The Mystery of the Ramsey Fringe that Didn't Chirp

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Abstract

We use precision microwave spectroscopy of magnetically trapped, ultra-cold ^{87}Rb to characterize intra- and inter-state density correlations. The cold collision shifts for both normal and condensed clouds are measured. The results verify the presence of the sometimes controversial "factors of two", in normal-cloud mean-field energies, both within a particular state and between two distinct spin species. One might expect that as two spin species decohere, the inter-state factor of two would revert to unity, but the associated frequency chirp one naively expects from such a trend is not observed in our data.

1 Introduction

When one studies the statistics of arrival times of photons emitted from an incoherent source, one finds that immediately after detecting a photon, one is twice as likely to detect a second photon than one would expect from the time-averaged detection rate. This "photon bunching" effect can be understood as arising naturally from the quantum statistics of a noisy bosonic field. If one detects a photon, one can infer that the randomly fluctuating boson field is near a peak in its amplitude. Small wonder then that one is likely to detect another photon soon. Similar effects are seen in the correlations in the arrival times of bosonic atoms falling from a cold cloud [1]. Within an atomic cloud itself, these statistical effects are best thought of as density fluctuations. Just as the short-time peak in photon arrival statistics is suppressed in a coherent (laser) beam of photons, the density fluctuations in a cloud of bosonic atoms is suppressed if the atoms are Bose-condensed. This effect has been seen in the analysis of expansion energy of condensates [2, 3] and in the comparison of three-body recombination rates in condensates versus thermal clouds [4].

In a recent series of experiments we examined the effects of these density fluctuations on the hyperfine transition frequency in ultra-cold normal and in Bose-condensed rubidium [5]. The MIT hydrogen group performed early work in this area [6]. In this shorter conference proceedings, we review our spectroscopic study [5] with particular emphasis on the effects of decoherence on the density correlations between two distinct hyperfine states. A cloud of thermal atoms begins initially in a single hyperfine state. A microwave pulse coherently splits the cloud into two distinct hyperfine states with a well-defined relative phase. Ramsey spectroscopy, sensitive to the density effects, shows that the two states initially have the same factor of two in their inter-state density correlations as each does in its intra-state density correlations. What we find counter-intuitive is that as time evolves and the two spin species begin to decohere, we see no corresponding shift in the frequency of the Ramsey fringes. Thus, with apologies to Arthur Conan Doyle, we came up with the title of the present manuscript.

2 Hyperfine Spectroscopy

Spatial inhomogeneity of the transition frequency was minimized through the use of a pair of energy levels which experience the same trapping potential. At a magnetic field of ~ 3.23 G the $|1\rangle \equiv |F = 1, m_f = -1\rangle$ and $|2\rangle \equiv |F = 2, m_f = 1\rangle$ hyperfine levels of the $5S_{1/2}$ ground state of ^{87}Rb experience the same first-order Zeeman shift. For a normal cloud at 500 nK, each energy level is Zeeman shifted by $\sim$10 kHz across the extent of the cloud, however at 3.23 G the *differential* shift of the two levels across the cloud is $\sim$1 Hz. Compared to the differential Zeeman shift, the energy shift due to cold collisions is then a relatively large effect at high densities, making measurements of collisional shifts in this system possible. The small inhomogeneity allows for long coherence times, $\sim$2 seconds and longer for low-density clouds, making this system attractive for precision measurements as well as for the study of coherence in finite temperature systems.

