Abstract. Metastable triplet helium is an interesting atom, next to the alkalis and atomic hydrogen, to pursue Bose–Einstein condensation. In this paper an overview of the relevant physics of triplet helium and experimental progress in Amsterdam towards reaching Bose–Einstein condensation is described.

cold atoms / metastable helium / Bose–Einstein condensation / magnetic trap / evaporative cooling

1. Introduction

In the field of laser cooling and trapping most research is focused on the alkalis and atomic hydrogen. This is especially true for work on Bose–Einstein condensation (BEC). So far BEC is achieved in the alkali elements Rb, Na and Li, and H, all one-electron atoms. The reason for this is merely the possibility of efficient laser cooling in these atoms, as two-level systems are difficult to find in other atoms. However, the noble gases also allow laser cooling, albeit using a long-lived metastable level as the lower level. Helium in the metastable triplet state \( ^2S_1 \) \( (\text{He}^*, \text{lifetime } 8000 \text{ s}) \) is a promising candidate for studies of ultracold atomic clouds in the quantum degeneracy regime [1]. For \(^4\text{He}^*\) Bose–Einstein condensation is expected, whereas the \(^3\text{He}\) isotope allows the study of a fermionic system. The \(^4\text{He}\) level scheme including most transitions that may be useful for cooling and/or probing is shown in figure 1. The cooling transition most often used is the \(^2S_1 - ^2P_2\) transition at 1083.3 nm. The lifetime of the \(^2P_2\) state is 98 ns, which is...
relatively long compared to the upper state lifetime of other elements that are laser cooled. As a result the Doppler force that can be exerted on a He* atom is relatively weak. A larger force can be exerted using the $2^3S - 3^3P$ transition at 389 nm. This transition, however, cannot be used for Zeeman slowing due to a 10% leak via the $3^3S$ state. The ground state of the He* system is $J = 1$. The $M = +1$ magnetic substate is a low-field seeker and atoms in this state can be trapped magnetically. In case of $^3$He the $I = 1/2$ nuclear spin splits the $2^3S$ state into an $F = 1/2$ and $F = 3/2$ state (hyperfine splitting 6.7 GHz). Here the $M = +3/2$ state is the state to be trapped magnetically.

In this contribution I will first discuss why metastable triplet helium is an interesting atom to pursue BEC, both from the theoretical and the experimental point of view. Then I will discuss the experimental setup that is in operation in Amsterdam and give results of our most recent measurements. In the final section options to bring fermionic $^4$He* to quantum degeneracy will be discussed.

2. Triplet helium for BEC

If one considers new candidates for BEC certainly metastable helium in the $2^3S_1$ state (triplet helium) is promising. The $^3\Sigma_u^+$ potential, for scattering between $M = +1$ $^4$He* atoms, can be calculated ab initio with surprisingly high accuracy [2]. The potential holds 15 bound states and the least bound state has a binding energy of 66 MHz. From this number and the stated 1% accuracy (due to the variational type of calculation the potential can only get deeper) of the potential curve Shlyapnikov and Bohn have calculated a scattering length $a_{BB} = +10^{+5}_{-3}$ nm. We can therefore be sure that the scattering length is large and positive, implying a stable condensate with large mean-field interaction.

From the experimental point of view $^4$He* has interesting possibilities allowing new ways to nondestructively detect a condensate. This is due to the high internal energy of the atom that makes life for the experimentalist harder but also provides new opportunities. An experimental problem is the small fraction of atoms that can be transferred to the metastable $2^3S$ state. Only $\sim 0.001%$ of the atoms is transferred to the triplet state by a dc discharge. This means almost all atoms stay in the ground state that cannot be laser-cooled. Ground state atoms therefore have to be removed to prevent losses by collisions with cold trapped triplet metastables. A further problem is large losses in a He* MOT hampering high
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Laser cooling and trapping of metastable He densities. These losses are due to Penning ionization: two colliding He* atoms have 40 eV internal energy (see figure 1), which is sufficient to ionize one of the collision partners while transferring the other to the ground state. This process is particularly effective in the presence of light [3]. For unpolarized atoms in the dark this loss rate is two orders of magnitude smaller [4] but still far too large for experiments on BEC. Only when the atoms are spin-polarized (all in \( M = +1 \)), as in a magnetic trap, the loss rate is predicted to be sufficiently small and comparable to that for alkali atoms (\( \sim 10^{-14} \) cm\(^3\)/s) [5,6]. In practice this means that one has to work with large traps at low density in the MOT stage. Only in a magnetic trap the density can be increased without inducing too much losses.

