

Stroboscopic back-action evasion in a dense alkali-metal vapor.

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We explore experimentally quantum non-demolition (QND) measurements of atomic spin in a hot potassium vapor in the presence of spin-exchange relaxation. We demonstrate a new technique for back-action evasion by stroboscopic modulation of the probe light. With this technique we study spin noise as a function of polarization for atoms with spin greater than $1/2$ and obtain good agreement with a simple theoretical model. We point that in a system with fast spin-exchange, where the spin relaxation rate is changing with time, it is possible to improve the long-term sensitivity of atomic magnetometry by using QND measurements.

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Quantum non-demolition (QND) measurements form the basis of many quantum metrology schemes [1–3]. A QND measurement can drive the system into a squeezed state conditioned on the measurement result. In this state the uncertainty of the measured variable is reduced below the standard quantum limit (SQL) at the expense of an increase in the uncertainty of the conjugate variable. A key ingredient in QND measurements is a back-action evasion mechanism that decouples the measured variable from the quantum noise of the probe field.

Here we explore a new back-action evasion scheme in a dense alkali metal vapor in a finite magnetic field. A QND measurement of an atomic spin component can be made by Faraday paramagnetic rotation of off-resonant probe light [4]. By stroboscopically pulsing the probe light at twice the frequency of Larmor spin precession, we achieve back-action evasion on one of the spin components in the rotating frame, while directing the quantum noise of the probe beam to the conjugate rotating component. The stroboscopic modulation of the probe was first suggested in the context of mechanical oscillators [5]. In atomic systems with non-zero Larmor frequency only more complicated schemes involving two oppositely polarized vapor cells have been realized to achieve back-action evasion [6].

The QND measurements in a dense alkali-metal vapor allow us to study atomic spin noise in the presence of various relaxation mechanisms. The behavior of collective spin in the presence of decoherence is not trivial [7–9]. We quantitatively measure spin noise as a function of atomic polarization for K atoms ($I = 3/2$) with spin-exchange, light scattering, and spatial diffusion as the dominant sources of relaxation and obtain good agreement with a simple model for quantum fluctuations.

Although QND measurements have been shown to increase the measurement bandwidth without loss of sensitivity [10, 11], it has been known for some time that spin squeezing in the presence of a constant decoherence rate does not significantly improve long-term measurement sensitivity [12, 13]. We point out that spin-exchange collisions, which are the dominant source of relaxation

in a dense alkali vapor, cause non-linear evolution of the atomic density matrix with a relaxation rate that changes in time. Under these conditions we show theoretically that QND measurements can, in fact, improve the long-term sensitivity of atomic magnetometers.

The experimental setup is shown in Fig. 1. The atomic vapor is contained in a cylindrical, D-shaped glass cell, orientated in such a way that the probe beam goes through the long, 55 mm in length, dimension. We use a mixture of potassium in natural abundance, 50 Torr of N_2 buffer gas for quenching and 400 Torr of 4He to slow down the diffusion of alkali atoms. The cell is heated in an oven with flowing hot air, and is placed inside a double layer μ -metal and a single-layer aluminum shield. A low noise current source generates a homogeneous DC magnetic field in the \hat{z} -direction, corresponding to a Larmor frequency of 150 kHz for K atoms. First order gradients of this field along the direction of the probe beam are canceled with the use of a gradient coil. In order to suppress current source noise and noise pickup of the cables, passive low pass filters are placed inside the shields. Narrow linewidth, amplified DFB lasers for the pump and probe beam are used, and acousto-optic modulators provide fast amplitude modulation of the light. The circularly polarized pump beam creates atomic orientation in the \hat{z} -direction. It is turned off after 10 msec of pumping before probe measurements. The profile of the pump beam is shaped using spherical aberration effects so that the intensity is slightly higher at the edges of cell, where the pumping requirements are higher due to the larger spin-destruction rate from the wall relaxation. A linearly polarized probe beam far detuned from the D1 line of K ($\lambda_{pr} \simeq 770.890$ nm) and propagating along the \hat{x} -direction experiences Faraday paramagnetic rotation which is measured with balanced polarimetry. The signal is digitized with a fast, low noise A/D card and recorded with a computer.

