Chapter 6

Coherence effects in a finite temperature condensate

Multiple spin-component Bose-Einstein condensates have permitted many studies of global symmetries and quantum statistical correlation effects in macroscopic quantum systems[67, 68, 25]. Interparticle correlations, or coherences, are fundamental properties in ultra-cold atomic gases as well as in the field of quantum optics. First-order coherences, referring to the deterministic nature of the phase of a system, can be seen in both fields. First-order coherence has been seen by overlapping two Bose-Einstein condensates and observing spatial density fringes [69], which is a counterpart to interference between two laser beams. We investigate further first-order correlations by watching finite-temperature condensate melting due to decoherence of the normal cloud. Using the Bose-Einstein phase transition as calibration, we examine the thermodynamics of the system to gain understanding of the correlations between atoms.

In this chapter we study how correlations affect the condensing and melting process in a condensate. We start by discussing the properties of the states in which we will study loss of coherence. We use two dressed states in ^{87}Rb, because these states enhance the natural symmetries of the system and allow us to more easily measure the correlations. Studies of the dressed states include measurements of stability of the states against transitions and experiments to determine the equilibrium spatial density distribution. Next we discuss the situation where we cool through the transition temperature with a partially coherent cloud to examine the symmetry of the condensed state, and finally how loss of coherence leads to melting of the condensate.

6.1 Dressed states

The dressed-state formalism is useful to describe a two-state system coupled by a radiation field [26]. The energies of the bare states

$$E_{e/g} = \pm\frac{1}{2}\hbar\omega_0 \tag{6.1}$$

are shifted by the presence of the coupling field to

$$E_g = -\frac{1}{2}\hbar\omega_0 + N\hbar\omega \tag{6.2}$$

$$E_e = +\frac{1}{2}\hbar\omega_0 + (N-1)\hbar\omega, \tag{6.3}$$

where ω_0 is the frequency difference between the two bare states, ω is the frequency of the coupling field, and N is the number of photons in the field. Solving for the eigenstates of the new Hamiltonian including the coupling field produces two eigenstates that are linear combinations of the bare states. These dressed states

$$|+\rangle = e^{-i(\Omega'_R-\delta-\omega_o)\frac{t}{2}}\left[\sqrt{\frac{1}{2}(1+\frac{\delta}{\Omega'_R})}|1\rangle + e^{-i\omega t}\sqrt{\frac{1}{2}(1-\frac{\delta}{\Omega'_R})}|2\rangle\right] \tag{6.4}$$

$$|-\rangle = e^{i(\Omega'_R-\delta-\omega_o)\frac{t}{2}}\left[-e^{-i\omega t}\sqrt{\frac{1}{2}(1-\frac{\delta}{\Omega'_R})}|1\rangle + \sqrt{\frac{1}{2}(1+\frac{\delta}{\Omega'_R})},|2\rangle\right] \tag{6.5}$$

are separated in energy by the effective Rabi frequency

$$\Omega'_R = \sqrt{(\omega_0-\omega)^2+\Omega_R^2}, \tag{6.6}$$

where Ω_R is the resonant Rabi frequency. A diagram of the dressed states as a function of detuning from resonance is shown in Fig. 6.1. When the coupling field is detuned far red of resonance the ground state is essentially the $|-\rangle$ state, and the excited state is essentially the $|+\rangle$ state. As the detuning approaches zero the dressed states become

