Concurrent Spin Squeezing and Light Squeezing in an Atomic Ensemble

Shenchao Jin,[1,2,3] Junlei Duan,[3] Youwei Zhang,[3] Xichang Zhang,[3] Han Bao,[3,4] Heng Shen,[5,2] Liantuan Xiao,[1,2] Suotang Jia,[1,2] Mingfeng Wang,[6,*] and Yanhong Xiao[1,2,3,†]

[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan, Shanxi 030006, China*

[2]*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China*

[3]*Department of Physics, State Key Laboratory of Surface Physics and Key Laboratory of Micro and Nano Photonic Structures (Ministry of Education), Fudan University, Shanghai 200433, China*

[4]*QUANTUM, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*

[5]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-electronics, Shanxi University, Taiyuan, Shanxi 030006, China*

[6]*Department of Physics, Wenzhou University, Zhejiang 325035, China*

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Squeezed spin states and squeezed light are both key resources for quantum metrology and quantum information science, but have been separately investigated in experiments so far. Simultaneous generation of these two types of quantum states in one experiment setup is intriguing but remains a challenging goal. Here, we propose a novel protocol based on judiciously engineered symmetric atom-light interaction, and report proof-of-principle experimental results of concurrent spin squeezing of 0.61 ± 0.09 dB and light squeezing of $0.65^{+0.11}_{-0.10}$ dB in a hot atomic ensemble. The squeezing process is deterministic, yielding fixed squeezing directions for both the light field and the collective atomic spin. Furthermore, the squeezed light modes lie in the multiple frequency sidebands of a single spatial mode. This new type of dual squeezed state is applicable for quantum enhanced metrology and quantum networks. Our method can be extended to other quantum platforms such as optomechanics, cold atoms, and trapped ions.

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Entanglement states such as squeezed spin states (SSSs) and squeezed light [1–3] have been under active investigations due to their relevance for precision measurements [4–6], such as light interferometers [7] and spin sensors [8–14]. However, the generation and utilization of light squeezing and spin squeezing have largely been separate in different setups. The flying spin (light) and stationary spin (atoms) often involve distinct schemes [6] for squeezing, although their squeezed states both involve pairs of correlated excitations [15–18]. Studying the analogies and differences between atoms and light in the context of quantum squeezing is an intriguing topic, with other studies in view of wave-particle duality and mathematical description of their coherent states [19]. Practically, concurrent squeezing of the two can save resources and have applications in quantum metrology and quantum information science.

Despite a few theory proposals [20,21], concurrent light squeezing and atomic spin squeezing remain an experimental challenge because the two squeezings require different physics processes in general. Light squeezing is usually based on nonlinear atom-light interactions (such as wave mixing [22] or parametric processes [23]) and leaves atomic states nearly intact, whereas in light-mediated spin squeezing, light serves as the agent in correlating the spin while the spin often does not provide the necessary feedback mechanism for light squeezing [24–26]. A generic form of Hamiltonian $\hat{H} = \mu_- \hat{b}^\dagger \hat{a}^\dagger + \mu_+ \hat{b}^\dagger \hat{a} + \mathrm{H.c.}$ [27–31] has been studied, where light ($\hat{a}$) and spin ($\hat{b}$) act as quantum bus for one another and in principle allow concurrent squeezing. In practice though, the spin oscillator often has finite frequency Ω and the additional term $\Omega \hat{b}^\dagger \hat{b}$ induces quantum backaction noise by rotating and mixing the two orthogonal quantum quadratures, which can spoil spin squeezing. Up to now, Hamiltonians of such type in atomic and optomechanical systems have led to either entangled spin [32], or entangled (or squeezed) light [27,33], but not both.

Here, we propose a novel protocol enabling squeezing of both light and a collective spin oscillator, and report proof-of-principle experiments. By using stroboscopic atom-light interaction with periodic short optical pulses of coherent states, the frequency mismatch between light and atoms is compensated as in Floquet engineering [34,35]. This allows generation of a comblike squeezed vacuum light state that then transfers to atoms producing spin squeezing. Previously, stroboscopy was employed in backaction

