Measurements of intensity correlations of scattered light from laser-cooled atoms

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We report measurements of the intensity correlations of scattered light from atoms in optical molasses. For small numbers of atoms, the observations are consistent with recent models of the Rayleigh and Raman contributions to the frequency spectrum. Magnetic fields on the order of 100 mG significantly broaden the spectrum. Radiation trapping results in reduction of the size of the correlations as well as broadening of the spectrum. [S1050-2947(96)03605-0]

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A fundamental characteristic of any sample of laser-cooled atoms is the frequency spectrum of the light that is scattered from the atoms. For optically thick clouds of trapped atoms, Walker, Sesko, and Wieman [1] showed that the frequency spectrum is extremely important for determining the strength of repulsive radiation-trapping forces. The frequency spectrum of the light also plays an important role in understanding the heating of the atoms due to radiation trapping [2,3]. In addition, the spectrum gives useful, noninvasive information about the characteristics and local environment of the atoms. For example, using a heterodyne detection method, Westbrook *et al.* [4] observed Dicke narrowing of the frequency spectrum of cooled Na atoms, showing that it is possible to confine laser-cooled atoms in the standing-wave potential wells formed by the cooling lasers. Further studies of quantized motion were made using observations of the frequency spectrum [5]. Complementary to the heterodyne method for spectral analysis is the well-known use of homodyne or intensity autocorrelation techniques. In the homodyne method, the intensity correlations $\langle I(t)I(t+\tau)\rangle$ of a single spatial mode of the scattered light are detected. In a recent experiment Jurczak *et al.* [6] used an electronic spectrum analyzer to measure the Fourier transform of the intensity fluctuations from atoms cooled by optical molasses. They also observed a narrow spectral feature due to the localization of the atoms.

In this paper we demonstrate the use of direct digital correlation to measure the intensity fluctuations of light emitted by laser-cooled atoms and use the measurements for spectral analysis of the light. Due to the long coherence times of the scattered light, the correlations can be readily performed with standard photon-counting techniques and fast TTL electronics. We show that at zero magnetic field a simple model of the intensity correlations based solely on the Doppler broadening of the Rayleigh-scattered light gives temperatures that are consistent with those determined from ballistic measurements. Recently, additional Raman contributions to the frequency spectrum were predicted by Gao [7]. We observe these contributions by applying a small magnetic field to enhance their effects on the correlations. In addition, when the number of atoms in the cloud is increased, we observe that the coherence of the light decreases and the spectrum broadens. We attribute these affects to radiation trapping.

The principle of the measurement is based on the well-known relationship between the degrees of second- and first-order coherence of a polarized light wave from a chaotic sample [8,9]:

$$g^{(2)}(\tau)\equiv\frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}=1+S|g^{(1)}(\tau)|^2. \qquad (1)$$

The factor S depends on the spatial coherence of the light-detection system and is independent of τ. The degree of first-order coherence $g^{(1)}(\tau)$ is the Fourier transform of the frequency spectrum $I(\omega)$. Thus $g^{(2)}(\tau)$ gives spectral information about the light produced by the sample.

For optically cooled two-level atoms, the frequency spectrum usually consists of a narrow (subnatural linewidth) Rayleigh scattering peak and a broad resonance fluorescence spectrum [10]. At low laser intensities and large detunings, as are usually used for optimum laser cooling, the Rayleigh scattering contribution dominates. The width of the Rayleigh scattering peak is determined by Doppler broadening, except under circumstances where the atoms are confined in the microscopic potential wells formed by the standing waves of the laser beams [4], resulting in Dicke narrowing. The temperature of the atoms can be deduced from the width of the peak. At temperatures below 100 μK, the full width is less than 300 kHz for Rb atoms. This corresponds to a coherence time τ of greater than 1 μs for the degree of second-order coherence. These long coherence times make it feasible to use standard digital electronics to compute the correlation.