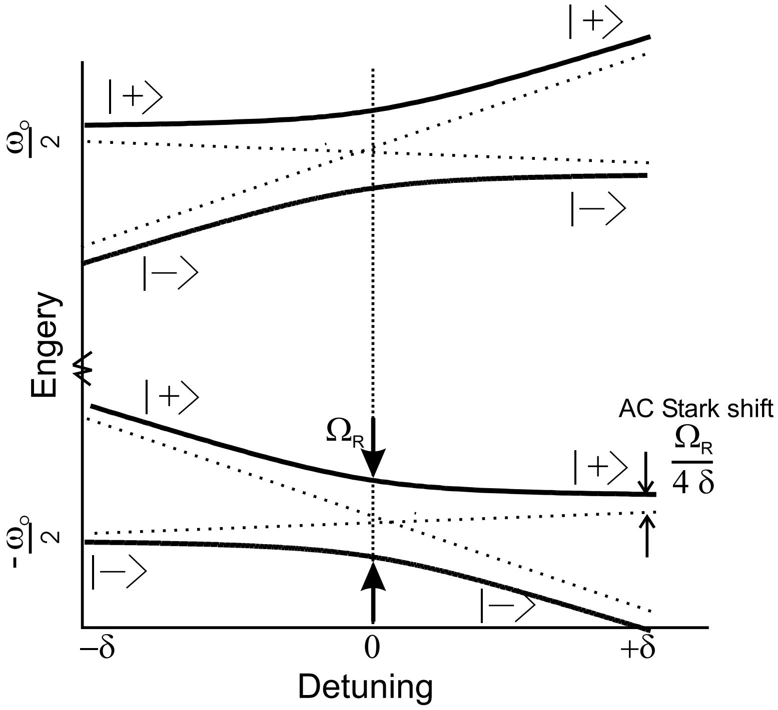

Figure 6.1: Energy level diagram of the dressed states showing the avoided crossing.

equal superpositions of the bare states. Finally, if the detuning increases in the blue direction the $|-\rangle$ state is now the excited state.

An atom initially in one dressed state will remain in that dressed state if the detuning is changed adiabatically. Adiabaticity is maintained if Υ is much greater than one, where Υ, the adiabaticity parameter, is

$$\Upsilon = \frac{\Omega_R^2}{\left|\frac{d\delta}{dt}\right|}, \tag{6.7}$$

where $\frac{d\delta}{dt}$ is the time rate of change of the detuning from resonance. The probability that an atom will make a transition to another dressed state is [70]

$$P = e^{-2\pi\Upsilon}. \tag{6.8}$$

6.2 Symmetries of the dressed-state system

Before looking at correlation effects, we must first understand the properties and symmetries of the dressed state system. The dressed states on resonance, being equal superpositions of the bare states, have convenient properties that are not present in the bare state system. These properties include identical collisional and loss rates as well as nearly identical trapping potentials.

A study of the symmetries includes the stability of atoms in a single dressed state. A collection of ultra-cold atoms in a binary mixture of two spin states has two global U(1) symmetries, which correspond to conservation of particle number in each species. However, when a coupling radiation field is tuned to the transition frequency between the spin states, one of the U(1) symmetries is broken. The symmetry is broken by the constant phase relation between the two species imposed by the field. The symmetry that remains corresponds to a conservation of total atom number. If the energy between the two states could be reduced to zero the system would be fully SU(2) symmetric. Such as system would be ideal to produce proposed Schrödinger cat states [71], but is excessively difficult with our system.

The experimental system is similar to the one described in Chapter 2. The system consists of a sample of atoms in the $|1\rangle$ hyperfine ground state of ^{87}Rb cooled to below 500 nK in the HIP trap. The dressing field consists of a microwave photon ($\sim$ 6.8 GHz) and a rf photon (3 MHz) that couples atoms to the $|2\rangle$ state through the intermediate state $|2,0\rangle$ [72]. Typical resonant Rabi frequencies are between 0.1-8 kHz and can be varied dynamically during an experimental run. The atoms can be prepared in a single dressed state by adiabatically ramping the dressing-field detuning from a large positive or negative value to zero. The atoms can also be prepared in an equal coherent superposition of the two dressed states by diabatically turning on a resonant dressing field.

We can selectively image atoms in either the dressed- or bare-state basis. To image atoms in the dressed basis we adiabatically ramp the dressing-field frequency far from resonance in either direction before turning off the field. For example ramping the frequency to a larger frequency transforms the $|+\rangle$ state into the $|1\rangle$ state and the $|-\rangle$ state into the $|2\rangle$ state. We can then use absorption imaging to probe the atoms only in the $|1\rangle$ state. We can also quickly turn off the dressing field while still on resonance to project the atoms into the bare-state basis, and therefore probe the coherence of the dressed states, which manifests itself as Rabi flopping in the bare states.

6.2.1 Stability of dressed states

We are unaware of any symmetry that implies conservation of atom number separately in each dressed state, and thus transitions between dressed states are not explicitly forbidden. We set out to observe transitions between dressed states because we thought transitions might be possible when the energy splitting of the dressed states is less than the thermal energy $k_B T$.

