Quantum Nondemolition Measurements using Cold Trapped Atoms

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We have investigated possible implementations of optical quantum nondemolition measurements, using rubidium atoms in a magneto-optical trap as a nonlinear medium. Using a Λ-type three-level system in the $D1$ line of ^{87}Rb, the observed performances are quantitatively the best obtained so far for a single back action evading measurement. Moreover, the magneto-optical trap and the quantum nondemolition effect are both running continuously at the same time and mutual perturbations have been avoided by using a "dark spot" technique. This experiment demonstrates clearly the interest of using cold atoms for controlling the quantum fluctuations of light. [S0031-9007(96)02247-8]

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Significant effort was made during recent years for implementing the idea of "quantum nondemolition" (QND) measurements, which was initially introduced theoretically by Braginsky [1] and Thorne [2]. The principle of QND measurements is to overcome the measurement noise, which is introduced in a physical system when a quantum measurement is performed, by repeatedly "hiding" this noise in an observable which is not of interest. A scheme where the measurement noise is entirely kept in an observable which is conjugated with the measured quantity is usually said to be "back-action evading" (BAE). Though proposed and initially studied for mechanical oscillators [3,4], QND ideas were first implemented in quantum optics [5–14]. In the standard situation encountered with propagating laser beams, where the quantum fluctuations are small compared to the mean intensities, quantitative criteria have been developed for evaluating the QND or BAE efficiency of a given experimental setup [15,16]. An important quantity to look at is the quantum correlation between the two outputs of the measurement system (signal and meter), which can be measured through the conditional variance $V_{S|M}$ of the signal output S, given the measurement M [15,16]. It is also necessary to consider the transfer coefficients T_S and T_M, which quantify the transfer of the signal to (quantum) noise ratio of the input signal beam towards, respectively, the output signal and meter [16,17]. These quantities have boundaries which define necessary conditions for QND operation of the device [16]: Giving the conventional value 1 to the signal shot-noise level (SNL), $V_{S|M} < 1$ indicates nonclassical operation, in the same sense as used for squeezed states of light [18]. For a coherent input signal [16], a value of $T_S + T_M$ larger than 1, up to the maximum of 2, can only be obtained by using a phase-sensitive device, and is therefore related to noiseless amplification methods [19].

Many experiments have been devoted to the demonstration of BAE measurements [6–14]. These works culminated in the recent demonstration of repeated BAE measurements, which constitutes a full demonstration of the QND original idea [14]. This experiment, like several previous ones [11–13], uses second-order ($\chi^{(2)}$) optical nonlinearities, which have the important advantages of being well understood, and of adding very small excess noise to the output light beams. On the other hand, third-order ($\chi^{(3)}$) optical nonlinearities are usually accompanied by significant excess noise from the nonlinear medium [6–10]. Third-order nonlinearities in atomic media have, nevertheless, the advantage of having extremely large values, and can operate with very small optical power. Moreover, theoretical analysis done for motionless atoms predicts that it should be possible to achieve very good QND efficiency provided that appropriate laser powers and detunings are used [20]. However, such calculations do not include the atomic motion, which causes Doppler effect and excess fluctuations in the refractive index, even in an atomic beam [10], and therefore degrades quantum noise reduction effects. An open way for reducing motion-induced fluctuations is clearly to use a medium of cold trapped atoms; an encouraging result was the recent observation of transient squeezing from a cloud of falling atoms released from a magneto-optical trap (MOT) [21].

In this Letter we present the implementation of a BAE device using trapped rubidium atoms to provide a nonlinear coupling between two light beams: The intensity of a "signal" beam is thus read out on the phase of a "meter" beam. By tuning the two lasers close to the resonances of a Λ-type three-level system, the measured performances are $V_{S|M} = 0.45$, $T_S = 0.90$, and $T_M = 0.65$, which are the best obtained so far in a single BAE device. The optical powers used in the experiment are in the microwatt range, emphasizing the very high values of the effective nonlinearities. Special care has been taken to minimize the mutual perturbations of the trapping and QND effect, by using two different optical transitions and a "dark spot" configuration for the trap [22]. As a consequence, both the MOT and the QND effect are running continuously at the same time.