*Contact author: mfwang@wzu.edu.cn
†Contact author: yxiao@fudan.edu.cn

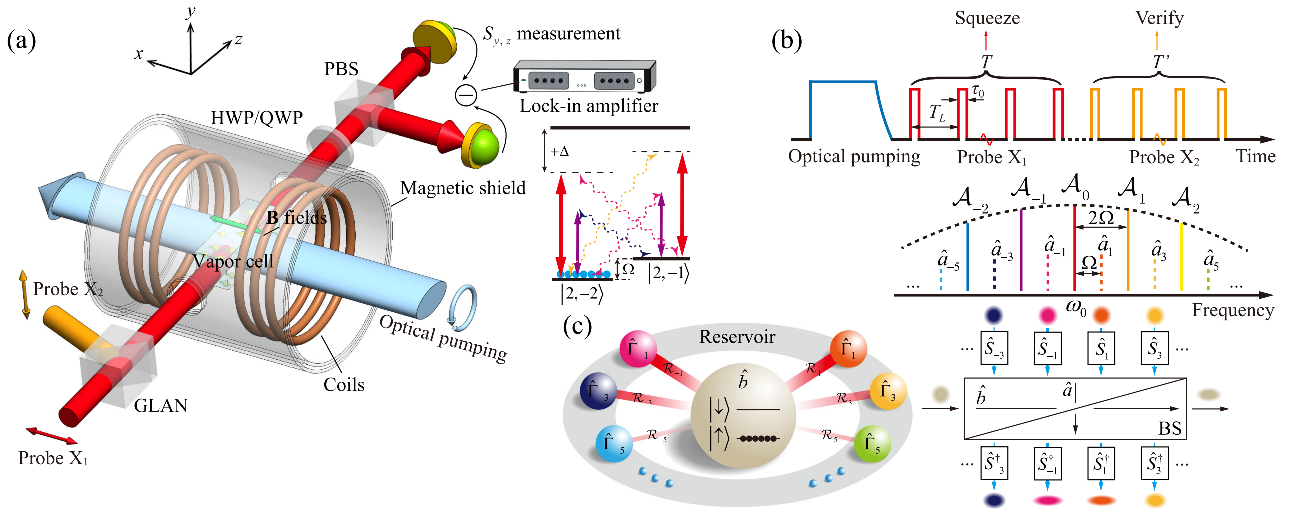

FIG. 1. (a) Experimental schematics. The paraffin-coated rubidium vapor cell is located in a four-layer magnetic shield, with a Zeeman splitting of $\Omega = 2\pi \times 499.60$ kHz from a bias magnetic field. The optical pumping light travels along x axis. Both X_1 and X_2 probe lasers propagate along the z axis, and their Stokes components S_z and S_y will be respectively demodulated at the Larmor frequency and recorded by a lock-in amplifier. HWP, half-wave plate; QWP, quarter-wave plate; PBS, polarization beam splitter; GLAN, Glan-laser calcite polarizer. Right: level diagram of the probe X_1 with stroboscopic driving frequency $\omega_m = 2\Omega$. The red solid arrows are the carrier (zeroth sideband) of probe X_1 with frequency ω_0 while the purple solid arrows denote the first sideband with frequency $\omega_0 - 2\Omega$. The dashed arrows represent the Stokes and anti-Stokes quantum fields in the y polarization (viewed along z axis). (b) Time-domain representation of pulse sequence (top) and the corresponding spectrum of the probe pulses (bottom). Before interaction, the optical pumping pulse prepares the atoms to CSS. Then the stroboscopic probe X_1 pulse creates spin squeezing of the atomic ensemble, while the output X_1 pulse itself is squeezed at the same time. An extra stroboscopic probe X_2 pulse then verifies the generated SSS. All three pulses have slowly varying rising and falling edges [52] to minimize excess noises. (c) Pictorial representation of the atom-light interaction. It can be understood as either (left) an atomic mode interacting with a squeezed reservoir or (right) an atom-light beam splitter (BS) evolution sandwiched between the sideband squeezing evolutions (see text).

evading measurements and conditional spin squeezing [26,36]. We experimentally demonstrate deterministic and unconditional spin squeezing, with fixed squeezing directions for both light and spin.

The principle of our scheme for concurrent squeezing is illustrated in Fig. 1. A ^{87}Rb atomic ensemble with $N_A > 10^{11}$ atoms is prepared in the ground state sublevel $|\uparrow\rangle \equiv 5^2S_{1/2}|F=2, m_F=-2\rangle$ to produce a coherent spin state (CSS) along a bias magnetic field [37] in the x direction, which can be treated as a two-level system with the neighboring sublevel $|\downarrow\rangle \equiv |F=2, m_F=-1\rangle$. The creation of the atomic excitation can be described by the collective operator $\hat{b}^\dagger = \sum_{i=1}^{N_A} |\downarrow\rangle_i\langle\uparrow|/\sqrt{N_A}$, satisfying the commutation relation $[\hat{b}, \hat{b}^\dagger] = 1$. A train of ultrashort and relatively strong linearly x-polarized light pulse with central frequency ω_0 is sent through the sample to experience a near-resonant interaction, producing Raman scattered and collectively enhanced quantum field $\hat{a}$ in the y polarization. These square-wave pulses have a width τ_0 and are $T_L = \pi/\Omega$ away from each other in the time domain to ensure that each pulse enters the ensemble encountering exactly either the $+z$ or the $-z$ component of the atomic angular momentum (which undergoes Larmor precession around the B field), as shown in Fig. 1(b). With such setting, the periodically changing temporal profile function of the incident light in the frequency domain is $\phi(t) = \sum_{n=-\infty}^{\infty} \mathcal{A}_n e^{i2n\Omega t}$, with the Fourier coefficients $\mathcal{A}_n = d\,\mathrm{sinc}(\pi n d)$ and the duty cycle $d = \tau_0/T_L$. Obviously, this spectral distribution is a frequency comb [38] with central frequency ω_0, overall width $\propto 1/d$, and comb-tooth separation 2Ω [Fig. 1(b)]. The system can be described by canonical variables under the Holstein-Primakoff approximation [39], $\hat{x}_A = -\hat{J}_y/\sqrt{|J_x|} = (\hat{b} + \hat{b}^\dagger)/\sqrt{2}$, $\hat{p}_A = \hat{J}_z/\sqrt{|J_x|} = -i(\hat{b} - \hat{b}^\dagger)/\sqrt{2}$ for the collective spin and $\hat{x}_L = \hat{S}_y/\sqrt{|S_x|} = (\hat{a} + \hat{a}^\dagger)/\sqrt{2}$, $\hat{p}_L = \hat{S}_z/\sqrt{|S_x|} = -i(\hat{a} - \hat{a}^\dagger)/\sqrt{2}$ for light, where $\hat{J}_i$ are collective angular momenta of the atomic ensemble and $\hat{S}_i$ are Stokes operators for light with $i = x, y, z$, and the minus sign before $\hat{J}_y$ comes from the atomic polarization direction (see Sec. 1 of the Supplemental Material [40]).