There are several mechanisms that can transfer population between dressed states. The most interesting type of transfer arises from collisions. During a collision the relative phase between the $|1\rangle$ and $|2\rangle$ bare parts of the wavefunction may acquire a phase shift, which results in population transfer in the dressed basis. Another mechanism of transfer is driven resonantly by the magnetic trapping fields. As atoms oscillate in the harmonic trap there appears, in the atoms' frame, to be an oscillating magnetic field. If the energy splitting between the dressed states, *i.e.* Rabi frequency, is tuned such that it is twice the trap oscillation frequency, the atoms have a probability of making a transition between dressed states. The radial frequency is large compared to the collision rate which allows an atom to oscillate freely in the trap for several cycles before a collision takes place and changes the effective oscillating magnetic field seen by the atom. This resonant transfer is an incoherent process, because the phase of the oscillating field for each atoms depends on its position and velocity, which are distributed thermally. The populations in each state should therefore not oscillate coherently but relax instead to an equal mixture.

Besides collisionally and resonantly induced transfer, atoms can make a transition between dressed state via the Landau-Zener process [73, 74]. If an atom cannot adiabatically follow the torque applied by the dressing field it may transfer between dressed states. If $d\delta/dt > \Omega_R'^2$, where δ is the detuning of the dressing field, there is a large probability an atom will undergo a Landau-Zener transition, as described in section 6.1. The detuning from the intermediate state varies spatially across the cloud due to the non-uniform density profile, leading to a spatially dependent mean-field energy shift, and also due to the Zeeman energy shift from the magnetic trapping fields. As the atoms oscillate in the trap they experience a time rate of change of detuning as they sample different densities and magnetic fields, which induces transfer.

We measure the rate of transfer between dressed states by adiabatically dressing the atoms in purely one dressed state on resonance and detecting atoms appearing in the other state. We start with the atoms in the $|-\rangle$ state and wait up to two seconds. We then ramp the drive detuning $10 \times \Omega_R$ in either direction to adiabatically convert one of the dressed states into the $|1\rangle$ state, which we image using absorption. We determine the transfer rate at different Rabi frequencies by extracting a linear slope of the fraction transferred as a function of time (Fig.6.2).

There are two features to note with the data in Fig. 6.2. First, there is a resonant increase in transfer where the Rabi frequency is twice the radial frequency for the reason described above. Second there is a background rate, which decreases as Rabi frequency increases, which is most likely due to Landau-Zener transitions. We can estimate the transfer probability per collision far from the resonance, above 3 kHz, to be no more than $4(2) \times 10^{-5}$. Although collisional transfer from the $|-\rangle$ to the $|+\rangle$ state is endothermic, it is energetically allowed because the atoms' thermal energy is larger than the splitting