The experimental setup has been previously described [7] and will be briefly summarized here. Approximately 10^9 ^{87}Rb atoms are loaded into a vapor cell magneto-optical trap (MOT). The atoms are then optically pumped into the $|F = 1\rangle$ state by turning off the repump beam while the MOT beams remain on. Then the trapping beams are turned off and the MOT coils are ramped to a high current, forming a 250 G/cm gradient to trap $|1, -1\rangle$ atoms in the quadrupole field of the coils. The quadrupole coils are mounted on a linear servo-motor controlled track which then moves the coils 44 cm, from the MOT region to a Ioffe-Pritchard trap in the ultra-high vacuum region of the system. The Ioffe-Pritchard trap consists of two permanent magnets which provide a 450 G/cm radial gradient. Two pairs of electromagnetic coils, a pinch and a bias, provide confinement in the axial direction, which is aligned perpendicular with respect to gravity. At a typical bias field of 3.23 G atoms in the $|1, -1\rangle$ state experience $\{230, 230, 7\}$ Hz trap frequencies. The sample is further cooled by rf evaporation, and condensates of up to 10^6 atoms can be formed. Imaging is performed by the use of adiabatic rapid passage to transfer atoms from the $|1, -1\rangle$ state to the $|2, -2\rangle$ state. Anti-trapped $|2, -2\rangle$ atoms rapidly expand for 2-5 ms and then are imaged through absorption by a 20 μs pulse of $5S_{1/2}$ $|2, -2\rangle \rightarrow 5P_{3/2}$ $|3, -3\rangle$ light.

A two-photon microwave-rf transition is used to transfer atoms between the $|1\rangle$ and $|2\rangle$ states. A detuning of 0.7 MHz from the $|2, 0\rangle$ intermediate state provides a two-photon Rabi frequency of ~ 2.5 kHz. Ramsey spectroscopy of the $|1\rangle \rightarrow |2\rangle$ transition is performed by measuring the total number of atoms remaining in state $|1\rangle$ after a pair of $\frac{\pi}{2}$ pulses separated by a variable time delay is applied [8]. The frequency of the resulting Ramsey fringes is the difference between the transition frequency ν_{12} and the two-photon drive frequency. In previous work we measured local variations of ν_{12} by detecting the number of atoms remaining in state $|1\rangle$ at specific spatial locations along the axis of the normal cloud [7]. By analyzing the spatio-temporal variations of ν_{12}, combined with the measured evolution of the $|1\rangle$ state after a single $\frac{\pi}{2}$ pulse, we were able to spatially resolve the evolution of spin waves [9]. In this work, in order to perform measurements of ν_{12} insensitive to spin waves, one of the following two techniques was used. With one technique the entire cloud, rather than specific spatial locations, was monitored to average out the effects of spin waves. Alternatively Ramsey spectroscopy was restricted to interrogation times short compared to the spin wave frequency [10].

One effect which shifts the transition frequency ν_{12} is the differential Zeeman shift. The Breit-Rabi formula predicts a minimum in ν_{12} at $B_0 = 3.228917(3)$ Gauss, thus

the $|1\rangle$ and $|2\rangle$ energy levels experience an identical Zeeman shift at $B = B_0$. The differential Zeeman shift about B_0 can be approximated as $\nu_{12} = \nu_{min} + \beta(B - B_0)^2$ [11]. Measuring ν_{12} for different magnetic fields allows us to calibrate our magnetic field from the expected dependence. By working at the vicinity of $B = B_0$ we greatly reduce spatial inhomogeneity of ν_{12} and also become first-order insensitive to temporal magnetic field fluctuations.

3 Density Shifts

A second effect which shifts ν_{12} arises from atom-atom interactions. In the s-wave regime, where the thermal de Broglie wavelength of the atoms is greater than their scattering length, atoms experience an energy shift equal to $\alpha\frac{4\pi\hbar^2}{m}an$, where α is the two-particle correlation at zero separation, n is atom number density, a is the scattering length, and m is the atom mass. Therefore for a two-component sample the expected energy shift of each state is

$$\delta\mu_1 = \frac{4\pi\hbar^2}{m}(\alpha_{11}a_{11}n_1 + \alpha_{12}a_{12}n_2) \tag{1}$$

$$\delta\mu_2 = \frac{4\pi\hbar^2}{m}(\alpha_{12}a_{12}n_1 + \alpha_{22}a_{22}n_2), \tag{2}$$

where n_1 and n_2 are the $|1\rangle$ and $|2\rangle$ state densities and

$$\alpha_{ij} = \frac{\langle\Psi_i^\dagger\Psi_j^\dagger\Psi_i\Psi_j\rangle}{\langle\Psi_i^\dagger\Psi_i\rangle\langle\Psi_j^\dagger\Psi_j\rangle}. \tag{3}$$

