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We report on the study of the noise properties of laser light propagating through a cold ^{87}Rb atomic sample held in a magneto-optical trap. The laser is tuned around the $F_g = 2 \rightarrow F_e = 1$, 2 D_1 transitions of ^{87}Rb. We observe quadrature-dependent noise in the light signal, an indication that it may be possible to produce squeezed states of light. We measure the minimum and maximum phase-dependent noise as a function of detuning and compare these results to theoretical predictions to explore the best conditions for light squeezing using cold atomic Rb.

Keywords: quantum fluctuations; squeezed states; polarization self-rotation; atomic noise

1. Introduction

The electromagnetic wave quantum operator is described in terms of two quadrature operators $X_+ = \frac{1}{2}(a^\dagger + a)$ and $X_- = \frac{i}{2}(a^\dagger - a)$ [1,2]. The Heisenberg uncertainty principle sets the limit on how small the fluctuations of these quadratures can be: $\Delta X_+ \Delta X_- \geq 1/4$. The case when $\Delta X_+ = \Delta X_- = 1/2$ is called the standard quantum limit (SQL), or shot-noise limit. Coherent states (typically generated by lasers) and the vacuum are well known examples of field states where the SQL is achieved. There is currently much effort to reduce the measurement noise below this limit with so-called 'squeezed' states of light, where the quantum fluctuations of one of the quadratures is reduced to below the SQL [2].

The applications of squeezed states extend well beyond precision measurements; they were recently studied as a carrier and probe for a quantum memory based on atomic ensembles [3–5]. One of the difficulties for these studies is the lack of a strong squeezing source at atomic transition frequencies. While nonlinear crystal-based squeezers can generate an impressive 11 dB of squeezing at 1064 nm [6], they fail to deliver high amounts of squeezing at shorter wavelengths, since the crystal windows of transparency lie at higher wavelengths. So far, the record value of squeezing at 795 nm is 5 db [7].

An alternative way of generating squeezed states based on the polarization self-rotation (PSR) effect [8–12] was suggested in [13]. PSR is a nonlinear optical effect observed when elliptically polarized light, with wavelength tuned near an atomic transition, experiences a rotation of its polarization ellipse while propagating through an atomic medium. Since the intensity of the left and right circular polarization components are different in elliptically polarized light, this leads to unequal AC-Stark shifts and optical pumping of the different atomic Zeeman sublevels resulting in circular birefringence. Phase differences in the propagation of the two circular components of the light result in the polarization ellipse rotation [9,14]. Unlike the Faraday effect, PSR is observed at zero magnetic field.

Several research groups [15–20] have explored the generation of squeezing using the PSR effect in hot Rb vapor. In all of these cases, the amount of squeezing was about 1 dB below the SQL, which is smaller than the original prediction of Matsko in [13]. This is attributed to excess atomic noise and an inefficient light–atom interaction due to Doppler broadening in the hot Rb vapor samples used in the experiments.

Several groups have suggested that in a cold atomic cloud, the PSR effect will yield higher squeezing through the reduced thermal motion of the interacting atoms [17,18]. Our group has recently reported the study of the PSR effect in a cold ^{87}Rb cloud held in a magneto-optical trap (MOT) [21].

In this paper we report on our theoretical and experimental studies of the light quantum noise modification under conditions of PSR in an ultracold ^{87}Rb cloud. In the following sections, we first review our theoretical approach, and some results. This is followed by description of the experimental apparatus and details pertinent to the measurements.

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After presentation and discussion of the results, we close with a summary and brief perspective on application of the PSR effect in an ultracold gas to generate squeezed states of light.

2. Polarization self-rotation squeezing theory

According to the original PSR squeezing theory [13], linearly polarized light slightly detuned from a transition resonance of an atom generates a squeezed vacuum in the polarization orthogonal to that of the incident light as it propagates through the atomic medium. The amount of squeezing is expected to increase in proportion to the PSR effect. However, it was quickly understood that the original treatment, based on the nonlinear susceptibility of the atomic medium, is too simplistic since it does not account for the excess noise introduced by the atoms. Although atomic absorption, which degrades the squeezing, was phenomenologically taken into account, sources of excess noise, such as amplified spontaneous emission, were not considered [18]. However, excess noise is present in all experimental observation of PSR squeezing [15–17,20]. Under some experimental conditions, it dominates the light fluctuations and observation of squeezing becomes impossible [18].

