Chapter 1

Introduction

In this chapter, a brief introduction on (ultra)cold atom experiments is given, starting with the early experiments on laser cooling, the realization of quantum degenerate atomic samples, and the evolution of the field to include experiments with ultracold heteronuclear mixtures. A description about the atomic species used in our experiment, namely helium (in its metastable triplet state) and alkali atoms (in particular Rb), is presented.
1.1 Ultracold atomic gases

Experiments with cold neutral atoms started around the 1980's with the demonstration of laser cooling of sodium atoms [1–6]. Immediately, the topic attracted fast growing interest, and with the demonstration of various cooling and trapping techniques such as Doppler cooling [7], magneto-optical trapping [8] and evaporative cooling in a magnetic trap [9, 10], neutral atoms could be confined with average velocities close to zero and sample temperatures were pushed down below 1 mK, which is called the ultracold regime. In 1997, the Nobel prize in Physics was awarded jointly to Steven Chu, Claude Cohen-Tannoudji and William Phillips for their pioneering work on laser cooling. In 1995, the group of Cornell and Wieman and the group of Ketterle demonstrated cooling of a dilute gaseous sample containing neutral atoms (Rb: NIST group [11] and Na: MIT group [12]) to temperatures of a few µK down to a few hundreds of nK, reaching a new state of matter known as a Bose-Einstein condensate (BEC). In 2001, the Nobel prize in Physics was also awarded jointly to Eric Cornell, Carl Wieman and Wolfgang Ketterle for their work on realizing and characterizing a BEC. The success of cooling down neutral atoms towards BEC owes mainly to the efficiency of the evaporative cooling technique, which relies on sufficiently fast rethermalization by means of elastic collisions between the trapped atoms. Bose-Einstein condensation occurs when an ensemble of identical particles with integer spin (bosons) are cooled down to ultralow temperature where the interatomic separation becomes comparable to or smaller than the de Broglie wavelength such that the individual atomic wave functions overlap, and a significant fraction of the ensemble occupies the lowest available quantum state. In contrast, particles with half-integer spin (fermions) obey the Pauli exclusion principle, and are governed by Fermi-Dirac statistics. The evaporative cooling technique applicable to bosons does not directly apply to fermionic species, simply because at ultralow temperature, indistinguishable fermions do not collide. Nonetheless, it did not take long before cooling a fermionic species to quantum degeneracy was also reported. In 1999, DeMarco and Jin demonstrated quantum degeneracy of fermionic potassium ($^{40}$K) using the same laser cooling and magnetic trapping techniques applied for bosons, however, using two distinguishable Zeeman states [13].

While the first BECs and quantum degenerate Fermi gases (DFGs) were realized in a magnetic trap, there have been efforts and proposals in the earlier development of the field to prepare cold atom samples in an optical trap [14]. Among the various motivations is that, in contrast to a magnetic trap, an optical trap can in principle provide confinement independent of the spin-state, thereby allowing trapping of high-field seeking states and zero magnetic moment atoms such as the alkaline-earth. Another example is the case of Cs, for which evaporative cooling in a magnetic trap is not favorable because of strong two-body losses [15]. First principles of pure
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optical trapping were already introduced in 1986 by Steven Chu [16] but it was only until 1998 that the first realization of trapping a BEC in an optical dipole trap was reported by the group of Ketterle [17]. It was a significant breakthrough, and was immediately followed by the observation of magnetically induced Feshbach resonances [18], for which a trapping potential that is independent of magnetic field is essential. A Feshbach resonance occurs when the energy of a colliding atom pair becomes degenerate with a bound molecular state, and for ultracold atoms such a resonance can be induced by an applied magnetic field. A comprehensive discussion about Feshbach resonances in ultracold atomic gases can be found in the review paper by Chim et al. [19]. Around a Feshbach resonance, the elastic and inelastic collision properties are strongly modified, opening the realization of BEC for atomic species that have unfavorable collision properties at zero magnetic field, such as $^{85}$Rb [20] and Cs [21], and more generally gives rise to quantum gases with tunable interaction strength. Furthermore, because of the coupling with a bound molecular state, Feshbach resonances can be used to associate ultracold molecules from ultracold atoms [22, 23], which paved the way for the creation of ultracold ground state molecules [24–26].

Several atomic species (bosonic and fermionic) have been cooled down to quantum degeneracy including all the stable alkali isotopes [11–13, 20, 21, 27–30]. An alkali atom has a relatively simple electronic structure with a single valence electron. Laser cooling can be easily applied in which only one additional laser is needed for repumping due to the presence of hyperfine structure. Later, quantum degenerate samples of alkaline-earth (Sr [31] and Ca [32]), metastable He [33–36], Cr [37] and lanthanides (Yb [38, 39], Dy [40, 41] and Er [42]) were also realized.