The shift of the transition frequency in Hz can then be written as

$$\begin{aligned}\Delta\nu_{12} &= (\delta\mu_2 - \delta\mu_1)/h \\ &= \frac{2\hbar}{m}(\alpha_{12}a_{12}n_1 + \alpha_{22}a_{22}n_2 - \alpha_{11}a_{11}n_1 - \alpha_{12}a_{12}n_2) \\ &= \frac{\hbar}{m}n(\alpha_{22}a_{22} - \alpha_{11}a_{11} + \\ &\quad (2\alpha_{12}a_{12} - \alpha_{11}a_{11} - \alpha_{22}a_{22})f)\end{aligned} \tag{4}$$

where

$$f = \frac{n_1 - n_2}{n} \tag{5}$$

and $n = n_1 + n_2$.

For non-condensed, indistinguishable bosons, $\alpha = 2$ due to exchange symmetry, therefore $\alpha_{11}^{nc} = \alpha_{22}^{nc} = 2$ in a cold normal cloud (where the superscript c or nc refers to condensed of non-condensed atoms respectively). Distinguishable particles do not maintain exchange symmetry, making $\alpha_{12}^{nc} = 1$ for a incoherent two-component mixture. However if a two-component sample is prepared by coherently transferring atoms from a single component, such as in Ramsey spectroscopy, then the excitation process maintains exchange symmetry, and we might expect $\alpha_{12}^{nc} = 2$ [12]. In this scenario the collisional shift should be calculated using $\alpha_{11}^{nc} = \alpha_{22}^{nc} = \alpha_{12}^{nc} = 2$, leading to a predicted frequency shift of

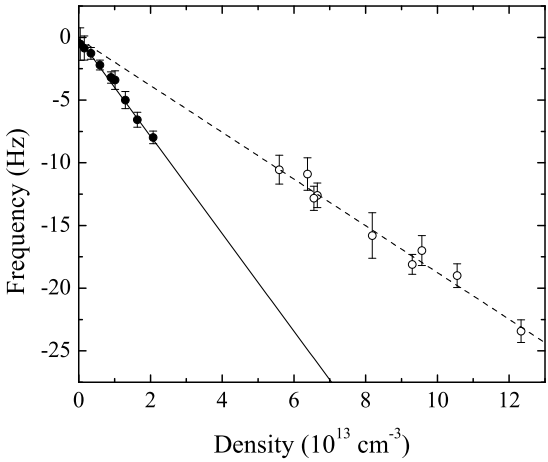

Figure 1: Measurement of the cold collision shift. Solid and open circles represent measurements of the normal cloud and condensate respectively. The solid line is a fit to the normal cloud data $\Delta\nu_{12} = 0.1(0.4) - 3.9(0.3)10^{-13}n$; the dashed line is a fit to the condensate data $\Delta\nu_{12} = -0.1(1.4) - 1.9(0.2)10^{-13}n$ where $\Delta\nu_{12}$ is in Hz and n is in cm^{-3}.

$$\Delta\nu_{12} = \frac{2\hbar}{m} n(a_{22} - a_{11} + (2a_{12} - a_{11} - a_{22})f). \tag{6}$$

This result can also be obtained by solving the transport equation [13, 14]. From spectroscopic studies [15] the three ^{87}Rb scattering lengths of interest have been determined to be $a_{22} = 95.47a_0$, $a_{12} = 98.09a_0$, and $a_{11} = 100.44a_0$, where a_0 is the Bohr radius. The frequency shift can then be written as

$$\Delta\nu_{12} = \frac{2\hbar}{m} a_0 n(-4.97 + 0.27f). \tag{7}$$

If on the other hand the $|1\rangle$ and $|2\rangle$ states do *not* maintain exchange symmetry, such that $\alpha_{12}^{nc} = 1$, then the frequency shift would instead be

$$\Delta\nu_{12} = \frac{2\hbar}{m} a_0 n(-4.97 - 97.82f). \tag{8}$$

These two models are clearly distinguished by the dependence of ν_{12} on f.

