Squeezing with cold atoms

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Abstract. - Cold atoms from a magneto-optic trap have been used as a nonlinear ($\chi^{(3)}$) medium in a nearly resonant cavity. Squeezing in a probe beam passing through the cavity was demonstrated. The measured noise reduction is 40% for free atoms and 20% for weakly trapped atoms.

Soon after the first implementations of magneto-optic traps [1, 2], the strong nonlinear properties of laser cooled atoms were recognized. It was shown that a probe beam going through a cloud of cold atoms could experience gain due to Raman transitions involving the trapping beams [3, 4]. When the atoms were placed in a resonant optical cavity, laser action corresponding to that gain feature was demonstrated [5]. Meanwhile, when cold atoms are driven by a slightly detuned probe laser beam inside an optical cavity, bistability is observed at very low light powers [6]. This high nonlinear dispersion comes from the fact that, since the atoms are virtually motionless, the Doppler width is smaller than the natural linewidth and the probe frequency can be set close to atomic resonance. Such nonlinear behavior indicates that the system is capable of significantly modifying the quantum fluctuations of a probe beam, in particular leading to squeezing. The generation of squeezed light through interaction with nonlinear media has been subject of extensive theoretical and experimental studies (see for example [7]). The use of atomic media looked particularly promising in the absence of Doppler broadening [8, 9, 10]: laser-cooled atoms should therefore be ideal. However, no experiment performed so far has used cold atoms for squeezing, while those which relied on atomic beams failed to live up to expectations.

In this paper we report quantum noise reduction in a probe beam that has interacted with cold atoms in an optical cavity. Quadrature squeezing as large as 40% (uncorrected for detection efficiency) was measured at the output of the cavity. This value is the largest ever measured in an atomic medium. Furthermore it is in good agreement with the theoretical predictions. It therefore has very good prospects for leading to much higher levels of squeezing when the apparatus is suitably improved. The squeezing was first observed in a free cloud, just after the trap had been turned off. It was also observed in a weakly bound trap with trapping beams turned down by a factor of 10 as compared to the...
original trap. In light of the rapid development of atom-cooling technology, it is conceivable that a set-up of this type be constructed on a much smaller scale, relying exclusively on diode lasers. This could lead to the realization of a compact and efficient quantum “noise eater”.

Up to now, all experiments of this type had been performed on atomic beams, where the transverse Doppler effect is small but often not completely negligible\[1, 2, 3\]. The best value of quantum noise reduction measured in that case is of the order of 20%, while theory predicts higher figures that have never been obtained.

In contrast to atomic beams, cold atoms constitute a well controlled medium, where theoretical models can in principle be fully tested against experimental results, including realistic conditions such as the spatial character of the laser beam and additional noise sources. In such conditions one is able to accurately model the squeezing data theoretically for the first time, whereas in the atomic beam experiments no quantitative explanation has been given of the discrepancy between the measured squeezing and the significantly higher theoretical predictions.

To fit our experimental data, we have developed a theoretical model which fully takes into account the transverse structure of the probe beam \[4\] and which also considers the influence of additional noise sources like atomic number fluctuations \[5\]. With this treatment we have not only obtained a correct prediction for the magnitude of the quadrature squeezing, but also a continuous prediction for the minimal and maximal noise power as a function of cavity detuning, which fits the experimental result well.

The experimental set-up used to demonstrate squeezing with cold atoms has been described in detail elsewhere \[6\]. Here, we will only recall its main features. A circularly polarized probe beam is sent into a resonant optical cavity containing a cloud of cold Cesium atoms prepared in a standard magneto-optic trap\[1, 2\]. With large and rather intense trapping beams, detuned by 3 times the linewidth below resonance of the $6S_{1/2}, F = 4$ to $6P_{3/2}, F = 5$ transition, we obtain a cloud of 1cm in diameter, with densities on the order of $10^9$ atoms/cm$^3$.

The temperature of the atoms is of the order of some mK. The number of atoms interacting with the probe beam is measured with a method described below.

