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## Polarization squeezing with cold atoms

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atoms from being optically pumped to the  $6S_{1/2}$ ,  $F=3$  state, we superimpose a diode laser tuned to the  $6S_{1/2}$ ,  $F=3$  to  $6P_{3/2}$ ,  $F=4$  transition to the trapping beams. We use a 25 cm long linear cavity built around the cell. The cavity is close to the hemifocal configuration with a waist of  $260 \mu\text{m}$ . The coupling mirror has a transmission coefficient  $T$  of 10%, the rear mirror is highly reflecting. Hence, the cavity is close to the bad cavity limit for which the cavity linewidth ( $\kappa = 5 \text{ MHz}$ ) is larger than the atomic linewidth ( $\gamma = 2.6 \text{ MHz}$ ). We probe the atoms with a linearly polarized laser beam detuned by about 50 MHz in the red of the  $6S_{1/2}$ ,  $F=4$  to  $6P_{3/2}$ ,  $F=5$  transition. The optical power of the probe beam ranges from 5 to  $15 \mu\text{W}$ . Under these conditions, the number of atoms interacting with the light beam is about  $10^6$ - $10^7$ . The polarization of the light transmitted by the cavity is analyzed with a quarter-wave plate and a polarizing beam-splitter (PBS1), so that Vs1 and Vs2 give the amount of respectively left-handed ( $I_+$ ) and right-handed ( $I_-$ ) circular light.

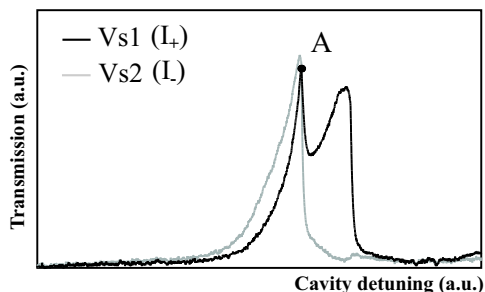


FIG. 2: Analysis of the circular polarization content of the light transmitted by the cavity and detected by the photodiodes shown in Fig. 1. Polarization switching occurs at point A. The power of the incident light is  $7 \mu\text{W}$ .

A typical recording of the transmitted intensities  $I_{\pm}$  as a function of the cavity length is shown in Fig. 2: starting from the left up to point A, the polarization remains linear (nearly equal amount of circular polarized light on both photodiodes), then it becomes circular. This polarization switching was known to occur in Fabry-Perot cavities containing atomic vapors with degenerate sub-levels in the ground state [9, 10]. In the experiment the probe beam is nearly resonant with the  $6S_{1/2}$ ,  $F=4$  to  $6P_{3/2}$ ,  $F=5$  transition: in principle, all the 20 Zeeman sub-levels are involved in the interaction. In order to get a qualitative physical insight into this problem, avoiding too heavy calculations, we model the atomic medium as an X-like four-level system [see Fig. 3].

The competitive optical pumping between the circular component  $\sigma_{\pm}$  of light makes the linear polarization unstable inside the cavity above some intensity threshold. The optical pumping is responsible for polarization switching and the general shape of the cavity resonance curve [see Fig. 2] is well understood within this theo-

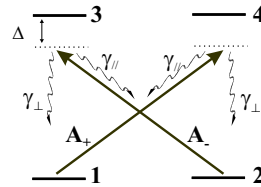


FIG. 3: Schematic energy level diagram for the X-like four-level system:  $\gamma_{\perp} + \gamma_{\parallel} = \gamma$  is the optical dipole decay rate;  $\Delta$  is the (large) detuning from resonance.