When we perform Ramsey spectroscopy with a pair of $\frac{\pi}{2}$ pulses, the populations of the $|1\rangle$ and $|2\rangle$ states are equal, and thus $f = 0$ during the interrogation time. From Eq. (4) it is apparent that with $f = 0$ the collisional shift is sensitive only to α_{ii}^{nc} and a_{ii} terms. For these measurements the bias field was set to B_0, and the transition frequency was measured for a range of densities. To adjust density of the sample, the number of atoms in the initial MOT load was varied. All normal cloud data was

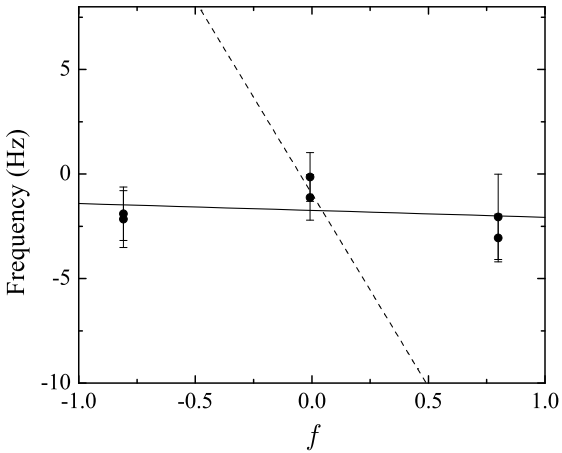

Figure 2: Testing the exchange symmetry between the $|1\rangle$ and $|2\rangle$ states. The transition frequency is measured as f is varied for a normal cloud at fixed peak density of 7×10^{12} cm^{-3} and temperature of 510 nK. The solid line is the fit, which yields $\alpha_{12}^{nc}/\alpha_{11,22}^{nc} = 1.01(2)$, which is to say, inter- and intra-state density correlations are quite accurately the same. The dotted line indicates the expected slope for $\alpha_{12}^{nc}/\alpha_{11,22}^{nc} = 1/2$.

taken at the same temperature of 480 nK, and all condensate data was taken with high condensate fractions in order to minimize effects due to the normal cloud. The density for the normal cloud was found by fitting Gaussian profiles to absorption images of the clouds and extracting the number, temperature, and density. To measure condensate density Thomas-Fermi profiles were fit to absorption images of the condensates and the total number, N_0, in the condensates and the Thomas-Fermi radius along the long axis, Z, were extracted.

The results of this measurement are shown in Fig. 1. Comparing the collisional shift measured for the normal cloud to that measured for a condensate gives $\alpha_{ii}^{nc}/\alpha_{ii}^{c} = 2.1(2)$. If instead we *assume* $\alpha_{ii}^{nc} = 2$ and $\alpha_{ii}^{c} = 1$, then the data for both the condensate and normal cloud can be used to obtain a value for the difference in scattering lengths of $a_{22} - a_{11} = -4.92(28)a_0$, in agreement with values determined from molecular spectroscopy [15].