In the weak excitation limit, one may adiabatically eliminate the atomic excited states and obtain the effective interaction Hamiltonian (Sec. 1 of [40]) of the type

$$\hat{H}_{\mathrm{int}} \propto \hat{b}^\dagger \sum_{k=-\infty}^{\infty} \mathcal{R}_k \left(\hat{a}_k \cosh r_k - \hat{a}_k^\dagger \sinh r_k\right) + \mathrm{H.c.}, \qquad (1)$$

where the integer $|k|$ is odd and $\hat{a}_k^\dagger$ denotes creation operator of the sideband mode with frequency $\omega_0 + k\Omega$. The sideband-dependent coupling constant $\mathcal{R}_k = \sqrt{\mathcal{C}_+\mathcal{C}_-}$ and the parameter $r_k = \ln(\mathcal{C}_+/\mathcal{C}_-)$ with $\mathcal{C}_\pm = \mathcal{A}_{\frac{1}{2}(k-1)}\mu_+ \pm \mathcal{A}_{\frac{1}{2}(k+1)}\mu_-$, where $\mu_\pm = \kappa(1 \pm \zeta^2)/2\sqrt{L}$ describes Stokes and anti-Stokes scattering rates, with total interaction length L, coupling strength κ (proportional to the square root of N_A times the incident photon number), and ζ^2 proportional to the ratio of the coefficients of the vector and tensor parts of the atomic polarizability. This interaction has a simple and interesting form. It describes a beam splitter (BS) type interaction between the atomic mode $\hat{b}$ and the photonic Bogoliubov mode $\hat{\Gamma}_k$ $(\equiv \hat{S}_k^\dagger \hat{a}_k \hat{S}_k = \hat{a}_k \cosh r_k - \hat{a}_k^\dagger \sinh r_k)$, where the squeeze operator $\hat{S}_k = \exp[r_k(\hat{a}_k^2 - \hat{a}_k^{\dagger 2})/2]$. The Bogoliubov modes $\{\hat{\Gamma}_k\}$ bear close analogy to the "squeezed vacuum reservoir" [53,54], passing squeezing to atoms as in Eq. (1) and illustrated in Fig. 1(c). More specifically, the evolution of such interaction is equivalent to $\hat{S}_k^\dagger \hat{b}^\dagger \hat{a}_k \hat{S}_k + \text{H.c.}$, i.e., an atom-light BS evolution sandwiched between the sideband squeezing evolutions $\{\hat{S}_k\}$ and $\{\hat{S}_k^\dagger\}$, as shown in Fig. 1(c). The vacuum sideband modes are first squeezed by $\hat{S}_k$ (along $\hat{x}_L$) and then the squeezing properties are transferred from light to atoms via the BS evolution, which returns light to coherent state but yields spin squeezing along $\hat{p}_A$, and finally the light modes are squeezed via $\hat{S}_k^\dagger$ along $\hat{p}_L$. This explains why both light and spin are squeezed in the $\hat{p}$ quadrature, i.e., along S_z and J_z, respectively.

The propagation and evolution equations of the canonical variables can be derived (Sec. 1 of [40]) as follows:

$$\frac{\partial \hat{x}_L}{\partial z} = \frac{\kappa}{\sqrt{L}}\phi \tilde{\hat{p}}_A, \qquad \frac{\partial \tilde{\hat{x}}_A}{\partial t} = \Omega \tilde{\hat{p}}_A + \frac{\kappa}{\sqrt{L}}\phi \hat{p}_L, \tag{2a}$$

$$\frac{\partial \hat{p}_L}{\partial z} = -\frac{\zeta^2\kappa}{\sqrt{L}}\phi \tilde{\hat{x}}_A, \qquad \frac{\partial \tilde{\hat{p}}_A}{\partial t} = -\Omega \tilde{\hat{x}}_A - \frac{\zeta^2\kappa}{\sqrt{L}}\phi \hat{x}_L. \tag{2b}$$

Here, $\tilde{\hat{x}}_A$ and $\tilde{\hat{p}}_A$ denote the quadratures for an atomic slice around a given z. These equations describe the information exchange between light and atoms. One can clearly see that the flying photons evolve along the propagation distance, while the residing atoms evolve with time, showing the difference between light and spins. The motivation for stroboscopy can be also seen here: squeezing in $\hat{p}_A$ is mediated by $\hat{x}_L$, but the Ω rotation term brings antisqueezing noise in $\hat{x}_A$, which must be eliminated by stroboscopy in ϕ as defined before. In the frequency domain, frequency sidebands due to stroboscopy enable the excitation of correlated spin pairs responsible for spin squeezing, as illustrated in Fig. 1(a), via the two Raman processes containing the generated quantum light (two violet wavy arrows), the input light's carrier (red straight arrow) and first order sideband (violet straight arrow).

