Experiments on two-component quantum gases on an atom chip

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Chapter 4
Thermodynamics of a one-dimensional two-component Bose gas

4.1 Introduction

Ultracold gases trapped on atom chips offer unique opportunities to study fundamental problems in quantum (many-body) physics, as may have already become evident from the previous chapters. The one-dimensional (1D), single-component Bose gas with repulsive interactions has emerged as a paradigm system because exact solutions are available from the Lieb-Liniger model \[13\] for the ground- and excited quantum many-body states for any interaction strength. Furthermore, the thermodynamics can also be exactly calculated from the Yang-Yang equations \[14\] for this system.

As was already alluded to in chapter \[2\] it is interesting to extend the experimental studies to the multicomponent case. Here, we are interested in the case of the two-component Bose gas. As mentioned, this system has three natural interaction parameters (scattering lengths), and exact eigenstates can be calculated via the Bethe Ansatz if (and only if) these three parameters are all equal. For this specific case also results from the Thermodynamic Bethe Ansatz (TBA) have recently been obtained \[17\]. It was found that the polarization (the difference in population of the two states) shows some remarkable features, in particular in the polarization at low (but finite) temperatures. Motivated by these predictions, we have investigated the opportunities for experiments with a two-component gas of $^{87}\text{Rb}$ trapped on an atom chip.

We start from a single-component gas at relatively high temperature (in the non-degenerate regime), create a two-component cloud with a transfer pulse, and then proceed with evaporative cooling. The aim is to achieve a one-dimensional two-component gas at thermal equilibrium and finite temperature, and compare to predictions such as those of ref. \[17\]. Although conceptually very similar to the experiments of chapter \[5\], it turns out that there are a number of challenges to overcome, and we will describe these below.

The outline of this chapter is as follows. In section \[4.2\] we describe the experimental procedure that was used. We discuss some of the difficulties that were encountered, such as the (re)population of undesired additional states, and how these were circumvented and/or mitigated. In section \[4.3\] we present the key experimental results, consisting of density profiles of the trapped two-component Bose gas near thermal equilibrium. Section \[4.4\] discusses the results and to what extent these can be compared to existing theories. Finally, we also present an outlook on desirable future experiments.
4.2 Experimental procedure

The experimental sequence from initial cooling and trapping of atoms to evaporative cooling and finally reaching degeneracy has been described in detail in [90]. We will begin this section with a summary of this sequence. This will be followed by a description of the experimental procedure used to produce a two-component one-dimensional Bose gas.

We begin by pulsing a $^{87}$Rb-dispenser first at 20 A for 350 ms and then at 11 A for 850 ms. This releases rubidium atoms into the vacuum chamber. This is followed by switching on two pairs of counter-propagating, red-detuned (with respect to the cycling transition of the D2 line) laser beams. Together with a magnetic field gradient of 15 G/cm generated by the MOT coils, the lasers create a magneto-optical trap (MOT) below the atom chip surface. One pair of laser beams is reflected off the gold-coated chip surface at an angle of 45°, resulting in a mirror-MOT configuration [120]. All laser beams are overlapped with repumping laser beams, which serve to optically pump atoms from a dark state back into the cooling cycle. After a short compressed MOT phase, the atoms are optically pumped into the $|F=2, m_f=2\rangle$ state. At this point, all lasers as well as the MOT coils are switched off and the cloud is trapped magnetically using the mini-wires underneath the atom chip. After a transfer from this wire trap to the chip trap, generated by atom chip wire 5, the trap is drastically compressed, increasing the inter-atomic collision rate. This a perfect starting point for forced evaporative cooling, which we perform by applying a RF-ramp to chip wire 4. At this point, cooling to degeneracy with an RF ramp down to $\approx 2.27$ MHz leads to an almost pure condensate of $4.5 \times 10^4$ atoms. The overall experimental cycle time is 10 s.

