Bose-Einstein condensation with high atom number in a deep magnetic trap

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Chapter 8

Cold clouds and Oort clouds

8.1 Introduction

Evaporative cooling in a magnetic trap as described in this thesis is a valuable tool to control the properties of ultra-cold gas samples at the BEC phase transition. A number of intrinsic phenomena related to BEC depend directly on the observation and control of temperature and atom number of the gas, e.g. the formation of the condensate [Miesner et al., 1998, Gardiner et al., 1998], the determination of the critical temperature [Ensher et al., 1996], the damping of elementary excitations [Jin et al., 1997, Fedichev et al., 1998], the existence of a critical velocity of a Bose-condensed gas [Raman et al., 1999], and Bosonic stimulation in inelastic decay of the condensate [Burt et al., 1997].

In the context of control over experimental parameters it is in particular interesting to study BEC related phenomena at the onset of the hydrodynamic regime with large samples of high density and atom number. Under these conditions the properties of quantum gases change fundamentally, but the control over the experimental parameters is difficult because of the presence of loss mechanisms and heat loads. A discussion of the origins of heating and loss has been presented by [Cornell et al., 1999, Myatt, 1997]. Here, two classes of processes should be distinguished. The first class concerns primary processes. At high densities intrinsic processes as three-body recombination and dipolar relaxation are limiting the life time of the sample. These inelastic density dependent processes give rise to particle loss as well as heating. Other primary limitations are due to the experimental techniques applied to produce the cold samples. Residual gases of the vacuum background can lead to collisional loss from the sample. Also photon scattering from near resonant stray light coming from an unshielded laser system leads to particle loss.

In addition to the above mentioned primary processes one may point to a class of secondary processes that give rise to particle loss and heating in a delayed fashion after a primary event. For example a grazing incidence collision with a background gas atom can result in a trapped atom of high energy. The presence of a cloud of such atoms will lead to heating of the cold cloud over extended periods of time.
In [Mewes et al., 1996a, Myatt, 1997, Burt et al., 1997, Stamper-Kurn et al., 1998a] the possible existence of a magnetically trapped cloud at energies much larger than the temperature of the cold cloud is discussed. In this context the name ‘Oort cloud’ was introduced. The name was given in analogy to the cloud of comets traveling far outside the orbit of Pluto, but being still bound to the gravitational field of the sun. The existence of this cloud was first proposed by the astronomer J. H. Oort [Oort, 1950].

Another example of a secondary process applies to the situation of small Knudsen numbers. In this case, the mean free path in the cold cloud is small and energetic atoms originating from an internal (3-body recombination) or external (Oort cloud) source will dissipate their energy in a cascade of collisions in the cold cloud.

Several groups reported heating and loss strongly depending on the density of the cold sample, but in the literature not much information can be found. So far, no comprehensive model of the underlying processes has been formulated. In general it was observed that heating and loss could be suppressed by limiting the depth of the magnetic trapping potential by means of an rf-shield preventing the possible build up of an Oort cloud. Also in the work for this thesis, if samples with a large particle number at high densities were produced, strong heating and loss in the absence of an rf-shield were observed.

In this chapter emphasis is put on the evidence for the existence and origin of Oort clouds as well as the consequences of the presence of an Oort cloud for the investigation of quantum gases. To investigate Oort cloud related phenomena cold clouds under conditions just above the BEC phase transition were used. Such clouds allow to study the essential phenomena and to trace the origin of the Oort cloud without the added complexity of the presence of a condensate. It will be demonstrated, how the effects of the Oort cloud on the cold cloud can be suppressed by means of rf-shielding. With the origin of the Oort cloud identified, a method for the reduction of the Oort cloud atom number will be demonstrated, and the effect of the Oort cloud on the cold cloud will be compared for large and reduced Oort clouds. The studies of secondary processes were done in the absence of an rf-shield, as in the presence of a rf-shield strong heating would lead to massive particle loss and could therefore not be distinguished from other loss processes. Finally, the consequences of the observations on the non condensed samples for the possibilities of entering the hydrodynamic regime with a Bose-Einstein condensate are discussed.

8.2 Time evolution of trapped cold clouds

Figure 8.1 shows how temperature, atom number, and density of an evaporatively cooled cloud are evolving in time. Evaporative cooling was followed by a trapping period $t$, during which the rf-power was switched off and the cloud was warming up. After this time the cloud was released from the trap. The expanded cloud was probed by absorption imaging. As the imaging is destructive the cloud was repeatedly produced for various trapping times $t$ with the same initial conditions present after evaporative cooling. This procedure was carried out for two different initial conditions obtained by extending the evaporation ramp to different final temperatures. First, Type I clouds (circles) with $6.8 \times 10^8$ atoms at $1.6 \mu$K temperature and $2.7 \times 10^{14}$ cm$^{-3}$ density were produced. This corresponds to a cloud of $r_{0,r} = 5.8 \mu$m radial and $r_{0,z} = 135 \mu$m axial size, and a
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\[ T(t) = D + (A + B + C) t \]

\[ A = 8.33 \mu K \]
\[ B = 60.1 \mu K s^{-1} \]
\[ C = 3.55 \mu K s^{-2} \]
\[ D = 4.24 \mu K \]