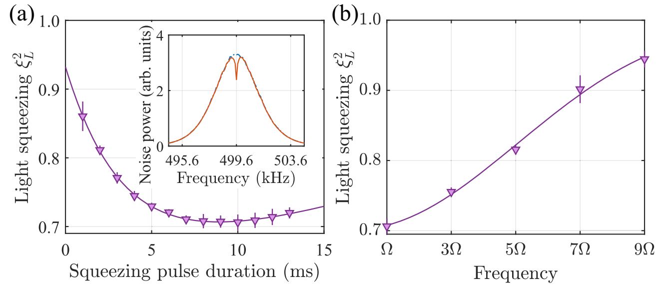

FIG. 2. (a) Light squeezing vs squeezing time T, with mean power 1.18 mW and duty cycle $d = 0.08$. Inset: exemplary squeezed light spectrum of the light X_1 around $\omega = \Omega$. The red solid curve denotes the power spectrum of the homodyne signal $\hat{p}_L$, while the blue dash-dotted line represents the measured shot noise reference. The noise spectrum is averaged from 10 000 runs of the pulse sequence as shown in Fig. 1(b). (b) Light squeezing at different frequencies. For each data point, the demodulation frequency of the lock-in is set to the corresponding x-axis value. In the inset and (b), $T = 10$ ms. In (a) and (b), the triangle with error bar is the experimental data with 1 standard deviation from five identical experiments (each with 10 000 runs of the pulse sequence), and the solid curves are the model fits (Sec. 1 of [40]). The shot noise limit is 1.0.

Our experiment [Fig. 1(a)] utilizes a hot atomic vapor cell with paraffin coating [55]. The atoms are first optically pumped to $|\uparrow\rangle$, with a measured degree of polarization about 97.9%, which has 6% extra noise in spin variance compared to an ideal CSS of 100% polarization. Then, a stroboscopic laser pulse X_1 is sent through the atoms to induce squeezing for both the spin and the light. Light squeezing is verified by measuring X_1's Stokes component S_z ($\hat{p}_L$ quadrature). To verify spin squeezing, another stroboscopic and far-detuned laser pulse X_2 is applied to create a standard backaction evading quantum non-demolition interaction $\propto \hat{p}_L \hat{p}_A$ [36], where $\hat{p}_A$ can be read out by detecting X_2's S_y ($\hat{x}_L$) component (Sec. 2 of [40]).

We first characterize the multimode light squeezing. The balanced homodyne S_z measurement on X_1 yields the $\hat{p}_L$ signal, with a typical power spectrum shown in the inset of Fig. 2(a). From the noise spectrum, one can see that there exists an apparent dip at the Larmor frequency $\omega = \Omega$, indicating light squeezing. A careful calibration from the spectrum normalized to that of the photon shot noise gives the degree of squeezing in Fig. 2(a), showing that squeezing increases first with the length of the X_1 pulse because of larger coupling strength, and then slowly degrades due to the decay of the atomic macroscopic spin (Sec. 2 of [40]). The optimal light squeezing is $-10\log_{10}(\xi_L^2) = 1.51 \pm 0.07$ dB with squeezing pulse duration $T = 10$ ms. By using different demodulation frequencies, we can obtain squeezing at frequencies $m\Omega$ $(m = 1, 3, 5, 7, \ldots)$ [Fig. 2(b)], showing that the amount of squeezing decreases for higher frequencies, following a trend consistent with our theoretical prediction (Sec. 1 of [40]). The

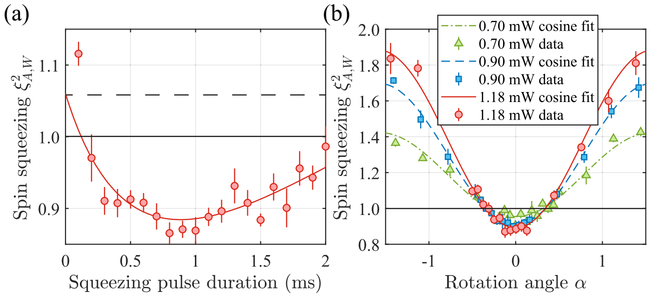

FIG. 3. (a) Spin squeezing vs squeezing time T, with mean power 1.18 mW and duty cycle 0.08. The circle with error bar is the experimental data extracted from the pulse X_2 detection with decaying time mode $f(T') = e^{-\gamma' T'}$, $\gamma'^{-1} = 1.3$ ms, mean power 1.24 mW, and duty cycle 0.1. The line is fixed to 1.06 at $T = 0$ (shown by the black dashed line) because of the 97.9% spin polarization. The first data point deviates from the fitted curve due to excess technical noise originating from an overly short and sharp pulse violating the adiabaticity condition [52]. (b) Spin squeezing for different spin quadrature directions in the y-z plane, with $T = 1.0$ ms, mean power 1.18 mW, and duty cycle 0.08. The rotation angle α is the angle relative to $\hat{p}_A$. In (a) and (b), the solid lines are the model fits (Sec. 1 of [40]), and the error bars (1 standard deviation) are derived from five identical experiments, each including 10000 repetitions of the pulse sequence shown in Fig. 1(b). The black line at 1.0 is the PNL.