The ultracold regime offers exquisite control over the internal and external quantum degrees of freedom. This makes ultracold atomic gases an ideal platform to study various fascinating physical phenomena. One example in few-body physics is the observation of Efimov quantum states using an ultracold sample of Cs atoms [43]. A review about the application of ultracold atoms to study few-body system can be found in the paper by Wang et al. [44]. Ultracold atomic samples also offer a range of applications in many-body physics (see e.g. review paper by Bloch et al. [45]), for instance in quantum simulations, such as experiments with optical lattices to simulate condensed-matter systems (e.g. the study of the superfluid to Mott insulator transition [46]). A review about quantum simulations with ultracold gases can be found in the article by Bloch et al. [47]. Furthermore, ultracold samples have also been used for high precision spectroscopy, in which a good handle on the systematics (e.g. precise knowledge of the lineshape) and long interaction times are possible, allowing to probe very weak transitions [48, 49].
1.2 Ultracold mixtures

Experiments with ultracold atoms have been extended to mixtures of chemically distinct atomic species. In general, working with ultracold mixtures poses additional experimental challenges because in principle it requires twice the infrastructure for laser cooling as compared to the single species. There are also additional losses in a magneto-optical trap (MOT) due to interspecies inelastic collisions [50, 51]. More often, the distinct magnetic properties of the atomic species involved put additional constraints for forced evaporative cooling in a magnetic trap. Another example is the separation of the atomic clouds caused by a differential gravitational sag. Still, ultracold mixtures offer fascinating scientific opportunities. To name a few, for atomic species in which typical evaporative cooling will not work (like fermions or bosons with unfavorable collision properties), it enables the realization of ultracold samples via sympathetic cooling with another species [28, 52, 53]. Another example is the creation of ultracold heteronuclear molecules (via association of two distinct ultracold atomic species), that can possess an electric dipole moment [25], in contrast to homonuclear molecules. Ultracold mixtures have also been used to study impurities immersed in Bose or Fermi gases [54–56], and testing the universality for free-fall [57].

Mostly, ultracold mixtures of chemically distinct atomic species consist of alkali atoms [28, 52, 58–65]. These experimental efforts laid the foundation for the creation of ultracold heteronuclear ground-state molecules, which possess a large permanent dipole moment: KRb [25], RbCs [66, 67], NaK [68] and NaRb [69]. Another example is the observation of successive Efimov states in Li+Cs [70, 71], benefiting from the largest possible mass ratio within the alkali group. Recently, mixtures of alkali and alkaline-earth [72] or Yb [73–77] atoms have also been reported where the main interest comes from the doublet $^2\Sigma^+$ molecular ground state potential that gives rise to both electric and magnetic tunability of the associated molecules, in contrast to the singlet $^1\Sigma^+$ ground state potential of bialkali molecules.

The main goal of this thesis is to realize an optically trapped ultracold mixture of an alkali and helium in the metastable triplet $^3S_1$ state (denoted as He*). Ultracold mixtures of alkali atoms and fermionic $^3\text{He}^*$ or bosonic $^4\text{He}^*$ provide new Bose-Bose, Bose-Fermi and Fermi-Fermi mixtures, with an extended range of possible mass ratios.

1.3 Metastable He and Penning ionization

The two naturally occurring abundant isotopes of He are $^3\text{He}$ (fermion) and $^4\text{He}$ (boson). In our experiment, we are only using bosonic $^4\text{He}$. Thus, the succeeding sections and chapters only refer to $^4\text{He}$ unless otherwise specified. The He atom, having only two electrons, has a relatively simple electronic...
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Figure 1.1: Energy level scheme of the first few states of the He atom. The metastable triplet state and the ionization limit lie 19.8 eV and 24.6 eV, respectively, above the ground state.

structure (see Fig. 1.1 for the energy level scheme of the first few states of the He atom). In contrast to alkali atoms, laser cooling of He in its ground state is not (yet) possible as the required wavelength is in the extreme ultraviolet. However, one can use the metastable triplet state $2 \, ^3S_1$ ($\text{He}^*$), which can be accessed using a dc-discharge. The lifetime of this metastable state is about 8000 s, which is more than sufficient to perform laser cooling and subsequent trapping experiments. For laser cooling, the $2 \, ^3S_1 \rightarrow 2 \, ^3P_2$ transition at 1083 nm can be used, for which fiber lasers are available.

