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We have demonstrated a new technique for fluorescence detection of ultracold atoms. Fluorescence from two spatially separated clouds of ultracold atoms illuminated by a mutual probe laser was imaged onto opposite quadrants of a position-sensitive detector. The populations in the two separated atomic clouds were measured by integrating the quadrant detector photocurrents. Simultaneous detection of the populations of the two atomic clouds was used to reduce noise caused by fluctuations in detection laser amplitude and frequency. Using this technique we observed quantum projection noise limited detection signal-to-noise ratios exceeding 2000:1. To demonstrate the application of our highly sensitive detection, we compared two atomic clocks with interrogation times of only 80 ms to obtain a relative frequency stability of $1 \times 10^{-13}\tau^{-1/2}$ where τ is the integration time in seconds.

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Low Noise Simultaneous Fluorescence Detection of Two Atomic States

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We have demonstrated a new technique for fluorescence detection of ultracold atoms. Fluorescence from two spatially separated clouds of ultracold atoms illuminated by a mutual probe laser was imaged onto opposite quadrants of a position-sensitive detector. The populations in the two separated atomic clouds were measured by integrating the quadrant detector photocurrents. Simultaneous detection of the populations of the two atomic clouds was used to reduce noise caused by fluctuations in detection laser amplitude and frequency. Using this technique we observed quantum projection noise limited detection signal-to-noise ratios exceeding 2000:1. To demonstrate the application of our highly sensitive detection, we compared two atomic clocks with interrogation times of only 80 ms to obtain a relative frequency stability of $1 \times 10^{-13}\tau^{-1/2}$ where τ is the integration time in seconds.

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Laser cooled atoms are used in a variety of instruments of scientific and technological importance. Cold atom clocks,[1] gravimeters,[2] gyroscopes[3] and gravity gradiometers[4] are each at the forefront of their respective measurement classes. The performance of each of these instruments requires low-noise detection of ultracold atoms. In this Letter we present a simple detection technique using simultaneous imaging of fluorescence from two spatially separated atomic clouds onto a quadrant photodiode that has yielded a signal-to-noise ratio (SNR) greater than 2000:1.

Standard techniques for atom detection include measuring scattered fluorescence or absorption from a probe laser beam. Probe laser frequency or amplitude noise can be a limitation to achieving high SNR. Background scatter can also be a limitation if substantial thermal vapor is present. This can be overcome by using pump-probe modulation-transfer spectroscopy to distinguish between cold atoms and thermal vapor.[5] If noise contributions due to laser scatter from a thermal vapor are negligible, fluorescence detection can be effectively used.

In the best fluorescence detection based interferometer experiments[1] coherent superposition of two internal atomic states are measured at different times, requiring a narrow linewidth laser ($\sim$ 100 kHz), and a high-stability oscillator to demonstrate high SNRs. In our approach, we detect atoms in both states simultaneously to relax this constraint on the detection laser linewidth, while gaining a level of rejection of noise due to shot-to-shot atom number fluctuations and phase noise on the frequency chain.

We begin with trapping a large number of atoms in an ultra-high vacuum (UHV) environment by loading a 3-dimensional magneto-optical trap (3D MOT) from a Cs vapor cell based 2D MOT source.[6] A flux of $\sim 10^{10}$ atoms/sec is generated in the 2D MOT using two orthogonal retro-reflected trapping beams with 19 mW of power and an approximate beam size of 1 cm $\times$ 4 cm. Rectangular quadrupole coils surrounding a rectangular all-glass cesium vapor cell are used to generate a $\sim$ 10G/cm magnetic field gradient. The trapping light is detuned -10 MHz (red) from resonance on the F= 4 $\rightarrow$ F'= 5 cooling transition and overlapped with resonant F= 3 $\rightarrow$ F'= 4 repumper light. The cold beam of cesium atoms generated by the 2D MOT exits the vapor cell through an aperture and enters a glass UHV cell with a mean longitudinal velocity of 7m/s and a 50 mrad divergence. A MOT is formed in the UHV cell using three retro-reflected beams with an intensity of 3 mW/cm^2 and a weak magnetic field gradient of $\sim$ 2G/cm. The 3D MOT beams are also detuned by -10 MHz while the trap is loading. A total of 10^9 atoms is trapped in about 100ms with a 3 mm $1/e^2$ radius. The atoms are sub-Doppler cooled to 3μK before being released from the trap.