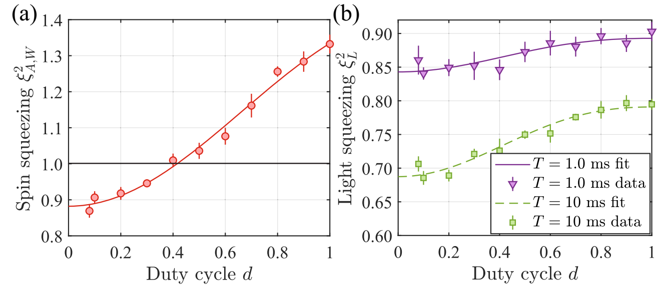

FIG. 4. (a) Spin squeezing and (b) light squeezing (measured at $\omega = \Omega$) vs duty cycle. Red circles, purple triangles, and green squares are experimental data. The curves are the model fits (Sec. 1 of [40]) with function $b_1 + b_2 \mathrm{sinc}(\pi d)$ for (a) and function $c_1 + c_2 \mathrm{sinc}^2(\pi d)$ for (b). The mean power of X_1 is kept at 1.18 mW in (a) and (b), while X_2 has a mean power 1.24 mW with duty cycle 0.1 in (a). $T = 1.0$ ms in (a). The error bars (1 standard deviation) are derived from five identical experiments, each including 10 000 repetitions of the pulse sequence shown in Fig. 1(b). The black line at 1.0 indicates the PNL in (a) and shot noise limit (not shown) in (b).

multisideband squeezing here is closely related to a multipartite entanglement state [56] applicable for quantum information processing [57].

Then we proceed to spin squeezing evaluated by Wineland criterion [58] $\xi^2_{A,W} = e^{2T/T_1}\mathrm{Var}(\hat{p}_A)_{\mathrm{SSS}}/\mathrm{Var}(\hat{p}_A)_{\mathrm{PNL}}$, where $\mathrm{Var}(\hat{p}) = \langle \hat{p}^2 \rangle - \langle \hat{p} \rangle^2$ and the prefactor e^{2T/T_1} denotes the effect of the macroscopic-spin decay with relaxation time $T_1 = 18$ ms. The projection noise limit (PNL) $\mathrm{Var}(\hat{p}_A)_{\mathrm{PNL}}$ is equal to $4/5$ times the measured noise of the thermal state [26,36]. Figure 3(a) presents the measured time evolution of spin squeezing, which agrees well with the theoretical result, as shown by the solid line fit. The competition between the coherent interaction and decoherence leads to an optimal spin squeezing $-10\log_{10}(\xi^2_{A,W}) = 0.63 \pm 0.08$ dB at $T = 0.8$ ms, which has suffered a degradation of about 0.39 dB due to the main spin vector shortening induced by spontaneous emission and other decoherences during squeezing.

To examine the spin squeezing direction, we measure the spin quadrature along a direction α: $\hat{q}_\alpha = \hat{p}_A \cos(\alpha/2) + \hat{x}_A \sin(\alpha/2)$, where α is varied by tuning the time interval between the X_1 and X_2 pulse. During this interval, the transverse spin ellipse undergoes Larmor precession for a fraction of a Larmor period and the spin decoherence is negligible. The spin direction is experimentally calibrated by radio frequency signal excitation. Figure 3(b) plots the amount of squeezing in different directions, indicating that the squeezing direction is along $\hat{p}_A$ even for different interaction strength. This proves that our method produces deterministic SSSs with fixed squeezing direction. In fact, The interaction (1) always squeezes the spin component parallel to the propagation direction of the light and broadens the orthogonal component at the same time. In contrast to SSSs produced by quantum non-demolition schemes [59,60] that depend on the measurement results and SSS via one-axis twisting [17] whose squeezing direction varies with the interaction strength, SSSs with fixed squeezing direction may be convenient for use in quantum metrology and quantum information applications [14,57,61,62].