To properly describe the light fluctuations after interaction with the atomic sample, the quantum fluctuations of the atomic operators need to be incorporated into the treatment. This can be achieved via the Heisenberg–Langevin equations that incorporate the atomic fluctuations through the use of stochastic forces. Such an approach for the description of PSR vacuum squeezing was first attempted in [18] on a model four-level scheme and in [19] for a two-level system including the complete Zeeman degeneracy. The first successful numerical modeling of an experimental observation of PSR squeezing was reported in [17]. There, it was shown that the complete excited state hyperfine structure plays an essential role in the determination of the noise properties of the light. In the present work we have used the numerical treatment used in [17] applied to an ensemble of cold atoms. The details of this calculations can be found in [19]. We briefly remind the reader of the essential ingredients.

Since in our experiment the probe laser is scanned in the vicinity of the $F_g=2\rightarrow F_e=1,2$ transitions of the ^{87}Rb D_1 line (see Figure 1), we have taken into account both relevant upper hyperfine states of ^{87}Rb ($F_e=1, 2$). The ground level $F_g=1$ was neglected since it is detuned by 6.8 GHz from the transition of interest. The complete Zeeman structure of all three levels is considered. The decay rate of the upper states is Γ

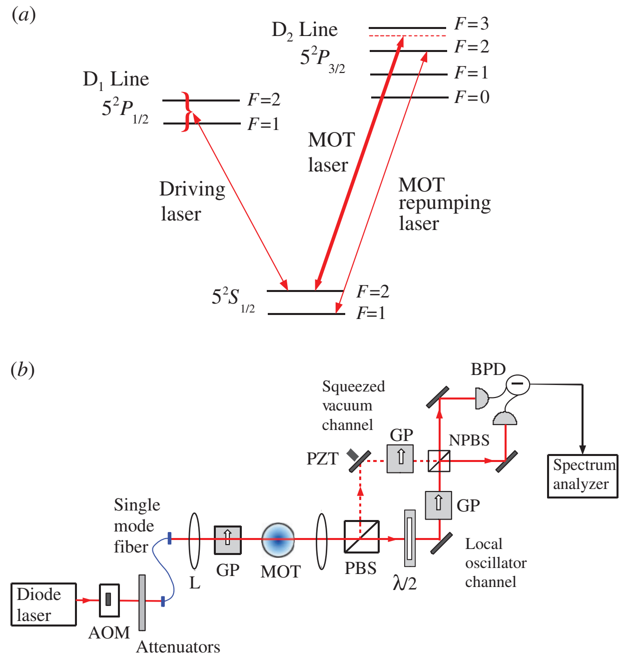

Figure 1. (a) Relevant laser fields on transition diagram showing D_1 and D_2 ^{87}Rb lines. (b) Schematic diagram of the experimental setup. (The color version of this figure is included in the online version of the journal.)

($\Gamma=2\pi\times 6\,\mathrm{MHz}$) and the overall phenomenological decay rate for atomic coherences and populations is γ ($\gamma\ll\Gamma$). The ambient static and spatially uniform magnetic field is B. The incident linearly polarized driving field, assumed to be in a coherent state, has a Rabi frequency $\Omega=\mu E/\hbar$ where E is the strength of the probe light electric field and μ the reduced dipole moment matrix element for the $5S_{1/2}\rightarrow 5P_{1/2}$ D_1 transition. The atomic medium is characterized by its 'cooperativity' parameter $C\equiv\frac{\eta L\omega\mu^2}{2\varepsilon_0\Gamma c\hbar}$ where η is the atomic density, L the medium length. We note that the cooperativity parameter is equal to 1/4 of the reduced resonant optical density of the medium.

The Heisenberg–Langevin equations for atoms and fields are numerically solved at steady state. For this, the loss of atoms at rate γ is compensated by source terms representing the arrival of fresh atoms isotropically distributed in the ground state Zeeman sublevels. As a consequence, the parameter γ governs, at the same time, the decay of coherence (in the absence of light) and the arrival of fresh atoms into the system.

