Observation of spinor dynamics in optically trapped $^{87}$Rb Bose-Einstein Condensates

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We measure spin mixing of $F=1$ and $F=2$ spinor condensates of $^{87}$Rb atoms confined in an optical trap. We determine the spin mixing time to be typically less than 600 ms and observe spin population oscillations. The equilibrium spin configuration in the $F=1$ manifold is measured for different magnetic fields and found to show ferromagnetic behavior for low field gradients. An $F=2$ condensate is created by microwave excitation from $F=1$ manifold, and this spin-2 condensate is observed to decay exponentially with time constant 250 ms. Despite the short lifetime in the $F=2$ manifold, spin mixing of the condensate is observed within 50 ms.

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self in different ways depending on the scale of the ferromagnetic energy compared with the Zeeman energy. For a typical density of \( n = 4 \times 10^{14} \text{ cm}^{-3} \) in our optical traps, the ferromagnetic energy \(|H|c_2/n| \) is only 28 Hz, and hence, observation of the low field ground state, \(|F = 1, m_F = 1| \), requires that the first order (linear) Zeeman shift \( E_Z = m_FB \times (700 \text{ Hz/mG}) \) be smaller than \(|H|c_2/n| \), and hence requires zeroing the magnetic field \( B \) to less than 40 \( \mu \text{G} \), typically requiring a magnetically shielded environment.

Even at much larger fields (up to \( \sim 500 \text{ mG} \) in our case), however, the ferromagnetic interactions can still play a dominant role in determining the spin ground state due to constraints imposed by angular momentum conservation. If we start with a non-equilibrium spin mixture, the system will relax to the minimal energy state via rapid condensation. In this work, we employ a time evolution for different magnetic fields. With non-equilibrium initial conditions and following its time evolution for different magnetic fields.

Our experiments employ an all-optical BEC technique previously described in [17]. The atoms are loaded directly from a magneto-optical trap into an optical dipole force trap formed by a CO\(_2\) laser. Lowering the laser power forces evaporative cooling in the optical trap, leading to rapid condensation. In this work, we employ a large period (5.3 \( \mu \text{m} \)) 1-D lattice made by a CO\(_2\) laser standing wave [18] which provides a strongly anisotropic pancake shape trap, allowing clear distinction between thermal clouds and condensates. The lattice is loaded by transferring atoms from an orthogonal travelling wave trap. We create condensates in only one lattice site by adjusting the trap power during transfer. The condensates contain 30,000 atoms in a single lattice site with measured trap frequencies \( 2\pi(120, 120, 2550) \text{ rad/s} \), and no observable thermal component. The density in the optical trap is estimated to be \( 4.3 \times 10^{14} \text{ cm}^{-3} \), and the Thomas-Fermi condensate radii are \((7.6, 7.6, 0.36) \mu\text{m}\). The \( 1/e \) lifetime of the condensates in our optical trap is about 3 \( s \).

To control the initial spin population, we apply different magnetic field gradients during the evaporation process [18]. To create a pure \( F = 1, m_F = 0 \) condensate, we apply a field gradient of 28 G/cm during the final \( 1 \) s of evaporation. To create an equally mixed \( m_F = -1,0,1 \) condensate, a smaller gradient (14 G/cm) is applied. We can also create a pure \( m_F = -1 \) by applying a 28 G/cm gradient at an earlier time before the transfer to the lattice. Typical spinor condensates with different spin configurations are illustrated in Figure 1.

To study the spin mixing dynamics, we begin with pure \( m_F = 0 \) condensates as the initial condition. After condensation, the field gradient is turned off, and a variable magnetic bias field is adiabatically ramped up in 10 \( ms \). This field can be directed either along the tight (axial) or weak (radial) axes of the confinement potential. The condensate is then allowed to evolve for a variable amount of time, and then the spin populations are measured using absorptive imaging following 6 \( ms \) of free expansion. To spatially separate the spin components, a weak Stern-Gerlach field is applied during the first 2 \( ms \) of expansion. Typical results for 2 \( s \) of spin mixing are shown in Figure 2. We note from these three images taken under identical conditions that there is significant variation on the degree
of mixing from run to run of the experiment. However, in each case, the magnetization appears to be conserved. Generally, the components of the spin mixtures are identical in shape to the original cloud to within our imaging resolution. Occasionally one or more of the components will appear to have either a thermal component or a distorted shape.

