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Observation of intensity correlations in the fluorescence from laser cooled atoms

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Abstract

We report the observation of intensity correlations in the fluorescence from a three dimensional Rb optical molasses. This constitutes a new, non-destructive, *in situ* probe of laser cooled atoms. The power spectrum of the photocurrent displays a 100 kHz wide feature corresponding to the Doppler width of the atomic velocity distribution, and a narrow peak interpreted as being due to the localization of the atoms in wavelength sized potential wells. As the atoms rms velocity decreases, the height of the narrow peak increases while its width decreases to as little as 2 kHz. We discuss the potential for new applications of this method.

Despite the simplicity of the initial proposals [1], three-dimensional laser cooling continues to show a remarkably rich variety of phenomena. In the first generation of experiments [2], time of flight (TOF) methods were used to show that the velocity distribution of the atoms was much narrower than expected from a simple two-level atom theory. More recently, atom localization, quantized atomic motion, and Raman processes with extremely long relaxation times have been observed [3–5]. In the later examples, unlike in the TOF observations, the phenomena were observed by measurements done *in situ*, giving information about the atoms while they interacted with the laser fields. A second contrast with TOF methods is that the newer observation methods are *non-destructive*: the atomic sample is not significantly perturbed during the measurement. We present here the demonstration of a new, non-destructive, *in situ* probe of laser cooled atoms which relies on the well known technique of intensity correlations or equivalently, self-beating spectroscopy.

Ever since the experiments of Ref. [6], which showed that intensity correlation measurements could give spectral and spatial information about a light source, this technique has enjoyed great popularity in fields from quantum optics [7] to nuclear physics [8] to fluid dynamics and biophysics [9]. One can see the idea of our intensity correlation experiment from the schematic diagram in Fig. 1. A collection of atoms in a magneto-optical trap or optical molasses, scatters light from the laser beams into a photodetector giving a current $i(t)$. The atoms are moving at various velocities and so the light from different atoms has different

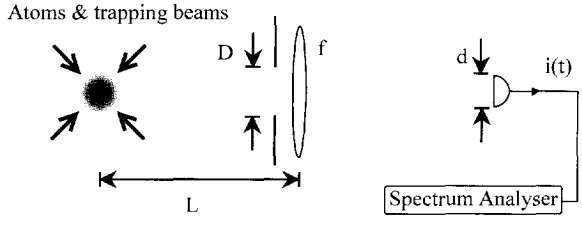

Fig. 1. Schematic diagram of our optical setup.

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Doppler shifts. These different frequencies can beat against each other causing $i(t)$ to fluctuate. If the scattering is purely elastic, the power spectrum of these fluctuations is simply related to the motion of the atoms.

To be more precise [10], we measure the power spectrum $P_i(\omega)$ of the photocurrent, which is proportional to the Fourier transform of the normalized light intensity correlation function $g_2(\tau)$:

$$g_2(\tau) = \frac{\langle I(t)\, I(t+\tau)\rangle}{\langle |I(t)|\rangle^2} = \frac{\langle E^-(t)\, E^-(t+\tau)\, E^+(t+\tau)\, E^+(t)\rangle}{\langle E^-(t)\, E^+(t)\rangle^2}. \quad (1)$$

Here $E^{+(-)}$ represents the positive (negative) frequency part of the scattered electric field at the detector, and $\langle\rangle$ denotes a statistical average [11]. In the case where the scattered light field is a sum of contributions from a large number of independent radiators (giving a "random Gaussian field" [12]), and if the size of the detector is negligible, the intensity correlation function is related to the *field* correlation function by

$$g_2(\tau) = 1 + |g_1(\tau)|^2, \quad (2)$$

where the field correlation function g_1 is given by

$$g_1(\tau) = \frac{\langle E^-(t)\, E^+(t+\tau)\rangle}{\langle |E(t)|^2\rangle}. \quad (3)$$

Since $g_1(\tau)$ is the Fourier transform of the optical power spectrum $P_o(\omega)$ of the light emitted by the atoms, there is a relation between our intensity correlation measurement and the heterodyne measurements of Refs. [3] and [4]. In these experiments the optical power spectrum $P_o(\omega)$ was measured, not the power spectrum of the photocurrent $P_i(\omega)$. If our source satisfies the conditions leading to Eq. (2), one sees by a Fourier transform that $P_i(\omega)$ consists of a DC contribution which is eliminated by our spectrum analyzer, and the autoconvolution of $P_o(\omega)$. If, for example, the light source is a group of radiators with a thermal velocity distribution, the expected spectrum is a Gaussian centered at frequency zero with a width $\sqrt{2}$ times the Doppler width of the optical spectrum. Note that there is also a flat, shot noise spectrum, and $P_i(\omega)$ constitutes an "excess noise" above this background.