For the experiments described in this chapter, we interrupt the evaporative cooling at $2.4$ MHz when the gas can still be considered non-degenerate. The atom are confined in a trap with trap frequencies $\omega_\perp/2\pi = 1.9$ kHz and $\omega_\parallel/2\pi = 26$ Hz. We then create a mixture of atoms in two clock states of $^{87}$Rb, $|1\rangle = |F=1, m_f=-1\rangle$ and $|2\rangle = |F=2, m_f=1\rangle$, and finally continue evaporative cooling, reaching degeneracy.

In order to create the mixture of states $|1\rangle$ and $|2\rangle$ we use the following sequence. As a first step after the initial evaporative cooling, we apply a short ($8 \mu$s) RF pulse, resonant with the level splitting between $m_F$-states, thereby transferring half of the atoms from $|F=2, m_f=2\rangle$ to $|2\rangle$. Next, a coherent superposition of states $|1\rangle$ and $|2\rangle$ is prepared using a resonant two-photon RF and microwave (MW) coupling [84, 111] as shown in figure 2.1. The microwave frequency is introduced via an external antenna (see section 3.2) while the RF-field is applied directly to the atom chip wires.

To increase the collision rate and thereby also the efficiency of evaporative cooling, the magnetic potential is tightened prior to the final cooling stage. Since state $|2\rangle$ decays faster than state $|1\rangle$ we chose to start evaporation after making an uneven mixture of the two states with an excess of atoms in state $|2\rangle$. This compensates for higher collisional losses experienced by state $|2\rangle$ during evaporative cooling and ensures an even mixture afterwards. For the same reason, the overall time of the final evaporation stage needed to be as short as 350 ms.

Initially, we employed a radio-frequency sweep alongside a constant microwave pulse to
expel the unwanted remaining population of $|F = 2, m_F = 2\rangle$ atoms from the trap. This two-photon scheme led to enhanced losses of both states $|1\rangle$ and $|2\rangle$ at the evaporation frequency 2.3 MHz, possibly due to an unintentional cross-resonance between radio-frequency- and the microwave sweeps. It was therefore replaced by a microwave sweep from 7.6 GHz to 6.75 GHz directly coupling the $|F = 2, m_F = 2\rangle$ to the untrapped $|F = 1, m_F = 1\rangle$ state. Furthermore, we found that the purity of the system benefits from an additional 15 ms microwave sweep from 6.75 GHz to 7.2 GHz at the end of this procedure.

The release from the trap and sequential state-selective imaging are performed as described in detail in Appendix A and in section 5.2, with the only difference being a shorter time-of-flight (1 ms). The experimental procedure detailed above was created to ensure the purity of the system and the absence of oscillations in position or shape. It results in a degenerate Bose gas with two components which we expect to be close to thermal equilibrium.

### 4.3 Results and analysis

Following the procedure of the previous section, we obtained absorption images of the two-component Bose gas close to thermal equilibrium (figure 4.1). While taking these images naturally sums over the atomic density in the $z$-direction, we integrate the resulting 2D density maps along the $y$-axis to obtain the 1D density profile along the $x$-axis. The peak densities (see figure 4.2) do not exceed 100 atoms/µm. For our trap parameters, this means that we can treat the clouds as 1D gases, similar to what was done for the single-component case [41, 121]. In figure 4.2 we show the measured 1D density profiles of the states $|1\rangle$ and $|2\rangle$ for six frequency values of the final evaporative cooling, illustrating the transition from the non-degenerate to the degenerate regime. A complication that arose in these experiments was that upon cooling to degeneracy, the experimental 1D profiles in figure 4.2 show strong fluctuations in the number of atoms and in the relative populations of the clock states.

We now want to compare our experimental data to the results from the thermodynamic Bethe Ansatz (TBA) calculations of ref. [47]. This is computationally intensive and requires searching in a multidimensional parameter space. Therefore we first calculate approximate parameters using a computationally simpler scheme, based on the single-component TBA (Yang-Yang) equations [41]. We now first describe this model. This will also be useful for the extension to the two-component case that we introduce subsequently.