For multilevel atoms, there are additional contributions to the frequency spectrum [7]. For a zero-velocity atom in zero magnetic field, the most important such contribution is incoherent Raman scattering, which produces fluctuations in the polarization and angular distribution of the emitted light and therefore broadens the frequency spectrum. Multilevel calculations of Gao for ^{85}Rb [7,11] predict that the Raman effect is responsible for 47% of the total scattered light, with a Lorentzian line shape of 85 kHz in width for a linearly polarized 3-mW/cm^2 laser field detuned 1.8Γ from resonance.

The experimental setup is depicted in Fig. 1. A vapor-loaded magneto-optical trap (MOT) of Rb [12] was produced inside an ion-pumped stainless-steel vacuum chamber ($\sim 10^{-9}$ Torr), using light from an external-cavity-stabilized diode laser operating 1–3 natural linewidths below the $5S_{1/2}(F=3)\rightarrow 5P_{3/2}(F'=4)$ transition of ^{85}Rb. This provided a source of cold atoms for optical molasses, on which the temperature measurements were made. The total laser intensity (sum of all six beams) at the position of the trapped atoms was 3.0 mW/cm^2. The number of atoms in the trap varied from 10^5 to 10^7, depending on the detuning of the

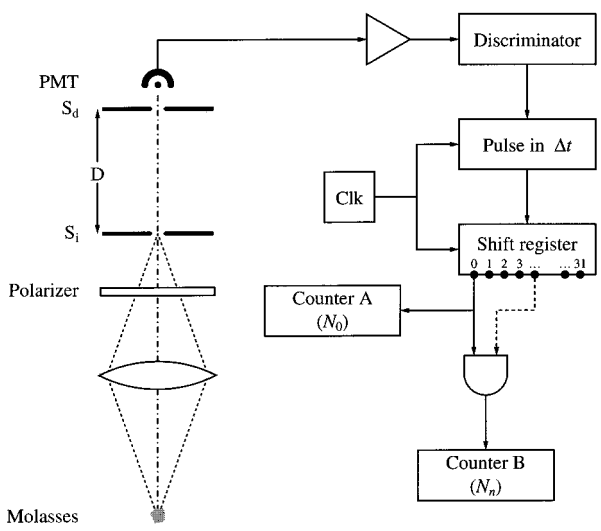

FIG. 1. Schematic diagram of the apparatus for measurement of the degree of second-order coherence of the light scattered by a sample of laser-cooled atoms. Light from the atoms is made partially spatially coherent by a pair of pinholes and detected by a photomultiplier tube. The required correlations are performed by TTL circuitry.

