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Jonathan Kohler, Nicolas Spethmann, Sydney Schreppler, and Dan M. Stamper-Kurn

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Cavity-assisted measurement and coherent control of collective atomic spin oscillators

Jonathan Kohler,^{1,*} Nicolas Spethmann,^{1,2} Sydney Schreppler,¹ and Dan M. Stamper-Kurn^{1,3,†}

¹*Department of Physics, University of California, Berkeley, CA 94720, USA*

²*Department of Physics and Research Center OPTIMAS,*

Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

³*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

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We demonstrate continuous measurement and coherent control of the collective spin of an atomic ensemble undergoing Larmor precession in a high-finesse optical cavity. The coupling of the precessing spin to the cavity field yields phenomena similar to those observed in cavity optomechanics, including cavity amplification, damping, and optical spring shifts. These effects arise from autonomous optical feedback onto the atomic spin dynamics, conditioned by the cavity spectrum. We use this feedback to stabilize the spin in either its high- or low-energy state, where, in equilibrium with measurement back-action heating, it achieves a steady-state temperature, indicated by an asymmetry between the Stokes and anti-Stokes scattering rates. For sufficiently large Larmor frequency, such feedback stabilizes the spin ensemble in a nearly pure quantum state, in spite of continuous measurement by the cavity field.

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Quantum systems are invariably perturbed by measurement. For a repeated or continuous measurement, the measurement back-action perturbing the system generally adds noise to the subsequent measurement record, reducing the precision of state estimation and measurement sensitivity of external forces [1]. However, this additional noise carries useful information about the measurement-induced perturbation, allowing for feedback that suppresses the effects of back-action and controls the evolution of the quantum system [2]. Such feedback may be either measurement-based, where the quantum system is driven externally based on classical information gleaned from quantum measurements [3–8], or autonomous, where feedback is implemented through coherent [9] or dissipative [10–12] dynamics inherent to the system itself.

Atomic spin ensembles in cavity quantum electrodynamic systems have been demonstrated as prototypical examples of quantum measurement and control. Many recent experiments with spin-cavity systems have focused on avoiding back-action to overcome standard quantum limits [13] and to prepare squeezed states for improved metrology through quantum non-demolition [14–18] or back-action evading [19] measurements. Here, we focus instead on continuous weak detection of non-stationary observables in order to study quantum-limited back-action and autonomous stabilization effects using the cavity’s finite lifetime.

In this Letter, we report the observation of back-action effects from weak continuous measurement of the Larmor precession of an atomic spin ensemble within a driven high-finesse optical cavity. By recirculating the light probing the spin ensemble, the cavity allows the optical modulation induced by the precessing spin to act back on the subsequent spin dynamics. The cavity thereby condi-

tions a feedback loop that allows the accumulated noise from measurement back-action to be suppressed and the collective spin to be stabilized near either its lowest- or highest-energy state, chosen by the detuning of the cavity probe light from the cavity resonance. We find that, for sufficiently large Larmor frequency, such a feedback-stabilized spin oscillator remains in a nearly pure quantum state, in spite of continuous interaction with the probe field.

Consider an ensemble of N identical atoms in their electronic ground state, each with spin f . The dimensionless collective spin, $\hat{\mathbf{F}}$, is sensed optically via the circular birefringence of the atoms. Specifically, a beam of circularly polarized light propagating along the \mathbf{z} axis acquires a phase shift proportional to \hat{F}_z , the projection of the collective spin onto the axis of optical angular momentum.

An applied magnetic field \mathbf{B} induces the Hamiltonian $\mathcal{H}_B = -\hbar\gamma\mathbf{B} \cdot \hat{\mathbf{F}}$, where γ is the atomic gyromagnetic ratio. When \mathbf{B} is oriented away from \mathbf{z} – say, along \mathbf{x} (see Fig. 1a) – the light measures oscillations of one transverse spin component, allowing real-time observation of Larmor precession of the collective spin. The light acts back on the precessing spin as an effective magnetic field $\mathbf{B}_{\text{opt}} \parallel \mathbf{z}$, proportional to the probe light intensity. Measurement back-action arises from quantum fluctuations of the light intensity, and, hence, of \mathbf{B}_{opt} . The resulting fluctuations in the torque produced by \mathbf{B}_{opt} affect both the phase of Larmor precession and the energy of the spin ensemble.