In a real experiment, the detector has a finite size. Eq. (2) then has to be modified by multiplying the $|g_1(\tau)|^2$ term by a factor η related to the spatial coherence of the light field over the detector [9,10]. This factor approaches 1 as the detector size is made small compared to the first Fresnel zone associated with the scattering volume.

We implement this idea with the following optical setup (see Fig. 1). A 150 mm focal length lens, placed at a distance $L = 300$ mm from the atoms, images the atom source on a photodetector. The detector is an avalanche photodiode, running in a photon counting mode, passively quenched, with an integrated preamp and discriminator (model SPCM100 from EG&G Canada). Its active diameter d is approximately 150 μm, and its nominal quantum efficiency is 30% to 40% at our wavelength of $\lambda = 780$ nm. The detector produces pulses with a 200 ns deadtime, and has a dark count rate of 250 counts per second (cps). The aperture on the lens has a diameter $D = 3$ mm. The detection solid angle thus corresponds to four coherence areas [12] (or to the first four Fresnel zones) of the part of the source imaged onto the detector. A calculation of η for our geometry taking into account the spatial profile of the photon detector given by the manufacturer gives a value of approximately 0.15. A smaller value of D would increase η, but only at the cost of signal, which varies quadratically with D [10].

Our atomic source is very similar to that of Ref. [13]. A magneto-optical trap (MOT) is loaded by a chirp-cooled ^{85}Rb atomic beam. The MOT laser beams come from a 100 mW laser diode, which is injected by a second, external cavity stabilized diode (linewidth < 2 MHz), which is locked to a saturated absorption line. Unlike Ref. [13], however, the three pairs of $\sigma^+\sigma^-$ beams are not mutually orthogonal; two pairs of horizontal beams propagate in a plane parallel to the magnetic field coils along the [100] and [010] directions while a third is at 45° (the [111] direction), and the light is detected along the [110] direction. The waist of each trapping beam is 3.5 mm. The intensities of each pair are equal to within 20%. (We conventionally give the intensity as the sum of the three one-way intensities at the center of the beams.) The trap is loaded for 1 s using a laser intensity (≈ 50 mW/cm^2) and detuning from the $F = 3$ to $F' = 4$ resonance (-9 MHz) optimized for capture. Approximately 5×10^7 atoms are loaded into a roughly 1 mm^3 volume during this time. When the atoms have been captured, the magnetic field is switched off in 200 μs and the laser detuning and intensity are changed to produce colder atoms

[13]. After a delay of 10 ms to allow the sample to equilibrate in the optical molasses, the spectrum is acquired for 300 ms. The photon counting rate during the measurement phase, ranged from 5×10^4 to 4×10^5 counts per second (cps) of which less than 8000 cps was due to stray laser light inside the vacuum system. These count rates were sufficiently low to neglect dead time effects of the detector.

The recording of $P_i(\omega)$ is done by a commercial FFT spectrum analyzer with a 200 kHz span and 4 kHz resolution bandwidth. The square pulses from the detector are filtered by the input stage of the spectrum analyzer so that aliasing of the high frequency components of the pulses is avoided. The analyzer acquires and processes one such spectrum in 4 ms and thus records and averages about 70 such spectra during one 300 ms measurement cycle. The loading-measurement cycle is then repeated, typically 10^2 to 10^3 times to achieve the signal to noise in the data shown in the figures. During the spectrum measurement, we use a gated counter/timer to record the number of counts and the elapsed time during which the spectrum analyzer was acquiring and processing data. Alternatively, we can perform time of flight (TOF) measurements of the atoms velocity distribution, by releasing the atoms and collecting the fluorescence from a probe laser placed 1 cm below the MOT.