**FIGURE 8.1:** Heating and loss of magnetically trapped clouds of Type I (circles) and Type II (squares). Based on the parameterization of temperature (solid line in a)) the density drop is calculated (dotted lines in c)). Including the parameterization of the atom number (solid line in b)) describes the density dependence (solid line in c)). Based on the density dependence the particle loss due to three-body recombination (dotted line in b)) and dipolar relaxation (dashed line in b)) is calculated.
mean free path of $\lambda_{\text{mfp}} = 4.7 \mu m$, slightly smaller than the radial size. Therefore, under initial conditions the cloud is in the transition region between the collisionless and the hydrodynamic regime with a Knudsen number of $K_n = 0.8$. Here, the Knudsen number

$$K_n \equiv \frac{\lambda_{\text{mfp}}}{r_{0,\rho}}$$

(8.1)
is defined as the ratio between the mean free path and the radial sample size. The second set of initial conditions, Type II clouds (squares), was a temperature of $7.5 \mu K$ with $2.4 \times 10^7$ atoms at $8.4 \times 10^{13} \text{cm}^{-3}$ density. The dimensions of this cloud were $r_{0,\rho} = 12.6 \mu m$ and $r_{0,z} = 292 \mu m$, with a $\lambda_{\text{mfp}} = 15.1 \mu m$ mean free path. In this case $K_n = 1.2$.

The measurements exhibit strong heating of both types of cold clouds at initial rates of $20 \mu K/s$ (circles) and $6.8 \mu K/s$ (squares). After 10 s of trapping time the temperature increase becomes linear in time with rates of $1.2 \mu K/s$ (circles) and $2 \mu K/s$ (squares). The temperature behaviour can be nicely parametrized by the following test function

$$T(t) = D + \sqrt{A + B t + C t^2}$$

(8.2)

with the parameter values given in Figure 8.1,a). In this chapter emphasis is put on experiments with a large number of atoms. Transferring a reduced atom number into the magnetic trap leads to a reduced heat load.

The decay of the atom number is given in Figure 8.1,b). In order to parameterize the observed decays the data are fitted to an exponential decay where in addition a third order decay of the atom number is assumed

$$N(t) = \left( \frac{\alpha N^2(0)}{\alpha e^{2\alpha t} - lN^2(0) + lN^2(0)e^{2\alpha t}} \right)^{1/2}$$

(8.3)
The resulting parameters are shown as the solid lines in Figure 8.1,b).

The density as calculated for Type I and Type II clouds on the basis of measured temperature and atom number is shown in Figure 8.1,c). It is good to point out that the steep initial decline of the density is dominated by the rapid initial increase of the effective volume along with the temperature. To illustrate this point the dotted curves in Figure 8.1,c) show the density dependence calculated using the parameterization (Equation (8.2)) and neglecting the particle loss ($N \equiv \text{const.}$). At short times the calculated curves describe the decline of the density, as can be seen from the inset. The calculated curves deviate for longer times when the particle loss contributes noticeably to the decrease of the density. If both parameterizations for the increase of temperature and for the atomic loss are taken into consideration, the decline of the density is well described (solid lines).

Based on the measured density dependence the three-body decay can be calculated using to the literature value of the rate constant $L = 1.8 (5) \times 10^{-29} \text{cm}^6\text{s}^{-1}$ for the $|F = 2, m_F = 2 \rangle$ state as measured by [Söding et al., 1999]. The result of this calculation is plotted in Figure 8.1,b), (dotted lines). For comparison also the dipolar decay is presented in Figure 8.1,b), (dashed lines). For this calculation the upper boundary of the rate constant $G = 2 \times 10^{-15} \text{cm}^3/s$ as given by [Julienne et al., 1997] was used.
Recent calculations suggest a value smaller than $1 \times 10^{-15}$ cm$^3$/s [Verhaar, 2000]. Rapidly, particle loss due to three-body recombination and dipolar relaxation becomes negligible. Only at short times three-body recombination is expected to enhance the decay, which is not inconsistent with the observed data. However, one should be reluctant in interpreting the observed evolution of the atom number in terms of intrinsic loss as for Type I clouds with slightly higher density even an initial increase of the atom number was found (see Figure 8.6,b)). Such an increase can possibly originate from atoms of the Oort cloud which have lost their kinetic energy after several collisions with atoms from the cold cloud and merge with the cold cloud.