The back-action of the probe originates from the AC Stark shift caused by quantum fluctuations of the circular polarization of the light. For the conditions of our experiment, with large detuning, high buffer gas pressure, and

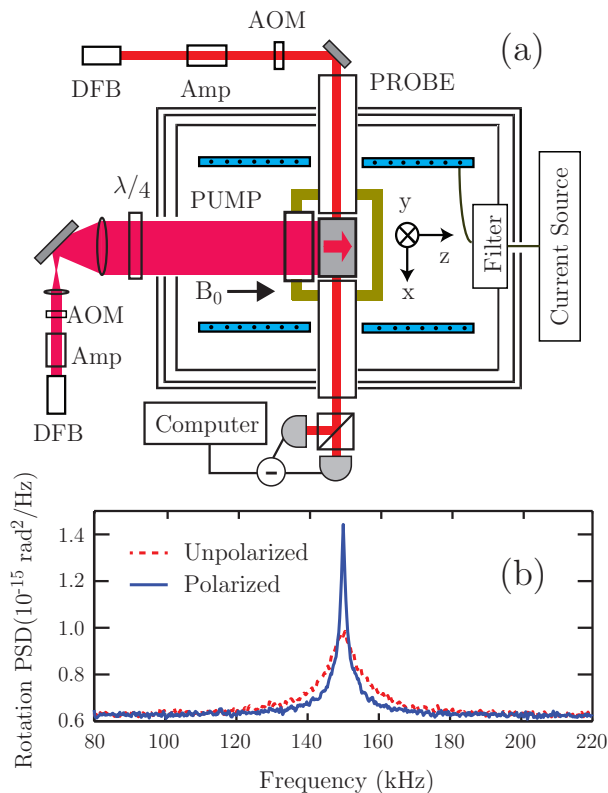


FIG. 1: (color online) (a) Experimental apparatus for QND RF magnetometer. (b) Measured PSD for unpolarized (dashed) and highly polarized atoms (solid). Each curve is the average of 1000 repetitions. Both curves were taken with the same probe intensity and 10% duty cycle. The atomic density was 10^{14} cm^{-3} .

large optical density, the tensor polarizability has a negligible contribution [14, 15]. Then, the light shift noise can be effectively described by a stochastic magnetic field along the direction of the probe beam. During a short measurement of F_x by the probe beam this stochastic magnetic field rotates F_z polarization into the F_y direction, thus ensuring that the product $\Delta F_x \Delta F_y$ satisfies the quantum uncertainty relationship. In the presence of a DC magnetic field in the \hat{z} -direction, the x and y components of the collective spin undergo Larmor precession, so that over timescales larger than the Larmor period both F_x and F_y accumulate the back-action noise. The effect of back-action on the F_x measurement in the rotating frame can be suppressed using stroboscopic probe light that turns on and off at twice the Larmor frequency. This way a measurement is performed only when the squeezed distribution is aligned with the probe axis in the laboratory frame.

The power spectral density (PSD) of a 3.6 msec recording of the polarimeter output is shown in Fig. 1 for both unpolarized and highly polarized atoms. The longitudinal spin polarization does not change significantly on this time scale. The PSD can be described by a sum of