The MOT is built in a large ultrahigh vacuum (UHV) chamber, designed in order to set up the sensitive parts of the experiment directly around the cold atom cloud. The

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present setup uses ^{87}Rb, with nuclear spin $I = 3/2$. The trap is loaded by slowing down an atomic beam using the standard chirped-frequency technique [23]. The atoms are trapped using a standard six-beam $\sigma+/\sigma-$ MOT configuration [24]. The trapping lasers are two 100 mW laser diodes, injection locked to a master laser and detuned by four natural linewidths $[\Gamma/(2\pi) = 6$ MHz$]$ to the red of the $F = 2$-$F' = 3$ transition (see Fig. 1). The total power on the trap is typically 3×30 mW, with a beam diameter of 20 mm. A repumping beam locked on the $F = 1$ to $F' = 2$ line pumps back the atoms from the $F = 1$ ground state. This beam is superimposed with the trapping beams along two axes, and its central part is screened by a dark spot imaged at the trap location [22]. This allows one to have about 90% of the population of the cloud in the $F = 1$ ground state, and will be essential for the continuous operation of the QND effect. The diameter of the trap, measured either in fluorescence ($F = 2$) or in absorption ($F = 1$), is close to 3.5 mm FWHM. The estimated population in the $F = 1$ dark state is 10^9 atoms, corresponding to a density of 5×10^{10} atoms/cm^3. For the following experiments, the Doppler width of the atomic medium has to be smaller than the natural linewidth Γ; this is easily fulfilled by the techniques that are used here.

A schematic overview of the optics of the QND experiment is shown in Fig. 2. The signal and meter beams are emitted by two independent frequency-stabilized titanium-sapphire lasers, which are shot-noise limited in both intensity and phase for noise analysis frequencies above 2 MHz. The two beams are carried onto the optical table by optical fibers, which ensure very good spatial mode quality, and then mode matched to the vertical optical cavity which is set up inside the UHV chamber around the cold atom cloud. The signal and meter beams have orthogonal linear polarization inside the cavity, and the input and output beams are separated using polarization beam splitters and Faraday rotators (see Fig. 2). The cavity mirrors have a 60 mm radius of curvature, and their distance is adjustable from 64 to 68 mm, using screws and piezo-electric transducers which are outside the UHV chamber. The lower, input/output cavity mirror has a 5% transmissivity. The upper mirror has a low transmissivity ($T < 10^{-4}$), which is used to monitor the intracavity intensities using two photomultipliers and another polarization beam splitter. The cavity finesse is 125, and typical mode-matching efficiency in the cavity fundamental mode is above 99%. The output signal beam is directly detected, while the meter beam is detected after interfering with a "local oscillator" beam (phase-sensitive homodyne detection [18]). The maximum fringe visibility of this interferometer (or homodyne efficiency) is 96%. The quantum efficiency of all photodiodes is 92%. The transmission of the optical system (not including the photodiodes) is 90%, and the on-resonance losses of the cavity are negligibly small.

The level scheme which is used for the QND effect is shown in Fig. 1. While the trapping and repumping lasers are tuned on the D2 line at 780 nm, the signal and meter beams are tuned on the D1 line at 795 nm. The linearly polarized signal is tuned close to the $5s_{1/2}$ $F = 2$ to $5p_{1/2}$ $F' = 2$ transition, with a typical input power of 15 μW. The signal acts therefore as a "depumper" with respect to the trap, increasing the population of the ground $F = 1$ level. The meter beam, on the $F = 1$ and $F' = 2$ transition, is linearly polarized orthogonally to the signal, and is detuned negatively (to the red) with respect to the dressed levels due to the signal-atom coupling. The typical meter input power is 0.25 μW. The contributions of the different Zeeman sublevels to the two-beam coupling is shown in the inset of Fig. 1. Note that, if this system was considered alone, all the population should be pumped in the $F = 2$, $m = 0$ ground state. However,

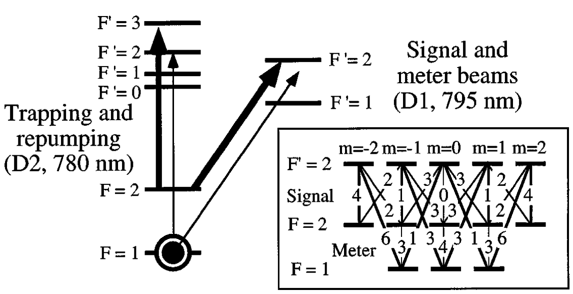

FIG. 1. Level scheme used in the experiment. The inset shows the relevant relative oscillator strengths for coupling the signal and meter beams, which have orthogonal linear polarizations.