Inside a high-finesse cavity, optical fluctuations persist for a finite life-time, allowing them to coherently alter the subsequent spin dynamics. In particular, when the cavity is driven off-resonance, the precessing spin induces amplitude modulation of the probe field. This amplitude

modulation acts back on the precessing spin through the effective magnetic field \mathbf{B}_{opt} , which varies synchronously with the Larmor precession. The finite cavity lifetime leads to a delay between the oscillating spin displacement $\hat{F}_z(t)$ and the modulation of the intra-cavity photon number $\hat{n}(t)$ (Fig. 1b).

The modulation of \mathbf{B}_{opt} has two effects, which become clear when considered in a frame co-rotating with the precessing spin around \mathbf{B} [20]. Under the rotating-wave approximation, the modulation component in-phase with the oscillation of \hat{F}_z generates a net torque tangential to the instantaneous trajectory of the precessing spin (Fig. 1c), shifting the effective Larmor frequency. The out-of-phase component generates an average torque acting perpendicular to this trajectory, causing the atomic spin to nutate toward either the low-energy or the high-energy pole, depending on the sign of the optical modulation. The relative phase between the spin precession and the cavity field modulation is controlled by the probe detuning from cavity resonance Δ_{pc} , and by the ratio of ω_L to the cavity half-linewidth $\kappa = 2\pi \times 1.82$ MHz.

This Letter extends concepts from cavity optomechanics [21] to the cavity-based detection and control of collective spin modes, which was discussed theoretically in Ref. [20], and also recently in terms of solid-state cavity opto-magnonics [22–24]. The autonomous feedback driving the collective spin toward or away from either the low- or high-energy states is analogous to cavity-induced damping [25–28] or amplification [29] of motion. We also observe feedback-induced shifts in the Larmor frequency that correspond to the optical spring effect [30, 31]. Furthermore, similar to experiments in cavity optomechanics [32, 33], we observe asymmetry between sidebands generated by optical Stokes and anti-Stokes processes, allowing us to characterize the effective spin temperature reached by the balance of coherent and incoherent back-action effects.

Our experiments are performed on gases of about $N = 3500$ ^{87}Rb atoms placed within a Fabry-Pérot cavity [34]. The atoms are evaporatively cooled to around $5\ \mu\text{K}$ and trapped within a couple adjacent sites of a $64\ \mu\text{K}$ deep, one-dimensional, spin-independent optical lattice, created by driving a TEM_{00} mode of the cavity with light at a wavelength of $860\ \text{nm}$. A uniform magnetic field \mathbf{B} is applied along \mathbf{x} , transverse to the cavity axis (Fig. 1a), and its magnitude sets the Larmor frequency $\omega_L = |\gamma\mathbf{B}|$, which we vary from $\omega_L/2\pi = 100\ \text{kHz}$ to several MHz. The atoms are prepared initially in the $|f = 2, m_F = +2\rangle$ hyperfine state (with the quantization axis along \mathbf{B}). The collective atomic spin, with total spin $F = 2N \sim 7000$, is thus prepared in its highest energy state, since $\gamma < 0$ for the $f = 2$ hyperfine level of ^{87}Rb . Alternately, the ensemble can be rotated to its lowest-energy spin state by applying a π pulse to the atoms using a radio-frequency magnetic field.