a constant photon shot noise (PSN) background and a Lorentzian-like atomic noise contribution [10]. The deviation from the Lorentzian profile is notable in our experiment due to the effect of diffusion in and out of the probe beam (beam waist $\sim 220 \mu\text{m}$). As the atoms diffuse through the probe beam, the measured collective spin undergoes a random walk with correlation time characteristic of the diffusion timescale. Note that for a coherent spin excitation with an RF field diffusion through the probe beam does not lead to decoherence. This is a manifestation of the general characteristic that entangled states are more fragile. As discussed in [10], the shape of the atomic noise peak does not influence the total optical rotation noise $\text{var}[\phi_{at}]$, given by the area under the PSD curve. For unpolarized atoms this noise area is a good measure of fundamental atomic shot noise (ASN), since it is not affected by light-shift or stray magnetic field noise, and the scattering of photons has an insignificant effect on the quantum noise properties [11]. It provides a good reference for the characterization of the atomic spin noise with polarized atoms. In the fully polarized ensemble the spin-exchange collisions between alkali atoms do not contribute to spin relaxation [16], and the spin noise linewidth is much smaller, as can be seen in Fig. 1.

The back-action evasion of the stroboscopic measurement is demonstrated in Fig. 2. The atomic noise is evaluated by numerical integration of the measured PSD after subtracting the constant PSN background. For polarized atoms, as the strobe frequency departs from the resonance condition of twice the Larmor frequency, light-shift noise is added to the ASN, and the total noise increases until it reaches a maximum plateau. The difference of the maximum and minimum values is a measure of the back-action noise of the probe. In the case of unpolarized atoms, there is no contribution of light-shift to the total noise, which remains independent of the probe modulation frequency at the value of the ASN. The back-action evasion is also observed when the noise is plotted as a function of the duty cycle of the stroboscopic probe. In the inset of Fig. 2 we normalize each point by the corresponding unpolarized ASN and show that the light-shift suppression is stronger for small duty cycle probe pulses.

In Fig. 3 the noise ratio for (partially) polarized to unpolarized atomic ensembles is plotted as a function of the longitudinal polarization for three different densities. The ensemble polarization is found from the optical rotation induced in the probe beam due to a known, small magnetic field in the probe direction ($B_x \ll B_z$), slowly ac modulated to allow for a lock-in detection of the signal. The largest uncertainty in this measurement originates from the determination of the atomic density. For this, we measure the coherent RF resonance curve at low polarization and associate the measured linewidth with the spin-exchange rate between alkali atoms [17]. At large values the ensemble polarization can also be directly estimated from the transverse relaxation rate [16]. The two

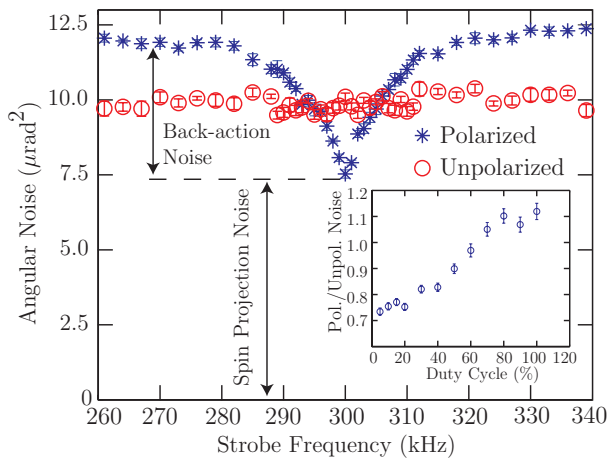


FIG. 2: (color online) Measurement of spin variance for unpolarized and polarized ($P \approx 85\%$) atomic ensembles as a function of stroboscopic frequency. The Larmor frequency is 150 kHz. While for the unpolarized case the noise does not depend on the frequency, for polarized atoms extra light shift noise appears at detunings from the resonant condition. The data were taken using a probe with 10% duty cycle. Inset: Ratio of polarized to unpolarized noise (not including PSN) as a function of the duty cycle of the strobe light. All data points were acquired with the same average intensity.

