle on the physics of scattering off the bubble, it is useful to remember the mechanism of the scattering of light by a refracting medium. According to the microscopic theory of reflection of light, the refracting medium can be decomposed into successive layers of scatterers which diffract the incoming plane wave, the thickness of a layer reflects the mean interspacing between scatterers d. The first layer scatters the incoming wave as a diffracting grid. Each successive layer reinforces the intensity of the diffracted wave and sharpens its momentum distribution. As more layers contribute to the interference, the diffracted waves resemble more and more the full transmitted and reflected waves. This occurs *only* because the wave penetrates the wall *coherently* over a distance large compared to the interspacing of the scattering sites $\ell \gg d$.

Inspired from the above, we slice the bubble into successive layers which scatter the incoming wave. The wavefunction for a quasiparticle reflected from the bubble is the superposition of the waves reflected from each of the layers. The bulk of the broken phase can be viewed as a distribution of scatterers whose mean spacing d is the inverse quark mass. However, in contrast with the scattering of light by a refractive medium, the coherence length $\ell \sim 1/100 \text{GeV}^{-1}$ of the quasiparticle is much shorter than the interdistance between scatterers $d \sim 1/m_q$. That is, the quasiparticle does not penetrate the bubble coherently over a distance large enough to be fully reflected and its reflection amplitude is suppressed by the ratio $\ell/d \sim m_q/(100 \text{ GeV}) \ll 1$. In addition, flavor changing processes have to occur along some reflection paths. Their amplitudes are suppressed by quark masses and mixing angles; the resulting mean interspacing d_F between scatterings is then much larger than the coherence length: $\ell \ll d_F$. These processes are rare events inside the outer layer of the bubble where coherent reflection takes place and their contribution to the reflection amplitude is suppressed by $\ell/d_F \ll 1$.

The generation of a *CP* violating observable results from interference of reflected waves and necessarily involves several flavor-changing scatterings inside the bubble in order to pick up the complex phase of the CKM matrix and several chirality flips. Altogether, the *CP* asymmetry $\Delta(\omega)$, produced by the scattering when decoherence is properly taken into account, will be smaller than the amount found by Farrar and Shaposhnikov by several factors of ℓ/d and ℓ/d_{F}.

From these physical considerations, it is easy to elaborate quantitative methods for computing the reflection of quasiparticles with a finite coherence length.

A simple model is obtained by expressing that when a quasiparticle wave reaches a layer a distance z into the bubble, its amplitude will have effectively decreased by a factor $\exp(-z/2\ell)$. We can take this into account by replacing the step-function bubble profile with a truncated profile such as $m_q(z) = m_q e^{-z/\ell}$, $z > 0$ and $m_q(z) = 0$, $z < 0$. The analog in the theory of light scattering is the scattering of a light ray by a soap bubble. It is clear that truncating the bubble in this way renders the bubble interface transparent to the quasiparticle.

Another method of computing $\Delta(\omega)$ is to solve an effective Dirac equation in the presence of the bubble, including the decoherence that results from the imaginary part of the quasiparticle self-energy. Green's functions are extracted which allow to construct all possible paths of the quasiparticles propagating in the bulk of the bubble, each path being damped by a factor $\exp(-\mathcal{L}/2\ell)$ where $\mathcal{L}$ is the length of the path. Paths occurring within a layer of thickness ℓ dominate the reflection amplitudes, in agreement with the previous considerations.

In Ref. 21, $\Delta(\omega)$ was computed using both methods. They give results qualitatively and quantitatively in close agreement. They yield the "baryon per photon" ratio

$$\left| \frac{n_B}{s} \right| < 10^{-26} \ .$$

It is 16 orders of magnitude too small to account for a significant fraction of the asymmetry observed today, $(n_B/s)_{Obs.} \sim 10^{-10}$.

Discussion

The arguments developed above are powerful enough to establish more generally that *the complex phase allowed in the CKM mixing matrix cannot be the source of CP violation needed by any mechanism of electroweak baryogenesis in the minimal standard model or any of its extensions.* Indeed, the generation of a CP-odd observable requires the quantum interference of amplitudes with different CP-odd and CP-even properties and whose coherence persists over a time of at least $1/m_q$. On the other hand, QCD interactions restrict the coherence time to be at most $\ell \sim 1/(g_s^2 T)$, typically three orders of magnitude too small. Because any CP-violating observable proceed through interference between amplitudes with multiple flavor mixings and chirality flips, the asymmetry between quarks and antiquarks appears to be strongly suppressed by many powers of ℓm_q and mixing angles. This line of argument does not rely on the details of the mechanism considered and can be applied to rule out any scenario of electroweak baryogenesis which relies on the phase of the CKM matrix as the only source of CP violation.

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