The results of our numerical calculations are presented in Figure 2. The dependence of the maximum and minimum quadrature noise levels in the output field polarization component perpendicular to that of the incident driving field is shown as a function of the driving laser detuning from the $F_g=2\rightarrow F_e=1$ transition. Results for different values of C and γ are

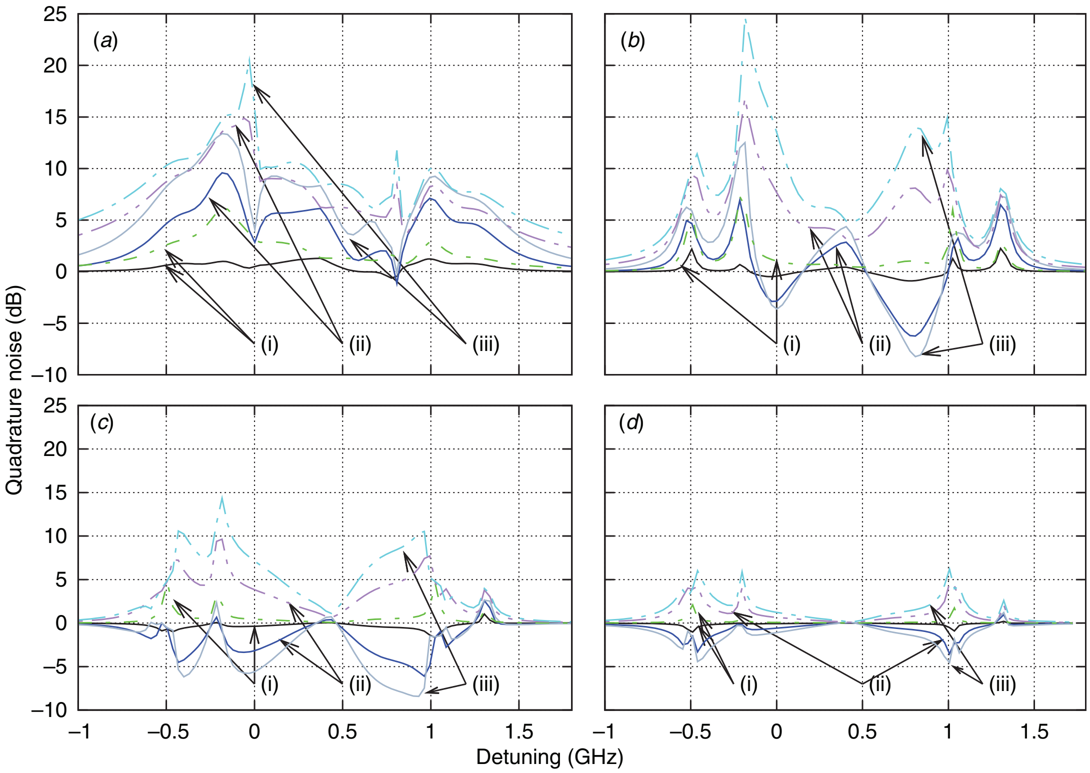

Figure 2. Phase-dependent noise versus detuning for different cooperativity parameters and decay rates. For a given cooperativity parameter, the solid (dashed) line corresponds to the minimum (maximum) noise level. Parameters are $\gamma = 10^{-1}\Gamma$ (*a*), $\gamma = 10^{-2}\Gamma$ (*b*), $\gamma = 10^{-3}\Gamma$ (*c*), and $\gamma = 10^{-4}\Gamma$ (*d*); (i) C = 100, (ii) C = 900, (iii) C = 1700; $\Omega = 30\Gamma$, $B = 0$ in all cases. (The color version of this figure is included in the online version of the journal.)

presented. It can be seen that the level of squeezing as well as the contrast (difference between maximum and minimum quadrature noise) grows with increased cooperativity parameter (optical density). The contrast diminishes as the laser detuning increases. As expected, the noise approaches the SQL noise level for both quadratures for a very far detuned laser since in this case the light does not interact with the atoms. Interestingly enough, there is an optimum in the transient decay rate ($\gamma \sim 10^{-2}$), which gives the highest amount of noise suppression below the SQL. This may seem counter-intuitive since it is generally believed that PSR squeezing is due to coherent effects and should increase for longer ground state coherence times. However, the ground state coherence time also depends on light intensity through the off-resonance optical pumping rate $\alpha \sim \frac{\Omega^2\Gamma}{\Delta^2}$ (Δ is the excited states hyperfine levels separation). Only when $\gamma \geq \alpha$, will the decoherence mechanisms represented by γ limit the squeezing efficiency. On the other hand, increasing values of γ correspond to larger number of 'fresh' atoms participating in the nonlinear interaction process resulting in larger modifications of the light fluctuations.

