Summary

The exquisite control of the internal and external degrees of freedom makes ultracold atomic samples an ideal platform to study various fascinating physical phenomena, examples of which can be found in few-body physics such as the observation of Efimov quantum states and many-body physics where ultracold samples could be used to simulate condensed-matter systems. The ultracold regime implies samples that are below a millikelvin, and to reach these temperatures, techniques such as laser cooling, magneto-optical trapping, and evaporative cooling in a magnetic or optical trap are employed. Sample temperatures can even reach below a microkelvin and surpass a critical limit such that Bose-Einstein condensation (bosons) or a quantum degenerate Fermi gas (fermions) is realized. Experiments with ultracold samples are not limited to single atomic species but also involve chemically distinct atomic mixtures, application for example is the creation of ultracold heteronuclear molecules. Mostly, ultracold mixtures consist of alkali atoms while recently also mixtures between alkali and alkaline-earth atoms are explored.

The main goal of the experiment described in this thesis is to realize an ultracold mixture of helium (in its metastable state: \(^4\)He\(^*\)) and rubidium (\(^{87}\)Rb) atoms in an optical dipole trap. Generally, mixtures between alkali and metastable helium atoms are still unexplored and prior to this experiment, trapping in an optical dipole trap had not been achieved. Pure optical trapping allows trapping of atoms in any spin state and is essential in applications where the interaction requires tuning using an external magnetic field via a so-called Feshbach resonance. The application of metastable helium in ultracold atom experiment could provide an extended range of possible mass ratios for heteronuclear mixtures. The metastable state of helium is used for laser cooling as ground state atoms cannot be directly laser cooled because the wavelength needed is in the extreme ultraviolet and no laser is available at that wavelength. The metastable state cannot decay directly to the ground state and has a lifetime of approximately 8000 s, which is more than sufficient to perform any (ultra)cold atom experiment. Another important property of metastable helium is the large internal energy of 19.8 eV. This provides a strong inelastic two-body process known as Penning ionization, which limits the trapping lifetime, however is strongly suppressed for
a mixture prepared in a doubly spin-stretched state. The Penning ionization reactions, in mixtures prepared in various spin-state combinations, have been investigated in a single-beam optical dipole trap by measuring trapping lifetimes. Details of this experiment are presented in Chapter 5, where control of Penning-ionization reactions by internal atomic state preparation was demonstrated.

The approach to realize an ultracold sample is based on a relatively simple scheme that starts with laser cooling and magneto-optical trapping to slow down, collect and cool atoms from basically room temperature. In the experiment, $10^8 - 10^9$ atoms are confined at temperatures between 1 and 2 millikelvin ($^{4}\text{He}^+$) and a few hundreds microkelvin ($^{87}\text{Rb}$) in a magneto-optical trap. To efficiently transfer atoms into an optical dipole trap, the sample is first transferred to a pure quadrupole magnetic trap, which is the simplest configuration among magnetic traps. Forced evaporative cooling is performed by lowering the quadrupole magnetic trap depth in a controlled way such that the more energetic atoms can escape and the remaining atoms rethermalize to a lower temperature. Afterward the sample is transferred into a single-beam optical dipole trap via a recently invented scheme known as a hybrid trap, which is simply a single-beam optical dipole trap combined with a weak quadrupole magnetic trap. In the hybrid trap or single-beam optical dipole trap, typical sample temperatures for both Rb and He$^+$ reach below 25 microkelvin.

One major limitation of using a quadrupole magnetic trap is the presence of Majorana spin-flips at the bottom of the trap, which limits the lowest temperature that can be achieved by evaporative cooling and puts constraints on the subsequent transfer into an optical dipole trap. The Majorana effect scales inversely with mass and is more pronounced for light atomic species such as helium. In fact, it is for this reason that the hybrid trap scheme is applied mostly to heavy atomic species such as rubidium. Furthermore, in the hybrid trap scheme the weak quadrupole magnetic field gradient should provide a force that is equal or lower than the force due gravity, which is known as the levitation gradient, to ensure that atoms are confined by the single-beam optical dipole trap and not by the weak quadrupole magnetic trap. Thus, for light atomic species the extra confinement provided by the weak quadrupole magnetic gradient is also limited due to the small levitation gradient.

In a single species preparation, sufficiently low temperature could be reached (below 1 microkelvin) such that Bose-Einstein condensation of $^{87}\text{Rb}$ atoms was achieved using the hybrid trap scheme. Similarly, also Bose-Einstein condensation of $^{4}\text{He}^+$ atoms was realized both in the hybrid trap and in a single-beam optical trap (details of the experiment are discussed in Chapter 3), which is a remarkable achievement given the constraints mentioned earlier. However, in the mixture preparation (details are presented in Chapter 4), the additional interspecies losses and constraints due to the
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Majorana effect reduced the transfer efficiency into the hybrid trap or single-beam optical dipole trap by at least an order of magnitude compared to the single-species preparation. The limited number of atoms of both species hinders further forced evaporative cooling in the hybrid trap or single-beam optical trap towards dual Bose-Einstein condensation. In Chapter 6, changes in the existing experimental setup that can improve the transfer efficiency of the mixture into the single-beam optical dipole trap are proposed.

The work described in this thesis did not only demonstrate the first realization of an optically trapped ultracold mixture of an alkali and metastable helium atoms but also triggered theoretical work about the scattering properties of this mixture. For instance, _ab initio_ calculations of the interaction potentials have been performed for various alkali (Li, Na, K and Rb) and metastable helium (\(^3\)He* and \(^4\)He*) combinations revealing important information such as the scattering lengths, which is in good agreement with experiments (for example in \(^{87}\)Rb and \(^4\)He* mixture). In addition, the detailed outline of the experimental issues and features presented in this thesis, for example the successful application of simultaneous microwave (\(^{87}\)Rb) and radiofrequency (\(^4\)He*) based forced evaporative cooling in the magnetic trap, will guide future experiments using these type of mixtures. Moreover, from the observed near-universal loss and dependence of the Penning ionization reaction on the internal state preparation of the atoms, one can estimate the two-body losses in other alkali and metastable helium isotope combinations.