The starting point is the numerically obtained equation-of-state in the form $n_{YY}(\mu, T)$ for the 1D density as a function of chemical potential $\mu$ and temperature $T$. For later reference, it is useful to point out here that convenient scaled units can be obtained as follows [122]. For a 1D coupling strength $g$, the relevant energy scale is

$$E_g = \frac{mg^2}{2\hbar^2}, \quad (4.1)$$
and the relevant length scale is

$$l_g = \frac{\hbar^2}{mg}. \quad \text{(4.2)}$$

Temperature and chemical potential are then most conveniently expressed in units of $E_g$, while 1D density $n_{YY}$ is in units of $1/l_g$. For instance the famous Lieb-Liniger parameter is given by

$$\gamma = \frac{1}{n_{YY}l_g}. \quad \text{(4.3)}$$

The thermodynamic relation $n_{YY} (\mu, T)$ can be combined with the local-density approximation (LDA) to obtain the in-trap density distribution via a local chemical potential $\mu(x) = \mu(0) - V(x)$. An important practical extension is that we also need to account for population in radially excited states, since our temperatures are on the order of the radial level splitting $\hbar \omega_\perp$. This is done by treating each radially excited state (radial quantum number $j$, degeneracy $j + 1$) as an independent ideal 1D Bose gas in thermal equilibrium with the radial ground state, at the same temperature $T$,

$$\mu_j = \mu(x) - j\hbar \omega_\perp. \quad \text{(4.4)}$$

The total linear density $n_l$ is then given by

$$n_l (\mu(x), T) = n_{YY} (\mu(x), T) + \sum_{j=1} (j + 1)n_e (\mu(x), T). \quad \text{(4.5)}$$

For the radially excited states we use the result of the LDA for the 1D ideal Bose gas,

$$n_e (\mu(x), T) = \frac{1}{\Lambda_T} g_{j/2} (\exp(\mu/k_BT)) \quad \text{(4.6)}$$

where $g_{j/2}$ is a Bose function and $\Lambda_T$ is the thermal de Broglie wavelength

$$\Lambda_T = \sqrt{\frac{2\pi \hbar^2}{mk_BT}}. \quad \text{(4.7)}$$
As a first step, we fit the expression (4.5) to the experimental density distributions of each component separately. This neglects the interaction between the two states, and hence is not justified. Nevertheless, we expect that this will yield reasonably good values for the temperature, as we elaborate below, and reasonable starting values for the chemical potentials of the two components. The resulting best fits are shown in figure 4.2 as dashed curves. These fits are surprisingly good, considering the fact that this model ignores the interspecies interactions. The temperatures and chemical potentials extracted from these fits are shown in figure 4.3. The reason we expect the extracted temperatures to be reliable, is that these are dominated by the tails of the distribution, where effects of degeneracy and interaction become small. In that regime, neglecting the interspecies interaction should be justified. Indeed, for each RF value, the temperatures extracted from the two components are in good agreement. Based on the fitted parameters, we then proceed to obtain fit parameters from the two-component model.

For the TBA solution of the homogeneous two-component 1D Bose gas, the relevant parameters are the coupling strength $g$ (required to be state-independent), the temperature and the two chemical potentials $\mu_{maj}$ and $\mu_{min}$. We have used the TBA code kindly provided by the authors of [47]. This code takes the scaled values of temperature

$$t = \frac{k_B T}{E_g} \quad (4.8)$$

the average chemical potential

$$\tilde{\mu} = \frac{\mu_{maj} + \mu_{min}}{2E_g}, \quad (4.9)$$

and the difference in chemical potential

$$\Omega = \frac{\mu_{maj} - \mu_{min}}{2E_g}. \quad (4.10)$$

To obtain density curves that can be compared to the experiment, again the LDA is used, and the radially excited states are accounted for in the same way as in (4.5), with a separate peak chemical potential for the two components $\mu_{maj}$ and $\mu_{min}$. We fix the temperature to the average of the two values obtained from the single-component fits (except for the data of figure 4.2(a), where the temperature of the majority component dominates). Next, we vary $\mu_{maj}$ and $\mu_{min}$ to be close to the peak (central) density of each component. The resulting density profiles are shown as solid curves in figure 4.2, while the used temperatures and resulting chemical potentials are shown in figure 4.3.