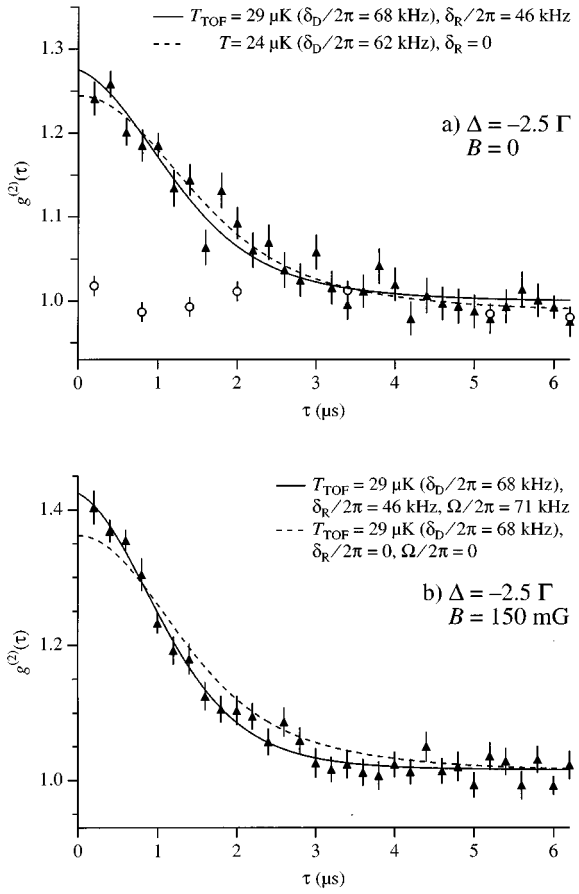

FIG. 2. Measurements of the degree of second-order coherence as a function of delay time. The dashed lines are fits assuming only Rayleigh scattering, while the solid lines include the Raman contribution to the line shape. The circles are measurements of an incandescent source. (a) Zero magnetic field. (b) With an applied magnetic field of 150 mG, the Raman contribution causes the correlations to decay more rapidly, even though the temperature does not change.

laser and the size of the laser beams, and the diameter of the cloud was roughly 0.5 mm. Microwave modulation of the laser at 2.9 GHz [13,14] provided the necessary hyperfine optical pumping to keep the atoms from accumulating in the $5S_{1/2}(F=2)$ state. A pair of magnetic-field coils external to the vacuum chamber provided the magnetic-field gradient for the MOT. The magnetic-field gradient was turned on and off at 500 Hz, so optical molasses was produced in a transient manner during the off periods of the magnetic field. All data reported here were collected during the off periods. The decay time for the magnetic field was measured to be 60 μs. The polarization of the MOT laser beams was not changed during the optical molasses part of the cycle, so the molasses was of the $\sigma^+\sigma^-$ type. The temperature of the atoms was measured with a standard time-of-flight (TOF) technique [15], using the fluorescence signal from a probe beam located 10 mm below the position of the cloud of trapped atoms.

Light from the optical molasses was collected with a lens system, polarized along the $\hat{z}$ direction, and imaged with unit magnification at the first pinhole of diameter $s_i=190$ μm. A second aperture of $s_d=2.5$ mm diameter was placed $D=310$ mm from the first pinhole, thus collecting most of the light from the principal Fraunhofer diffraction peak from the first pinhole, giving sufficient spatial coherence without excessive reduction of count rates. The light was detected with a photomultiplier tube (quantum efficiency 10%), using a standard amplifier and discriminator system for photon counting. The background rate of typically 100 s^{-1} resulted from both dark counts and scattered laser light. The output of the discriminator was converted to TTL levels and then sent to a synchronously clocked TTL circuit that performed the correlation. This consisted of a set of three D-type flip-flops that determined whether a pulse was received in a given clock cycle and provided input to a 32-channel shift register. Counts (N_0) accumulated from channel 0 of the shift register reflected the raw intensity $\langle I(t)\rangle$, while counts from the nth channel, when ANDed with the first, gave coincidence counts (N_n) that reflected the product $\langle I(t)I(t+n\tau_c)\rangle$. After counting for a time T_1, the degree of second-order coherence was calculated from the relation $g^{(2)}(n\tau_c)=N_nT_1/\tau_cN_0^2$, where $\tau_c=200$ ns is the clock period. Typical raw count rates varied from 3000 to 15 000 s^{-1}. For the long (>1 μs) coherence times of the Rayleigh and Raman components of the light, the 200-ns time resolution of our system did not appreciably smear the spectrum. The electronics were tested by making correlation measurements with a dc white-light source as well as with scattered light from the laser; both gave $g^{(2)}(\tau)=1$ within statistical error.