In order to characterize our detection and analysis system, we first observe the spectrum of our laser as well as another light source as close as possible to white noise. In Fig. 2 we show a comparison of a spectrum produced by the molasses laser $P_i^{\text{laser}}(\omega)$, and that of a battery powered incandescent light. The spectrum $P_i^{\text{laser}}(\omega)$ was acquired by deliberately misaligning a laser beam to greatly increase the scattered light in the vacuum system. The measured incandescent light spectrum $P_i^{\text{white}}(\omega)$ was normalized according to:

$$P_i'^{\text{white}}(\omega) = P_i^{\text{white}}(\omega) \times \frac{R^{\text{laser}}}{R^{\text{white}}}, \tag{4}$$

where $R^{\text{laser(white)}}$ is the count rate during the acquisition of the laser (white light) spectrum. With this normalization, we correct for the fact that the shot noise power level is proportional to the photon count rate. The statistical accuracy of the count rate allows us to make the correction of Eq. (4) with a 1% uncertainty in the average power level. We see then that the two

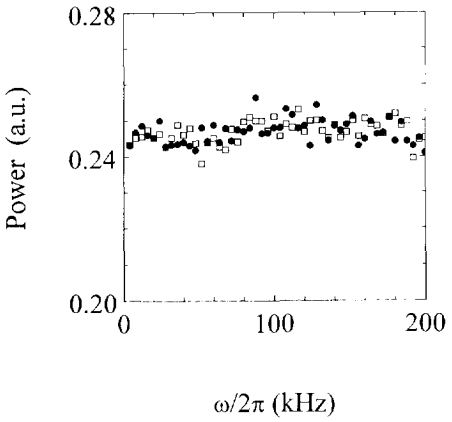

Fig. 2. Comparison of two power spectra approximating white noise. Solid circles: spectrum of laser light $P_i^{\text{laser}}(\omega)$ (count rate: 1.36×10^5 cps). Open squares: spectrum of a battery powered incandescent lamp, normalized to the same average count rate, $P_i'^{\text{white}}(\omega)$; see Eq. (4) (count rate: 1.72×10^5 cps). The first channel shown is centered at 4 kHz; the channel at 0 kHz contains a much larger power than the others due to various low frequency noise sources and has been deleted.

spectra $P_i^{\text{laser}}(\omega)$ and $P_i'^{\text{white}}(\omega)$ are statistically identical. Therefore we attribute the non-flatness we see to the frequency response of our detector and spectrum analyzer. That our laser noise spectrum is nearly shot noise limited at these low intensities has also been verified by deliberately intensity modulating the laser, and confirming that the signal to noise of that modulation, detected by our detection system, corresponded to the shot noise limit. We have also checked that this spectrum remains constant at the 1% level for at least one day.

Since the observed power spectrum of our laser intensity is not perfectly flat, the measured power spectrum in the presence of the atoms $P_i^{\text{atoms}}(\omega)$ is slightly distorted. The true signal due to the atoms is proportional to the ratio of the measured power spectrum taken in the presence of the atoms to that corresponding to the laser [10]. Accordingly, in what follows, we shall show spectra corresponding to the ratio of the atoms' spectrum to that taken by looking at scattered laser light, and we shall also normalize the result, as in Eq. (4) by the ratio of the count rates, R^{atoms} and R^{laser} respectively:

$$P_i'^{\text{atoms}}(\omega) = \frac{P_i^{\text{atoms}}(\omega)}{P_i^{\text{laser}}(\omega)} \times \frac{R^{\text{laser}}}{R^{\text{atoms}}}. \tag{5}$$

Thus, in the spectra in Fig. 3, the level 1 corresponds to the shot noise level, and $P_i^{\text{atoms}}(\omega)$ corresponds to the fractional "excess power" due to the presence of the atoms, and is the experimental realization of the $P_i(\omega)$ discussed above.

In Figs. 3a and 3b we show two power spectra due to the atoms. Fig. 3a was taken with the atoms having a 1D rms velocity v_{rms} of 5 cm/s according to our TOF measurement (corresponding to 28 μK, with the temperature T defined by $k_B T = m v_{\text{rms}}^2$). Fig. 3b corresponds to a $v_{\text{rms}} = 3.5$ cm/s (16 μK). In both spectra one sees a broad feature of order 100 kHz in width, which corresponds approximately to the expected Doppler width (see below). An additional narrow peak is also evident; this peak is much more pronounced in the data corresponding to the colder atoms. In Fig. 3b the width of the peak shown is limited by our 4 kHz resolution, though in higher resolution scans, we have observed peaks as narrow as 2 kHz. Following Ref. [3], we interpret this peak as a manifestation of the Lamb-Dicke effect. At these very low temperatures, atoms are localized in sub-wavelength sized potential wells created by the 3D configuration of the laser beams. This localization means that the phase of the radiation is undisturbed for a significant time, giving a spectral feature narrower than the Doppler width. According to this interpretation, the width of the narrow peak is related to the lifetime of the atoms in the well.