retical frame [8, 9, 10]. Alternatively, the polarization switching threshold may be interpreted as a laser oscillation threshold for the mode orthogonal to the main polarization mode [8]. Here, we are interested in the quantum fluctuations of the light, which can be strongly modified via the interaction with the atoms. When the polarization of the light is circular, the situation is analogous to the previous experimental scheme when the incoming field was circularly polarized [6]. We will therefore focus in the following on the case for which the polarization remains linear along the  $x$ -axis. The saturation of the  $\sigma_{\pm}$  components of light causes the medium to behave as a Kerr-like medium for the mean field  $\hat{A}_x$ . In addition, the vacuum orthogonal  $\hat{A}_y$  mode experiences a non-linear dephasing via cross-Kerr effect [2, 8]. This system is then expected to generate quadrature squeezing for both modes; in the large detuning limit [ $\Delta \gg \gamma$ ], the equation for the vacuum mode fluctuations reads [8]

$$\begin{aligned} \frac{d\delta\hat{A}_y}{dt} &= -[\kappa + i(\Delta_c - \Delta_0)]\delta\hat{A}_y \\ &\quad -i\Delta_0 \frac{s_x}{2} \left[ 2\delta\hat{A}_y - \frac{\langle\hat{A}_x\rangle^2}{|\langle\hat{A}_x\rangle|^2} \delta\hat{A}_y^\dagger \right] + \frac{2\kappa}{\sqrt{T}} \delta\hat{A}_y^{in} \end{aligned} \quad (1)$$

with  $\Delta_c$  the cavity detuning,  $\Delta_0 = 2Ng^2\kappa/\Delta T$  the linear atomic dephasing,  $s_x = 2g^2|\langle\hat{A}_x\rangle|^2/\Delta^2$  the saturation parameter and  $\delta\hat{A}_y^{in}$  the incident field fluctuations. The cross-Kerr induced term has two contributions: a dephasing ( $\propto |\langle\hat{A}_x\rangle|^2 \delta\hat{A}_y$ ) and the term in  $\langle\hat{A}_x\rangle^2 \delta\hat{A}_y^\dagger$ , responsible for the squeezing of this mode. A similar equation can be derived for the mean field  $\hat{A}_x$ , for which the squeezing is then generated via the usual Kerr term ( $\propto \langle\hat{A}_x\rangle^2 \delta\hat{A}_x^\dagger$ ). These equations are valid when the large excess noise due to optical pumping can be neglected, that is for times smaller than the optical pumping time, in contrast with [5]. Squeezing is then predicted for noise frequencies higher than the inverse optical pumping time. Using the experimental set-up described in Fig. 1, we have measured the quadrature noise of both modes. The signal recorded at the output of the cavity (see Fig. 2) is used to lock the cavity length on the regime where the polarization remains linear. After interacting with the atoms, both fields are mainly reflected by BS and then mixed on PBS2 with a 10 mW local oscillator beam (LO).

Using the half-wave plate  $\lambda/2a$ , we are able to send either the mean field mode or the orthogonal vacuum mode to PBS3 and perform the usual homodyne detection. By varying the relative phase of the LO with respect to the probe beam we can detect the noise features of all the quadratures of the field. In agreement with the theoretical predictions, we observe quadrature squeezing on both the main mode and the orthogonal mode. The results are 5% (7% after correction for optical losses, mainly due to BS) of noise reduction for the main polarization mode at 6 MHz and 13% (18% after correction) for the squeezed vacuum state at 3 MHz, as shown in Fig. 4. This system is then able to produce simultaneously two squeezed modes, for which the relative phases are intrinsically fixed. Let us note that these two squeezed modes can be used to generate a pair of entangled beams, which will be presented in a forthcoming publication [11].

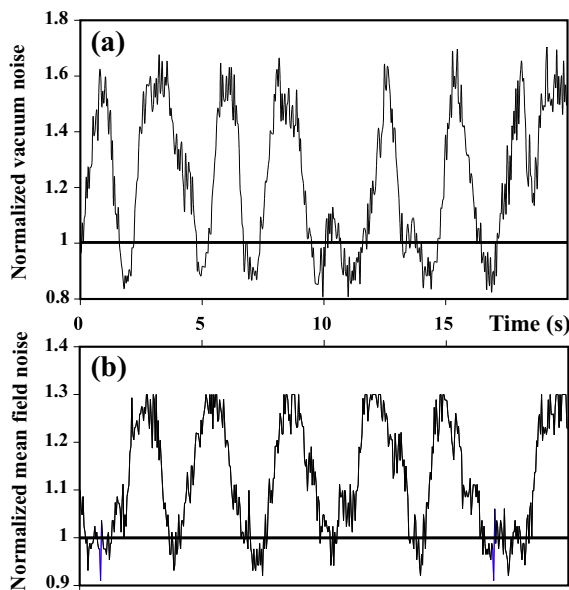


FIG. 4: Normalized quadrature noise for the vacuum field mode at 3 MHz (a) and for the mean field mode at 6 MHz (b). The best squeezing is 13% for the vacuum mode and 5% for the mean field mode.