The most striking feature of the data is the fast heating in presence of only a moderate particle loss. This heating rate can not be explained by relaxation heating, for instance due to three-body decay (‘anti-evaporation’) [Walraven, 1996]. This can explain initial heating rates of 0.8 $\mu$K/s and 0.3 $\mu$K/s, much smaller than the observed initial rates for Type I and Type II clouds respectively. Clearly, it is likely that for gas clouds with a small atom number a substantial fraction of the recombination energy is dissipated in the cold cloud. Assuming full dissipation of the recombination energy to the highest vibrational level of the Rb$_2$ molecule ($\approx$ 1.1 mK [Verhaar, 2000]) results in a heat load of $4 \times 10^{-20}$ W, which is about a factor four bigger than the initial heat load of the sample.

A number of other possible origins of heating can also be excluded: First, during the measurements the atomic sample was carefully shielded from near resonant stray light from the laser system, which would induce atomic transitions to untrapped states. After such transitions the released hyperfine or Zeeman energy turns into kinetic energy of the atoms, which heat the cold cloud by collisions.

Second, rubidium atoms from the room temperature vacuum background gas can collide with atoms from the cold cloud. For grazing incidence collisions the kinetic energy transferred to the atoms in the cold can be smaller than the depth of the magnetic trap so that the atoms remain trapped, and the cloud is heated after thermalization by elastic collisions [Bali et al., 1999]. In order to obtain a measure for the amount of heating originating from background rubidium gas, the rubidium partial pressure in the UHV cell was reduced by desorbing the Rb atoms from the quartz cell with 250 W of light from halogen lamps put at a short distance of about 1 cm from the quartz surface. After a few minutes of exposure the rubidium partial pressure was reduced. The partial pressure was determined by measuring the capture rate from the background into the MOT without loading from the atomic beam source as has been described in Section 5.3. Although the accurate measurement of the absolute partial pressure depends critically on the knowledge of the capture velocity, the method allows to determine the relative reduction of the rubidium partial pressure. Even for a reduction of the rubidium partial pressure by a factor of 4 no reduction of the heating and atomic loss was noticed. It is emphasized here that with the argument presented in Section 5.3 it follows that also the effusive beam of rubidium atoms from the vapor cell does not contribute measurably to the observed heating and loss. This is in contrast to observations in experiments in which a Zeeman-slower is used as an atomic beam source. Due to limitations in differential pumping of the source significant rubidium partial pressure in the UHV cell can build up and contribute to the heating and loss [Aspect, 2000].

Third, it was also verified that no significant change in heating and losses occurred
FIGURE 8.2: Heating rate a) and decay time b) of a magnetically trapped cloud. The solid data points are obtained from measuring between 5 s and 10 s, the open triangles in b) are obtained after the first five seconds. During trapping rf-shielding was applied constantly (circles, triangles) at a truncation energy $\epsilon_t$. In another measurement (squares), after 4 s of trapping at $\epsilon_t = 4.7 \text{ mK}$, the rf-shield was ramped down within 0.5 s to a final energy $\epsilon_t$ before set to 4.7 mK again. The error-bars result from averaging over 5 repeats.

when the vacuum restgas pressure (air) was increased to the $10^{-10}$ mbar level.

In the literature rf-shielding methods are described to minimize the heating of the cold cloud [Cornell et al., 1999]. The argument presented is that atoms from an Oort cloud can give rise to a substantial heat load on the sample. This can be avoided by lowering
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the depth of the trapping potential using an rf-shield. To investigate the effects of rf-shielding on the heating rate and particle loss the truncation energy $\varepsilon_t$ of the rf-shield was varied between 100 $\mu$K and 4.5 mK. Without the shield the trap depth was 12 mK. For these measurements a ‘Type I -like’ evaporatively cooled sample with $1.5 \times 10^7$ atoms at a temperature of 2.7 $\mu$K and a density of $2.4 \times 10^{14}$ cm$^{-3}$ was repeatedly produced. After evaporative cooling the truncation energy was increased to a constant value followed by a magnetic trapping time during which the cloud warmed up and the atom number was decaying. The measured heating and loss rates are the averaged quantities for the change in temperature and atom number between 5s and 10s, Figure 8.2, (circles). At these times the density has dropped to below $10^{13}$ cm$^{-3}$. As shown in Figure 8.2 the heating rates were strongly reduced by the rf-shield. With increasing truncation energy the heating rate increases linearly to a value of about 2 $\mu$K/s. This is supporting the picture in which an Oort cloud gives rise to the observed heating. It is remarkable that the 18 s decay time observed in the interval $5 - 10$ s does not significantly depend on the truncation energy. Therefore, it is concluded that the observed decay is uncorrelated with the heating. As background collisions with rubidium and air restgas particles can be excluded, another loss process has to be assumed, but remains so far unexplained.

The initial decay over the first five seconds is shown in Figure 8.2, b), (triangles). For low truncation energies the decay time is seen to decrease. As under these conditions the density decay due to heating as observed in Figure 8.1, c), is strongly reduced, enhanced particle loss due to density dependent loss mechanisms must become visible. The initial decay time of 7 s observed for the lowest truncation energy is consistent with this picture. Three-body recombination loss was studied for low truncation energies by [Söding et al., 1999, Schuster et al., 2000].