An important feature of $\text{He}^*$ is the high internal energy of 19.8 eV, enough to ionize almost any atom or molecule, in a process that is known as Penning ionization (PI). For ultracold $\text{He}^*$ samples, collisions between $\text{He}^*$ atoms are relevant, where besides PI (leading to a ground state neutral He atom and a Hel ion) also a molecular ion via associative ionization (AI) can be formed:

$$\text{He}^* + \text{He}^* \rightarrow \begin{cases} \text{He} + \text{He}^+ + e^- \\ \text{He}_2^+ + e^- \end{cases} \quad (1.1)$$

These strong two-body inelastic processes, to which we both refer to as PI, lead to trap loss. Initial experiments with $\text{He}^*$ in a MOT suffered from strong PI loss, limiting the number of atoms in the trap on the order of $10^4$ [78]. However, later experiments demonstrated that using a large capture volume and far-detuned laser cooling light allows trapping of at least $10^7$ [79] and up to $10^9$ [80] atoms in a MOT. Moreover, it was also shown that PI can be suppressed by several orders of magnitude in spin-polarized samples due
to spin conservation [81–83]. This can be explained as follows: A He* atom has a total electron spin \( s = 1 \) thus the left side of the PI reaction described in Eq. 1.1 can in principle carry a total spin \( S = 0,1,2 \) (corresponding to the singlet, triplet or quintet interaction potentials, respectively). The right hand side (product side) of the PI reaction however can only carry \( S = 0,1 \). Thus, PI can only proceed via the singlet \( (S = 0) \) or triplet \( (S = 1) \) potentials, and is forbidden for the case of pure quintet scattering \( (S = 2) \). Evaporative cooling is also favorable (for the bosonic \(^4\text{He}^* + ^4\text{He}^*\)) because of the large quintet scattering length \( a = 142a_0 \) [84], where \( a_0 \) is the Bohr radius. In 2001, realization of \(^4\text{He}^*\) BEC’s were reported [33, 34]. In 2006, DFG of \(^3\text{He}^*\) was also realized using \(^3\text{He}^*\) to sympathetically cool \(^3\text{He}^*\) [36]. To suppress PI, a pure quintet spin-state combination is also necessary for the \(^3\text{He}^* + ^4\text{He}^*\) mixture. Note that the scheme of using two distinguishable Zeeman states as for instance applied for the fermionic \(^6\text{Li}\) and \(^40\text{K}\) will not work for \(^3\text{He}^*\) due to the presence of PI loss. The large internal energy of 19.8 eV also provides additional detection schemes that are not possible for other atomic species, most prominently, one can use microchannel plates (MCP). A overview on (ultra)cold metastable noble gas experiments, with an emphasis on He*, can be found in a review paper by Vassen et al. [85].

1.4 He*+alkali mixtures

With He* having electron spin \( s = 1 \) and an alkali atom with electron spin \( s = 1/2 \), the scattering properties of a He*+alkali mixture are described by two interaction potentials, namely the shallow quartet \(^4\Sigma^+\) (total spin \( S = 3/2 \)) and the much deeper doublet \(^2\Sigma^+\) (total spin \( S = 1/2 \)) potentials (see Fig. 1.2 for the specific case of He*+Rb). In addition, similar to the homonuclear He* case, there is also the possibility of Penning ionization:

\[
\text{He}^* + A \rightarrow \begin{cases} 
\text{He} + A^+ + e^- \\
\text{He}A^+ + e^-
\end{cases}
\] (1.2)

leading to trap loss. The left hand side of the PI reaction in Eq. 1.2 can carry a total spin \( S = 1/2 \) or \( S = 3/2 \) while the right hand side can only carry \( S = 1/2 \). Thus, like in the homonuclear case, PI can be also suppressed if the mixture is prepared in the doubly spin-stretched spin-state combinations corresponding to a magnetic and hyperfine quantum numbers as \(|m_s = \pm 1\rangle_{\text{He}^*} + |f = f_{\text{max}}, m_f = \pm f_{\text{max}}\rangle_A\), where \( f_{\text{max}} = i + 1/2 \) and \( i \) is the nuclear spin of the alkali isotope. This combination corresponds to pure quartet scattering. Here, the main assumption is that the first excited ionic state is not accessible, which is true for all alkali atoms except Cs, where the energy of the first excited ionic state is only 17.2 eV [86]. PI proceeds predominantly via the doublet interaction potential. The possibility of suppression of PI for particular spin-state combinations is quite unique,
1.4. He* + alkali mixtures

Figure 1.2: Doublet $^2\Sigma^+$ (red) and quartet $^4\Sigma^+$ (blue) interaction potentials for the case of He*+Rb. The quartet potential is an exact trace based on \textit{ab initio} calculation [87, 88] while the doublet potential is an approximate trace based on the position of the minimum energy and well depth [89].

present in He*+He*, He*+H and He*+alkali collisions, but not for various other combinations with He* like with the alkaline-earth atoms. The stable doubly spin-stretched spin-state combination can be used for the preparation stage to reach the ultracold regime, possibly reaching doubly quantum-degenerate mixtures. However, the study of Feshbach resonances or Penning ionization requires a mixture with scattering properties given by both doublet and quartet potentials. Feshbach resonances are in principle possible for this collision system due to the hyperfine coupling between the doublet and quartet interaction potentials.