4.4 Discussion and outlook

The obtained fitted density distributions are in reasonable agreement with the experimental data. Before discussing possible reasons for the discrepancies, we first make a few more general remarks.

First, it should be pointed out that the usual bimodal description of partially condensed clouds does not work in 1D, as elaborated upon in ref. [41]. The main reason for this is that
Figure 4.2: Averaged density distribution of two-component Bose gas near thermal equilibrium as a function of the final evaporation frequency. The densities of states $|1\rangle$ and $|2\rangle$ are colored red and blue, respectively. The overall density is colored green. The experimental data is represented by dots. To obtain the profiles, for each state 50 density images were recorded under identical conditions and averaged. The plots show the atomic density summed along the $z$-direction, i.e. the 1D-density. A single component fit to the data is indicated by dashed lines, while the solid lines represent a fit based on the thermodynamic Bethe-Ansatz (TBA) according to [47].
Figure 4.3: Temperature (a) and chemical potential (b) of the two-component 1D Bose gas as function of the final evaporation frequency. Fits based single-component calculations are shown as dashed lines. States $|1\rangle$ and $|2\rangle$ are colored red and blue, respectively. The solid purple line in (a) represents the temperature values used for the two-component TBA calculations, that yield chemical potentials shown as solid curves in (b).
the 1D ideal Bose gas exhibits a diverging density as the chemical potential approaches zero from below, so that the crossover from ideal-gas to (quasi-)condensate cannot be properly described. The same argument holds for the two-component case, so that the two-component TBA solutions are an important tool in describing our data.

Second, the obtained chemical potentials for the two-component case are different from the separate chemical potentials from the single-component fits. This is to be expected from the results of ref. [47], which show that at low temperatures, the gas favors a strong polarization (difference in densities of the two components) even for small differences in chemical potential between the two components. This shows up in figure 4.3(b) as a much reduced difference in chemical potential for the two-component TBA fit, as compared to the two chemical potentials from the single-component TBA fits. In the experiments, the atom number is set (within experimental limitations). Hence, for a near-equal mixture, the required difference in chemical potentials in the two-component TBA rapidly diminishes as degeneracy is reached.

The main message of this work is that the two-component TBA calculations are very useful for our experimental results. There are, however, also several reasons why discrepancies are to be expected. First, as detailed in chapter 2, the interactions are not strictly state-independent because of the slight differences in scattering lengths among the two clock states of $^{87}$Rb. For relatively high temperatures ($k_B T > n \Delta g$) one might expect these small differences to be of minor relevance. For our densities of order 50 per micron, the relevant energy scale is $n \Delta g / k_B = 1 \text{nK}$. Our temperatures are higher than this scale (see figure 4.3(a)), so that this may not be a limiting factor. On the other hand, as we will see in the next chapter, these small energy differences can lead to significant dynamics at long time scales ($\approx 100 \text{ms}$). This is comparable to the time of evaporative cooling used here.

Another, harder to address, issue is the coherence between the two states. The goal has been to eliminate this coherence by the losses and dissipation of the evaporative cooling process. It is, however, hard to test to what extent this leads to complete decoherence.

For a completely coherent mixture, one would actually expect the single-component description to work for the total density. For the fully decoherent mixture the two-component TBA description should be applicable. Our experimental data shows similar agreement to best fits for both models, so that we are unable at this point to decide on the achieved (de)coherence based on this comparison.

Generally, the visibility of effects associated with the two-component gas and the comparison to TBA theory would benefit from a strong increase in interaction strength. For a more strict adherence to the condition of state-independent interactions (allowing a more detailed comparison to TBA theory) it would be desirable to extend the experiments of this chapter by combining this approach with the techniques of the following chapter. Namely, a next step would be to try and obtain thermal equilibrium in a two-component Bose gas via evaporative cooling, while tuning the one-dimensional interaction parameters to the point of integrability (via state-dependent potentials). While this natural combination of ideas has not escaped our attention, it is beyond the scope of the present thesis. Pursuing further investigations along these lines is left as a challenge for others.