**Summary**

Trapped ultracold dilute gases constitute an excellent example of so-called macroscopic quantum systems. In these systems, the effects of typical quantum phenomena such as wave-particle duality, Heisenberg uncertainty and quantum statistics become visible at a length scale much larger than the size of an atom.

This thesis describes experiments in which ultracold samples are created of helium atoms in the metastable $^2\text{S}_1$ state. Metastable helium is special because of its high internal energy, which allows detection not only by absorption imaging, but also by particle detectors such as microchannel plate (MCP) detectors. Furthermore, collecting ions produced by collisions between cold metastable helium atoms provides a means of extracting information about a trapped cloud of atoms in a non-destructive way. The temperature and number of atoms of an atomic cloud can be determined by releasing it onto an MCP detector.

The process of trapping and cooling of the atoms is described in detail in chapter 4. In short, a vacuum chamber is filled with helium gas. The atoms are brought into the metastable state by electron bombardment in a discharge. The radiation pressure of photons from laser beams is used to create a collimated beam of metastable atoms. Another laser beam is directed against the propagation direction of the beam and slows the atoms down over a distance of more than two metres. The slowed atoms are captured in a magneto-optical trap (MOT), consisting of a quadrupole magnetic field and a configuration of six orthogonal laser beams that overlap at the centre of the trap. The MOT contains about $10^9$ helium atoms at a temperature of 1 mK. After the MOT is loaded, the atoms are transferred to a purely magnetic trap and cooled further by a weak laser beam. Next, the effective depth of the trap is slowly reduced by applying a radio frequency electromagnetic field, allowing the most energetic atoms to escape. The remaining atoms redistribute their energy by elastic collisions, thereby reducing
the temperature of the sample.

After evaporative cooling, the atomic cloud has a temperature of a few \( \mu \text{K} \) and a density of the order of \( 10^{12} - 10^{13} \) atoms per cm\(^3\). In this ultracold cloud, the effect of quantum statistics on two isotopes of helium, \(^3\text{He}\) and \(^4\text{He}\), can be observed. \(^4\text{He}\)-atoms are bosons and \(^3\text{He}\)-atoms are fermions. Two-particle wave functions are symmetric (antisymmetric) for bosons (fermions). As a result, each quantum state can only be occupied by one fermion, whereas the number of bosons per state is not limited. This leads to a striking difference in behaviour between \(^3\text{He}\) and \(^4\text{He}\) if the atoms are cooled down to sufficiently low temperatures, and the occupation numbers of the lowest lying energy levels of the magnetic trap become relatively high.

At ‘high’ temperatures (roughly above 10 \( \mu \text{K} \)), when the atoms can be treated as distinguishable particles, the size of a cloud of weakly interacting atoms trapped in a harmonic potential is proportional to the square root of the temperature (and independent of the number of atoms). Lowering the temperature will cause the atomic cloud to shrink gradually. This changes when the cloud is cooled down into the regime where the de Broglie wavelength of the atoms becomes of the order of the interparticle distance: chapter 5 describes the collapse of bosonic \(^4\text{He}\)-atoms into the ground state of the trap, a process called Bose-Einstein condensation (BEC). The atoms then form a coherent system, consisting of up to ten million atoms that all behave like a single entity with a size of a few hundred microns.

The fermionic \(^3\text{He}\), on the other hand, behaves in more or less the opposite way: below a certain temperature, the lowest energy levels are each occupied by a single atom and a further reduction of the temperature does not change the size of the cloud. Such a quantum degenerate Fermi gas was created in our lab, using \(^4\text{He}\) atoms as a refrigerant to sympathetically cool \(^3\text{He}\). Since we were able to create a BEC of \(^4\text{He}\) at the same time, we produced the first quantum degenerate Bose-Fermi mixture consisting of metastable atoms. The publication describing this accomplishment is included as chapter 6. Chapter 2 serves as a theoretical introduction to chapters 5 and 6.

Finally, the opposite symmetry of the two-particle wave functions of both isotopes of helium was observed in a different kind of experiment. As described in chapter 3 measuring correlations in the positions of atoms in an atomic cloud released from a trap, provides information about the nature of the cloud as it was trapped. Quantum interference between probability amplitudes for two indis-
tistinguishable processes, both leading to simultaneous detection of two atoms, increases the probability of detecting two bosonic $^4\text{He}$-atoms within a distance called the correlation length. This is called ‘bunching’ of bosons, also known as the Hanbury Brown and Twiss-effect. In contrast, the probability of finding two $^3\text{He}$-atoms close to each other is smaller than expected for classical (distinguishable) particles: fermions show ‘antibunching’ behaviour.

Together with the cold helium group from the Institute d’Optique in Orsay (now Palaisau), we were able to measure and compare these pair correlations for the fermionic and bosonic isotopes of helium. The Nature paper that resulted from this collaboration is reproduced in chapter 7.