Typical correlation data obtained for small numbers of atoms ($\sim 10^5$) are shown in Fig. 2(a) for detuning $\Delta=-2.5\Gamma$. The error bars reflect counting statistics. The observed value for $g^{(2)}(0)$ is consistent with the calculated spatial coherence factor $S=0.35\pm0.03$ for our geometry, assuming a uniform spatial distribution for the atom cloud. Variations in S occur due to nonuniformities in the spatial distribution of the atoms. The fit curves in the figure are calculated from Eq. (1), using the function

$$|g^{(1)}(\tau)| = |g_D^{(1)}(\tau)||g_A^{(1)}(\tau)|, \quad (2)$$

which results from assuming that the frequency spectrum is a Doppler broadened convolution of the spectrum of the atom at rest. The Doppler contribution is

$$|g_D^{(1)}(\tau)| = \sum_j a_j \exp(-\alpha_j \delta^2 \tau^2/2), \quad (3)$$

where the sum is over the four laser beams that travel in the $\hat{x}$ and $\hat{y}$ directions, with the $\hat{z}$ beams being excluded due to the $\hat{z}$-oriented polarizer. The parameter $\delta = \omega_0 \sqrt{k_B T/Mc^2}$ is the standard Doppler width and $\alpha_j = 2(1-\cos\theta_j)$ gives the dependence of the Doppler shift on the angle θ_j between the observation direction and the propagation direction of laser beam j. The weighting coefficients a_j are proportional to the intensity of each individual laser beam and are also proportional to an angular distribution factor. For our geometry $a_j = \frac{1}{4}$.

The form of the atomic contribution $g_A^{(1)}(\tau)$ is determined by assuming that the spectrum has both Rayleigh (strength $1-r$) and Raman contributions (strength r)

$$g_A^{(1)}(\tau) = [(1-r) + r g_R^{(1)}(\tau)]. \quad (4)$$

In zero magnetic field the Raman frequency spectrum is well approximated by a Lorentzian centered about the laser frequency, so $g_R^{(1)}(\tau) = \exp(-\delta_R \tau/2)$. The factor $r = 0.47$ was calculated by Gao [7] for the case of linearly polarized light. For the three-dimensional $\sigma^+ - \sigma^-$ molasses studied here, linear polarization is produced only for certain values of the relative phase of the three orthogonal sets of laser beams. In general, the polarization varies spatially as well. Thus the value chosen for r should be considered a reasonable estimate. There should also be an incoherent Rayleigh contribution to the signal, which results from fluctuations of the component of the atomic dipole moment along the laser polarization [7]. This effect should contribute only a few percent to the signal, so we ignore it in our analysis.

If the Raman contribution is ignored, i.e., if we take $g^{(1)}(\tau) = g_D^{(1)}(\tau)$, the deduced temperature from the data in Fig. 2(a) is 24 ± 4 μK, in agreement with the TOF measured value of 29 ± 3 μK. The dashed line shows the fit. A similar measurement at $\Delta = -1.5\Gamma$ gave a temperature of 59 ± 8 μK, again agreeing with the TOF value of 53 ± 5 μK. Thus the $g^{(2)}(\tau)$ measurements are in reasonable agreement with the TOF method, assuming only Rayleigh scattering. Inclusion of the Raman contribution gives the solid line in Fig. 2(a). Thus the Rayleigh and Raman contributions are not well distinguished in this case.

The Raman contribution becomes more apparent with the addition of a weak magnetic field. The magnetic field was originally approximately nulled to within 50 mG for this experiment by either maximizing the lifetime of the optical molasses or by minimizing the TOF temperature [15]. However, changing the magnetic field by 50 mG produced clear changes in the intensity correlations, increasing the spectral width but hardly affecting the temperature. Thus zero magnetic field was assumed to occur when the spectral width was minimized. To lowest order, when the magnetic-field direction is along the laser polarization the Raman spectrum splits into two Lorentzians shifted from the Rayleigh component by the ground-state Larmor precession frequency $\Omega/2\pi = 2\mu_B B/(2I+1)h = B \times 470$ kHz/G. These correspond to $\delta m_F = \pm 1$ Raman transitions. In a transverse magnetic field two additional weak $\delta m_F = \pm 2$ Raman peaks are obtained. Thus $g_R^{(1)}(\tau)$ becomes a sum of damped oscillating exponentials. Figure 2(b) shows data taken with a 150-mG magnetic field. The solid line shows the expected correlations from the measured TOF temperature, calculated Raman width of 42 kHz, and calculated Larmor precession frequency of 71 kHz. Alternatively, we fit the data ignoring the Raman contribution, allowing the temperature to vary. The resulting temperature of 40 ± 4 μK disagrees with the TOF measurement of 29 ± 3 μK. Thus the inclusion of the Raman contribution is necessary to quantitatively explain the observed correlations. To further illustrate the effects of the Raman contribution, the dashed line in Fig. 2(b) also shows the expected correlations for a Doppler-broadened line whose temperature is given by the TOF value.