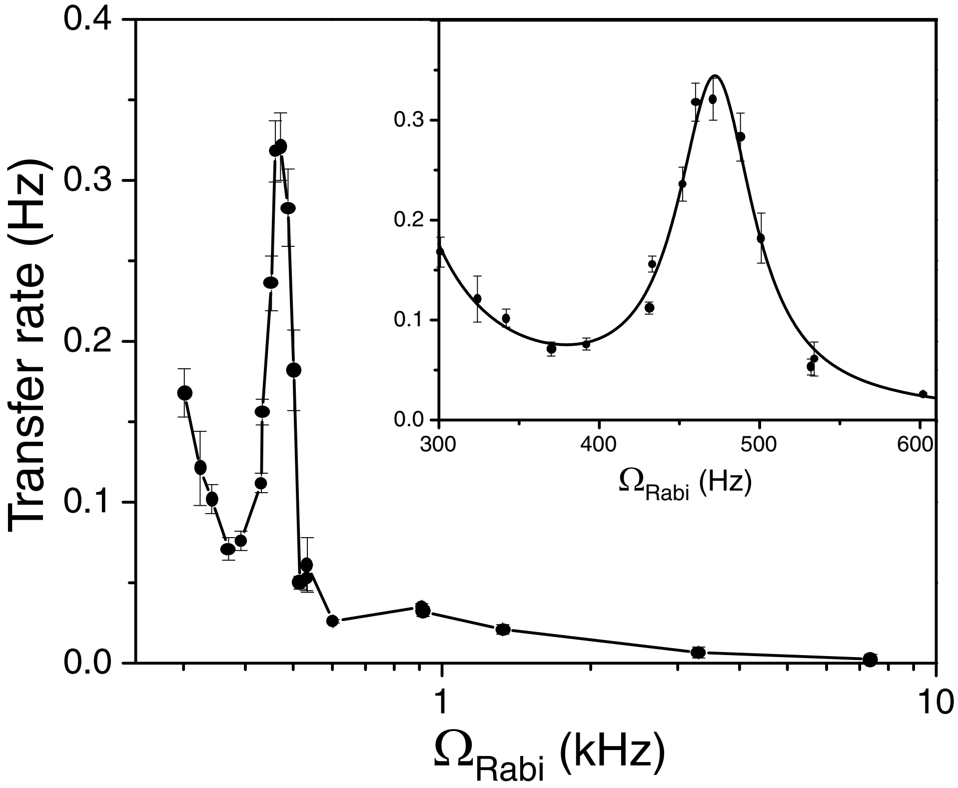

Figure 6.2: Transfer rate is shown as a function of Rabi frequency. The inset graph highlights the resonant transfer at twice the radial trap frequency (ν_{radial} = 230.5Hz); the solid line is a fit to a plausible functional form of a decaying exponential plus a Lorentzian. The error bars reflect the statistical uncertainty in the fitting. Initial cloud parameters are T = 300 nK and density = 2×10^{13}cm^{-3}.

between the dressed states. Collisional transitions maybe suppressed in ^{87}Rb because the triplet and singlet scattering lengths are nearly identical, which reduces the rate for atoms to spin-flip between hyperfine ground states during collisions. The small collisionally induced transfer rate implies an approximate symmetry. The system is not free to explore fully the entire SU(2) space, which would be useful for verifying several theoretical predictions such as Mermin-Ho vortices [75]. For our purposes, the stability of atoms in the dressed states is fortunate. We want to compare the thermodynamics of atoms in an equal superposition of states to that of atoms in one dressed state. This would not be possible if the atoms, initially prepared in one state, would over short times equilibrate to an equal populations in both states.

6.2.2 Separation of dressed states

Working with dressed states instead of bare states can also increase the spatial symmetry of a two-component condensate. A condensate in a superposition of two bare states will spatially separate in the trap to reduce the total energy of the system [48, 76]. The two spin states we work with in ^{87}Rb have slightly different mean field interactions, which drives the separation. In other work it has been shown that the $|1\rangle$ state, the state with a larger s-wave scattering length, will move to the lower density region of the condensate, and the $|2\rangle$ state will concentrate in the center of the cloud where the density is the highest [48].

The dressed states on resonance, on the other hand, are composed of equal superpositions of bare states. The mean-field interaction energy between the dressed states is equal and therefore does not drive spatial separation. However any significant spatial gradient in the differential potential between the dressed states, such as produced by a spatially inhomogeneous Rabi frequency, will cause separation. Atoms at different positions in the harmonic trap are detuned differently from the intermediate state, $|2, 0\rangle$, due to the Zeeman effect. The spatial variation of the intermediate state detuning results in a variation of the Rabi frequency across the cloud. Typically the Rabi frequency varies by at most a few percent across the entire condensate. However at large Ω_R, a few percent can mean 100 Hz difference, more than enough to drive spatial separation. The Rabi frequency inhomogeneity has the functional form of the magnetic trap: parabolic. When we operate with large Rabi frequencies (>1kHz) and negative intermediate state detuning, the dressed states separate with the $|-\rangle$ occupying the outer region of the condensate and the $|+\rangle$ in the center (Fig. 6.3). Changing the sign of the detuning causes the states to reverse positions in the trap. The goal for spectroscopy is to have the two states overlapped as much as possible in the trap. The dressed states in the condensate remain completely overlapped, within experimental resolution, when the intermediate state detuning is increased to 1.4 MHz and the Rabi frequency is decreased 300 Hz as shown in Fig. 6.3 .