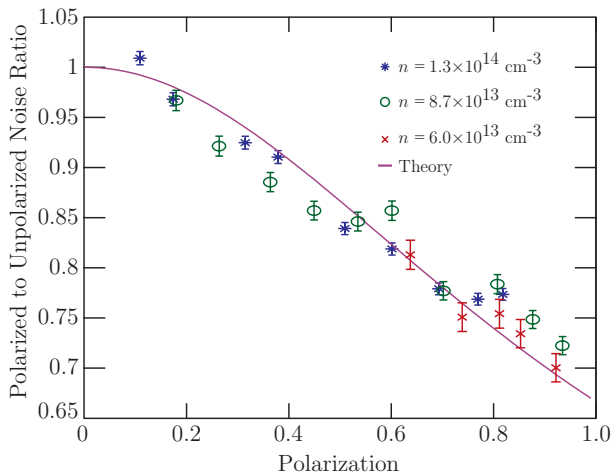


FIG. 3: (color online) Ratio of polarized to unpolarized ASN (variance) as function of the mean longitudinal polarization of the ensemble for three different densities. The duty cycle of the probe was 10%.

measurements give similar results for low atomic density, but differ by 10% at the highest density. We believe this discrepancy results from a nonuniform polarization profile of the atomic ensemble, which becomes more pronounced at high densities due to limited pumping power. Using gradient imaging we have measured and minimized the polarization non-uniformity of the vapor.

The measured noise ratio can be described well with a simple theoretical model. For the conditions of our

experiment the density matrix can be approximated for arbitrary longitudinal polarization P by the spin temperature distribution [18]: $\rho = e^{\beta F_z}/Z$, where Z is the partition function and $\beta = \ln[(1+P)/(1-P)]$. Then, taking into account the two hyperfine manifolds of the alkali-metal atoms [10], the ASN variance of the collective spin composed of N_a atoms can be written:

$$\langle F_x^2 \rangle = \sum_{m=-a}^a \frac{e^{\beta m} [a(a+1) - m^2]}{2N_a Z} + \sum_{m=-b}^b \frac{e^{\beta m} [b(b+1) - m^2]}{2N_a Z} \quad (1)$$

Here, $a = I + 1/2$ and $b = I - 1/2$, with I being the nuclear spin. One can see that in contrast to a spin-1/2 system, for $I = 3/2$ the ASN power is smaller for polarized atoms by a factor of 2/3 compared with unpolarized atoms, in agreement with the experiment. These data address some of the issues raised in [8] regarding collective measurements on partially polarized atomic states. They also disprove the claim in [7] that correlated spin relaxation due to spin-exchange collisions does not lead to atomic noise.

As can be seen in Fig. 1, the resonance linewidth is significantly reduced for high spin polarization due to suppression of the spin-exchange relaxation. In the time domain this is manifested by a non-exponential decay of the transverse spin polarization, shown in Fig. 4(a). In a highly polarized vapor the initial spin relaxation rate is suppressed. This allows one to improve the overall long-term measurement sensitivity using QND measurements.

To model this behavior quantitatively we consider a measurement scheme using two short pulses of probe light [19]. The first pulse is applied immediately after turn-off of the pump beam and the second after a measurement time t_m . The best measurement of the magnetic field is obtained using an estimate $S_x(t_m) - S_x(0) \text{cov}[S_x(0), S_x(t_m)] / \text{var}[S_x(0)]$, where $S_x(0)$ and $S_x(t_m)$ are measurements of spin projection from the two probe pulses. For simplicity we consider a spin-1/2 system here. One can show that $\text{var}[S_x] = (1 + 1/\epsilon \text{OD}) N_A / 4$, where ϵ is the strength of a far-detuned probe pulse, given by the product of pulse duration and photon scattering rate, OD is the optical density on resonance, and N_A is the number of atoms. The covariance of the two measurements is given by (for $t_m > 0$) [20]

$$\text{cov}[S_x(0), S_x(t_m)] = (N_A/4) \exp\left[-\int_0^{t_m} R(t') dt'\right], \quad (2)$$

where $R(t)$ is a time-dependent transverse spin-relaxation rate. In the presence of spin-exchange collisions the relaxation rate can be approximated by $R(t) = R_{sd} + (1 - P_z) R_{se}$ [16]. Using this model we optimize the measurement procedure with respect to the strength of first and second probe pulses and t_m . We assume that the