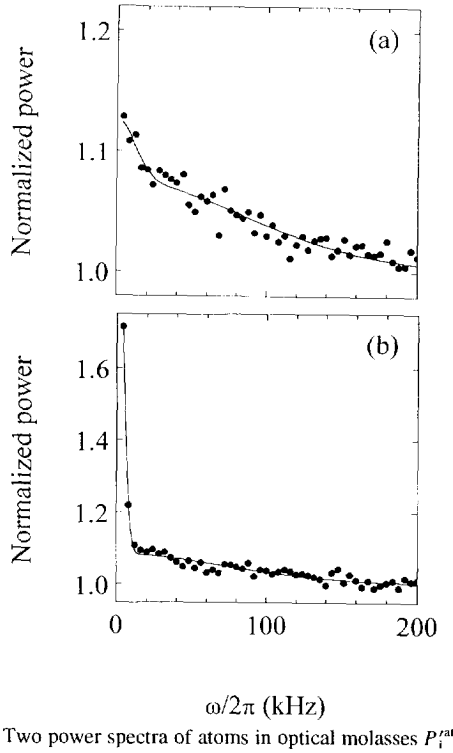

Fig. 3. Two power spectra of atoms in optical molasses $P_i^{\text{atoms}}(\omega)$ normalized according to Eq. (5). As in Fig. 2, the channel at 0 kHz is not shown. The lines are the fits described in the text. (a) Intensity 7 mW/cm^2, detuning −33 MHz, count rate 2.40×10^5 cps, $v_{\text{rms}} = 5$ cm/s. (b) Intensity 7 mW/cm^2, detuning −51 MHz, count rate 2.03×10^5 cps, $v_{\text{rms}} = 3.5$ cm/s. (Rb natural linewidth 6 MHz, $I_{\text{sat}} = 1.6$ mW/cm^2.) The height of the localization peak increases dramatically as the rms velocity decreases.

With this interpretation in mind we attempt to fit our results to a simple model in which we suppose first that the electric field at our detector is a random Gaussian field, i.e. that Eq. (2) is valid. Further we assume that the power spectrum of the light emitted by the atoms $P_0(\omega)$, has a broad Gaussian peak due to the Doppler width [2], and an additional narrow Gaussian peak due to the Lamb-Dicke narrowing. Since our measurement yields the power spectrum of the photocurrent, and not that of the optical field received by the detector, our spectrum in this model corresponds to the autoconvolution of the two peaked spectrum. It therefore consists of three peaks: one narrow peak, one peak corresponding to the convolution of the Doppler and the narrow peaks, and finally a broad pedestal corresponding to $\sqrt{2}$ times the Doppler width. The fits shown in the figures were done with this three peaked function. There were four adjustable parameters: the heights and widths of the narrow and Doppler peaks. For Fig. 3a the fit gives widths at half maximum of 120 kHz and 13 kHz respectively for the Doppler and narrow peaks, while in Fig. 3b the fit gives 115 kHz and 5 kHz respectively. (The 5 kHz figure is mainly our resolution.) According to the fits, the ratio of the power in the narrow peak to the total power in $P_i(\omega)$ was 6% for Fig. 3a and 30% for Fig. 3b. With our present setup, the run to run reproducibility of the fitted Doppler width is within 20% and the narrow width within about 50%.

Having demonstrated the intensity correlations, it is natural to ask whether they can be used as an efficient diagnostic tool for laser cooled atoms. Currently our

[2] Strictly, in our geometry, Doppler broadening would result in a broad peak having six Gaussian contributions, see Ref. [3]. Here we approximate this function by a single Gaussian. We have verified that this results in a negligible error compared to experimental uncertainties.

total integration time is 300 to 1000 s, but the duty cycle of our data acquisition and processing system could be increased by an order of magnitude, rendering the integration time quite acceptable. This is despite the limited amount of scattered light available at our large detunings and low intensity. An alternative method of data acquisition is to measure the correlations directly by a time correlator [14]. This method is well adapted to the observation of broad spectral features (short correlation times) as in our Doppler peak. Frequency domain measurements, on the other hand, seem well adapted to measurements of very narrow spectral structures.