In the following we focus on the study of the noise of the mode with orthogonal polarization with respect to the main mode, commonly referred to as *polarization noise*. The characterization of the quantum features of the polarization state relies on the measurement of the quantum Stokes parameters [12]. They are defined from their classical counterparts

$$\begin{aligned}\hat{S}_0 &= \hat{A}_x^\dagger \hat{A}_x + \hat{A}_y^\dagger \hat{A}_y, & \hat{S}_1 &= \hat{A}_x^\dagger \hat{A}_x - \hat{A}_y^\dagger \hat{A}_y \\ \hat{S}_2 &= \hat{A}_x^\dagger \hat{A}_y + \hat{A}_y^\dagger \hat{A}_x, & \hat{S}_3 &= i(\hat{A}_y^\dagger \hat{A}_x - \hat{A}_x^\dagger \hat{A}_y)\end{aligned}$$

These operators obey the commutation relations  $[\hat{S}_0, \hat{S}_i] = 0$  and  $[\hat{S}_i, \hat{S}_j] = \epsilon_{ijk} 2i\hat{S}_k$  ( $i = 1, 2, 3$ ).

Their spectral noise densities satisfy uncertainty relations  $V_{\hat{S}_i}(\omega)V_{\hat{S}_j}(\omega) \geq |\epsilon_{ijk}\langle \hat{S}_k \rangle|^2$ . In our case the light is linearly polarized along the  $x$ -axis, then  $\langle \hat{S}_0 \rangle = \langle \hat{S}_1 \rangle = \alpha_x^2$  and  $\langle \hat{S}_2 \rangle = \langle \hat{S}_3 \rangle = 0$ , where  $\langle \hat{A}_x \rangle = \alpha_x$  is chosen real. Then the only non trivial Heisenberg inequality is  $V_{\hat{S}_2}(\omega)V_{\hat{S}_3}(\omega) \geq \alpha_x^4$ . *Polarization squeezing* is then achieved if  $V_{\hat{S}_2}$  or  $V_{\hat{S}_3}$  is below the coherent state value  $\alpha_x^2$ . The fluctuations of  $\hat{S}_2$  and  $\hat{S}_3$  are related to the fluctuations of the quadratures of the vacuum orthogonal mode

$$\delta\hat{S}_2 = \alpha_x(\delta\hat{A}_y^\dagger + \delta\hat{A}_y), \quad \delta\hat{S}_3 = i\alpha_x(\delta\hat{A}_y^\dagger - \delta\hat{A}_y) \quad (2)$$

The physical meaning of the Stokes parameters fluctuations is the following: the  $\delta\hat{S}_2$  fluctuations lead to a geometric jitter of the polarization axis, whereas the  $\delta\hat{S}_3$  fluctuations are linked to ellipticity fluctuations. It can be seen from Eq. (2) that these fluctuations are related to the amplitude and phase fluctuations of  $\hat{A}_y$ . Therefore polarization squeezing is equivalent to vacuum squeezing on the orthogonal mode.

The measurement of the Stokes parameters can be carried out directly by means of two balanced photodiodes and suitable combinations of half-wave and quarter-wave plates [12]. In our set-up, however, the power of the probe beam interacting with the atoms ( $\sim 10\mu\text{W}$ ) is not sufficient, so that we need a LO for the detection. The fluctuations of the vacuum mode  $\hat{A}_y$  are measured using the homodyne detection described above. Following Eq. (2) the photocurrent can be expressed in terms of the fluctuations of  $\hat{S}_2$  and  $\hat{S}_3$ :

$$\delta i_{hd} \propto \cos\theta_{hd}\delta\hat{S}_2 + \sin\theta_{hd}\delta\hat{S}_3 \equiv \delta\hat{S}_{\theta_{hd}} \quad (3)$$