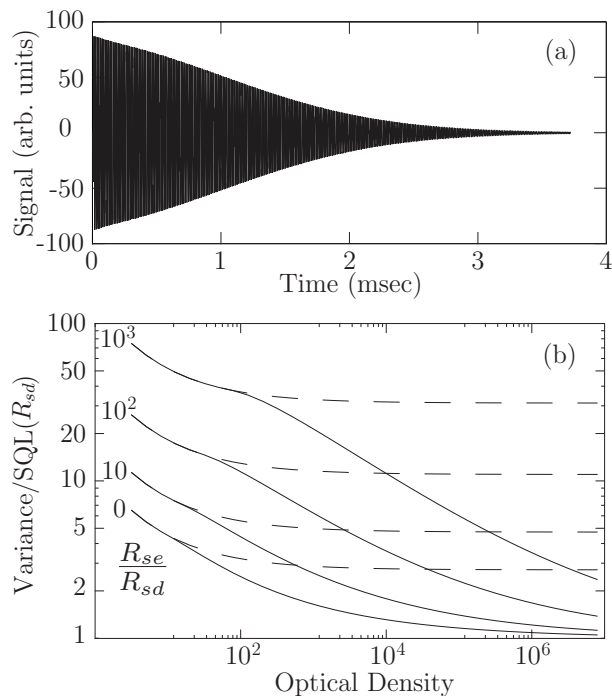


FIG. 4: (a) Experimental measurement of F_x at high density ($n \approx 6 \times 10^{13} \text{ cm}^{-3}$) following a short magnetic field pulse, showing changes in the transverse relaxation rate. For this data the probe beam scattering rate was increased. (b) Calculated variance in the estimate of the magnetic field relative to SQL as a function of the optical density for various spin-exchange rates. Dashed lines – single-pulse measurement, solid-lines – two pulse measurement with spin-squeezing.

initial state preparation time is negligible and the measurement repetition time is equal to t_m . The results of the model are plotted in Fig. 4 for varying spin-exchange rates. For comparison, we also plot the variance of a single-pulse measurement after time t_m , which does not rely on spin-squeezing. The results are scaled relative to the SQL limit for N_A atoms with spin relaxation rate R_{sd} , $\delta B_{SQL}^2 = 2R_{sd}/(N_A t \gamma^2)$, where t is the total measurement time and γ is the gyromagnetic ratio.

It is instructive to compare our results with those of [12]. In the absence of spin-squeezing and spin-exchange relaxation, the smallest possible magnetic field variance is given by $e\delta B_{SQL}^2$, in agreement with [12]. Using the two-pulse measurement one can reduce the variance by a factor of e , the same factor as obtained in [12] with partially entangled states. In the presence of spin-exchange relaxation, the sensitivity is degraded for the one-pulse scheme, but reaches the same δB_{SQL}^2 using two pulses. Therefore, QND techniques can eliminate the effects of spin-exchange relaxation, but cannot significantly exceed the sensitivity corresponding to a constant relaxation rate. These results also apply to hyperfine transitions which are broadened by spin-exchange [21], and, more generally, to other relaxation effects due to non-linear interactions, such as solid-state dipolar spin coupling [22].

In summary, we have explored quantum non-demolition measurements of collective spin in a dense alkali-metal vapor. We demonstrated a new stroboscopic technique for back-action evasion and used it to measure atomic spin noise as a function of spin polarization in the presence of several spin-relaxation mechanisms. We considered QND measurements in a system with non-linear spin relaxation and showed theoretically that they can improve the long-term sensitivity in atomic spectroscopy. This work was supported by NSF and ONR MURI.

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