We have measured the spin mixing for different evolution times following preparation of the $m_F = 0$ condensates. The time to reach equilibrium of the spin mixing is typically less than 600 ms, and this time decreases slightly with increasing magnetic field. Fig. 3 shows the average time evolution of $n_0$ and $M$ for 50 repeated measurements. First, we note that the magnetization, $M$, is conserved throughout the mixing to within a few percent. Although the data does suggest a drift of $M$ below zero by a small amount -3.5±2% (the uncertainty here and error bars in the data are purely statistical), the deviation, if any, is comparable to our uncertainties in measuring populations (~3%), limited by the absorptive imaging technique. Secondly, there is an almost 10-fold reduction in the statistical noise of the magnetization relative to that of the total population, which varies 17% from shot to shot. This suggests that the fluctuations of $n_1$ and $n_{-1}$, which are coupled from the mixing processes in Eq. (1), are quantum correlated. These correlations underly theoretical predictions for spin squeezing and entanglement in the system [6]. Thirdly, the relaxation of $n_0$ to the steady state value is not monotonic but instead shows a damped oscillation at 4 Hz. Such oscillations are a natural outcome of coherent spinor mixing as shown theoretically in [19].

We attempted to directly measure the phase relationship between the spinor components [20] by performing an interference experiment between two spinor condensates created in adjacent lattice sites. In the absence of dephasing mechanisms, we would expect to see clear interference fringes in time-of-flight measurements both before and after spin mixing. In the measurement, clear interference fringes were visible initially, while fringes were typically not observed after mixing. It is quite possible however that the observed dephasing of the interference pattern was caused by small field variations between two sites due to a stray magnetic field gradient (< 20 mG/cm) [21].

To make comparison with theoretical predictions [10], we measure the degree of mixing for different applied magnetic fields. Fig. 4 shows the results of spin mixing for 3 s, in which $n_0$ is plotted vs. the applied field. Also shown in this figure are theoretical curves for both the antiferro- and ferromagnetic cases in a magnetic field with and without a small (20 mG/cm) field gradient [10]. As evidenced by the data, the spin mixing agrees with the ferromagnetic predictions and is inconsistent with the anti-ferromagnetic prediction. When the field is larger than 700 mG, the quadratic Zeeman effect completely dominates the spin interaction, and the condensates remain in the $m_F = 0$ state. Note that magnetic fields are applied either along tight trap or weak trap axes with different polarities; however, no significant difference in the measurements is observed.

We also measured spin mixing for fields less than 100 mG but found that our results were affected by the stray ~10 mG AC magnetic fields present in the chamber. These fields are capable of driving off-resonant rf-
transitions between the Zeeman sub-levels. We observed this directly by creating a $F = 1, m_F = -1$ condensate (for which there is no spin mixing due to conservation of magnetization) and measuring the final spin population. For magnetic fields greater than 100 mG, the magnetization remains conserved, while at lower fields, the $m_F = -1$ atoms are quickly pumped by the AC fields (within 100 ms for fields < 10 mG) to other Zeeman states.

To study $F = 2$ spinors, we coherently excite the pure $F = 1, m_F = 0$ condensates to $F = 2, m_F = 0$ using microwave fields tuned to 6.8 GHz. Additionally, by controlling the bias field, the microwave frequency, and the initial Zeeman state in the $F = 1$ manifold, we can pump the condensate to any Zeeman sub-level of the excited hyperfine manifold. The $F = 2, m = 0$ condensate is observed to decay as shown in Fig. 5(a). Following an initially rapid decay, it decays exponentially with a time constant of 250 ms. Despite the short lifetime in the excited hyperfine manifold, we still observe spin mixing within 50 ms, and magnetization conservation is also observed during the mixing, as shown in Fig. 5(b).

In summary, we have observed spin mixing of $^{87}$Rb spinor condensates in $F = 1$ and $F = 2$ hyperfine manifolds in an optical trap. The observed equilibrium spinor configurations of the lower manifold confirms that $F = 1$ $^{87}$Rb is ferromagnetic. The magnetization was conserved within the measurement errors during the entire spin mixing process. The reduced noise of magnetization suggests quantum correlation of the spin dynamics, which underlies spin squeezing and spin entanglement. Future work will study the coherence of spin mixing, spin squeezing, and entanglement.

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[21] To determine magnetic fields at trap location, we employ microwave spectroscopy on the field sensitive $F = 1 \rightarrow F = 2$ hyperfine transitions which is sensitive to within 2 mG. Furthermore, the field gradient is determined to be < 20 mG/cm by measuring fields at different trap locations.