We probe the ensemble through its influence on a dif-

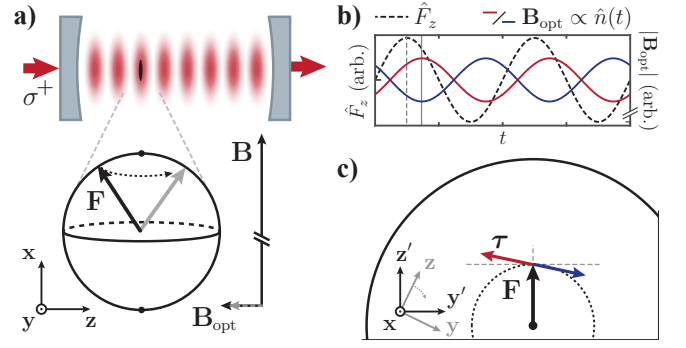


FIG. 1. (color online) (a) Schematic of the experimental system. Atoms trapped at an anti-node of the cavity field experience an effective magnetic field \mathbf{B}_{opt} due to interaction with circularly polarized light. A large external magnetic field \mathbf{B} along \mathbf{x} defines the Larmor frequency ω_L and high- and low-energy stable poles of the dynamics. (b) The oscillating transverse spin component \hat{F}_z couples to the cavity field, causing amplitude modulation for a cavity driven either above (blue) or below (red) resonance. The optical response is delayed due to the finite cavity linewidth κ . (c) The average torque $\boldsymbol{\tau}$ acting on the spin due to this optical feedback, in a rotating frame. The in-phase modulation generates torque tangential to the spin trajectory, shifting the Larmor precession frequency. The out-of-phase component generates torque perpendicular to this trajectory, causing spin nutation toward or away from the poles.

ferent TEM_{00} mode of the cavity, whose resonance frequency ω_c is detuned by $\Delta_{\text{ca}}/2\pi = -42\ \text{GHz}$ from the ^{87}Rb D2 transition (with wavelength $780\ \text{nm}$). At this large detuning, the atom-cavity interaction is predominately dispersive. Because the detuning is also much larger than the excited-state hyperfine splitting, the interaction is dominated by scalar and vector terms, and higher-order tensor interactions are negligible.

The cavity supports modes of two independent polarizations at frequencies near ω_c . Driving the cavity with a weak coherent beam of one circular polarization of light, with helicity along either $\pm\mathbf{z}$, and neglecting the small linear birefringence of our cavity [35], the resulting evolution is described by the effective system Hamiltonian

$$\mathcal{H} = \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_L\hat{F}_x + \frac{\hbar g_0^2}{\Delta_{\text{ca}}}\hat{a}^\dagger\hat{a}(\alpha_0 N \pm \alpha_1 \hat{F}_z), \quad (1)$$

obtained by adiabatically eliminating the atomic excited states. Here, \hat{a} is the creation operator for cavity photons, and the coefficients $\alpha_0 = 2/3$ and $\alpha_1 = 1/6$ describe the relative strength of the scalar and vector parts of the ac Stark shift, determined by summing over all excited-state hyperfine levels. The position-averaged vacuum Rabi coupling $g_0/2\pi = 13\ \text{MHz}$ is evaluated by considering the geometry of the cavity mode [34]. In this work, atoms are trapped near antinodes of the cavity probe field to minimize linear optomechanical effects. The coupling of the cavity field to the environment is further de-

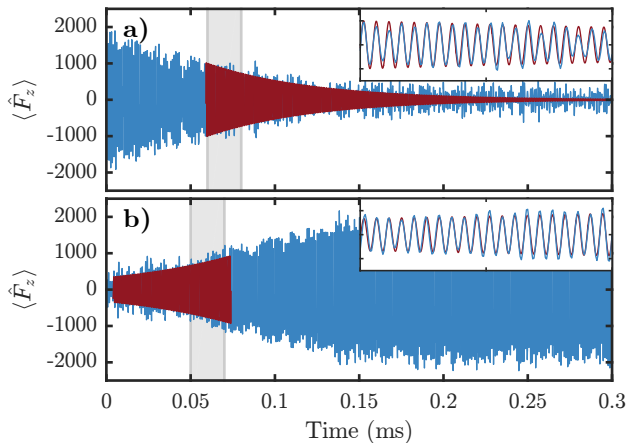


FIG. 2. (color online) Coherent damping and amplification of Larmor precession of a spin ensemble with $\omega_L/2\pi = 1.0$ MHz, observed in the phase modulation of transmitted light, averaged over 30–40 repetitions (blue). Cavity probe light ($\Delta_{pc}/2\pi = 1.0$ MHz, $\bar{n} = 4$ average intracavity photons) drives the spin toward the high-energy pole. (a) Larmor precession of a spin ensemble, displaced from the high-energy pole by a $\pi/10$ rf pulse, coherently damps back to the pole at a rate $\Gamma_{opt}/2\pi = 4.9 \pm 0.2$ kHz. (b) A spin prepared near the low-energy pole, by application of a near π -pulse, is coherently amplified away at a rate $\Gamma_{opt}/2\pi = -4.6 \pm 0.4$ kHz. Exponential rates are extracted by simultaneous fits (red) of both amplitude and phase quadratures. Insets show the harmonic nature of the Larmor precession signal and quality of fit in the highlighted regions. The finite cavity linewidth causes the observed signal to saturate at around 2000.

scribed using the standard input-output formalism, and the modulated probe field transmitted through the cavity is measured with an optical heterodyne detector, with overall cavity photon detection efficiency $\epsilon = 0.12$.