To prepare a pure sample of atoms in the $6^2S_{1/2}$ F= 3, $m_f = 0$ hyperfine state we use a state selection sequence of radio-frequency (RF) microwave, repumper and blasting pulses. After the MOT is loaded, the repumper light is left on for a few hundred microseconds after the trap-

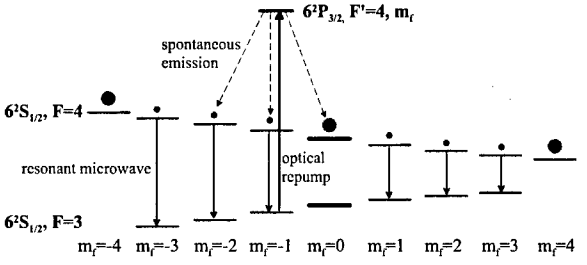

Fig. 1. Diagram of the energy levels for the pulse sequence used to enhance the number of atoms in the $F = 3$, $m_f = 0$ state. Resonant microwave transitions drive atoms to the F= 3 hyperfine state for all states except $m_f = 0$ and $m_f = \pm 4$. A repumper pulse redistributes atoms across the magnetic sublevels of the F= 4 state. After several cycles of microwave and repumper pulses, atoms will accumulate in the $m_f = 0$ and $m_f = \pm 4$ states.

ping light is extinguished to optically pump the trapped atoms into the $6^2S_{1/2}$ F= 4 state. A RF π-pulse, tuned on resonance to the F= 3, $m_f = 0 \rightarrow$ F= 4, $m_f = 0$ hyperfine transition ($0 \rightarrow 0'$), at 9.192631770 GHz, transfers atoms to the F= 3, $m_f = 0$ state with high efficiency. A magnetic field of 28.5 mG is applied to the atoms so that microwave transitions between different hyperfine states can be individually resolved. To "blast" away remaining F= 4 atoms, the trapping light is tuned 1MHz above resonance and is turned on for 500μs to heat the atoms out of the detection region. A second microwave π-pulse transfers atoms back to the F= 4, $m_f = 0$ state, followed by a repumping pulse. A final π-pulse, either a direct microwave or a two-photon optical, then followed by a second blasting pulse, prepares about 1/9 of the original distribution into the $F = 3$, $m_f = 0$ state with high purity.

To improve the efficiency of our state selection we have developed a scheme using a sequence of microwave and repumper pulses to enhance the number of atoms in the $F = 3$, $m_f = 0$ state. The $0 \rightarrow 0'$ resonant microwave field is frequency modulated (FM) with a modulation index of $m = 2.40$ and a modulation frequency of 20 kHz. This creates a comb of microwave frequencies with sidebands separated by 20 kHz while the carrier frequency is nulled. The modulation frequency matches the shift in the $\Delta m = 0$ microwave transition frequencies in the 28.5 mG magnetic field as shown in figure 1. 200 μs FM-microwave pulses transfers atoms from F= 4 to F= 3, for magnetic sublevels $m_f = \pm 1, \pm 2$, and ± 3, which is then followed by a 10 μs repumper pulse. The cycle of pulses is repeated up to 10 times. Throughout the process, the F= 4, $m_f = 0$ sublevel remains dark. Afterwards, the state selection sequence described above is performed, resulting in approximately a factor of two gain in the number of atoms prepared in the F= 3, $m_f = 0$ sublevel. This Zeeman-state optical pumping enhancement is limited by accumulation of atoms in the F= 4,$m_f = \pm 4$ states and by the presence of non-zero cross transitions due to a residual circular polarization of our RF field.

