Cold electroweak baryogenesis and quantum cosmological correlations

van der Meulen, M.P.

Citation for published version (APA):

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Throughout the course of time there have been many different ideas about cosmology, which is the study of the development of the universe on the largest scales. Nowadays the consensus is that the universe has reached its current state after a long period of expansion and cooling down. This idea is supported by ample observational evidence. Fred Hoyle, a scientist who was critical of the model of an expanding universe, described it derisively in a BBC radio show in 1950 as “this Big Bang model”, a term which has eventually become the name of this model.

There have also been many different ideas about the fundamental building blocks of nature. The branch of modern science that investigates nature at the smallest scales is called high energy physics or elementary particle physics. Particles are collided in accelerators, and the particles that are created in this process are studied. All the elementary particles and their interactions discovered in this way, are described very precisely by a quantum field theory called the Standard Model of particle physics. Despite the fact that the Standard Model explains the experimental data very well, there are indications that it is not yet complete.

Even though cosmology deals with the largest scales and high energy physics with the smallest, these two fields are connected. Many of the indications that the Standard Model is incomplete come from cosmology. An example that plays an important role in this thesis is inflation. This is a period in the early universe in which space expanded at an accelerated rate (in contrast with the decelerated expansion that occurred afterwards). From cosmology there are strong arguments that a period of inflation has occurred, but it seems impossible to explain this using the laws of the Standard Model. Apparently some extra ingredients have to be added. Other examples of the interconnection of cosmology and high energy physics are dark matter, dark energy and baryogenesis. This interconnection implies that cosmology provides an interesting alternative way to investigate the fundamental laws of nature.

This has only become a realistic possibility due to the many developments in cosmology over the past decades. New technologies, such as telescopes on satellites and large arrays
Summary

of detectors on earth, are providing large amounts of precise data. These developments changed the character of cosmology into a precision science. Expectations are that these developments will continue in the future and that cosmology will become more and more interesting for high energy physics.

In this thesis two subjects on the border between cosmology and high energy physics are treated. These are described more precisely in the following.

**Cold Electroweak Baryogenesis**

The first part of this thesis deals with the matter-anti-matter asymmetry. For every charged particle in the Standard Model there is a corresponding anti-particle with the opposite charge but otherwise identical characteristics. When a particle meets its anti-particle, they annihilate each other and radiation is emitted. Because we seldom see particle annihilation in everyday life, we know that there are nearly no anti-particles. There are also no indications of large amounts of anti-matter elsewhere in the universe. This leads us to conclude that there is a matter-anti-matter asymmetry. The process by which such an asymmetry is created is called baryogenesis.

It is not easy to determine whether or not such a process could have occurred within the laws of the Standard Model. For baryogenesis different numbers of particles and anti-particles have to be created, and there has to be a bias in favor of particles. Moreover, baryogenesis has to take place in a state that deviates strongly from thermal equilibrium. The Standard Model satisfies these conditions qualitatively in a scenario that is called Electroweak Baryogenesis. But quantitative analyses show that the asymmetry produced in this scenario is far too small. Therefore it is not possible to explain baryogenesis using purely Standard Model physics.

Over the course of time many other baryogenesis scenarios have been proposed, based on extensions of the Standard Model. One of these is Cold Electroweak Baryogenesis, which is based on a small extension of the Standard Model in which only an inflaton field is added. The interaction between the inflaton field and the fields of the Standard Model is such that it is possible for baryogenesis to take place directly after inflation, when the universe is still cold.

In the first part of this thesis the Cold Electroweak Baryogenesis model is studied more precisely. In chapter 3 the mechanism of particle production is studied using numerical simulations. The main conclusion is that certain field configurations, called ‘half-knots’, play an important role. These occur in the initial conditions, but can also be created later on. Those created later are likely to play a role in the generation of the asymmetry in this model.

In chapter 4 the possible degree of the asymmetry is investigated. This investigation leads
Summary
to the expectation that the asymmetry in Cold Electroweak baryogenesis is comparable to 
that of the original model of Electroweak Baryogenesis and therefore not large enough. 
Apparently this extension of the Standard Model by only an inflaton field is not sufficient 
to explain the asymmetry.

QUANTUM COSMOLOGICAL CORRELATIONS

The second part of the thesis deals with density fluctuations in the early universe. From 
observations of the background radiation (the radiation that was emitted approximately 
380 000 years after the Big Bang) we know that the matter in the universe was distributed 
very homogeneously at that time: fluctuations in the density were smaller than the average 
density by a factor of about 100 000. Under the influence of gravity these fluctuations 
have grown into the structure we observe today: stars, galaxies, clusters of galaxies and 
structures on even larger scales.

The question is where the first small density fluctuations come from. It is generally as-
sumed that they were generated by amplification of vacuum fluctuations during inflation. 
This effect, which applies to fluctuations with a large wavelength, is similar to the Haw-
king radiation that is emitted by black holes.

The observed fluctuations are characterized by correlation functions. Current observati-
ons indicate that their distribution is close to Gaussian, i.e. they are completely charac-
terized by their two point function, and that the power of the fluctuations is nearly scale-
independent. This corresponds to what one would expect for fluctuations generated during 
inflation. It will be interesting to see if more precise observations will lead to corrections 
to this distribution, because these corrections may teach us lessons about the physics of 
inflation.

For this reason a lot of effort is being put into the calculation of these quantum cosmo-
logical correlations generated in different models of inflation, in order to compare them 
to observations. These calculations use techniques from non-equilibrium quantum field 
theory and are rather complicated. Often, a part of the calculation is simplified by using 
classical field theory. One expects this to be a good approximation for a number of rea-
sons.

In chapter 7 a toy model is used to study these calculations more precisely. For this model 
the calculations (in quantum field theory) are formulated in such a way that they can easily 
be compared to those in classical field theory. The main conclusion is that a calculation 
in classical field theory can indeed be a good approximation of the corresponding one in 
quantum field theory, but that some higher order corrections cannot be reproduced. In 
addition we find that there is a certain freedom in defining the classical field theory and 
we discuss how this can be resolved. A detailed calculation is given as example.
Summary