High precision measurements are intimately linked to major advances in the modern Science. A very famous example of the impact of a precision measurement on our notion of the laws of physics is the Michelson-Morley experiment \[158\]. It was carried out at the beginning of the 20th century to measure the movement of the aether wind by interferometric means. However, the experiment failed, and instead provided the first strong evidence that the velocity of light is constant, and irrespective of the speed of the observer. The knowledge obtained in this measurement resulted in the theory of special and general relativity.

Half a century later another high-precision experiment, carried out by Lamb and Retherford \[35\], provided detailed information about the electronic structure of the hydrogen atom. Surprisingly they found that it was in disagreement with predictions of the quantum theory at that time. This kind of discrepancies are now called ‘Lamb shifts’, and it has subsequently been explained with quantum electrodynamics theory (QED). The extension of the body of the quantum theory with QED did perhaps not revolutionize the scientific paradigm to the same extent as special (or general) relativity did, but it provided major new insights and tools for the description of the interaction between light and matter, and therefore also e.g. of atomic structure.

A central notion in QED is that the vacuum (or space in general) is never really empty, but in fact full of so-called virtual particles. These particles can be thought to appear, and quickly disappear again, within the constraints of Heisenberg’s uncertainty principle for energy and time. The shorter the time scale, the bigger the energy uncertainty is, leading to e.g. spontaneous electron-positron pair creation (and annihilation). Heisenberg’s uncertainty principle implies that virtual particles can exist only for extremely short time intervals, shorter than e.g. electron dy-
Summary

Dynamics in an atom. However, there is a net effect, e.g. on the energy states of atoms and molecules, which is what QED calculates. The idea that empty space is in fact full of constantly appearing and disappearing particles was a big surprise, and still appears strange to many. However, despite its strangeness, QED has been extremely successful and is currently the best tested physics theory.

QED can be tested in several ways, e.g. by performing precision laser spectroscopy on atoms and molecules. Ideally, the spectroscopy is performed in the form of a frequency measurement as it enables the highest accuracy in precision tests. The ultimate limit on accuracy in this case is determined by the frequency reference, typically an atomic clock. The most common one, available in national metrology institutes all over the world, is based on a microwave hyperfine transition in Cesium and can reach a typical fractional accuracy in the range of $10^{-13}$ - $10^{-16}$. The latest atomic clocks based on an optical transition have even reached a precision on the order of $10^{-17}$ in a relative frequency measurement [11]. However, absolute measurements with this level of accuracy are presently impossible because the standard of time and frequency is still based on Cesium clocks.

To perform optical frequency measurements for laser spectroscopy is not trivial. Until about a decade ago, complex "frequency chains" were needed in order to transfer the accuracy of microwave atomic clocks to the optical region at frequencies of several hundred THz. This typically required a big lab, including a lot of lasers and electronics, and several people to run it. The invention of the optical frequency comb [10, 60] has changed all that, and optical frequency determinations have now almost become routine. Frequency combs are generally based on modelocked lasers which are often smaller than 1 m$^2$ in size, and can be operated by a single person. External feedback is used for precise control over the repetition rate and phase evolution of the optical pulses from such a laser. As a result the spectrum of the pulses is equal to typically hundreds of thousands of equidistant modes. The positions of the modes can be described by just two radio frequencies that can easily be measured electronically. The frequency comb laser can therefore act as a gear wheel transmission between the radio frequencies where most atomic clocks operate, and optical frequencies that are used for laser precision spectroscopy. This principle has caused a revolution in many
scientific fields. Frequency combs are now a vital part of the best optical atomic clocks, and play an important role in the field of attosecond physics, which studies phenomena that take place on a time scale of $10^{-18}$ seconds. However, up to now there have been no frequency comb devices that would allow measurements in the extreme ultraviolet.

In this thesis a method is demonstrated to test QED on the ground state of helium, by performing the first absolute frequency measurement in the extreme ultraviolet at 6 PHz (51 nm) with a frequency comb in the XUV. This XUV comb (XFC) is based on harmonic upconversion of a near-infrared frequency comb. The ground state ionization energy of helium obtained with the XFC has an unprecedented accuracy of $10^{-9}$. From this measurement a Lamb shift of the helium ground state is derived equal to 41247(6) MHz, which agrees with the most recent theoretical predictions of 41284(36) MHz [30], 41285(36) MHz [32, 31] and 41264(42) MHz [23], though challenging their precision. The measured value is precise enough to resolve the discrepancy between the previous measurements of the helium ground state energy. Correcting Eikemas [40] result for the missing recoil shift yields a Lamb shift of 41250(45), which is confirmed by the result presented here. Bergesons [41] value, however, is almost $3\sigma$ away.

The first two chapters of this thesis introduce the theoretical background of the energy structure of helium and of the employed experimental techniques. Chapter 3 then gives a systematic overview of the components of the XUV-frequency comb (XFC) source. An important ingredient is parametric amplification of frequency comb pulses. In chapter 4 an investigation is presented about the phase stability of broadband single-pulse parametric amplification. To convert a frequency comb to the XUV actually a minimum of two pulses from a comb laser need to be amplified. Such a system is presented in chapter 5, including a phase characterization of the amplified pulses. The final step to convert the frequency comb to the XUV takes place with high-harmonic generation using the amplified pulses. The generated light has been used to coherently excite helium from the ground state to one of the higher lying P states. In effect the excitation takes place with a frequency comb created at the $15^{th}$ harmonic of the original infrared pulse pair. The excited helium atoms were ionized by a 1064 nm laser pulse and detected in a time of flight mass spectrometer. Scanning of the XFC over the
transition is realized by changing the repetition rate of the fundamental oscillator. This gives rise to Ramsey fringes in the observed excited state population. Recording of the signal at (several) repetition rates between $100 - 185$ MHz allowed to determine the frequency of the observed transitions, and derive the ionization energy of the ground state. A detailed account of this experiment is given in chapter 6. Finally, in chapter 7, an outlook is given for future experiments with the developed extreme ultraviolet frequency comb.