where  $\theta_{hd}$  is the relative phase between the LO and the mean field. As  $\theta_{hd}$  is varied in time, we correspondingly detect the fluctuations of the Stokes parameter  $\hat{S}_{\theta_{hd}}$ . For instance,  $\theta_{hd} = 0$  (respectively  $\pi/2$ ) corresponds to the detection of the fluctuations of  $\hat{S}_2$  (respectively of  $\hat{S}_3$ ). Hence, in the experiment we can get the Stokes parameters simply by simultaneously measuring the relative phase  $\theta_{hd}$  and the quadrature noise of the vacuum mode. This measurement is readily performed by setting the half-wave plate before PBS2 in such a way that the  $\hat{A}_y$  mode is sent to the homodyne detection; the mean field  $\hat{A}_x$  goes through the other port of the beam splitter and is detected together with a portion of the LO by a photodiode (see Fig. 1). The phase is determined via the interference signal between LO and  $\hat{A}_x$  ( $i_\theta \propto \cos\theta_{hd}$ ). The two signals  $i_\theta$  and  $\delta i_{hd}$  are sent to the XY channel of the oscilloscope, giving the characteristic curves reported below.

In Fig. 5 the normalized quadrature noise of  $\hat{A}_y$ , obtained at a noise frequency of 3 MHz, is plotted

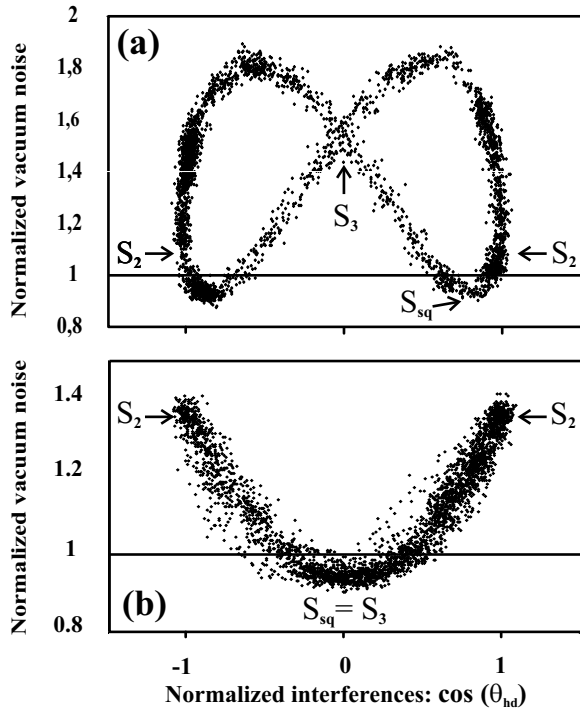


FIG. 5: Normalized quadrature noise at 3 MHz for the vacuum mode  $\hat{A}_y$  vs the normalized interference signal:  $\cos \theta_{hd}$ . The general case is shown in curve (a): polarization squeezing is achieved when  $\theta_{hd} = \theta_{sq} = \pm 30^\circ$ : a linear combination of  $\hat{S}_2$  and  $\hat{S}_3$  is squeezed. In curve (b),  $\hat{S}_3$  is squeezed ( $\theta_{sq} = \pm \pi/2$ ).

as a function of the relative phase between the mean field and the LO. In agreement with Eq. (3), it can be seen that the noise of  $\hat{S}_2$  is given by the extreme points  $\theta_{hd} = 0, \pm\pi$  on the diagram and that of  $\hat{S}_3$  by the center point  $\theta_{hd} = \pm\pi/2$ . In general, for an arbitrary squeezed quadrature, a linear combination of  $\hat{S}_2$  and  $\hat{S}_3$  is squeezed (Fig. 5a). We find that the polarization squeezing strongly depends on the operating point and on the noise frequency. For instance, in Fig. 5b, we see that  $\hat{S}_3$  is squeezed.

To conclude, we have demonstrated that the nearly resonant interaction of a linearly polarized laser beam with a cloud of cold atoms in an optical cavity can pro-

duce quadrature squeezing on the mean field mode *and* on the orthogonally polarized vacuum mode. We have shown that these results can be interpreted as polarization squeezing and developed a method to measure the quantum Stokes parameters for weak beams, using a local oscillator and a standard homodyne detection.

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