In the following section we compare our experimental data with the results of the numerical predictions.

3. Experimental arrangement

A schematic diagram of the experimental apparatus is shown in Figure 1(*b*). In order to reduce the thermal energy of the atoms, we use a standard six-beam magneto optical trap (MOT), which is described in detail in [22]. An external cavity diode laser, with a total power of ≈20 mW, detuned 18 MHz below the $F_g = 2 \rightarrow F_e = 3$ ^{87}Rb D_2 hyperfine transition is used to create the trapping beams. A weaker repumping laser, with a total power of ≈3 mW, is tuned to the $F_g = 1 \rightarrow F_e = 2$ D_2 transition, maintaining most of the atomic population in the $5^2S_{1/2}$ $F = 2$ ground state. See Figure 1(*a*) for a schematic diagram of the atomic energy levels and the applied laser fields. Absorption imaging of the atomic cloud shows that the MOT holds about 7×10^7 ^{87}Rb atoms in a spherical cloud with a Gaussian distribution, with Gaussian radius of about 0.5 mm. Ballistic expansion measurements indicate that the atoms are held at an average temperature of 300 μK and when the trapping lasers are turned off, the cloud expands at a rate of 200 $\frac{\mu m}{ms}$. The trap magnetic field gradient has a typical value of 5 G/cm. The sample has a peak density of about 7×10^9 atoms/cm^3 giving an optical depth on the order of 2 for the driving laser transition.

Our linearly polarized driving laser, with variable output power ($\mu W - 10$ mW), was tuned around the $F_g = 2 \to F_e = 1, 2$ transitions. Our previous study showed that if the MOT lasers are off, the typical lifetime of an atom in the beam is less then a millisecond (especially near resonance) due to the light pressure [21] exerted by the driving beam. Since we wanted to perform continuous squeezing experiments, we keep the MOT lasers on to continuously repopulate the cloud with Rb atoms. The presence of the MOT trapping beam helps to maintain the atomic cloud centered on the zero of the magnetic field. In previous observations, where the trapping beams were turned off, we could observe that light pressure and cloud expansion resulted in a non-zero average magnetic field of the order of $B = 10^{-5}$ Tesla [21].

The driving laser light travels through a single mode fiber to achieve a spatially clean Gaussian beam, and then passes through a Glan polarizer (GP) to enforce a linear polarization of the driving beam. We use a pair of lenses (L) to focus the driving laser in the interaction region to a beam diameter of around 250 μm (1/e intensity level). The Rb cloud is larger than the beam diameter and serves as a reservoir of cold atoms during the experiment. We then separate the linearly polarized strong driving field from the squeezed vacuum with a polarizing beamsplitter (PBS). The strong port is attenuated to 100 μW and serves as a local oscillator (LO) in the custom-made balanced homodyne detector (BPD). The LO field is rotated by an extra 90° with a half-wave plate in order to match the polarization of the vacuum channel. The vacuum channel and LO fields pass through Glan polarizers in order to improve the extinction ratio of the PBS, and are finally mixed on a non-polarizing beamsplitter (NPBS). The beamsplitter outputs are directed to two matched photodiodes (Hamamatsu S5106), each having a 93% quantum efficiency, where the two photocurrents are electronically subtracted. We analyze the remaining noise with a spectrum analyzer at 1.4 MHz with a resolution bandwidth (RBW) of 100 kHz. The overall mode matching of the vacuum channel to the LO mode is checked via observation of the interference fringes with visibility higher than 95%. The vacuum channel has a piezo-ceramic transducer (PZT) attached to one of the mirrors. This allows us to sweep the relative phase between the LO and vacuum channel, and consequently to measure the noise in the different quadrature projections. Figure 3 shows examples of such a sweep. The 0 dB noise level corresponds to the shot noise, which we determine by introducing a solid block into the vacuum channel. Noise below 0 dB indicates squeezing. We note that overall stability of the shot noise level is about ±0.02 dB, which is governed by the fluctuations of the LO power and stability of the spectrum analyzer.