The important advantage of Penning ionization as the major loss mechanism is the possibility to detect the losses. With a microchannel plate (MCP) detector, mounted close to the trap, one can attract all produced ions (either from collisions with background atoms or from two- or three-body ionizing collisions) and count them with near-unit detection efficiency. A second MCP detector, with in front a mesh at ground potential, can count neutral He* atoms, for instance those that escape continuously from the MOT by radiative escape. In particular, the on-line detection of lost particles allows non-destructive detection of the transition to a condensate. When the transition line is crossed the density is expected to increase strongly by population of the bosonic ground state. This should give rise to a sudden increase in the two- and three-body losses (loss-rate explosion) that should be visible directly on the MCP detectors.

3. Experimental setup

Our experimental setup is shown in figure 2. A pure beam of He* atoms is made in three stages. We start with a dc discharge to populate the metastable state. Atoms coming out of the discharge leave the source chamber through a skimmer and enter a collimation section. Here the diverging beam is collimated by applying transversal laser cooling over a length of 10 cm in two dimensions. The cooling laser beams are slightly focused to allow as large a capture angle as possible [7]. In the next 10 cm further transversal cooling is applied in the vertical direction while in the horizontal dimension the collimated beam is deflected over 1 degree. The collimation increases the flux of atoms (30-fold increase in the loading rate of our MOT) while the deflection allows separation of He* atoms from ground state atoms. Next the atomic beam is slowed in a Zeeman slower of about 2 m length and loaded into a MOT. We use large detuning, high saturation and large size laser beams to capture as many atoms as possible. To monitor our MOT we use a microchannel plate (MCP) detector detecting all positive ions produced and a CCD camera to detect the fluorescence. The latter only works for sufficiently large numbers of trapped atoms as the detection efficiency of a standard CCD detector goes to zero near 1100 nm. To measure temperature and numbers of trapped atoms we use a second MCP detector that is electronically connected so as to detect only metastables. By switching off the MOT, part of the released atoms is measured and from the time-

Figure 2. Experimental setup. Molasses beams from a laser diode are not shown.
of-flight signal number and temperature are deduced. A second, more reliable way to do this, which also allows size measurements, is using a probe laser and measuring the position dependent absorption on a photodiode or CCD camera.

We use two types of lasers in our experiment. An LNA laser is used for the collimation/deflection section, the Zeeman slower and the MOT. It provides 220 mW at a linewidth of 150 kHz, locked to a helium rf discharge cell with saturation spectroscopy. AOMs shift the laser frequency to the required detuning for the Zeeman slower (−250 MHz) and for the MOT (−35 MHz). For optical molasses and probing we use low-power DBR laser diodes with optical feedback, also locked to an rf discharge (linewidth 500 kHz).

The coils that generate the magnetic field for the MOT and the magnetic trap are mounted inside water-cooled boxes, positioned inside the vacuum chamber. The coil geometry for the magnetic trap is of the cloverleaf design; two of the axial coils are also used for the MOT. The design is made such that 4 cm optical access is available for the MOT beams. Currents up to 200 A can be applied.

