Cold electroweak baryogenesis and quantum cosmological correlations

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High energy physics is the field of research in which the fundamental laws of nature are studied: the elementary particles and their interactions. Large accelerators, in which particles collide with speeds close to the speed of light, have given very precise experimental data. This culminated in the Standard Model of particle physics that describes all the known elementary particles and three of the four fundamental interactions between them.

A seemingly unrelated direction of science is cosmology in which space and time on the largest scales are studied with the goal to find out how the universe has become what it is and how it will develop further. Observations in this field have often been plagued by large uncertainties.

However, in the past decades the situation has changed substantially. New technologies, often involving space satellites, have transformed cosmology into a precision science. As such, cosmology provides a new window on high energy physics because many of the problems in cosmology are closely related to high energy physics. Developments in the fields of dark matter, dark energy, density fluctuations and many others do not only advance the field of cosmology but also that of high energy physics.

In this thesis two subjects in theoretical cosmology that are closely related to high energy physics are studied. The goal of the preface is to provide some background information that puts these two subjects in a broader framework. Much more information can be found in standard textbooks, such as references [1, 2, 3].

THE BIG BANG MODEL

According to the Big Bang model the universe is expanding. Initially the temperature and density were high, but due to the expansion the universe cooled down and became more and more dilute. This is widely accepted as a good description of the evolution of the universe. The first observational evidence for the Big Bang model was obtained by Hubble, who found that distant galaxies are moving away from us which indicates that space is expanding.
The process of cooling down triggered a cascade of events. Some of these events are:

- The electroweak phase transition. In this phase transition the electroweak symmetry was broken, which caused the weak interaction (which is responsible for nuclear fission) to be separated from the electromagnetic interaction. It took place at around $10^{-10}$ seconds after the Big Bang. This phase transition is important for the model that will be studied in part I.

- Nucleosynthesis. Nucleons (protons and neutrons) were bound together to form the nuclei of some of the chemical elements, such as helium, lithium, and others. This process occurred approximately three minutes after the Big Bang. The relative abundances of these elements have been calculated in the context of the Big Bang model, and were found to be consistent with the observed values. Therefore cosmologists are confident that the Big Bang model is valid at least from this moment onward. Any adjustments to the Big Bang model (like inflation, which will be discussed below) should have taken place before nucleosynthesis.

- Photon decoupling and atom formation. Electrons were bound to the nuclei to form neutral atoms. This took place at around 380 000 years after the Big Bang and caused the universe to become transparent. The radiation that was emitted at this moment is the Cosmic Microwave Background (CMB) radiation. This radiation is observed by satellite and balloon experiments which give us the earliest picture of the universe that we have. From this picture we know that the temperature of the universe at the time of photon decoupling was nearly the same in all directions. The observations of small fluctuations in the temperature have accelerated many developments in cosmology in the past 15 years. The CMB has yielded two Nobel prizes: in 1978 to Penzias and Wilson for its discovery, and in 2006 to Mather and Smoot for the measurements of the CMB using the COBE satellite [4].

**INFLATION**

The classic Big Bang model is very successful, but it also has some inherent problems. One of them is the flatness problem. From observations we know that the universe is to a good approximation flat (the spatial curvature vanishes), but according to the theory of general relativity this is not a stable situation: if the spatial curvature deviates only a small amount from zero, it will grow quickly. The only possible explanation for the current flatness of the universe is that the spatial curvature was initially extremely close to zero. However, such an initial condition requires a high degree of fine tuning.

The flatness problem and other problems can be solved by introducing a period of inflation, which is a period in which the universe is expanding at an accelerated rate (in contrast to the decelerating expansion in the classic Big Bang model). For example, for
the flatness problem one can show that during inflation the curvature is quickly driven to zero. Therefore a period of inflation can provide the desired initial conditions for a subsequent Big Bang phase.

At the end of inflation the universe is empty and cold. In order to return to a Big Bang phase the universe should be ‘reheated’. To not be in conflict with other observations, the reheating temperature should at least be above the temperature of nucleosynthesis.

Inflation plays an important role in current research in theoretical cosmology and also in this thesis.

**Baryogenesis**

Because the universe is empty at the end of inflation there are no baryons (which are the most important constituents of the matter we observe) and also no anti-baryons. Therefore the total baryon number \( B \), which is the difference between the numbers of baryons and anti-baryons, is equal to zero.

In the current universe however we observe only matter and nearly no anti-matter. Thus \( B \) is nonzero, and there must have been a process after inflation (and before nucleosynthesis) in which this asymmetry was generated. This process is called baryogenesis. It is a quite nontrivial process, which is illustrated by the fact that up to now we have never witnessed a baryon number changing event in the laboratory. Many models of baryogenesis have been proposed in the past.

In the first part of this thesis a specific model is studied: *Cold Electroweak Baryogenesis*. It combines a model of inflation with a model of baryogenesis which takes place just after inflation, during the reheating process (which is called preheating in this particular model).

**Density Fluctuations**

The solution to the flatness problem and the other problems of the classic Big Bang model was the original motivation for inflation. Nowadays the biggest virtue of inflation is considered to be the fact that it provides an explanation for the origin of the density fluctuations. These density fluctuations are the seeds from which the large scale structure (stars, galaxies, etc.) in the current universe has grown. They have been observed in the CMB with increasing precision by the COBE [4] and WMAP [5] satellites and other experiments.

The statistical properties of the fluctuations are characterized by their correlation functions. Because these correlation functions depend on what happened during inflation,
observations of the correlation functions provide a window into the physics of inflation. This is not only interesting from the point of view of cosmology, but also from the perspective of high energy physics, because inflation may have occurred at energy scales that are much higher than can ever be reached in the laboratory.

In the second part of this thesis we study the calculation of the cosmological correlation functions from inflation in quantum field theory. Many calculations have been done using classical field theory, and we estimate to what extent this gives a good approximation to the quantum calculations.