Further evidence for the existence of an Oort cloud is obtained by applying a temporary rf-shield. For the measurement shown in Figure 8.3 (open circles) again a ‘Type I -like’ cold sample was produced with the same initial conditions as used in the measurements presented in Figure 8.2. In a first measurement (solid circles) after evaporative cooling the truncation energy was set constantly to $\varepsilon_t = 4.7$ mK. In a second measurement (open circles) after 4 s of magnetic trapping a rf-frequency ramp was started for a period of 0.5 s. The frequency was ramped down linearly such that a truncation energy of $\varepsilon_t = 420 \mu$K was reached. Subsequently, the truncation energy was reset jump wise to $\varepsilon_t = 4.7$ mK. As can be seen from the plot after applying the rf-ramp, the heating rate was strongly reduced by a factor of 6 from 2.5 $\mu$K/s to approximately 0.43 $\mu$K/s. The latter measurement was repeated with different final truncation energies of the ramp. The observed residual heating rate is shown in Figure 8.2. The data suggest that it is possible to further suppress the residual heating rate by extending the truncation ramp to lower final truncation energies and to perform the ramp less steep. At the same time the data put an upper limit for the heating rate which is continuously generated, as e.g. heating due to background collisions. For the same measurement no significant change in the decay of the atom number was observed. This is consistent with the above described case where the truncation was applied constantly. Before the heating rate caused by an Oort cloud is studied in more detail, first a more direct method for the detection of the Oort cloud is introduced in the following sections.
FIGURE 8.3: Temperature a), and atom number b) of a magnetically tapped cloud of initially $2.3 \times 10^7$ atoms at 2.7 $\mu$K. For a deep trap heating at 2.5 $\mu$K/s occurs (solid circles). Ramping down the trap depth at 4 s over a period of 0.5 s from a truncation energy of 4.7 mK to 420 $\mu$K (open circles) heating can be permanently reduced to 0.43 $\mu$K/s, whereas no significant change in the atomic loss was found.

8.3 Observation of the Oort cloud

This describes how the Oort cloud can be detected by release of the contents from the magnetic trap and subsequent recapture into a MOT. By first spilling the cold cloud out of the magnetic trap with the radio frequency knife before the release only atoms at high energy, the atoms of the Oort cloud, are recaptured. From a time-of-flight (TOF) analysis the Oort-cloud atom number and energy distribution is obtained.

As the Oort cloud is populated with only a few atoms over a wide energy range, it is not possible to achieve a detectable optical density for absorption imaging. In order to demonstrate the presence of the Oort-cloud and measure its atom number, the atoms were released from the magnetic trap and recaptured into a MOT. This was done after initially
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Producing an evaporatively cooled cloud of about $10^7$ atoms at a temperature of $2 \mu K$ (Type I cloud). The evaporative cooling ramp was followed by a period of 60 ms magnetic trapping, during which the radio frequency was kept constant. Subsequently, the atoms were released from the magnetic trap. In order to recapture the rapidly expanding Oort-cloud into a MOT additional power supplies were used allowing to switch on the MOT magnetic fields within 300 $\mu$s. By choosing a 14.6 G/cm magnetic field gradient along the z-direction and a laser detuning of $-25$ MHz the capture range of the MOT was extended over the whole vacuum quartz cell. Again, it was advantageous to work with a MOT with large laser beam diameters at high laser power so that the whole magnetic trapping volume was covered. Significant loading of the MOT from the vacuum background was prevented by limiting the MOT trapping time to 50 ms before the atoms were released again, and subsequently, the number of atoms was measured by absorption imaging as described in Section 5.2. In order to measure the energy distribution of the atoms in the cloud the expansion time $\tau_{\text{TOF}}$ between the release and recapture was varied, and by

**FIGURE 8.4**: Time-of-flight measurement of the number of atoms captured after release from the magnetic trap into a MOT. If the full trap contents were recaptured, a bimodal time-of-flight spectrum was measured (circles). Before release from the magnetic trap atoms at energies $> 250 \mu K$ were spilled out of the trap by an rf-knife and not recaptured (triangles down), resulting in a TOF spectrum of the cold gas cloud with less atoms left at short times. After spilling atoms of energies $< \epsilon_t = 250 \mu K$ only atoms from the Oort cloud were recaptured (triangles up) vanishing after short times in the TOF spectrum. The calculated TOF spectrum of 3 mK thermal cloud (solid line) is in fair agreement with the observation for the Oort cloud.
measuring the number of atoms still being recaptured a time-of-flight (TOF) spectrum was obtained. During the expansion atoms with high energy will stick to the walls of the vacuum cell first and will not be recaptured.

Figure 8.4 (circles) shows the TOF spectrum obtained by this measurement procedure. The TOF spectrum shows a bimodal structure. At short times ($\tau_{\text{TOF}} < 40 \text{ ms}$) corresponding to high energies the number of recaptured atoms drops by about $10^6$ atoms. This reflects fast atoms of the Oort cloud to escaping from the capture range of the MOT. At longer times ($\tau_{\text{TOF}} > 50 \text{ ms}$) the number of atoms vanishes as the cold cloud expands and also drops out of the capture region.