The spin dynamics imprinted on the cavity output field are observed in the demodulated heterodyne signal. For example, in Fig. 2, we compare the evolution of spins prepared near either the high- or low-energy poles when the cavity is driven by a blue-detuned ($\Delta_{pc} > 0$) probe. In both cases, the probe drives the spin toward the high-energy pole. For a spin prepared initially near the high-energy pole, cavity back-action coherently damps the Larmor precession amplitude, analogous to cavity optomechanical cooling. In comparison, the Larmor precession of a spin prepared near the low-energy pole is coherently amplified, analogous to regenerative optomechanical amplification. At longer times (not shown in the Figure), in the latter case, the ensemble's spin nutates past the equator of the Bloch sphere and also damps back to the high-energy pole. If instead we drive the cavity with red-detuned probe light ($\Delta_{pc} < 0$), we observe similar behavior, with the collective spin instead driven toward and stabilized at the low-energy pole.

The light-induced driving of a spin ensemble to either the low- ($\Delta_{pc} < 0$) or high-energy ($\Delta_{pc} > 0$) pole is rem-

iniscent of optical pumping [36]. However, unlike optical pumping, the dynamics in our experiment cannot spontaneously generate spin polarization. In addition, while optical pumping uses circularly polarized light to pump *angular momentum* into an atomic gas, the asymmetric fluctuation spectrum of the cavity optical field is used to pump *energy* into the atomic system. Indeed, we confirm that the dynamics are quantitatively the same for both circular probe polarizations (Fig. 3a-b).

These dynamics may also be described in terms of cavity superradiance [37–41]. Consider an atomic spin ensemble initialized in the low-energy spin state. The optically driven atoms lie in a virtually excited state from which they may decay by Raman scattering into the cavity mode. When the cavity is driven at a positive detuning, the cavity Purcell effect induces Raman emission preferentially on the Stokes sideband, creating transverse

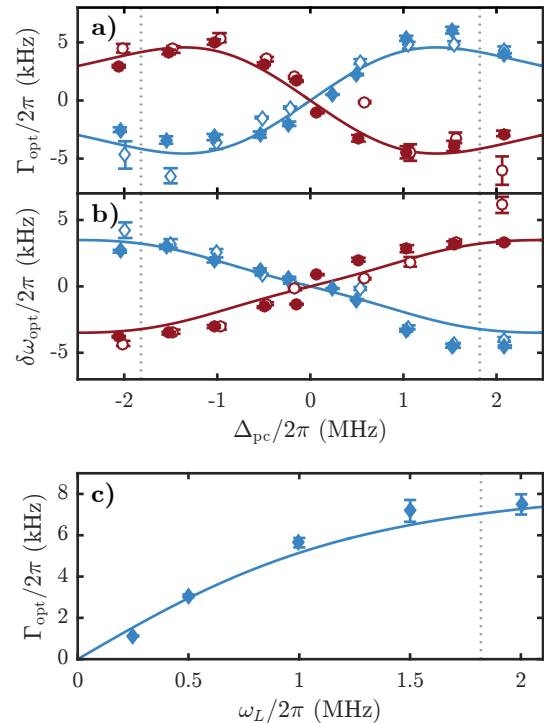


FIG. 3. (color online) (a) Optical damping rates and (b) frequency shifts of Larmor precession as a function of probe detuning Δ_{pc} , with fixed intracavity intensity $\bar{n} = 4$ and $\omega_L/2\pi = 1.0$ MHz. Diamonds (blue) label results for an ensemble initially prepared near the high-energy pole, and circles (red) for an ensemble initially near the low-energy pole. Measurements repeated with either σ^+ (solid symbols) or σ^- (open symbols) circularly polarized light demonstrate independence of optical helicity. (c) Peak damping rate as a function of Larmor frequency. Dotted vertical lines mark the position of the cavity half-linewidth κ . All theory lines are plotted with no free parameters. Error bars reflect statistical uncertainties from the fits. Additional systematic errors in the probe frequency stability and initial spin state preparation predominately affect data at small probe detuning.

coherence in the ensemble. Such coherence stimulates Raman scattering at an enhanced rate, driving the spins exponentially away from the low-energy pole.