Next, we present the result of concurrent spin and light squeezing and discuss their different behaviors. As shown in Fig. 4, with the same parameter $T = 1.0$ ms, concurrent squeezing can be observed for d smaller than 0.4, and when $d = 0.08$ we obtain concurrent spin squeezing of 0.61 ± 0.09 dB and light squeezing of $0.65^{+0.11}_{-0.10}$ dB. The measured squeezing for both the spin and light follows a similar trend. However, for large d, spin squeezing disappears, while light squeezing still exists even when $d = 1$. Therefore, stroboscopy is necessary for spin squeezing here but is only slightly beneficial for light squeezing. We note that, although the squeezing process for light mode $\hat{a}$ and spin mode $\hat{b}$ is similar as indicated by the Hamiltonian $\propto \mu_- \hat{b}^\dagger \hat{a}^\dagger + \mu_+ \hat{b}^\dagger \hat{a} + \mathrm{H.c.}$, their major difference is that, as shown by the propagation and evolution equations [Eq. (2a) and (2b)], atoms reside in the vapor cell and the atom-light interaction effects accumulate with time, rendering them more sensitive to noises, especially the residual quantum backaction noises, whereas the light field always enters the atomic medium fresh as a coherent state. Another distinction is that the collective atomic spin here is a single frequency harmonic oscillator, while the light pulse in free space is strictly speaking multimode in frequency [63].

Consequently, for light, it is possible to use the atomic mode as a mediator to establish entanglement between different light modes (for instance the two first order sidebands), which is the origin of light squeezing in absence of stroboscopy ($d = 1$); for atoms, there is only single-mode squeezing where stroboscopy of light is indispensable for frequency match in spin pair excitations.

Finally, we note that the moderate squeezing in our experiment is mostly due to the relatively small optical depth α_0, large spin decoherence rate and light losses. For a given α_0, the optimal spin squeezing follows $\xi^2_{A,W} \propto 2(\sqrt{1+\alpha_0}-1)/\alpha_0$, predicting higher squeezing for larger optical depth (Sec. 2 of [40]), while light squeezing follows a similar trend. Thus, improved squeezing in both atoms and light is expected by applying optical cavities [26], longer vapor cells [64], multipass schemes [24,65], or by enhanced quality in the antireflection coating as well as in the wall coatings [66], including those enduring higher temperatures [67].

Our protocol can be applied in other quantum systems such as optomechanical systems [27,28], cold atoms [29,30], trapped ions [68], and superconducting circuits [31], etc., where similar Hamiltonians can be engineered. Compared to separately prepared independent spin squeezing and light squeezing, concurrent squeezing is beneficial for various applications thanks to the spectral and bandwidth matching between the atoms and the squeezed light. For example, as we propose (detailed in Sec. 3 of [40]), in quantum metrology, one could first use the squeezed spin for sensing [61] and then use the concurrently produced squeezed light for efficient readout of the atomic state [69,70], which enhances the overall sensitivity; in quantum state preparation, reflecting the squeezed light back into the squeezed atoms again could further increase spin squeezing; in quantum networks [71], spin squeezed atomic ensembles can serve as low noise quantum nodes [72], while the simultaneously squeezed light can be utilized to connect and entangle these nodes [73,74], where spin squeezing can boost the entanglement generation efficiency.

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[1] A. Messikh, Z. Ficek, and M. R. B. Wahiddin, Spin squeezing as a measure of entanglement in a two-qubit system, Phys. Rev. A **68**, 064301 (2003).

[2] J. K. Korbicz, J. I. Cirac, and M. Lewenstein, Spin squeezing inequalities and entanglement of *N* qubit states, Phys. Rev. Lett. **95**, 120502 (2005).

[3] G. Tóth, C. Knapp, O. Gühne, and H. J. Briegel, Spin squeezing and entanglement, Phys. Rev. A **79**, 042334 (2009).

[4] V. Giovannetti, S. Lloyd, and L. Maccone, Quantum metrology, Phys. Rev. Lett. **96**, 010401 (2006).

[5] V. Giovannetti, S. Lloyd, and L. Maccone, Advances in quantum metrology, Nat. Photonics **5**, 222 (2011).

[6] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Quantum metrology with nonclassical states of atomic ensembles, Rev. Mod. Phys. **90**, 035005 (2018).

[7] M. Tse *et al.*, Quantum-enhanced advanced LIGO detectors in the era of gravitational-wave astronomy, Phys. Rev. Lett. **123**, 231107 (2019).

[8] D. Budker, W. Gawlik, D. F. Kimball, S. M. Rochester, V. V. Yashchuk, and A. Weis, Resonant nonlinear magneto-optical effects in atoms, Rev. Mod. Phys. **74**, 1153 (2002).

[9] F. Wolfgramm, A. Cerè, F. A. Beduini, A. Predojević, M. Koschorreck, and M. W. Mitchell, Squeezed-light optical magnetometry, Phys. Rev. Lett. **105**, 053601 (2010).

[10] C. Troullinou, R. Jiménez-Martínez, J. Kong, V. G. Lucivero, and M. W. Mitchell, Squeezed-light enhancement and backaction evasion in a high sensitivity optically pumped magnetometer, Phys. Rev. Lett. **127**, 193601 (2021).

[11] M. Koschorreck, M. Napolitano, B. Dubost, and M. W. Mitchell, Sub-projection-noise sensitivity in broadband atomic magnetometry, Phys. Rev. Lett. **104**, 093602 (2010).

[12] T. Horrom, R. Singh, J. P. Dowling, and E. E. Mikhailov, Quantum-enhanced magnetometer with low-frequency squeezing, Phys. Rev. A **86**, 023803 (2012).