In a second measurement (triangles down), a rf-knife was used to spill atoms from the magnetic trap after evaporative cooling and before the release. The rf-knife was ramped from a truncation energy of $\epsilon_t = 4.7 \text{ mK}$ down to $\epsilon_t = 250 \mu\text{K}$ in order to remove the Oort-cloud atoms from the trap. As a consequence, the first step in the TOF spectrum is not observed.

In the third measurement (triangles up), the cold cloud was spilled from the magnetic trap by applying a rf-truncation ramp starting from $\epsilon_t = 250 \mu\text{K}$ to the bottom of the trap. The obtained TOF spectrum shows how the Oort cloud escapes from the capture region. At $\tau_{\text{TOF}} = 0 \text{ ms}$ the number of Oort cloud atoms is read out. In this measurement at the end of evaporative cooling about $1.5 \times 10^6$ atoms were found populating the Oort cloud at energies $> 250 \mu\text{K}$.

The measured TOF spectrum of the Oort cloud was compared to a calculated curve (solid line). For simplification it was assumed that the Oort cloud obeys a Maxwell-Boltzmann distribution. The spatial integration of the expanded density distribution over the capture region of the MOT gives the number of recaptured atoms as a function of the expansion time. Figure 8.4 shows that a temperature of $3 \text{ mK}$, smaller than the $12 \text{ mK}$ trap depth, is suggested by the data. The Oort cloud is not expected to obey a Maxwell-Boltzmann distribution, as the calculated peak density of the Oort cloud in the magnetic trap is $8 \times 10^6 \text{ cm}^{-3}$, and thus a thermalization time in the order of $200 \text{ s}$ is to be expected.

### 8.4 Decay of the Oort cloud

The recapture of the magnetic trap contents into the MOT can be done at any time during magnetic trapping. This allows a time-resolved measurement of the Oort cloud population. In this section the decay of the Oort cloud in absence of the cold cloud is described. For the measurements, loading of the magnetic trap was done as described in Chapter 6. The evaporative cooling ramp was extended to a truncation energy less then the magnetic potential in the trap center in order to first produce a cold cloud and finally remove this cloud from the trap. Magnetic trapping of the Oort-cloud was followed by the transfer of the atoms into the MOT with energies larger than $250 \mu\text{K}$.

Two experimental situations are compared: First, the decay of the Oort cloud during magnetic trapping in absence of the cold cloud was measured. Second, this was compared to the decay of the Oort cloud, also without cold cloud, but in presence of an evaporative cooling shield at low truncation energy of $\epsilon_t = 12.5 \mu\text{K}$ during the magnetic storage. The rf-shielding experiment was done for two different rf-amplitudes, $B_{\text{rf}} = 40 \text{ mG}$ and
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![Graph showing decay of the Oort cloud atom number](image)

**FIGURE 8.5:** Decay of the Oort cloud atom number in the absence of a magnetically trapped cloud at low temperature: After 3 s the Oort cloud decays exponentially with a life time of 58 s (circles). In presence of an rf-shield at $\epsilon_t = 12.5 \mu K$ (squares) the initial relative decay rate was increased from 0.07/s to 0.125/s and not significantly depending on the rf-amplitude. The error-bars result from averaging over 3 repeats.

$B_{rf} = 110 \text{ mG}$. The measured decay curves of the Oort cloud atom number are shown in Figure 8.5. From the logarithmic scale of the graph it can be seen that the decay is not following an exponential law. The initial decay rate per atom is increased to 0.125/s in the presence of the rf-shield, with respect to a decay rate per atom of 0.07/s without the shield. Without the rf-shield the decay time after 3 seconds was 58 s. The observed decay was not significantly changed by increasing the rf-amplitude. Assuming an energy of 3 mK for an atom results in a Landau-Zener transition probability to untrapped states of 0.7 and 0.05 respectively (compare Figure 2.4), for the rf-amplitudes in use. From this follows, that the atom has to undergo several trap oscillations, before it is removed from the trap. However, the observed decay rate in presence of the shield is much longer than several times the $2\pi/\omega_z = 49 \text{ ms}$ axial oscillation time of the magnetic trap. The long decay time is then an indication that it takes a long time before the Oort cloud atoms reach the rf-shield.
8.5 Controlling the Oort cloud population

In order to control the Oort cloud population the mechanism how the Oort cloud becomes populated must be identified. In [Cornell et al., 1999] several possible origins have been discussed: For example, the Oort cloud population can arise after three body recombination or grazing incident collisions with background particles.