After the atoms are prepared into the F= 3, $m_f = 0$ sublevel they fall for ~100ms to the detection region. Atoms entering the detection region are typically in a coherent superposition of the F= 3 and F= 4 hyperfine states and are spatially overlapped. To spatially separate the two states, the F= 4 atoms are stopped using a 200μs pulsed, vertically oriented, retro-reflected laser beam derived from the trapping light and detuned by -10 MHz. The F= 3 ensemble continues to fall for an additional 13 ms, after which a 10μs repumper light is used to pump all atoms into the F= 4 state. The detuning of the vertical beam is switched to $\sim -\Gamma/2$,[7] where Γ is the natural linewidth of the transition ($2\pi \times 5$ MHz), and then applied for 5ms. The resulting scattered fluorescence from each spatially separated atom cloud is imaged onto separate quadrants of a quadrant photodiode (Hamamatsu S5981) through two stacked common 30 mm focal length aspheric lenses (Figure 2). The total

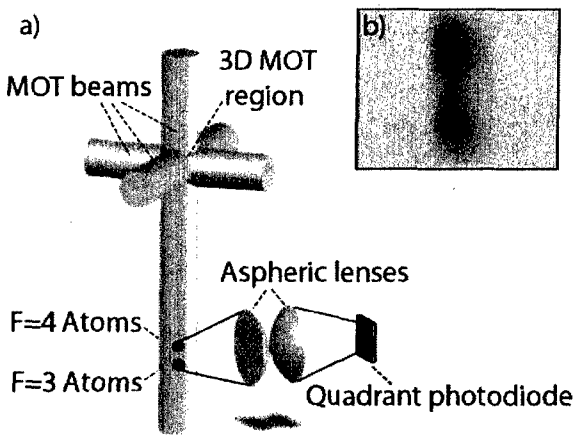

Fig. 2. Depiction of the detection setup shown in (A). The F= 4 and F= 3 atoms are imaged onto separate quadrants of the detector. A CCD image of the spatially separated F= 3 and F= 4 atoms is shown in (B).

photodetector area is 10 mm × 10 mm. The imaging system collects ≈ 0.5% of the light scattered by the atoms. Each quadrant photocurrent output is independently integrated over the detection time. The integrators are located on the same printed circuit board as the photodiode. After the photocurrent is integrated for the desired length of time, the quadrant voltages are held until they are read out separately through an analog multiplexer board. The electronic noise is less than 0.1 mV rms. The noise from scattered background light is typically 0.3mV

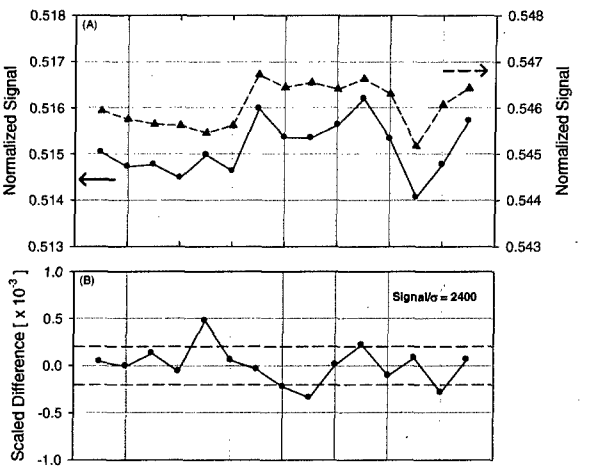

Fig. 3. (A) Normalized $F = 3$ signals from each interferometer following a microwave pulse exciting ≈ 1/2 of the atoms. The difference between the normalized signals is shown in (B). The rms of the residuals (shown by the dashed line) is 2.1×10^{-4}, corresponding to an SNR of 2400:1

rms, however it is correlated among quadrants to a level limited by the electronic noise floor of the detector.

To decrease the sensitivity to amplitude and frequency noise of the detection light, along with shot-to-shot variation of the atom number in the MOT loading sequence, we use the quadrant detector outputs to calculate the normalized number of atoms in the $F = 3$ state, $N_3 = V_3/(\epsilon V_4 + V_3)$. In this expression, V_3 is the integrated voltage from the $F = 3$ quadrant after accounting for scattered background light, V_4 is the corresponding $F = 4$ quadrant signal, and ϵ is a coefficient accounting for the difference in detection efficiencies for the $F = 3$ and $F = 4$ atoms. This coefficient is experimentally determined by using a microwave pulse to systematically vary the number of $F = 4$ atoms and is typically around 1.3.