4. MOT

By measuring the absorption of a probe laser we determined the number of trapped metastables to be $1 \cdot 10^9$ and the FWHM diameter of our cloud to be 6 mm [4]. A density of $4 \cdot 10^9 \text{ cm}^{-3}$ is then deduced, much lower than in MOTs common to the alkalis. The low density is due to Penning ionization in the MOT. The rate constant for this process is dependent on detuning and intensity of the trapping laser beams. We measured this rate constant switching off the loading process of the MOT and counting ions as a function of time. The decay was nonexponential and could be perfectly fitted with a Penning loss rate constant of $5 \cdot 10^{-9} \text{ cm}^3/\text{s}$ [4]. Collisions with background gas can be completely neglected at these densities.

In a second series of experiments we switched off our MOT for a short time (100 µs) every 0.1 s and applied a probe laser pulse in the MOT-off phase. Varying the probe laser frequency we studied the production of ions and fast metastables. In this way we discriminate between loss processes producing ions (Penning ionization) and loss processes producing fast metastables (radiative escape). For all detunings we found the radiative escape loss rate constant to be more than an order of magnitude smaller than the Penning ionization loss rate constant. We found a maximum in the total loss rate constant at small negative detuning of $1.3 \cdot 10^{-8} \text{ cm}^3/\text{s}$ [4], within the error bars in agreement with measurements in Paris [3] and Orsay [8] and in disagreement with measurements in Utrecht [9]. The ion signal as a function of detuning from the $2^3S - 2^3P_2$ resonance showed some surprising features. First, we did not observe any optical shielding of collisions at positive detuning although the probe laser intensity was quite large ($s = 50$). Secondly, we observed peaks in the ion signal on top of the smooth decrease of the ion signal with increasing negative detuning from resonance. These peaks were interpreted as photo-associative resonances although these were originally not expected due to the near-unit ionization probability for collisions between triplet metastables.

In a collaboration with the Utrecht group these resonances could be explained [10].

In a careful measurement of the small ion production rate in the dark (when the probe laser was off in the MOT-off phase), we determined the rate constant for ionization in our almost unpolarized cold cloud. We measured $K_{SS} = 1.3 \cdot 10^{-10} \text{ cm}^3/\text{s}$, close to measurements in Japan [11] and Utrecht [9]. For BEC experiments it is crucial that the loss rate constant in a magnetic trap is much smaller than this value. To get a value for the loss rate in a magnetic trap, with only spin-polarized atoms, and where the loss rate is expected to be around $10^{-14} \text{ cm}^3/\text{s}$ [5,6], we aligned the probe laser beam collinear with the slower beam. Applying circularly polarized light and keeping the second part of our Zeeman slower magnet on to provide the proper quantization axis we pumped all atoms into the $M = +1$ state and expected to see a large reduction in the ion production. Our measurement with and without optical pumping pulse are shown in figure 3. Indeed we see a reduction of at least a factor of 20, only limited by experimental imperfections [12]. This confirms the prediction but does not yet show that BEC is feasible.
5. Magnetic trap

In the summer of 1999 we took out the old MOT coils that could not handle currents higher than 50 A and were not water-cooled. Our new cloverleaf trap is water-cooled and can handle at least 200 A without appreciable increase in temperature. With this trap we can generate an axial curvature of 30 G/cm$^2$ and radial confinement of 70 G/cm, corresponding to trap frequencies of 46 Hz axially and 580 Hz radially. At the time when evaporative cooling should start an elastic collision rate of 50 s$^{-1}$ is then calculated, assuming the theoretical scattering length to be correct and assuming no losses during transfer from the MOT to a magnetic trap as well as during adiabatic compression.

In our cloverleaf trap we have trapped more than $10^8$ He* atoms. Applying optical pumping after molasses (see figure 2) we almost doubled the number of trapped atoms. The background pressure, measured with an ion gauge, was $4 \cdot 10^{-10}$ mbar when we performed the measurements presented in this section. The lifetime of the magnetic trap is 10 s at this background pressure. At the moment (summer 2000) our best value for the pressure is $1 \cdot 10^{-10}$ mbar when the whole apparatus is running. The measured trap decay was exponential so we assume that the lifetime is completely determined by collisions with background gas. Crucial was the implementation of a deflection section. Without deflection we found a much smaller lifetime of 2.2 s, which we ascribe to glancing collisions with hot ground state atoms flying through the trap. These collisions cause removal of atoms from the trap as well as heating of the trapped gas. We measured a heating rate in this case of $\sim 5 \mu$K/s. Loading 1 mK atoms in a spherical cloverleaf trap with only $\sim 3$ mK trap depth, with deflection, we observed cooling of the gas with a time constant of $\sim 2$ s. We interpret this as cooling due to spilling over the trap walls. These measurements, however, are difficult to interpret as the velocity distribution from which the temperature was deduced was far from Maxwellian. Anyway, these result look quite promising for pursuing Bose–Einstein condensation.