4. Experimental results

Owing to the relatively small number of atoms (≈10^5) interacting with the PSR driving beam, the overall noise contrast is below 0.8 dB (see Figure 3(a), for the highest contrast case), which is significantly smaller in comparison with the PSR squeezing contrast typically observed in hot Rb cells. It is important to note in this comparison that the number of interacting atoms in

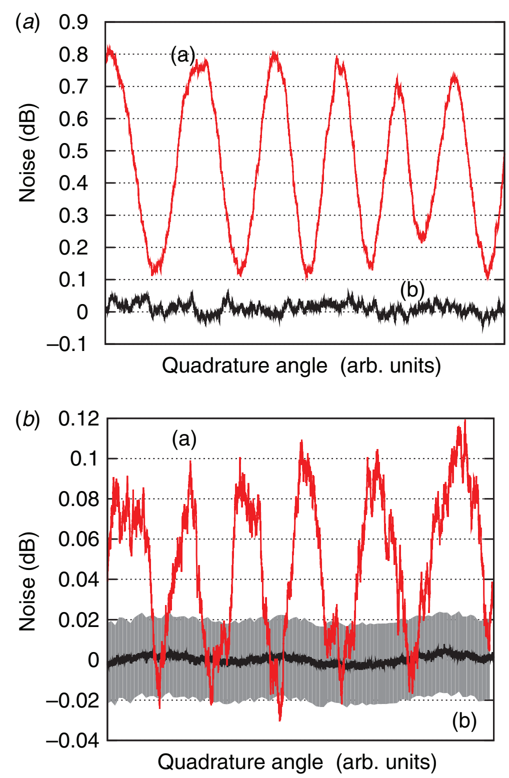

Figure 3. (a) Typical noise power dependence in the squeezed channel versus the quadrature angle. Phase-dependent excess noise: Laser power = 1.3 mW, Detuning = −200 MHz. (b) Experimental data with the highest observed degree of squeezing. Laser power = 6 mW, Detuning = −220 MHz; (a) modified quantum noise in the vacuum channel; (b) shot-noise level (shown with uncertainty band in lower panel). These noise traces are measured at 1.4 MHz central frequency of the SA, RBW = 100 kHz, and are averaged over 512 traces. (The color version of this figure is included in the online version of the journal.)

the hot cell is approximately one thousand times higher. The experimentally observed optical density is only around 2, which is far from the high cooperativity parameters required to achieve the significant noise contrast presented in Figure 2.

In order to record the minimum and maximum noise level dependence on the driving laser detuning, we set our laser to a given detuning (controlled with a commercial wave meter with 10 MHz accuracy), and recorded noise versus the quadrature angle dependence similar to that shown in Figure 3. On such a trace, we note the maximum and minimum noise levels, which provide two data points for each detuning shown in Figure 4(*a*), (*b*) and (*c*). Note that at detunings exactly matching the atomic transitions (0 and 815 MHz), we have zero noise contrast and the overall noise level drops to shot noise. We attribute this to the strong light pressure of the driving beam on the atoms at frequencies very close to the transitions, which blows away the atomic cloud. We take such contrast measurements versus detuning spectra at several driving laser powers and see that contrast initially grows with power since the nonlinear PSR interaction increases with laser power, but then the contrast decreases owing to a stronger effect of light pushing the atoms away from the interaction region with increased power. We also note that the highest contrast position moves away from the transition frequencies with increasing power (more negative for $F_g = 2 \rightarrow F_e = 1$ transition, and positive for $F_g = 2 \rightarrow F_e = 2$) due to power broadening of the transition resonance. This effect is often seen in the PSR squeezing with hot Rb [20]. The theoretical predictions of the noise spectra match the shapes of the experimental traces quite well, as shown in Figure 4(*d*). In this simulation, we have considered a typical value of the light intensity (which is not uniform in the atomic sample) and taken $\gamma = 0.1\Gamma$ and $B = 0$. The relatively large value of γ was chosen to account for the fact that the atomic ground state coherence is strongly perturbed by the MOT trapping and repumping beams. The ambient magnetic field in the MOT region is known from [21] to be on the order of $B = 0.01\Gamma$ (in units of the corresponding Zeeman frequency shift). Since $B \ll \gamma$ the magnetic field influence is negligible and the zero magnetic field approximation is justified.