As for extracting quantitative information from our spectra, we note that this is likely to be difficult with our present setup. We have only treated the atoms as classical radiators executing classical motion, but Raman transitions between light shifted magnetic sublevels and between vibrational levels in the potential wells can contribute to both the narrow and broad peaks, and affect their shape [3]. Optical lattices [5] offer a situation where all these effects are well controlled and an *ab initio* calculation of the spectrum should be possible [15]. Note that we can also adopt an empirical approach and calibrate the observations with the TOF results. This would provide a nearly real time diagnostic of the atoms.

Finally, a very interesting prospect is to look at situations where the information gained from correlation measurements is richer than that from heterodyne measurements. Correlations between spatially separated detectors could give information about the spatial distribution of the atoms, much as in the original experiments of Hanbury Brown and Twiss [6]. Periodic ordering, such as is present in optical lattices, as well as possible correlations between atomic dipoles should reveal itself as has already been demonstrated in colloidal liquids [16]. With an optical lattice, selection of detected light polarizations could also give information about the rate at which atoms hop between wells with different local polarizations. It is also possible to choose the directions of the laser and the scattered beams to isolate specific features of the atomic response [17]. Thus we believe that the method demonstrated here may turn out to be a very useful tool for the understanding of the interaction of atoms with laser beams.

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References

[1] T. Hänsch and A. Schalow, Optics Comm. 13 (1975) 68;
D. Wineland and H. Dehmelt, Bull. Am. Phys. Soc. 20 (1975) 637.

[2] For a review see: W. Phillips, in: Les Houches, Session LIII, Course 2, 1990, eds. J. Dalibard, J.-M. Raimond and J. Zinn-Justin (North Holland, Amsterdam, 1992).

[3] C. Westbrook, R. Watts, C. Tanner, S. Rolston, W. Phillips, P. Lett and P. Gould, Phys. Rev. Lett. 65 (1990) 33;
C. Westbrook, P. Jessen, C. Tanner, P. Lett, S. Rolston, R. Watts and W. Phillips, Atomic Physics 12, eds. J. Zorn and R. Lewis (Plenum, New York, 1990).

[4] P. Verkerk, B. Lounis, C. Salomon, C. Cohen-Tannoudji, J.-Y. Courtois and G. Grynberg, Phys. Rev. Lett. 68 (1992) 3861;
P. Jessen, C. Gerz, W. Phillips, S. Rolston, R. Spreeuw and C. Westbrook, Phys. Rev. Lett. 69 (1992) 49.

[5] A. Hemmerich and T. Hänsch, Phys. Rev. Lett. 70 (1993) 410;
G. Grynberg, B. Lounis, P. Verkerk, J.-Y. Courtois and C. Salomon, Phys. Rev. Lett. 70 (1993) 2249.

[6] A. Forrester, R. Gudmudsen and P. Johnson, Phys. Rev. 99 (1955) 1691;
R. Hanbury Brown and R. Twiss, Nature 177 (1956) 27.

[7] H. Kimble, M. Dagenais and L. Mandel, Phys. Rev. Lett. 39 (1977) 69.

[8] D. Boal, C. Gelbke and B. Jennings, Rev. Mod. Phys. 62 (1990) 553.

[9] See for example: B. Chu, Laser Light Scattering (Academic Press, Boston, 1991).

[10] We summarize here an account that can be found in:
H. Cummins and H. Swinney, Prog. in Optics, Vol. 8, ed. E. Wolf (North Holland, Amsterdam, 1970) p. 133.

[11] R. Loudon, The Quantum Theory of Light (Oxford University Press, Oxford, 1973).

[12] For a detailed discussion about the conditions leading to Eq. (2), see: J. Goodman, Statistical Optics (Wiley, New York, 1985).

[13] C. Gerz, T. Hodapp, P. Jessen, K. Jones, W. Phillips, C. Westbrook and K. Mølmer, Europhys. Lett. 21 (1993) 661.

[14] T. Walker, personal communication.

[15] P. Marte, R. Dum, R. Taïeb, P. Lett and P. Zoller, Phys. Rev. Lett. 71 (1993) 1335.

[16] N. Clark, B. Ackerson and A. Hurd, Phys. Rev. Lett. 50 (1983) 1459.

[17] P. Grangier, G. Roger, A. Aspect, A. Heidmann and S. Reynaud, Phys. Rev. Lett. 57 (1986) 687.