In this experiment another reason for the population of the Oort cloud was identified. As presented in Section 8.4 a substantial Oort cloud population was found to be present immediately after completing the evaporative cooling ramp. The major fraction of the Oort cloud population is attributed to residual atoms resulting from incomplete evaporative cooling occurring at high truncation energies [Desruelle et al., 1999]. From Equation 2.3 it follows that at a magnetic field amplitude of

\[
B = \sqrt{\frac{\hbar \omega_{\text{rf}} B_{\text{rf}}}{8 \mu_B g_F}} \quad (8.4)
\]

the difference in the energy of the transitions \(m_F = 2 \rightarrow m_F = 1\) and \(m_F = 1 \rightarrow m_F = 0\) due to the quadratic Zeeman effect becomes equal to the Rabi frequency \(\omega_R\) by which the transitions are driven. For a typical rf-magnetic field amplitude of 50 mG this condition is fulfilled at a magnetic field of 20G corresponding to a truncation energy of 1.3 mK. As a consequence, not all atoms at high truncation energies energies are removed from the magnetic trap [Desruelle et al., 1999]. As evaporative cooling starts with \(4 \times 10^9\) atoms and at a truncation energy of 1.3 mK about \(1.1 \times 10^9\) atoms remain, a fraction of about \(10^{-3}\) of the atoms on average have to remain in the trap in order to explain the observed Oort cloud.

It is often overlooked that not only in magnetic traps with large offset field [Desruelle et al., 1998] incomplete evaporation due to the quadratic Zeeman effect occurs, but also in magnetic trapping geometries as described by [Mewes et al., 1996a, Myatt et al., 1997, Esslinger et al., 1998] magnetic field strengths of relevant order are achieved.

In order to suppress the population of the Oort cloud in the present experiment a modified scheme was used, in which adiabatic compression and evaporative cooling were combined and the production of atoms at high energies was avoided. Loading of the magnetic trap was performed in the standard way followed by adiabatic compression until the third compression step was finished, as described in Section 6.2 and summarized in Table 6.1. The third step of the adiabatic compression was immediately followed by the compensation of the offset magnetic field (called fifth step in the table). At this point the quadrupole magnetic field gradient \(\alpha\), and thus the depth of the magnetic field has still to be increased to its maximum value. In order to allow this, but avoiding the production of atoms at high energies as the temperature of the compressed cloud rises, an evaporative cooling shield at a frequency of 14 MHz corresponding to a truncation energy of 1.3 mK with a rf-magnetic field amplitude of 100 mG is switched on. In the presence of this shield the magnetic field gradient \(\alpha\) is ramped up to its maximum value over a period of 8 s (formerly the fourth step of the compression). Subsequently, a fast frequency ramp starting from 50 MHz to 14 MHz was applied for 1 s in order to remove atoms at high energies. From 14 MHz on the evaporative cooling ramp was applied as described in Section 7.1. As a result of applying this modified compression and evaporative cooling
8.6. Heating due to the Oort cloud

The reduction of the Oort cloud population makes it possible to investigate the influence of the Oort cloud atom number on the heating of the cold cloud due to collisions. Figure 8.6 shows the time evolution during magnetic trapping of a) temperature, and b) atom number of the cold cloud, as well as c) the Oort cloud atom number. In these experiments a 'Type I-like' cloud was used with initially $10^7$ atoms at 1.7 $\mu$K temperature and a density of $4.2 \times 10^{14}$ cm$^{-3}$. Temperature and atom number of the cold cloud were measured without applying rf-shielding, using the procedure described in Section 8.2. This measurement was then followed by the measurement of the Oort cloud atom number for the same conditions of the cold cloud, using the method described in Section 8.3. These measurements were repeated in order to compare two situations: They were first done with a large initial number of atoms in the Oort cloud of $2.2 \times 10^6$ (solid data points). The measurements were then repeated for a reduced Oort cloud atom number of $3.7 \times 10^5$ (open data points) achieved by the method described in Section 8.5. At short times heating rates of $30.5 \mu$K/s for a large Oort cloud and $16.5 \mu$K/s for a reduced Oort cloud were measured. After five seconds of trapping the the heating rates were reduced to $2.3 \mu$K/s and $1.2 \mu$K/s. Thus, the heating rate was reduced by almost a factor 2, whereas the number of atoms in the Oort cloud was initially reduced by a factor of 6. In the measurement presented only atoms at energies higher than 250 $\mu$K are considered to belong to the Oort cloud. Clearly, the heating rate does not scale linearly with the Oort cloud population. However, this is not to be expected either, as the Oort cloud reduction procedure is expected to result in a different energy distribution of the Oort cloud atoms. Unfortunately, the small atom number in the reduced Oort cloud does not allow a measurement of the energy distribution. Moreover, atoms in the energy range up to 250 $\mu$K are not detected. Therefore, the strong residual heating after the reduction of the Oort cloud could be explained by heating due to trapped atoms with energies below 250 $\mu$K.