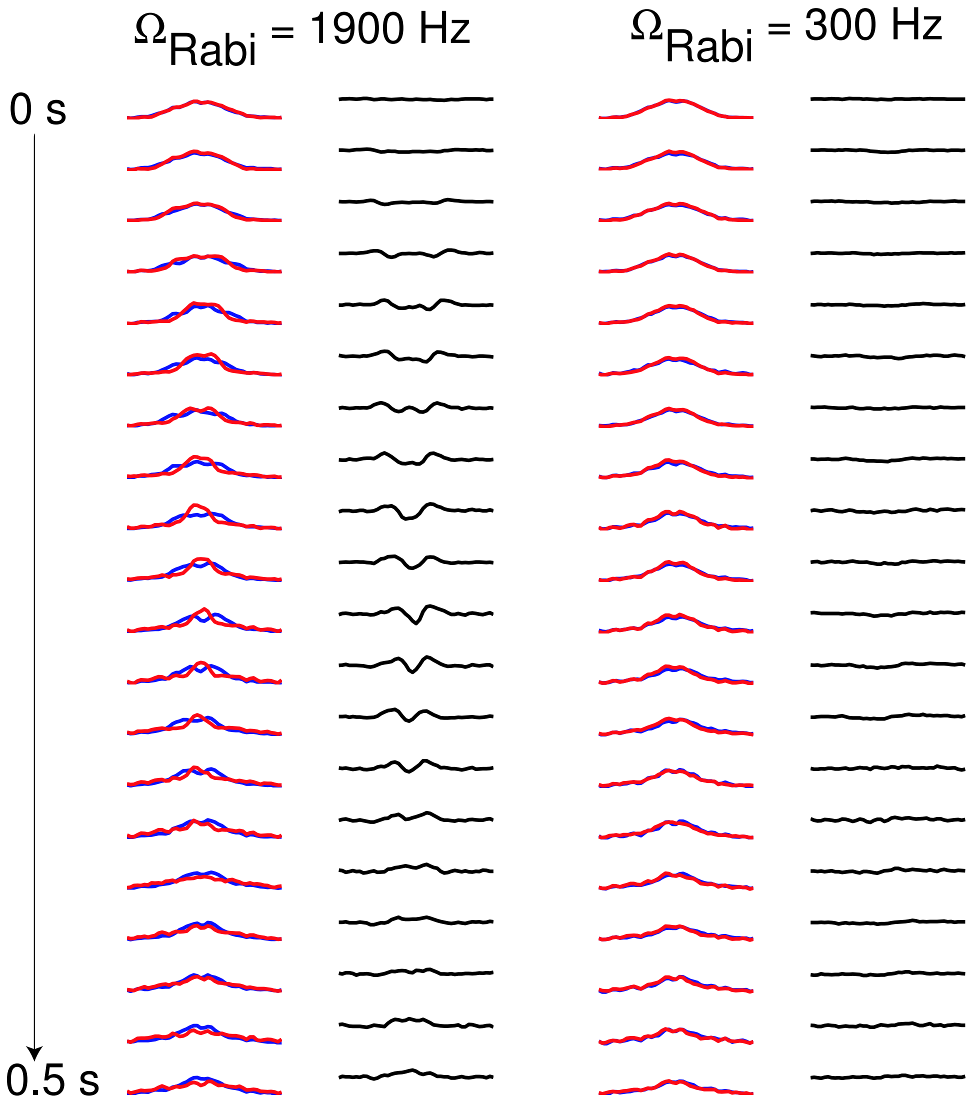

Figure 6.3: Normalized cross sections through the clouds comprised of $|+\rangle$ atoms in red and $|-\rangle$ in blue as a function of time; the difference between the cross sections is in black (second and fourth columns). There is significant separation of the two dressed states when the Rabi frequency is 1.9 kHz and $\Delta_{\mathrm{IM}} = 0.7$ kHz. Decreasing the Rabi frequency to 300 Hz and increasing $\Delta_{\mathrm{IM}} = 1.4$ MHz results in the clouds remaining overlapped for at least 0.5 seconds.

6.2.3 Evaporation of dressed states

We investigate the symmetries of the dress-state system also by condensing with the dressing field present. An interesting question to ask is how the condensation process is affected by the dressing field. Does the condensate form in the lowest energy state in the system or in an excited state such as a coherent superposition of dressed states? We examine these questions by starting with a cloud of atoms above the transition temperature, applying the resonant dressing field, and evaporatively cooling the cloud until a condensate forms.

We begin the experiment with a 50/50 fully-coherent superposition of $|+\rangle$ and $|-\rangle$ states, above the condensation temperature. During the evaporation the atoms dephase due to the spatial inhomogeneity of the Rabi frequency. The dephasing time is proportional to the magnitude of the Rabi frequency and is on the order of 100 ms for a Rabi frequency of 370 Hz. We cool the cloud in 120 ms using simultaneous microwave evaporation on both the $|1\rangle$ and $|2\rangle$ states. By the time the condensate forms the normal cloud has dephased significantly but not entirely. In this manner we can create a cloud with a condensate fraction up to 10%. After the condensate forms we investigate the state of the condensate by waiting a variable time before diabatically turning off the dressing field and imaging the atoms in the $|1\rangle$ state. We integrate the number through a column in the center of the cloud which includes most of the condensate and some of the normal cloud. The data in Fig. 6.4 show the number in the center of the cloud, which is 52(4)% condensate, Rabi flopping with 86(4)% contrast.