[13] E. Pedrozo-Peñafiel, S. Colombo, C. Shu, A. F. Adiyatullin, Z. Li, E. Mendez, B. Braverman, A. Kawasaki, D. Akamatsu, Y. Xiao, and V. Vuletić, Entanglement on an optical atomic-clock transition, Nature (London) **588**, 414 (2020).

[14] B. K. Malia, Y. Wu, J. Martínez-Rincón, and M. A. Kasevich, Distributed quantum sensing with mode-entangled spin-squeezed atomic states, Nature (London) **612**, 661 (2022).

[15] L.-A. Wu, H. J. Kimble, J. L. Hall, and H. Wu, Generation of squeezed states by parametric down conversion, Phys. Rev. Lett. **57**, 2520 (1986).

[16] L. M. Norris, C. M. Trail, P. S. Jessen, and I. H. Deutsch, Enhanced squeezing of a collective spin via control of its qudit subsystems, Phys. Rev. Lett. **109**, 173603 (2012).

[17] M. Kitagawa and M. Ueda, Squeezed spin states, Phys. Rev. A **47**, 5138 (1993).

[18] A. B. Matsko, I. Novikova, G. R. Welch, D. Budker, D. F. Kimball, and S. M. Rochester, Vacuum squeezing in atomic media via self-rotation, Phys. Rev. A **66**, 043815 (2002).

[19] F. T. Arecchi, E. Courtens, R. Gilmore, and H. Thomas, Atomic coherent states in quantum optics, Phys. Rev. A **6**, 2211 (1972).

[20] J. F. Sherson and K. Mølmer, Polarization squeezing by optical Faraday rotation, Phys. Rev. Lett. **97**, 143602 (2006).

[21] J. Zhu, Y. Mu, and G. Huang, Simultaneous quantum squeezing of light polarizations and atomic spins in a cold atomic gas, Phys. Rev. A **107**, 033517 (2023).

[22] R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley, Observation of squeezed states generated by four-wave mixing in an optical cavity, Phys. Rev. Lett. **55**, 2409 (1985).

[23] L.-A. Wu, M. Xiao, and H. J. Kimble, Squeezed states of light from an optical parametric oscillator, J. Opt. Soc. Am. B **4**, 1465 (1987).

[24] C. M. Trail, P. S. Jessen, and I. H. Deutsch, Strongly enhanced spin squeezing via quantum control, Phys. Rev. Lett. **105**, 193602 (2010).

[25] M. Wang, W. Qu, P. Li, H. Bao, V. Vuletić, and Y. Xiao, Two-axis-twisting spin squeezing by multipass quantum erasure, Phys. Rev. A **96**, 013823 (2017).

[26] G. Vasilakis, H. Shen, K. Jensen, M. Balabas, D. Salart, B. Chen, and E. S. Polzik, Generation of a squeezed state of an oscillator by stroboscopic back-action-evading measurement, Nat. Phys. **11**, 389 (2015).

[27] S. Barzanjeh, E. S. Redchenko, M. Peruzzo, M. Wulf, D. P. Lewis, G. Arnold, and J. M. Fink, Stationary entangled radiation from micromechanical motion, Nature (London) **570**, 480 (2019).

[28] E. E. Wollman, C. U. Lei, A. J. Weinstein, J. Suh, A. Kronwald, F. Marquardt, A. A. Clerk, and K. C. Schwab, Quantum squeezing of motion in a mechanical resonator, Science **349**, 952 (2015).

[29] M. Koschorreck, M. Kubasik, M. Napolitano, S. R. de Echaniz, H. Crepaz, J. Eschner, E. S. Polzik, and M. W. Mitchell, Polarization-based light-atom quantum interface with an all-optical trap, Phys. Rev. A **79**, 043815 (2009).

[30] E. G. Dalla Torre, J. Otterbach, E. Demler, V. Vuletić, and M. D. Lukin, Dissipative preparation of spin squeezed atomic ensembles in a steady state, Phys. Rev. Lett. **110**, 120402 (2013).

[31] A. Metelmann, O. Lanes, T.-Z. Chien, A. McDonald, M. Hatridge, and A. A. Clerk, Quantum-limited amplification without instability, arXiv:2208.00024.

[32] H. Krauter, C. A. Muschik, K. Jensen, W. Wasilewski, J. M. Petersen, J. I. Cirac, and E. S. Polzik, Entanglement generated by dissipation and steady state entanglement of two macroscopic objects, Phys. Rev. Lett. **107**, 080503 (2011).

[33] W. Wasilewski, T. Fernholz, K. Jensen, L. S. Madsen, H. Krauter, C. Muschik, and E. S. Polzik, Generation of two-mode squeezed and entangled light in a single temporal and spatial mode, Opt. Express **17**, 14444 (2009).

[34] S. Geier, N. Thaicharoen, C. Hainaut, T. Franz, A. Salzinger, A. Tebben, D. Grimshandl, G. Zürn, and M. Weidemüller, Floquet Hamiltonian engineering of an isolated many-body spin system, Science **374**, 1149 (2021).