Previous experimental studies of He*+alkali collisions have been performed at thermal energies in stationary afterglow and merged-beam experiments (see e.g. [89, 90]). It must be noted that here only the doublet potential is being probed because the measurements were based from electron spectra and/or losses that are related to PI. In contrast, experiments with ultracold gases allow to also probe the quartet potential via measurement of elastic cross-sections [88]. Recently, quartet scattering lengths for the various Ho*+alkali mixtures, obtained from \textit{ab initio} calculations, became available [87]. \textit{Ab initio} calculations of the doublet potential are not yet available. These are much more challenging than the quartet ones, because the PI channel needs to be implemented. But even without PI, the possible accuracy of doublet scattering lengths will be much less, as the doublet potentials are much deeper than the quartet ones (at least a factor of
10) [89], leading to a higher sensitivity of the calculated potentials to the scattering lengths.

1.5 $^4\text{He}^* + ^{87}\text{Rb}$

For the alkali partner, $^{87}\text{Rb}$ was chosen for two main reasons. First, it is experimentally convenient to prepare via standard laser cooling and trapping techniques, and therefore has been used extensively in various (ultra)cold atom experiments, including several mixtures. Second, among the various atoms in the alkali group (excluding Cs because the spin-stretched state suffers from strong two-body loss), Rb provides the highest mass ratio which is an interesting feature for a heteronuclear mixture (see e.g. [70, 71]).

Prior to the start of our experiment (2011), not much was known about the interaction potentials and collisional properties of $\text{He}^* + \text{Rb}$. The first simultaneous laser cooling and trapping of $^4\text{He}^*$ and $^{87}\text{Rb}$ was demonstrated by the Truscott group [91], and they measured an interspecies two-body loss rate of $(6 \pm 2) \times 10^{-10} \text{ cm}^3\text{s}^{-1}$ in a magneto-optical trap. They had also demonstrated pure magnetic trapping of the low-field seeking doubly spin-stretched spin-state combination, and measured an upper limit of the PI rate of $L_2 = 5 \times 10^{-12} \text{ cm}^3\text{s}^{-1}$ for pure quartet scattering by comparing the ion production signal with and without the presence of Rb [92]. In the first stage of our experiment, we performed magnetic trapping of the doubly spin-stretched spin-state and measured the time evolution of the number of atoms and temperatures of the sample in the trap, in which we were able to extract an upper limit for the pure quartet two-body loss rate of $L_2 = 1.5 \times 10^{-12} \text{ cm}^3\text{s}^{-1}$ [88]. In addition, from the thermalization measurements, we were also able to extract the elastic cross-section and found a small quartet scattering length [88], in agreement with ab initio calculations of the quartet $^4\Sigma^+$ potential [87, 88]. As already mentioned in Section 1.4, the knowledge on the doublet $^2\Sigma^+$ potential is limited [89], and the doublet scattering length is unknown.

In principle, the two Rb (85 and 87) and two He* (3 and 4) isotopes provide four possible mixture combinations. However, the small interspecies quartet scattering length of these combinations [87] will limit the efficiency of sympathetic cooling, which already excludes the possibility of using fermionic $^3\text{He}^*$. The small quartet scattering length for the case of $^4\text{He}^* + \text{Rb}$ means that forced evaporative cooling on both species is required. Forced evaporative cooling is much easier for $^{87}\text{Rb}$ than for $^{85}\text{Rb}$, so a mixture of $^4\text{He}^*$ with $^{85}\text{Rb}$ is also not favorable.
1.6 Outline of this thesis

In Chapter 2, a description about the experimental strategy is presented. These include: the laser systems, cooling and trapping techniques, detection schemes and technical details of the electronics used for evaporative cooling.

In Chapter 3, experimental details and results about the realization of a $^4\text{He}^*$ BEC are presented. Here, of particular interest is the discussion on the application of a simple method, known as the hybrid trap to light atomic species such as $^3\text{He}$. Prior to this work, such technique was only applied to heavy atomic species.

In Chapter 4, results of loading both $\text{He}^*$ and Rb into a pure optical trap are discussed, highlighting the comparison between single- and two-species loading.

In Chapter 5, results demonstrating control of Penning ionization reactions via internal state preparation of $\text{He}^*$ and Rb are discussed.

In Chapter 6, a general summary and outlook about our experiment and prospects towards dual-species BEC and Feshbach spectroscopy are outlined.