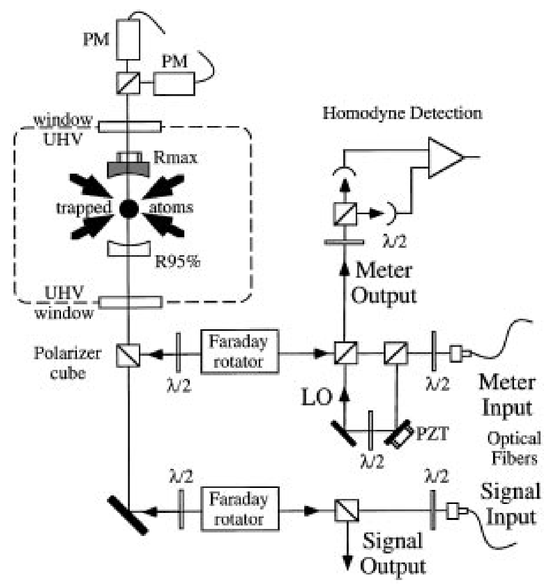

FIG. 2. Simplified view of the experimental setup. The input signal and meter beams are mode matched to an optical cavity surrounding the trapped atoms. Output beams are separated from the input ones using Faraday rotators. The signal beam is directly detected, while the meter beam undergoes a phase-sensitive homodyne detection.

the MOT laser recycles very efficiently the atoms which could be lost in this level, and most of the coupling comes from the two Λ level schemes with the largest Clebsch-Gordan coefficients. This system is therefore very close to the "ghost transition" scheme, which was studied theoretically in Ref. [20] and predicted to have good QND performances. In this scheme, the strong signal beam optically pumps the atoms into a ground level (here, the $F = 1$ level), from which the weak meter beam can probe the light shift induced by the signal on the upper level. The signal acts therefore on a nearly transparent transition, and its intensity fluctuations are almost unperturbed. Using experimental values [25] in the model described in Ref. [20], and correcting for losses in the optics, the calculated values are within a few percent of the results obtained in the experiment. This analysis, including the behavior of the mean fields, will be presented in another publication.

We note that the frequency difference between the signal and meter beam has to be close to the ground state hyperfine splitting of ^{87}Rb, which is 6.83 GHz. Since both beams also have to be resonant in the cavity, this detuning has to be close to an integer number of free spectral range (FSR) of the cavity. This is indeed the case when the cavity length is 66 mm, corresponding to a FSR of 2.27 GHz: The two frequencies are then approximately 3 FSR apart. We note also that the two standing wave patterns from the signal and meter beams have to be in phase at the atom location, so that the atoms see the appropriate Rabi frequencies [25] from each beam. This is achieved by placing the trapped atoms' cloud at one-third of the cavity length.

The experimental procedure for measuring the QND criteria is the following. A weak intensity modulation at 5 MHz, about 20 dB above the SNL, is applied on the signal beam. Then the detunings of the two beams are iteratively adjusted while scanning both the cavity and the homodyne detection, in order to maximize the transfer of the modulation from the signal onto the meter beam, while minimizing the degradation of the signal. This adjustment can be completed at a cavity position where both fields resonate together inside the cavity [10]. When the optimum detunings are found, the cavity scan is stopped at the resonance peak, and the noise levels are measured by scanning the spectrum analyzer (SA) around 5 MHz. Typical results are shown in Fig. 3. The lower trace (a) shows the SNL and the modulation of the output signal beam, taken off cavity resonance without the atoms; the width of the modulation peak is the 100 kHz rf resolution bandwidth of the SA. Over this trace are also shown as dots the SNL and modulation of the output signal beam, taken while the cavity is stopped at resonance in the presence of the atoms (operating conditions). There is clearly neither attenuation nor change in the noise of the signal beam. The nondemolition coefficient T_S is therefore limited only by the passive optical transmission of the system, which relates the output signal without atoms to the input one, i.e., $T_S = 0.90$ (-0.5 dB). From T_S and Fig. 3, one gets the input beam signal-to-noise ratio, which is 23.8 dB. The upper trace (b) is the phase-dependent noise and modulation of the output meter beam, taken in operating conditions while scanning the phase of the homodyne detection. The SNL of the meter beam has been electronically set at the same level as the one for the signal beam. The upper envelope of the fringes gives the meter phase information, and yields the output meter signal-to-noise ratio, which is equal to 21.9 dB. The measurement transfer coefficient is thus -1.9 dB, or $T_M = 0.65$. Finally, it can be shown that the conditional variance of the signal, given the measurement, is also the minimum noise which can be obtained when recombining the output signal and meter photocurrents, the latter being appropriately attenuated [14,16]. This recombined photocurrent is shown in Fig. 4, while scanning the phase of the homodyne detection. For optimum attenuation (12 dB) of the meter photocurrent, the recombined noise reaches a minimum value 3.5 dB below the SNL, which gives a conditional variance $V_{S|M} = 0.45$. Estimated uncertainties on T_S, T_M, and $V_{S|M}$ are ± 0.05. The values quoted here, which are corrected for the amplifier noise but not for the detector quantum efficiencies, are typical of many experiments which were done for different values of the input beam powers and detunings.