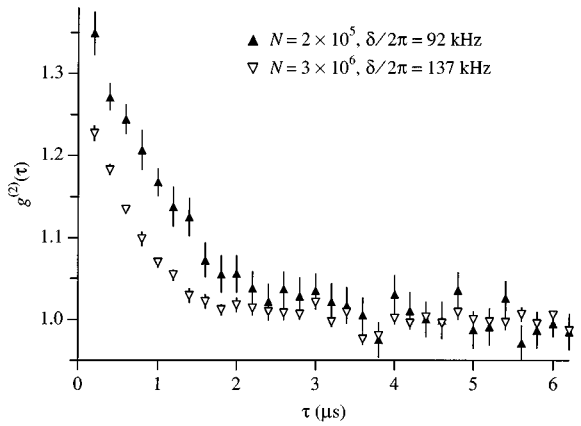

FIG. 3. Second-order coherence obtained from clouds with increased numbers of atoms. The multiple scattering shows up as reduced spatial coherence and increased spectral linewidth. The detuning is -1.85Γ.

The data discussed so far were all obtained with $\sim 10^5$ atoms in the trap, where radiation trapping effects are expected to be unimportant. In Fig. 3 we show data taken with a larger number (3×10^6) of atoms ($\Delta = -1.85\Gamma$). The main features are (i) the overall size of the correlation is reduced when the number of atoms is increased and (ii) the correlation time is reduced (the spectral width is increased). The increased spectral width is greater than can be accounted for by higher temperatures. For example, under the above conditions the correlation data imply a temperature of 120 μK, much higher than the 50 μK measured using the TOF method. The increase in the spectral width can be qualitatively accounted for by noting that the multiply scattered light has been broadened by each scattering event. Both Doppler and Raman effects will contribute to this further broadening.

One feature that does not stand out in our data is the Dicke narrowing observed by Westbrook *et al.* [4]. Such narrowing would not be readily seen with our technique because it shows up as a long tail at large τ that is easily obscured by the background. This points out the complementarity of our technique to the heterodyne method or direct Fourier analy-

sis of the photocurrent [6]. Both of these latter methods are sensitive to the shape of the spectral line near line center, but insensitive in the wings. On the other hand, our method is sensitive to the line wings but insensitive to the shape near line center. To check this, we have Fourier transformed the spectra from Ref. [4], calculated $g^{(2)}(\tau)$, and then fit the result to a single Doppler line shape ignoring the presence of the Dicke narrowed portion of the spectrum. The deduced temperature changed by less than 10%.

In conclusion, we have shown that intensity correlations can be used to make noninvasive measurements of the spectra of samples of optically cooled atoms. With the long coherence times, a simple digital circuit can be used to readily form the desired correlation. With faster electronics, it should be possible as well to study $g^{(2)}(\tau)$ at small τ, where inelastic contributions (in the sense of two-level atoms) arise. In particular, it may be of interest to study in greater detail the effects of multiple scattering of light on the degree of second-order coherence. Such studies will give important information about the correlations that arise between the trapped atoms and may provide valuable insights into the origins of the collective phenomena that occur in optically thick atom clouds [1,2]. Similar studies may also prove useful in probing and studying degenerate Bose gases, where atom-atom correlations that contribute to $g^{(2)}(\tau)$ may be very important.

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