The high contrast fringes demonstrate that the condensate, which is condensed out of a normal cloud with residual coherence, forms in a superposition of dressed states. One might expect this result because the normal cloud retains some local coherence when the condensate forms. However, it is still surprising that the condensate is created in a state that cycles between the bare states, despite the powerful statistical mechanical preference for groundstate condensation.

We are unable to fully answer the question of how correlations are lost, or what state a condensate is created in when the normal cloud has lost all correlations, because of the limited parameter space we can explore. By the time the condensate forms, the normal cloud has significantly decohered because of dephasing during the relatively long evaporation time. This limits the measurement to samples with already small correlations. On the other side, we can not form a condensate where the correlations have essentially disappeared. This inability to condense suggests that the correlations themselves could promote condensation. We can barely create a condensate when correlations are present because we lose a significant number of atoms due to dipolar relaxation in the $|2\rangle$ state. Therefore it is not surprising that we can not produce a condensate when the correlations are lost, because we would need a factor of 2 more atoms. Because of these limitations we also looked at the loss of correlations from the perspective of melting instead of condensing.

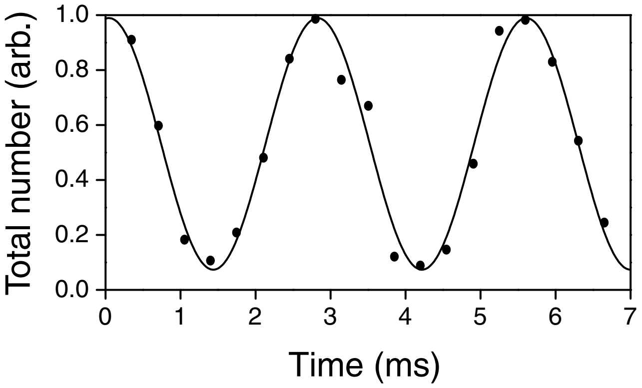

Figure 6.4: The density of atoms in the center of the cloud in the $|1\rangle$ state Rabi flopping as a function of hold time after evaporation. 52% of the central density consists of condensate atoms.

6.3 Decoherence induced melting of a finite temperature condensate

We use the statistics of the Bose phase transition to look at the correlations. A partially condensed system made up of fully coherent atoms in an equal superposition of two spin states is, in effect, composed of a single species of atom. If the noncondensed atoms dephase, due to an inhomogeneous potential, they become distinguishable particles and must be thought of atoms in two distinct populations. A condensate at finite temperature initially in equilibrium with a fully coherent normal cloud will presumably melt as the coherence is lost in the normal cloud. This can be understood by realizing the loss of coherence essentially reduces the effective number in the state by two ($N_{eff} = N/2$). The condensate must then melt to restore thermal equilibrium.

We observe condensate melting induced by decoherence in the normal cloud by initially creating a cloud in the $|1, -1\rangle$ state with about 45% condensate fraction. Next we dress the cloud in an equal coherent superposition of dressed states. We measure the temperature and density of the cloud over a time of 200 ms and calculate the apparent phase space density [77] of the normal cloud as the condensate melts. For a system in a single dressed state or a fully coherent superposition of states, the phase space density for the normal cloud should be equal to one, normalized by 2.61, as long as a condensate is present. If the system is an uncorrelated binary mixture of two states, the *total* normal cloud will appear to be at twice the phase space density. We also performed the same experiment with the sample in only one dressed state.

The one state data allows us to remove imaging and fitting systematics. There is a systematic error in calculating phase space density of the normal cloud when a condensate is present due to our fitting routine. We find the calculated phase space density increases linearly with increasing condensate fraction for the one component cloud, which should remain at a constant 2.61 when a condensate is present. We remove this systematic by fitting a line to the phase space density vs. condensate fraction data, and then we remove this slope from the both the single and superposition state data. Also, when we took these data we did not have enough microwave power to transfer 100% of the atoms via ARP for imaging. Therefore, we could not detect all of the atoms, which led to an underestimate of the phase space density. We eliminated this problem by normalizing each phase space density data point by the average of the single state phase space density.