The cavity is a 25cm-long linear cavity, with a waist of 260$\mu$m, built around the cell (fig.1). The input mirror has a transmission coefficient of 10% and the end mirror is highly reflecting. The cavity is thus close to the “bad cavity” case, where the linewidth of the cavity (5MHz) is larger than the radiative linewidth ($\gamma = 2.6$MHz), and which is expected to be the most favorable for squeezing. The cavity is in the horizontal symmetry plane of the trap, making a 45° angle with the two trapping beams propagating in this plane. The probe beam, generated by the same Ti:Sapphire laser as the trapping beams, can be detuned by 0 to 130MHz on either side of the $6S_{1/2}, F = 4$ to $6P_{3/2}, F = 5$ transition. We measure the probe beam intensity transmitted through the cavity with a photodiode located behind the end mirror.
The field coming out of the cavity is separated from the incoming one by an optical circulator, made of a polarizing beamsplitter and a quarter-wave plate, and mixed with a local oscillator beam using the second input port of the same beamsplitter. Orthogonally polarized at the output of the beamsplitter, the signal and local oscillator beams are split into equal-intensity sum and difference fields by a half-wave plate and a second polarizing beam splitter. Both parts are detected by photodiodes with a quantum efficiency of 96%. The total homodyne efficiency is of the order of 90%. The ac parts of the photodiode currents are amplified and subtracted. The resulting signal is further amplified and sent to a spectrum analyzer and to a computer.

When scanning the cavity resonance, bistability due to the nonlinear dispersion of the cold atoms is easily observed with incident powers as low as a few µW, as soon as the number $N$ of interacting atoms is large enough. The nonlinear phase shift of the cavity giving rise to bistability is proportional to the cooperativity parameter $C$ also called bistability parameter: $C = g^2 N / \gamma T$, where $g$ is the atom-light coupling coefficient, $\gamma$ the radiative linewidth of the transition and $T$ the energy transmission coefficient of the mirror). $C$ is determined for each recording by measuring the ratio between the amplitudes of the bistability curve and of the resonance curve of the empty cavity. We find a cooperativity of the order of 100 in presence of the trap. It should be noted that the atoms are partly saturated by the trapping beams, and that therefore the measured $C$ value is smaller than the one corresponding to the total number of atoms in the interaction area.

The fluorescence emitted by atoms excited by the trapping beams constitutes a source of excess noise, which decreases the amount of quantum noise reduction
attainable in principle. To avoid this effect, we turn off the trap during the noise measurements. With this method, the measurement time is limited to 20 to 30 ms, due to expansion and free fall of the atomic cloud. When the trap is turned off, the number of interacting atoms becomes time-dependent. The variation of the refractive index due to the escape of the atoms out of the probe beam provides a natural scan of the cavity across resonance. In this way, the resonance peak is scanned in about 10 ms. However, under these conditions, the $C$ value, being proportional to $N$, is no longer constant over the scan and it becomes necessary to adopt a specific model of its time-dependence in order to interpret the noise spectra. A model for the variation of $C$ with time can be obtained by calculating the variation of the linear phase shift caused by an expanding and falling ensemble of atoms in a Gaussian laser beam [15].

The atomic sample is assumed to have initially a Gaussian velocity and position distribution. Supposing according to experimental conditions the Rayleigh length of the beam to be much larger than the cloud size which itself is large compared to the beam waist, the variation of $C(t)$ is given by the product of a Lorentzian function representing the ballistic flight of the atom with an exponential function accounting for the effect of gravity:

$$C(t) = C(0) \frac{\tau_r^2}{\tau_r^2 + t^2} \exp \left( -\frac{t^4}{\tau_g^2 (\tau_r^2 + t^2)} \right)$$  \hspace{1cm} (1)

$C(0)$ is the cooperativity value right after the trap is turned off; the time constant $\tau_r = \sigma_r / \sigma_v$ is the time for the atoms with temperature $T$ at and with mean velocity $\sigma_v = \sqrt{kT/m}$ to fly through the cloud of radius $\sigma_r$ and $\tau_g = 2\sqrt{2}\sigma_v/g$ is the time it takes for the falling atoms to accelerate to $2\sqrt{2}$ times their original thermal velocity.

To check this model, the cooperativity was experimentally studied as a function of time. Fig. 2 shows the result of such a measurement. The experimental points are fitted by the theoretical expression (1). The line corresponds to the theoretical prediction for a cloud radius of 4 mm and a temperature of 5 mK, which are consistent with the characteristics of our trap. As the theoretical curve fits the experimental data very well, these parameters were subsequently used to calculate the noise spectrum.

While the cavity resonance is scanned by the escape of the atoms the field fluctuations of the output beam are monitored with the homodyne detection described above at a fixed analyzing frequency of 5 MHz. At the same time, the local oscillator phase is rapidly varied with a piezoelectric transducer to explore all noise quadratures of the probe beam. As we have only 20 – 30 ms for the measurement, the phase of the local oscillator must be scanned at frequencies on the order of kHz, which determines the analyzing bandwidth of the spectrum analyzer to be about 100 kHz. The video bandwidth of the spectrum analyzer should be adjusted to avoid any distortion of the spectrum. As the videofilter of our model (Tektronix 2753 P) did not have enough flexibility, we used numerical
filters in the processing of the spectrum.