4 Inter-state density correlations

Exchange symmetry between the $|1\rangle$ and $|2\rangle$ states can be tested by working at a fixed density and varying the relative $|1\rangle$ to $|2\rangle$ population by varying the length of the first Ramsey pulse [16]. In this case the first term in Eq. (4) will be constant and the measurement will test α_{12}^{nc} and a_{12} as well as the α_{ii}^{nc} and a_{ii} terms. To minimize sys-

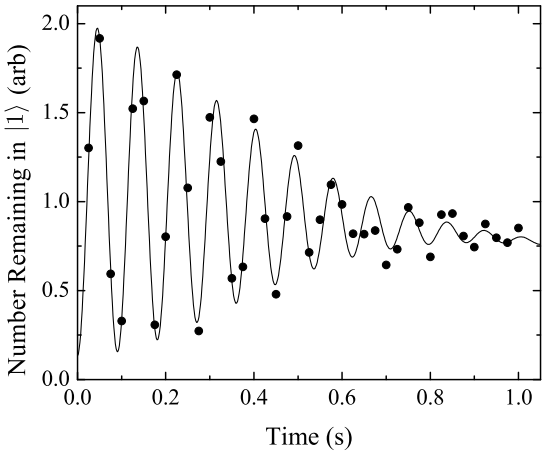

Figure 3: A data set of Ramsey fringes probing for frequency shifts as a function of coherence. For this measurement normal clouds at a temperature of 480 nK and a peak density of 3.2×10^{13} cm^{-3} were used.

tematics the interrogation times were kept short, making precise frequency determination difficult. Nevertheless, our measurement (Fig. 2) indicates $\alpha_{12}^{nc}/\alpha_{11,22}^{nc} = 1.01(2)$, where we have used the spectroscopically determined scattering lengths. This clearly indicates that exchange symmetry is maintained between the $|1\rangle$ and $|2\rangle$ states.

5 Where's the chirp?

As a thought experiment, imagine distinct thermal populations of $|1\rangle$ and $|2\rangle$ atoms, separately prepared, then mixed together, with the energy of interaction (proportional to α_{12}^{nc}) measured for instance calorimetrically. Surely in this case the density fluctuations in state $|1\rangle$ and in state $|2\rangle$ would be uncorrelated, and α_{12}^{nc} would be determined to be 1, not 2. We lack the experimental sensitivity to make such a calorimetric measurement, and our Ramsey-fringe method of measuring energy differences obviously would not work for incoherent mixtures. We speculated, however, that if $\alpha_{12}^{nc} = 2$ for coherent superpositions, and if $\alpha_{12}^{nc} = 1$ for incoherent mixtures, then for partially decohered samples, α_{12}^{nc} would take on some intermediate value. So by performing a measurement similar to that in Fig. 2 we might expect to see a more negative slope for a partially decohered sample; alternatively a frequency chirp in the Ramsey fringes may be seen as the sample decoheres.

We probed the time evolution of α_{12}^{nc} in a way similar to Fig. 2; however rather than varying f we set $f \simeq 0.8$ then measured ν_{12} with long interrogation times, looking for a frequency chirp as the fringe contrast decreased. This method has the advantage that there is a relatively small $|2\rangle$ state population, so effects arising from $|2\rangle$ loss are minimized. Seven data sets were taken for this measurement; an example is shown

in Fig. 3. By allowing a linear frequency chirp in the fit of the Ramsey fringes, the frequency shift can be constrained to $-0.2(3)$ Hz by the time the fringe contrast has reduced to $1/e$ [17]. However if we hypothesize that α_{12}^{nc} goes from 2 to 1 linearly as fringe contrast goes from 100% to 0% we would expect a frequency shift of $-20(2)$ Hz as the fringe decayed, while the experimental limit is a factor of 40 smaller. Clearly this appealing but unrigorous model is far too naive.

6 Conclusion

Where's the chirp? In truth we don't know. Our theorist friends tell us that our confusion arises from our assuming that the frequency shift $\Delta\nu_{12}$ arise from the difference in chemical potentials, $\mu_2 - \mu_1$. Instead, they say, we should directly evaluate the Boltzmann equations for the spin in an inhomogeneous system [13, 14]. This we have not as yet done, but even if this solves the mystery in a formal sense, we are reluctant to give up the cherished notion that the frequency of the transverse spin precession is a direct measurement of the energy difference between spin up and spin down. For those of us raised in the traditions of atomic physics, it is a pleasure to note that a two-level system can still yield surprises, 75 years after the advent of quantum mechanics.

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