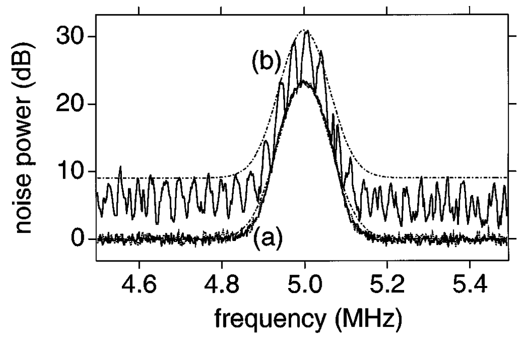

FIG. 3. Measurement of the transfer coefficient T_M. Curve (a), normalized to the SNL, corresponds to the output signal, modeled by a Gaussian peak (dash-dotted line). Two curves are actually displayed, and show no observable difference: one taken off resonance without atoms (line), and one taken on operating conditions (dots). Curve (b) is the outcoming meter, also taken on operating conditions, and modulated by scanning the phase of the homodyne detection. The upper envelope is fitted by a Gaussian peak of same width as in (a). The signal-to-noise ratios are obtained as the differences (in dB) between the fitted peaks and the flat backgrounds.

We also tried several other level schemes, using either "Λ" or "V" configurations, which, however, did not give as good results. Generally speaking, the experiment requires one to get control both on optical pumping effects, in order to avoid that the atoms be pumped outside the three-level scheme of interest, and on light-induced forces, so that the signal and meter beams do not expel the atoms from the interaction region or even from the trap. Further improvements, now under theoretical analysis, could be obtained if the atoms were attracted and trapped

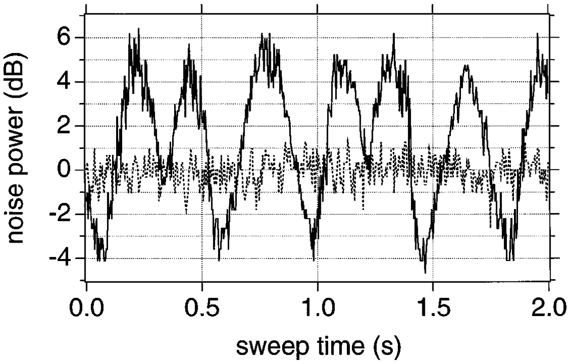

FIG. 4. Measurement of the conditional variance $V_{S|M}$. The dotted line is the signal beam shot-noise level at a noise analysis frequency of 5 MHz (rf bandwidth 100 kHz, video bandwidth 300 Hz). The full line is the noise from the recombined signal and meter photocurrents, recorded as the phase of the homodyne detection is scanned. The conditional variance appears as the minimum noise level on this curve.

at the common antinodes of the coupled beams; though we could not clearly demonstrate this effect so far, the used scheme yields, in principle, rectified dipole force [26] able to attract the atoms at the right position.

To summarize, we have observed very good BAE performances from a cloud of trapped rubidium atoms in an optical cavity, in a level configuration where the trap and the quantum noise effects are running continuously at the same time. This is obtained by controlling both the optical pumping and the light forces induced by the signal and meter beams. Beyond its success as a BAE device, this experiment demonstrates clearly that cold atoms do provide a very efficient and low-noise nonlinear medium for achieving control of the quantum fluctuations of light.

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