The spectrum shown in fig.3 was obtained in such a manner. The electronic noise was substracted from the signal provided by the spectrum analyzer before the filtering process. The averaged shot noise level (determined by blocking the cavity) is indicated by the straight line. It can be seen that the noise on the left hand side of the figure, when the cavity is out of resonance, is at shot noise, whereas it goes below shot noise on the lower branch of the bistability curve. The observed squeezing is $(40 \pm 10)\%$. On the upper branch (right hand part of the figure), large excess noise is observed in some quadratures. The powers of the probe laser and local oscillator were $25\mu W$ and $9mW$. The large ratio of these powers ensures the noise measured by the homodyne detection does not require any normalization, even if the probe beam reflected by the cavity does not have a constant intensity. The detuning from atomic resonance was $52MHz$ below resonance. The cooperativity parameter $C$ was found to be 220 right after turning off the trap. The error bar for the squeezing measurement is due to the width of the random noise of the signal which is generated within the measurement system itself. This random noise varies as the mean noise level and is estimated from the shot noise level to be $\pm 10\%$ at the minimum of fig.3. The variation of the transmitted field reproduced in the insert of fig.3 shows that the system is slightly below the bistability threshold. The spectrum presented in fig. 3 shows the best squeezing value obtained in a series of experiments where several parameters such as the detuning of the probe field from the cavity and atomic resonances, the analyzing frequency and the atomic number were varied.

In a second series of experiments, we have looked for quantum noise reduction in presence of the trap. As mentioned above, intense trapping beams produce
Figure 3: Noise signal taken with free atoms at a fixed observation frequency of 5MHz as a function of time, while the cavity resonance is scanned by the departure of the atoms. Oscillations correspond to phase scan of the local oscillator. The broken lines are theoretical predictions for the minimal and maximal noise, the solid line indicates the shot noise level. The probe beam was detuned by 52MHz below resonance and its power was 25µW. The error bar is due to the width of the noise trace. The insert shows the corresponding mean intensity.

too much excess noise to allow observation of squeezing. However, we have been able to find a compromise by first trapping the atoms from the vapor with intense laser beams, and then turning down the trapping beams to about 1/10 of their original power. Under these conditions, the cooperativity parameter is on the order of 20. The noise spectrum shown in fig.4 is recorded under similar conditions as above (detuning of 52MHz and incident probe power of 16µW) except that the cavity is scanned by means of a piezoelectric transducer while the number of atoms is constant during the measurement. The best value for squeezing obtained under such conditions is on the order of (20 ± 10)%. Here, the quantum noise reduction appears on the upper branch of the bistability curve.

An interesting feature of this result is that the steep edge on the left hand side of the bistability curve (upper trace in fig.4) is due to optical pumping, rather than to saturation which is responsible for squeezing. Indeed the two processes that can lead to bistability, saturation of the optical transition and optical pumping, are easily distinguished by their sign. Saturation of the atomic transition causes a decrease of the refractive index, whereas optical pumping increases it. Thus the bistability curves due to the two processes have steep edges on opposite sides. In the case shown in fig.4, the left hand side of the bistability curve can be unambiguously attributed to optical pumping. With increasing intensity of the probe beam, the dominant phenomenon becomes the saturation
Figure 4: Noise signal (measured at a fixed frequency of 5MHz) and mean intensity taken with weakly trapped atoms, while the cavity length was swept with a piezoelectric transducer and the local oscillator phase was modulated rapidly. The solid line indicates the shot noise level. The error bar is determined as in fig.3.

of the atomic transition [17] and the steep edge changes sides. In this second experiment squeezing is reproducibly observed only in the range of parameters where the bistability curve originates from optical pumping. However, squeezing is still linked to the saturation of the atomic transition and the observed features can be interpreted as a consequence of the dynamical processes that take place in the cavity. As the cavity length is scanned, light from the probe beam enters the cavity and pumps the atoms towards the sublevels with the highest magnetic quantum number. At that stage, saturation of the atomic transition starts to take place, and this non-linearity is at the origin of squeezing in the output field. As was shown in [17], the instabilities on the right hand side of the curve (after the region where the squeezing occurs) come from a competition between optical pumping, which is not fully completed here, and saturation of the atomic transition.