Another important experimental observation is described in the following. As already mentioned in Section 8.2, in the measurement presented in Figure 8.6,b) an increase of about $1.5 \times 10^6$ atoms in the atom number of the cold sample was observed during the first 500 ms of magnetic trapping in presence of a non-reduced Oort cloud (solid circles). At the same time the Oort cloud atom number is reduced by $6 \times 10^5$ atoms, as can be seen from Figure 8.6,c) (solid squares). For a reduced Oort cloud atom number this initial increase of the cold sample and the loss of Oort cloud atoms are not observed.
CHAPTER 8: COLD CLOUDS AND OORT CLOUDS

FIGURE 8.6: Heating a), and atom loss b) of the cold cloud (Type I), obtained by absorption imaging, in comparison for a large Oort cloud (filled data points) and a reduced Oort cloud (open data points). The Oort cloud atom number c), obtained by the recapture method, was initially reduced by a factor 6. The heating is reduced at short times as well as at long times by a factor of 2. In presence of a large Oort cloud an increase of the atom number of the cold cloud within the first 500 ms is accompanied by a reduction of the Oort cloud atom number. This is interpreted as capture of atoms from the Oort cloud into the cold cloud by collisions. For a reduced Oort cloud this behaviour is absent.
8.6. HEATING DUE TO THE OORT CLOUD

The question arises, how more atoms can be captured by the cold cloud than lost from the Oort cloud? As capture from the background gas can be excluded (no particle increase for reduced Oort clouds) this discrepancy is attributed to low energy Oort cloud atoms (< 250 µK) which are not recaptured in the MOT when measuring the Oort cloud atom number. Comparing the loss of atoms from the Oort cloud with the increase of atoms in the cold cloud is concluded that approximately 40% of the Oort cloud atoms are detected by recapture into the MOT. It is unknown which fraction of the reduced Oort cloud is detected. This uncertainty can at least partially explain the non-linear relation between the heating rate and the Oort cloud population. Calculating the heat load due to capture of atoms from the cold on the basis of the measured increase of the cold cloud atom number one finds that an average energy of $E/k_B \approx 130$ µK per captured atom is dumped into the cold cloud. This result is consistent with the picture in which the heating of the cold cloud is predominantly generated by the Oort cloud. For Type II clouds, as presented in Figure 8.1, (squares), a different behaviour was found: For a high as well as low initial atom number in the Oort cloud no initial increase in the atom number of the cold sample was found, and always a increase in the Oort cloud atom number during the first seconds of magnetic trapping. This behaviour is demonstrated by the measurements presented in Figure 8.7. In these measurements the initial Oort cloud population (squares) is compared with the Oort cloud atom number after 5 s of magnetic trapping (circles). This measurement was done under variation of the initial

![Figure 8.7](image_url)

FIGURE 8.7: Atom number of the Oort cloud after 5 s of interaction with a cold cloud for different initial temperature. For low initial temperature a loss in the Oort cloud atom number is observed (Type I). For high initial temperature the Oort cloud atom number increases (Type II).
parameters of the cold sample by extending the evaporative cooling ramp to different initial temperatures of the cold sample. In this way the initial conditions of the cold cloud were varied between Type I-like and Type II-like. While the initial number of the Oort cloud does not significantly depend on the type of the cloud, the Oort cloud population after five seconds of magnetic trapping linearly increases with increasing initial temperature. At high initial temperature of $11 \, \mu K$ (Type II cold cloud) the Oort cloud number doubles from $1 \times 10^6$ atoms to $2 \times 10^6$ atoms. At low initial temperature (Type I cold cloud) a decay of the Oort cloud atom number was found to accompanied by an increase of the atom number in the cold sample as shown in Figure 8.6.

The loss from the Oort cloud population accompanied by the increase in the cold sample is interpreted as capture of atoms from the Oort cloud by the cold sample. As for Type I clouds the mean free path is smaller than the size of the sample, Oort cloud atoms are indeed expected to be captured by the cold cloud in a cascade of collisions. Less than 10 collisional stages of the cascade are expected to be required for full thermalization. The presence of a d-wave resonance [Burke et al., 1998, Verhaar, 2000] in the elastic collisional cross-section is favorable for containment of the colliding atoms in the cloud.

For the Type II cloud the ratio of mean free path to the size of the sample (Knudsen number) is increased. For the Type I cloud described in Figure 8.6 the Knudsen number is $K_n = 0.6$, whereas for the Type II cloud of Figure 8.1 $K_n = 1.2$ is calculated. The measurements show that no initial increase of atom number is observed but only loss. Apparently, collisions are not leading to an appreciable capture of Oort cloud atoms in this case. In fact, the decay of cold cloud atom number is present right from the start and is accompanied by an increase of the Oort cloud number. Also the heat load per atom is strongly reduced. Comparing the Type I and Type II clouds from Figure 8.1 a reduction of the heat load per atom by a factor of 8 was measured, while the ratio of mean free path to the sample size increases by only 50%. Apparently, for Type II clouds the rate at which atoms are kicked out of the sample exceeds the recapture rate. No detailed model to describe the thermalization of the cold cloud with the Oort cloud was attempted.