5. Summary and outlook

We have observed overall quantum noise modification via the PSR effect in an ultracold ^{87}Rb atomic medium,

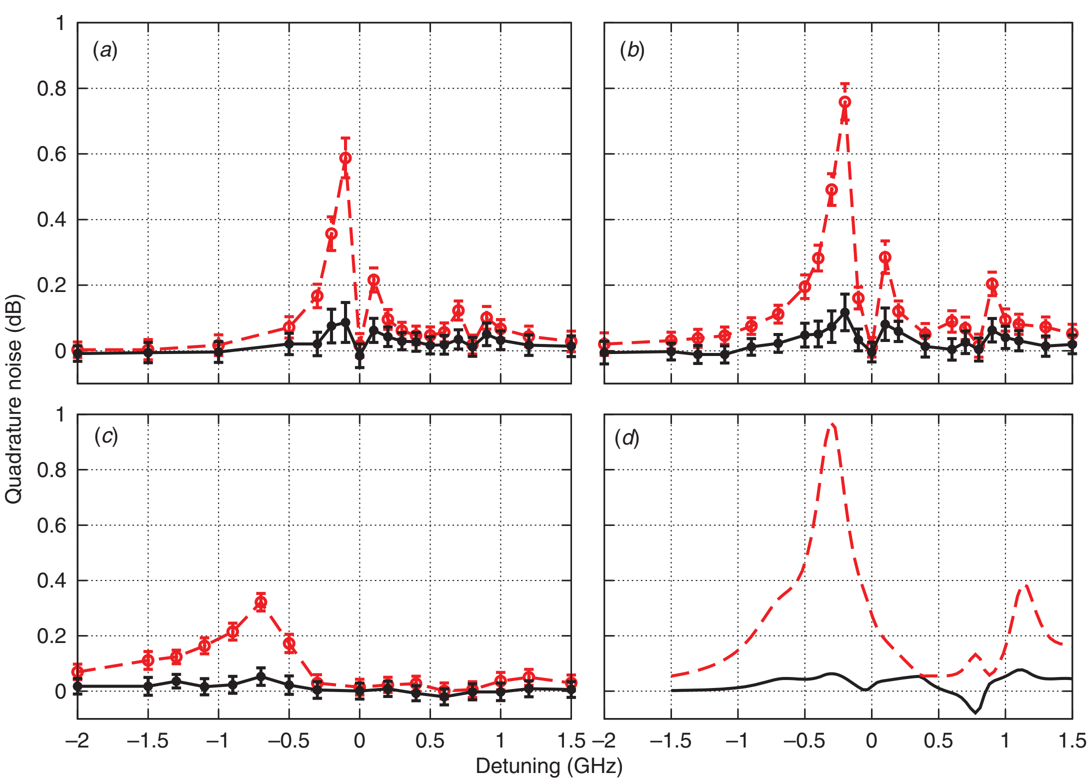

Figure 4. Results of the experiment ((*a*), (*b*), and (*c*)) and numerical simulations (*d*) for minimum (solid line) and maximum (dashed line) noise levels dependence on the PSR driving laser detuning for different PSR driving laser powers. (*a*) Laser power 0.47 mW; (*b*) 1.3 mW; (*c*) 7.5 mW. Parameters for numerical simulation; (*d*) power = 10 mW, beam cross-section 10^{-3} cm^2, $\gamma = 0.1\Gamma$, C = 10, $B = 0$. (The color version of this figure is included in the online version of the journal.)

which is in a good agreement with our numerical simulations.

We do not have compelling results showing squeezing below the SQL. Our results are limited by the levels of excess noise, which are relatively small and the predicted squeezing is on the order of a tenth of a dB, at the limit of our current resolution. We do however see clear phase-dependent excess noise and, depending on conditions, several points where the minimum noise level is very near shot noise and may be squeezed (see Figure 3(*b*), and traces in Figure 4(*b*) and 4(*c*)). We attribute the lack of obvious squeezing to a low number of atoms interacting with the PSR driving beam in our current cold atom arrangement. We believe that an instrument with a higher optical density will result in stronger squeezing with noise below the SQL, as predicted by our numerical simulations. Such cold atom instruments are well within the experimental reach of the current state of technology; for instance, it is possible to have a large magneto optical trap with up to 10^{10} atoms [23], or to create an asymmetric cigar-shaped MOT so that the longer dimension can be aligned with the PSR driving beam [24,25], thus achieving quite a substantial optical depth and a considerably higher number of interacting atoms.

With these improvements and more studies, we believe that generation of a squeezed vacuum with higher levels of noise suppression than seen in hot vapor cells is achievable using PSR in cold atoms.

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