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BARYOGENESIS AND STANDARD MODEL CP VIOLATION

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ABSTRACT

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 matter-antimatter asymmetry of the observable universe is a fundamental question which has been addressed only recently. The generation of a CP observable occurs through interference of quantum paths along which a sequence of flavor mixings and chirality flips take place. The coherence of this phenomenon in the primeval plasma is limited by the fast quark-gluon interactions. At the electroweak era, this phenomenon of decoherence forbids a successful baryogenesis based on the sole CP violation of the CKM matrix.

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1. A possible mechanism.

Farrar and Shaposhnikov[2](FS) were first to propose a physical mechanism of baryogenesis whose source of *CP* violation is provided by the CKM matrix. The setting is the epoch of electroweak symmetry restoration, at $T \sim 100$ GeV. At that epoch, spherical domains (bubbles) of broken phase might have been nucleated in the unbroken phase. As these bubbles expanded, they communicate their mass to particles in the plasma creating a non-equilibrium environment localized at the phase boundary (wall). The scenario is 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 anomalous baryon violating processes* while the excess inside is left intact, leading to a net baryon asymmetry. The whole calculation of the baryon asymmetry is reduced to the determination of a suitably-defined thermal average of the left-right reflection asymmetry $\Delta(\omega) = \mathrm{Tr}(|R_{LR}|^2 - |\bar{R}_{RL}|^2)$, 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 thermally averaged *CP*-odd quantity $\langle\Delta(\omega)\rangle_T$ vanishes unless interactions with the neutral and charged bosons are taken into account in the propagation of the quarks in order to differentiate between left and right chiralities and to provide mixing between flavors. Furthermore, gluon interactions ought to be included for they strongly affect the kinematics of the quarks. FS suggested that all the relevant plasma effects can consistently be taken into account by describing the process as a scattering of suitably-defined *quasiparticles.*[5]

2. CP violating observable.

$\Delta(\omega)$ is a *CP* violating observable. A CP-violating observable is obtained by interfering various amplitudes with different CP properties. FS 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. They identified the source of the phase separation of baryon number as resulting from the interference between a path 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.

In Ref. 3, it was pointed out that the above analysis ignores the quasiparticle width embodied by the imaginary part of the thermal self-energy $\gamma \simeq 0.15 g_s^2 T \simeq 20$ GeV.[5] These authors made the observation that this spread in energy is much larger

*Via the thermal production of electroweak sphalerons.

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 has appeared recently.[4]

What follows contains a summary of an independent and alternative analysis[1] made in collaboration with E. Sather, which *fully* takes into account all relevant properties of a (quasi-)quark, as it propagates through the bubble wall.

3. 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. To illustrate how these processes affect the coherence of the wave function of a propagating quark, we 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. The system is correctly described by a totally incoherent density matrix. 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 pure state solution of the Dirac equation. 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 now addressed.

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 $\ell = v_g/2\gamma \simeq 1/6\gamma \simeq (100 \text{ GeV})^{-1}$, where v_g is the group velocity of the quasiparticle ($\sim 1/3$). The distance ℓ is introduced in Ref. 1 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.

4. 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. 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 $\ell \sim 1/100\mathrm{GeV}^{-1}$ of the quasiparticle is much shorter than the interdistance between the 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 $\ell/d \sim m_q/(100\ \mathrm{GeV}) \ll 1$. 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, is smaller than the amount found by FS 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. 1, $\Delta(\omega)$ was computed using both methods. They give results qualitatively and quantitatively in close agreement and yield the "baryon per photon" ratio $|n_B/s| < 10^{-26}$. It is 16 orders of magnitude too small to account for a significant fraction of the asymmetry observed today, $(n_B/s)_{Obs.} \sim 10^{-10}$.

5. 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 detail 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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