6. Rf-induced trap losses

To reach BEC the temperature at which the magnetic trap is loaded should be as low as possible. We applied optical molasses with a separate set of six laser beams from a laser diode and reached a temperature of 0.2 mK, substantially above the Doppler limit of 40 µK. This temperature is, however, not as bad as it looks as the corresponding average velocity of the atoms is only 7 times higher than the recoil velocity of 9.2 cm/s and the (optical) density of the cloud is large.

A small rf coil has been placed 2 cm from the magnetic trap centre to allow rf-induced evaporation. As the magnetic moment of He* in the $M = +1$ state is twice as large as for alkali atoms in a $M = 1$ state and because helium is such a light atom relatively high rf frequencies are required when working at low bias magnetic field. We therefore use a 1 GHz tunable rf generator with a 7 W broadband amplifier. In
the spherical cloverleaf trap we blow out all trapped atoms at low rf frequency. Already at a frequency of
150 MHz we have observed removal of only high velocity atoms. Decreasing the rf frequency the remaining
atoms showed correspondingly lower velocity and the fraction of atoms that remained trapped decreased
as expected. All these observations were made with the MCP detector that detects the metastables after
releasing the atoms from the magnetic trap.

Computer simulations of the evaporation process, incorporating calculated values for scattering length
and two- and three-body loss rate constants [5], show that BEC in our cloverleaf trap at \( B_0 = 1 \) G may be
reached for \( 5 \cdot 10^8 \) atoms after molasses assuming a trap lifetime of 10 s. If the trap lifetime is 50 s \( 1 \cdot 10^8 \)
atoms should be sufficient to reach BEC, with \( \sim 10^6 \) atoms left.

7. Mixtures of \(^3\)He and \(^4\)He

The recent successes of cooling fermionic potassium into the quantum degeneracy regime has stimulated
us to investigate the options of bringing fermionic \(^3\)He* to quantum degeneracy. The \( F = 3/2 \) and \( F = 1/2 \)
states both allow magnetic trapping. However, we expect only the \( M = +3/2 \) state to be sufficiently stable.
Only this state is fully spin-polarized, a prerequisite for a two-body loss rate of the order \( 10^{-14} \text{ cm}^3/\text{s} \);
\( M = +1/2 \) states always couple to strongly Penning-ionizing potentials and are therefore unstable.
Consequently only one type of \(^3\)He* fermions can be trapped magnetically, in contrast to potassium
where two different fermions can be trapped and, by collisions, evaporatively cooled. Therefore we have to
conclude that it will be very difficult to bring \(^3\)He* to quantum degeneracy in this way.

A better option is a mixture of \(^3\)He* and \(^4\)He*. When both are spin-polarized, they may be trapped in
the same magnetic trap. Evaporative cooling of \(^4\)He* will then sympathetically cool \(^3\)He*. This will be a
very efficient process because the boson-fermion scattering length in this case is very large. Extrapolating
the molecular calculations for \(^4\)He\(^2\) to \(^3\)He*\(^4\)He* Bohn finds a very large scattering length (\( a_{BF} = +49 \) nm
assuming \( a_{BB} = +8 \) nm), very sensitive to the exact value of \( a_{BB} \). A mixture of both isotopes in the
quantum degeneracy regime with variable composition should be experimentally feasible. This opens the
way to studies of phase separation of bosons and fermions, predicted in the quantum degeneracy regime.

References