A quantitative treatment for the coherent dynamics near both poles can be derived classically, as in the theory of linear cavity optomechanics [21], by neglecting the quantum noise of the cavity field. We find that the inverse susceptibility of the spin oscillator to torque $\tau(\omega)$ at frequency ω is given by $\chi_s^{-1}(\omega) = \omega_L^2 - \omega^2 + \Sigma(\omega)$, with

$$\Sigma(\omega) = 2\beta\bar{n}g_s^2\left(\frac{\omega_L}{\omega - \Delta_{\text{pc}} + i\kappa} - \frac{\omega_L}{\omega + \Delta_{\text{pc}} + i\kappa}\right), \quad (2)$$

where $\beta = \text{sgn}(\hat{F}_x)$ labels the high-energy ($\beta = +1$) or low-energy ($\beta = -1$) state, \bar{n} is the average photon number in the cavity mode, and $g_s = \alpha_1 g_0^2 \sqrt{F/2}/\Delta_{\text{ca}}$ describes the relevant single-photon, single-excitation coupling [20]. The real and imaginary parts of Eq. 2 describe the cavity-induced Larmor frequency shift and the exponential damping or amplification rate, given by $\delta\omega_{\text{opt}} = \text{Re}[\Sigma(\omega_L)]/2\omega_L$ and $\Gamma_{\text{opt}} = -\text{Im}[\Sigma(\omega_L)]/\omega_L$, respectively.

Averaging the coherent heterodyne signal from up to 40 repetitions of the experiment to reduce statistical noise, we extract both Γ_{opt} and $\delta\omega_{\text{opt}}$ from early times in the measured transient response (Fig. 3a-b). For this, we simultaneously fit both quadratures of the heterodyne signal, restricting the fit to spin dynamics near the poles (within 0.8 rad, see Supplemental Material [42]).

The close agreement between our measurements and the theoretical predictions (Fig. 3) demonstrates the close analogy between cavity optomechanics and spin optodynamics. In addition, for a spin oscillator, ω_L can be tuned readily over a broad range. Therefore, we can observe optodynamical effects in the transition from the unresolved-to the resolved-sideband regime. For example, we demonstrate that the peak damping rate, measured for a range of Larmor frequencies, is maximized for $\omega_L/\kappa > 1$ (Fig. 3c).

In addition to coherent cavity back-action, the collective spin is also subject to quantum fluctuations of \mathbf{B}_{opt} , which cause diffusion of the collective spin away from its stable state. The balance between coherent and incoherent back-action effects leads the spin ensemble to achieve a steady-state temperature. This equilibrium between cavity-assisted damping and measurement back-action is similar to that achieved in cavity cooling of mechanical oscillators [44, 45]. Because the atomic spins are extremely isolated from their environment, high spin optodynamical cooperativity, where the optical coupling exceeds the intrinsic damping, is achieved already at minimal optical power. Therefore, the equilibrium spin temperature is determined solely by the quantum fluctuations of the cavity field, which are shaped by the cavity linewidth.