### 8.7 Summary and conclusions

In the following the results obtained in this chapter are summarized:

- Recapture of the magnetic trap contents into a MOT after removal of the cold cloud allowed for a observation of a magnetically trapped Oort cloud. This proved to be a useful method to gain information, at any desirable time, about the atom number and energy distribution of the Oort cloud. In the experiments presented in this chapter, an Oort cloud of a few million atoms was populating the magnetic trap at energies up to several mK.

- The primary origin of the observed Oort cloud, described in this chapter, was identified to be incomplete rf-evaporation of the atoms in high magnetic fields due to the quadratic Zeeman effect. Typically the quadratic Zeeman effect becomes important at a field strength of $20 \, G$, a value which also occurs in magnetic traps used by other groups. The Oort cloud atom number was strongly reduced to $3 \times 10^5$ by avoiding
the production of atoms at high trapping energies applying an experimental scheme which combines adiabatic compression and evaporative cooling.

- Aside from the initial creation of an Oort cloud also secondary development of the Oort cloud atom number was observed. Depending on the Knudsen number of the cold cloud either increase or decrease of the Oort cloud atom number was observed. For the lowest Knudsen numbers loss of atoms from the Oort cloud was accompanied by an increase of the atom number of the cloud by even $1.5 \times 10^6$ atoms. For obvious reasons three body decay never can explain the initial increase of the atom number observed for the cold cloud. The increase is attributed to capture of atoms from the Oort cloud in a collisional cascade. In contrast, using large Knudsen numbers an increase of the Oort cloud atom number was observed at the expense of atoms from the cold cloud.

- Atoms from the Oort cloud lead to substantial heating of the cold sample. The observed heating rate was strongly reduced by applying rf-shielding. A rough estimate of the heat load is consistent with this picture. The observed loss rate over the period 5 - 10s was was not influenced by the rf-shield. The initial decay time (over the first 5s) was seen to decrease for low truncation energies. This is consistent with three-body decay in the absence of additional heating. In case of a cold cloud of low density, removal of the Oort cloud by a short truncation ramp led to a permanent reduction of the heating rate. It is important to point out that to investigate the influence of the Oort cloud on the cold cloud it is advantageous to measure in the absence of rf-shielding, as done in the experiments for this thesis. In the presence of shielding strong heating will show as massive particle loss due to evaporation. In the latter case, it will be difficult to distinguish between intrinsic heating and loss mechanisms.

The existence of collisional cascades is of great importance for attempts to investigate Bose-Einstein condensates in the hydrodynamic regime, where even lower ratios of the mean free path to the sample size have to be achieved. Even in the presence of rf-shielding it seems important to remove an Oort cloud. A a certain fraction of the Oort cloud atoms will always travel through the cold sample leading to a collisional cascade, even if these atoms were flipped to untrapped states after entering the shielded region. In order to avoid this, rf-shielding at two different truncation energies can be helpful. Also confining the atoms in optical traps or micro-fabricated magnetic surface traps avoids the undesired effects of an Oort cloud, as the depth of these trapping potentials is small. Also, three-body decay is expected to give rise to collisional cascades at high densities. This has been investigated by [Schuster et al., 2000]. For a condensate the three-body recombination rate constant is suppressed by the quantum statistical factor $\approx 6$ with respect to the rate constant for the uncondensed cloud described in this chapter [Kagan et al., 1985, Burt et al., 1997]. However, as demonstrated in Chapter 7 the densities achieved in a Bose-Einstein condensate are typically a factor 2 - 3 higher than the density of the thermal cloud, compensating the quantum statistical factor. Therefore, it is a slight improvement to Bose-condense $^{87}$Rb in the $|F = 1, m_F = -1\rangle$ state, for which the three-body recombination rate constant is smaller by a factor of 3 [Burt et al., 1997] compared
to the $|F = 2, m_F = 2\rangle$ state. Moreover, using the $|F = 1, m_F = -1\rangle$ state incomplete evaporation due to the quadratic Zeeman effect is also avoided [Desruelle et al., 1999].

Working at a limited density, one possibility to enter deeply into the hydrodynamic regime could be to tune the elastic scattering length in the vicinity of a magnetically [Tiesinga et al., 1992] or optically [Fedichev et al., 1996a] induced Feshbach resonance [Inouye et al., 1998, Roberts et al., 2000], resulting in a reduced mean free path. However, it is theoretically predicted for the case that the scattering length exceeds the range of the interaction potential that the three-body recombination rate constant is increased proportionally to $a^4$ [Fedichev et al., 1996b, Bedaque et al., 2000]. Here, experimental investigation for the case of $^{87}$Rb is required. For Na and $^{85}$Rb large interactions in the vicinity of a Feshbach resonance have been realized and short life times of the condensate close to the resonance has been experimentally observed [Stenger et al., 1999a, Cornish et al., 2000]. For these experiments, the role of collisional cascades induced by three-body recombination products or by a potential Oort cloud is at the present not clarified.