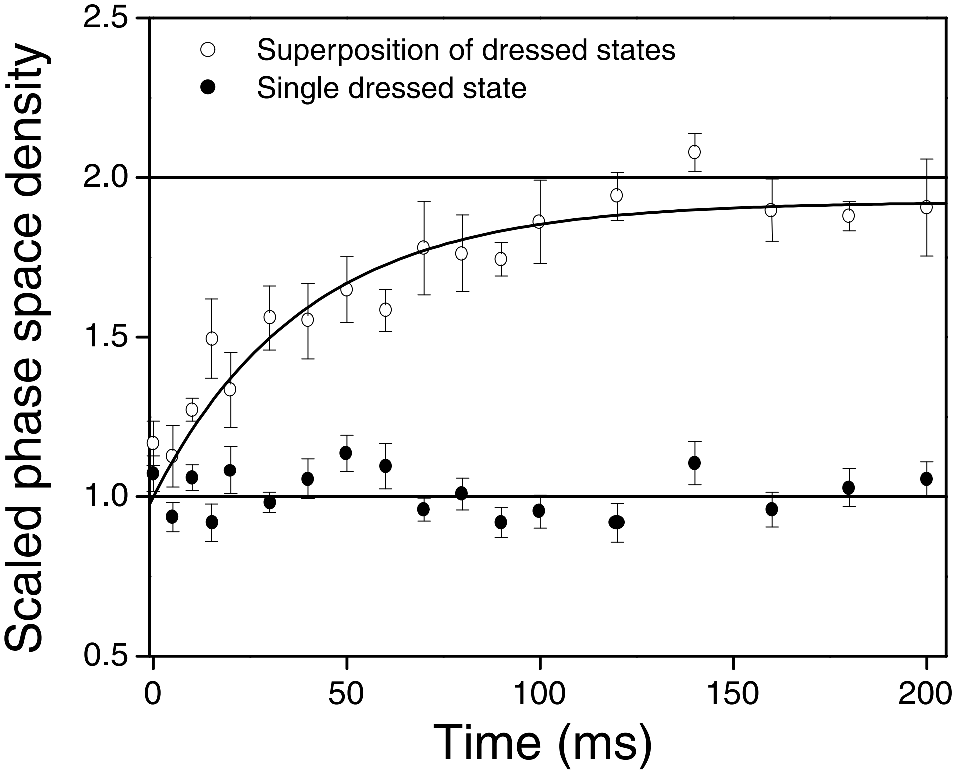

Figure 6.5: The measured phase space density (PSD), normalized by 2.61, as a function of decohering time. The solid circles are the PSD of the normal cloud in a single state, whereas the open circles represent the PSD of the normal cloud in an initially fully coherent superposition of dressed states. The superposition state PSD approaches two in a time scale of 40 ms, which is consistent with the normal cloud coherence time of 30(5) ms. Each point is a weighted average of nine independent measurements.

We are able to observe the apparent phase space density of the superposition case go from 1→∼2 [Fig. 6.5]. The time scale for the correlations to go away is on the order of 40 ms, as extracted from an exponential fit to the data in Fig. 6.5. One would expect the atoms to become uncorrelated on the same time scale as the decoherence, ignoring the thermal equilibration time of the system. We measure the coherence time of the thermal atoms at the edge of the cloud to give an estimate of the coherence time at the center of the cloud. We find the coherence time of the thermal atoms to be 30(5) ms which is consistent with the time for the correlations to disappear.

In the special case where the normal cloud has lost all correlations and can be thought of as a binary mixture of two states, the question arises what state describes the condensate? One possibility is that collisions into and out of the condensate from the normal cloud could create two condensates in a binary mixture. The two condensates would still have spatial coherence but would have lost internal coherence. There would be a distinct relative phase between the condensates in each dressed state but would vary from experimental shot-to-shot. In the end, any product of the decohering process would be a novel quantum state. Unfortunately we are currently unable to determine the state of the condensate after the decohering process, because by the time all of the correlations are lost there is very little to no condensate present due to the large loss rate in the $|2\rangle$ state.

In conclusion we have studied the properties of a two-state dressed system. Atoms in a dressed state show remarkable stability against relaxing to a different dressed state. This stability allows us to use these states to examine the effects of correlations on condensing and melting Bose-Einstein condensates. We were able to watch the correlations disappear and observe decoherence-induced melting in a finite-temperature condensate. The ultimate state of the condensate after all normal cloud correlations are gone would be interesting to study in the future.