Cold electroweak baryogenesis and quantum cosmological correlations
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CHAPTER 5

CONCLUSIONS

In this part we studied Cold Electroweak Baryogenesis, which is a model that combines low scale inflation and electroweak baryogenesis. This model of electroweak baryogenesis is quite different from electroweak baryogenesis models studied before, because it takes place during a tachyonic transition at zero temperature instead of during the electroweak phase transition at finite temperature. In previous work [58, 61] it has been confirmed, using numerical simulations in the $SU(2)$ Higgs model, that this model can work: there is indeed baryon production, and if there is $CP$ violation an asymmetry can be produced. Here this work is extended in two directions: the mechanism of baryon production in CEB is studied in detail, and the amount of $CP$ violation from the CKM matrix is estimated.

In chapter 3 we studied the mechanism of baryon production in detail. The baryon number is related to the Chern-Simons number $N_{CS}$ via the anomaly equation (2.70) of the gauge fields, which is in turn closely related to the Higgs winding number $N_w$. To obtain more insight in the evolution of these numbers, we studied their densities $n_{CS}$ and $n_w$.

It has been suggested [56] that the Chern-Simons number is changed by decaying Higgs winding configurations, that are created by the Kibble mechanism. We find a slightly different picture: there are no clear-cut Higgs winding configurations, because there is no mechanism that can concentrate an integer winding number in a limited region in space (as there is energy minimization for stable winding configurations like monopoles). But there are regions where the Higgs length is small. These ‘half-knots’ have a large winding number density $n_w$ and a total winding number of approximately $1/2$. The winding number in the total volume is still integer, the other half is spread out over this volume. When the Higgs length in the center of a half-knot vanishes, the sign of its winding number can change. The total winding number $N_w$ then changes by an integer. When the system re-
laxes to its vacuum, the Chern-Simons number $N_{\text{CS}}$ adjusts to the Higgs winding number $N_w$ and a baryon has been produced.

These half-knots can occur in the initial conditions by statistical fluctuations, in which case we call them ‘early half-knots’. We found that they can also be formed later on. These ‘late half-knots’ seem to occur in regions where the Higgs length oscillates about its new vacuum quite strongly, often not in phase with the overall oscillation of the Higgs length, and with very little damping. These regions are reminiscent of oscillons. Because interactions are necessary for creating a $CP$ asymmetry, we expect that only the late half-knots are important for baryogenesis.

In chapter 4 we estimated the size of $CP$ violating effect from the CKM matrix in CEB. We did this by analyzing the effective action that is obtained by integrating out the fermions of the Standard Model. In the expansion in fields of this effective action, the first $CP$ violating term comes in at fourth order in the gauge fields $W^\pm$ and at fourteenth order in the Higgs field $\varphi_d$, in a way that is similar to the estimate (1.20). The expansion is valid for large momenta compared to the fermion ‘masses’ $\lambda_i \varphi_d$. When the expansion is valid, the $CP$ violating term is automatically very small because it is proportional to high powers of the expansion parameters.

An alternative expansion is the derivative expansion, that is valid for small momenta compared to the fermion masses. As explained in [80], it is likely that the coefficients of the $CP$ violating terms are not suppressed by the factor (1.20) as is the case in the expansion in fields.

For the case of CEB we argue that the momenta are larger than the fermion masses, and consequently that the expansion in fields is expected to be valid and the $CP$ violating effect to be small. In models of baryogenesis that use the electroweak anomaly for baryon number violation, the energy scale of baryon violation is the electroweak scale, while the $CP$ violation from the CKM matrix is typically only significant at lower energy scales.

We conclude that CEB is an interesting alternative to more conventional baryogenesis models. The mechanism of baryon production is quite different and may involve oscillons. However we expect that CEB shares the problem of too little $CP$ violation from the CKM matrix with conventional electroweak baryogenesis models. To resolve this the model has to be adjusted, for example by somehow matching the energy scales of baryon violation and $CP$ violation, or by adding an extra source of $CP$ violation.