The experimental spectra for free atoms have been compared with the theoretical predictions given by the two-level atom model derived from ref.[14]. The measured experimental parameters are included in the model, which takes into account the Gaussian character of the beam. The minimal and maximal quantum noise were calculated in conditions reproducing those of the experiments, i.e. by including the variation in time of the cooperativity as represented in fig.2, and the homodyne efficiency of 90%. The resulting spectra are shown by the broken lines in fig.3. It can be seen that the agreement between theory and experiment is satisfactory.
As far as the squeezing in presence of the trap is concerned, one can calculate the value of squeezing from the same two-level atom theory. The expected quantum noise reduction is then 20%, in good agreement with the observed value. Squeezing is here limited by the lower value of the cooperativity which is on the order of 20.

We have evaluated the potential effect of spurious noise sources in the experiments. In the experiment with free atoms, the excess noise due to the atomic number fluctuations in the cold atom cloud in the process of expanding and of falling was shown to have a spectrum peaked at frequencies that are too low to affect the noise measurements at 5MHz. Additional causes of excess noise are the repumping laser and the weak trapping beams in the second experiment. Their effects have been evaluated with a calculation based on the atomic number fluctuations they produce. In the frequency range studied, we find their excess noise to be negligible for the rather low powers that are used for repumping and trapping beams.

This study shows that cold atoms provide a powerful medium for quantum optics. The measured squeezing is higher than any value observed in previous atomic experiments. Even higher values are expected by increasing the ratio of the cavity linewidth to the atomic linewidth, i.e. by going more towards the bad-cavity limit. One of the difficulties of our first set of experiments, in which the trap had to be turned off during the noise measurements, is avoided in the second kind of experiments. It should be possible to go further by working with cold atoms that do not interact at all with the trapping beams, for example, by using a “dark SPOT” set-up.

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References

[1] E. Raab, M. Prentiss, A. Cable, S. Chu, D. Pritchard, Phys. Rev. Lett. 59, 2631, (1987)
[2] C. Monroe, W. Swann, H. Robinson, C. Wieman, Phys. Rev. Lett. 65, 1571 (1990)
[3] D. Grison, B. Lounis, C. Salomon, J.Y. Courtois, G. Grynberg, Europhys. Lett. 15, 149 (1991)
[4] J. Tabosa, G. Chen, Z. Hu, R. Lee, H.J. Kimble, Phys. Rev. Lett. 66, 3254 (1991)
[5] L. Hilico, C. Fabre, E. Giacobino, Europhys. Lett. 18, 685 (1992)
[6] E. Giacobino, J.M. Courty, C. Fabre, L. Hilico, A. Lambrecht, in “Fundamental of Quantum optics III”, ed. F. Ehlotzky Springer-Verlag (1993)
[7] Quantum Noise Reduction in Optical Systems, eds Giacobino and Fabre, Appl. Phys. B55, 189 (1992)

[8] F. Castelli, L.A. Lugiato, M. Vadacchino, Nuovo Cimento B10 183 (1988)

[9] M.D. Reid Phys. Rev. A37, 4792 (1988)

[10] L. Hilico, C. Fabre, S. Reynaud, E. Giacobino, Phys. Rev. A46, 4397 (1992)

[11] M.G. Raizen, L.A. Orozco, M. Xiao, T.L. Boyd, H.J. Kimble, Phys. Rev. Lett. 59, 198 (1987)

[12] D.M. Hope, H.A. Bachor, P.J. Mansen, D.E. McLelland, P.T.H. Fisk Phys. Rev. A46, R1181 (1992)

[13] Ph. Grangier, J.Ph. Poizat, P. Grelu, F. Castelli, L.A. Lugiato, A. Sinatra, J. Mod. Opt. 41, 2241 (1994)

[14] A. Lambrecht, J.M. Courty, S. Reynaud, “Effect of transverse structure on squeezing with two-level atoms” preprint

[15] A. Lambrecht, E. Giacobino, S. Reynaud, “Atomic number fluctuations in a falling cold atom cloud” preprint.

[16] A. Lambrecht, J.M. Courty, S. Reynaud, E. Giacobino, Appl. Phys. B60, 129 (1995)

[17] A. Lambrecht, E. Giacobino, J.M. Courty, Opt.Commun. 115, 199 (1995)

[18] W. Ketterle, K.B. Davis, M.A. Joffre, A. Martin, D.E. Pritchard, Phys. Rev. Lett. 70, 2253 (1993)