Due to the quantization of the collective spin oscillator,

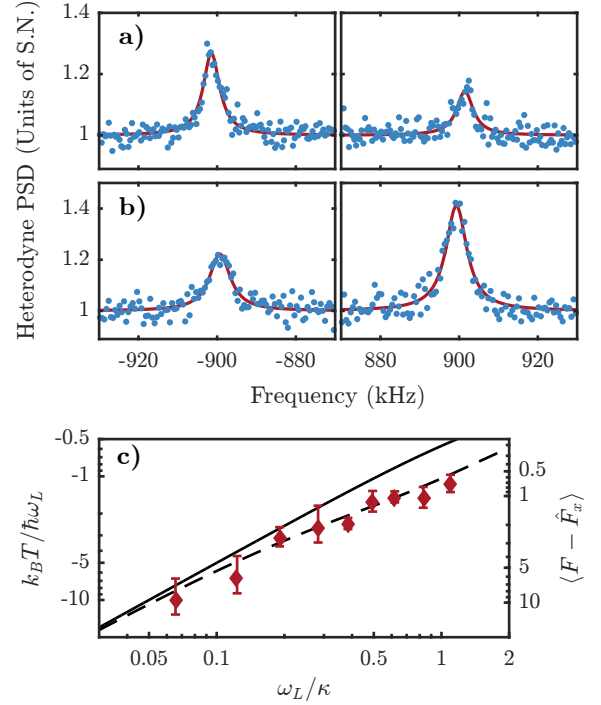


FIG. 4. (color online) Sideband-asymmetry thermometry of a spin oscillator. **(a)** Stokes and anti-Stokes sidebands observed in the averaged heterodyne PSD, normalized by the shot-noise level, showing the sideband asymmetry of a low-energy spin, with $\omega_L/2\pi = 900$ kHz, in equilibrium with an optical damping tone detuned by $\Delta_{\text{pc}}/2\pi = -1.5$ MHz with average photon number $\bar{n}_{\text{damp}} = 5.0$, and measurement back-action from an on-resonance probe with average photon number $\bar{n}_{\text{probe}} = 1.0$. **(b)** Inverted sideband asymmetry for a negative-temperature spin ensemble near its high-energy state, with $\Delta_{\text{pc}}/2\pi = 1.5$ MHz, $\bar{n}_{\text{damp}} = 4.3$, and $\bar{n}_{\text{probe}} = 2.0$. **(c)** Equilibrium temperature (left scale) and thermal occupation (right scale) of a high-energy spin oscillator, measured by sideband asymmetry, as a function of the Larmor frequency ω_L . Lines indicate expected temperature at equilibrium between coherent damping and incoherent back-action. The solid line indicates the ideal limit in the absence of the on-resonance probe, and the dashed line includes the additional back-action for the average probe cooperativity.

the equilibrium temperature can be determined from the asymmetry in its Raman scattering spectrum, recorded in the power spectral density (PSD) of the heterodyne signal. The amplitude of the Stokes sideband corresponds to the energy absorption rate Γ_+ and the anti-Stokes sideband corresponds to the emission rate Γ_- . Assuming the collective spin state to be in thermal equilibrium at temperature T , the ratio of these rates satisfies the detailed balance relation $\Gamma_+/\Gamma_- = \exp(\hbar\omega_L/k_B T)$.

We characterize the steady state of the atomic spin ensemble by driving the optical cavity with two coherent, primarily shot-noise limited tones: one strong tone at a detuning $\Delta_{\text{pc}} = \beta\sqrt{\kappa^2 + \omega_L^2}$ that provides damping toward either the high- or low-energy pole, and a

second weak tone on cavity resonance. The asymmetry of sidebands generated on the resonant tone is observed in our heterodyne receiver (Fig. 4a) and used to determine T . Whereas a spin oscillator stabilized in its low-energy state yields the conventional Stokes/anti-Stokes sideband asymmetry, consistent with positive temperature, for a spin oscillator in the high-energy state, the sideband asymmetry is reversed, indicating a negative temperature for the spin ensemble (Fig. 4b). Accounting for shot-noise-driven heating of the spin oscillator from both probe tones, the observed spin temperatures agree well with the theoretical model (Fig. 4c). As predicted [44, 45], autonomous feedback cooling yields increased purity of the quantum state ($k_B|T|/\hbar\omega_L < 1$) as the system enters the resolved-sideband regime.

In summary, we have demonstrated cavity based measurement of Larmor precession of the collective spin of an atomic ensemble and coherent control via autonomous feedback. These capabilities could be used to perform quantum-limited measurements of the collective spin or to realize a phase-preserving, quantum-limited amplifier for spin states. Furthermore, we demonstrate the ability to stabilize the ensemble in a nearly-pure quantum state with negative effective temperature. In this condition, the system can be described as a near ground-state, negative effective-mass oscillator. If measured jointly with a mechanical oscillator, such a spin oscillator could allow continuous QND position or force measurement via coherent quantum noise cancellation [46].

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* jkohl@berkeley.edu

† dmsk@berkeley.edu

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