To determine the SNR of the detection system, we measured the normalized number of atoms in the $F = 3$ state for two atom interferometers sharing a common microwave source. Each interferometer was controlled by the same timing sequence and used trapping, repumper and detection light from the same laser sources. Following state preparation into the F= 3, $m_f = 0$ state, a superposition of atoms in the two hyperfine ground states was created using a microwave π-pulse detuned from resonance by the amount required to excite 1/2 of the atoms into the $F = 4$, $m_f = 0$ state. The normalized number of atoms in the $F = 3$ state, N_3, was recorded for each atom interferometer with a repetition rate of 3Hz (Figure 3A). Phase noise in the RF field produces fluctuations in N_3 which are common between the two interferometers. If only one interferometer signal was available, the microwave phase noise would limit the measurement of the SNR of the detection system to $< 700 : 1$.

A typical characterization of the system SNR begins with a collection of data points taken with the above coherent superposition of states. A Gaussian elimination procedure is used to determining the multiplicative scaling and offset coefficients between the normalized signals from each interferometer over the length of the data run. The variance of the difference between the normalized output of one interferometer and the scaled output of the other, along with the amplitude of the on-resonant π-pulse transition, determines the SNR over the data set (Figure 3B).

By changing the loading time from the 2D MOT into the 3D MOT, along with selectively using the optical pumping scheme, we explored the sensitivity of the cross-interferometer SNR as a function of the initial atom number, N, in the interferometer (Figure 4). We found a $N^{1/2}$ scaling of the SNR consistent with that expected from quantum projection noise limited detection of a superposition of coherent states.[8] The atom number was determined from an average of the amplitude signals from the two interferometers, with the standard deviation reflecting the difference. Detection inefficiencies from optical depumping during the atom-stop sequence leads to an offset in our determination of atom number but does not affect the observed atom number scaling.

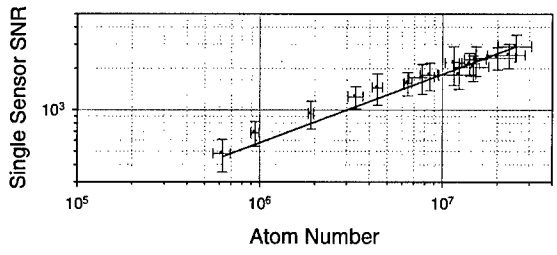

Fig. 4. SNR was measured as a function of atom number by varying the loading time. The measured $N^{1/2}$ dependence suggests that the detection is limited by quantum projection noise scaling. Depumping effects lead to a scaling offset.

To further characterize the sensitivity of our detection system, we performed an experiment to measure the relative frequency stability of two microwave based atomic clocks. We began with the state preparation sequence described above. Afterwards, the atoms in each setup entered a RF $\pi/2 - \pi/2$ interferometer, with a separation time of 80 ms between RF pulses. Here, a $\pi/2$ pulse creates a superposition of the two hyperfine states. The output of the interferometer is a sinusoidal dependence on the detuning of the RF from resonance. We chose an appropriate detuning to output atoms with nearly equal population in both atomic states. A data collection sequence and Gaussian elimination algorithm identical to above was used to determine the cross-interferometer signal to noise ratio. In one second of integration, we demonstrated a relative frequency stability of 1.0×10^{-13} (7.3×10^{-14} extrapolated per interferometer).

In conclustion, we have presented a new detection scheme of simultaneous measurement of two atomic states using scattered fluorescent light. The technique has demonstrated very high signal to noise ratios when compared between identical setups, with the capability of achieving quantum projection noise limited detection. Our scheme does not require ultra-narrow laser linewidths and high stability RF oscillators. A demonstrate relative frequency stability of $< 1 \times 10^{-13}$ was measured in one second of integration

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