In the world of science, scientific theories are used to describe features in the observable world. Often, such theories can be empirically tested on their correctness. Practically, one takes an observable variable like the charge of an electron or the wavelength of a light ray, and if the predicted theoretical value of this variable agrees with the experimentally obtained value, the theory is indicated to be correct. In this research, the theory named quantum electrodynamics has been experimentally tested with very high precision. This theory describes the mutual interaction between electrically charged particles and their interaction with light. As all ordinary atoms and molecules in the universe contain electrically charged particles, most phenomena are at a fundamental level described by this theory.

This thesis describes a measurement which is carried out on one of the simplest known molecules, HD\(^+\), which only consist of two nuclei (a proton and a deuteron) a single electron. The variable compared to theory, is the required energy to bring the molecule in a state of vibration. This energy is delivered by an infrared laser which is directed at a bunch of HD\(^+\) molecules in a laboratory setup. Such experiments, also called spectroscopy measurements, can be performed with very high accuracy, and in this case, a precision of less than one billionth is achieved.

In Chapter 1, the idea and motivation of this experiment are introduced, and a short summary of quantum electrodynamics is presented together with a historical overview of high precision measurements and high precision calculations on three body molecules.

During the experiment, HD\(^+\) molecules are trapped in an ion trap and cooled down to a fraction above the absolute zero temperature (−273.15 °C). The cooling is done indirectly by the use of very cold beryllium ions, which are cooled themselves with an ultraviolet laser. In Chapter 2, in which the setup of the experiment is described, the operation of the ion trap, lasers and the necessary electronic equipment is explained. In chapter 3 a new technique is presented which enables high speed tuning of the ultraviolet cooling-laser frequency over a large frequency range; this has been very useful during the experiment.
Chapter 4 is the core of this thesis and describes the spectroscopic measurement on HD\(^+\) in detail. During the measurement some chemistry processes were involved which could not be characterized in the laboratory directly, but affected the result significantly. The effect of those processes onto the result is determined with the help of computer simulations using supercomputers of SURFsara.

By repeating a single HD\(^+\) measurement almost two thousand times, sufficient data has been collected in order to obtain a spectroscopic result with an inaccuracy, as mentioned, of one about one billionth. This experimentally obtained value of vibrational energy in HD\(^+\) agrees, within its uncertainty, with the theoretically predicted value. Therefore, we can conclude that the theory of quantum electrodynamics describes the system of HD\(^+\) correctly onto the one part-per-billion level. This measurement is currently the most stringent test of quantum electrodynamics in an ordinary molecule.

In Chapter 5 the same experiment is explained in short and the spectroscopic result is used to determine a new value of the proton-to-electron mass ratio. Also new bounds are obtained on the presence of new physics, like the existence of ‘fifth forces’ between hadrons (particles like protons or neutrons). Furthermore a new upperlimit is given on the compactification radius of unobserved higher spatial dimensions.