[35] M. Jiang, Y. Qin, X. Wang, Y. Wang, H. Su, X. Peng, and D. Budker, Floquet spin amplification, Phys. Rev. Lett. **128**, 233201 (2022).

[36] H. Bao, J. Duan, S. Jin, X. Lu, P. Li, W. Qu, M. Wang, I. Novikova, E. E. Mikhailov, K.-F. Zhao, K. Mølmer, H. Shen, and Y. Xiao, Spin squeezing of 10^{11} atoms by prediction and retrodiction measurements, Nature (London) **581**, 159 (2020).

[37] C. K. Law, H. T. Ng, and P. T. Leung, Coherent control of spin squeezing, Phys. Rev. A **63**, 055601 (2001).

[38] N. Picqué and T. W. Hänsch, Frequency comb spectroscopy, Nat. Photonics **13**, 146 (2019).

[39] T. Holstein and H. Primakoff, Field dependence of the intrinsic domain magnetization of a ferromagnet, Phys. Rev. **58**, 1098 (1940).

[40] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.133.173604, which includes Refs. [41–51], for the details and derivations of the model, technical details of the experiments, and the supporting theory for the proposed applications of concurrent squeezing in the main text.

[41] B. Julsgaard, Entanglement and quantum interactions with macroscopic gas samples, Ph.D. thesis, University of Aarhus, 2003.

[42] G. Vasilakis, V. Shah, and M. V. Romalis, Stroboscopic backaction evasion in a dense alkali-metal vapor, Phys. Rev. Lett. **106**, 143601 (2011).

[43] Z. Y. Ou, S. F. Pereira, H. J. Kimble, and K. C. Peng, Realization of the Einstein-Podolsky-Rosen paradox for continuous variables, Phys. Rev. Lett. **68**, 3663 (1992).

[44] H. Vahlbruch, M. Mehmet, K. Danzmann, and R. Schnabel, Detection of 15 dB squeezed states of light and their application for the absolute calibration of photoelectric quantum efficiency, Phys. Rev. Lett. **117**, 110801 (2016).

[45] K. Hammerer, A. S. Sørensen, and E. S. Polzik, Quantum interface between light and atomic ensembles, Rev. Mod. Phys. **82**, 1041 (2010).

[46] K. Azuma, S. E. Economou, D. Elkouss, P. Hilaire, L. Jiang, H.-K. Lo, and I. Tzitrin, Quantum repeaters: From quantum networks to the quantum internet, Rev. Mod. Phys. **95**, 045006 (2023).

[47] R. Van Meter, T. D. Ladd, A. G. Fowler, and Y. Yamamoto, Distributed quantum computation architecture using semiconductor nanophotonics, Int. J. Quantum. Inform. **08**, 295 (2010).

[48] W. Ge, K. Jacobs, Z. Eldredge, A. V. Gorshkov, and M. Foss-Feig, Distributed quantum metrology with linear networks and separable inputs, Phys. Rev. Lett. **121**, 043604 (2018).

[49] R. Simon, Peres-Horodecki separability criterion for continuous variable systems, Phys. Rev. Lett. **84**, 2726 (2000).

[50] X.-L. Wang, L.-K. Chen, W. Li, H.-L. Huang, C. Liu, C. Chen, Y.-H. Luo, Z.-E. Su, D. Wu, Z.-D. Li, H. Lu, Y. Hu, X. Jiang, C.-Z. Peng, L. Li, N.-L. Liu, Y.-A. Chen, C.-Y. Lu, and J.-W. Pan, Experimental ten-photon entanglement, Phys. Rev. Lett. **117**, 210502 (2016).

[51] Z. Yan, L. Wu, X. Jia, Y. Liu, R. Deng, S. Li, H. Wang, C. Xie, and K. Peng, Establishing and storing of deterministic quantum entanglement among three distant atomic ensembles, Nat. Commun. **8**, 718 (2017).

[52] S. Jin, H. Bao, J. Duan, X. Lu, M. Wang, K.-F. Zhao, H. Shen, and Y. Xiao, Adiabaticity in state preparation for spin squeezing of large atom ensembles, Photonics Res. **9**, 2296 (2021).

[53] M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge University Press, Cambridge, England, 1997).

[54] G. S. Agarwal and R. R. Puri, Cooperative behavior of atoms irradiated by broadband squeezed light, Phys. Rev. A **41**, 3782 (1990).

[55] M. A. Bouchiat and J. Brossel, Relaxation of optically pumped Rb atoms on paraffin-coated walls, Phys. Rev. **147**, 41 (1966).

[56] S. T. Flammia, N. C. Menicucci, and O. Pfister, The optical frequency comb as a one-way quantum computer, J. Phys. B **42**, 114009 (2009).

[57] S. L. Braunstein and P. van Loock, Quantum information with continuous variables, Rev. Mod. Phys. **77**, 513 (2005).

[58] D. J. Wineland, J. J. Bollinger, W. M. Itano, and D. J. Heinzen, Squeezed atomic states and projection noise in spectroscopy, Phys. Rev. A **50**, 67 (1994).

[59] A. Kuzmich, N. P. Bigelow, and L. Mandel, Atomic quantum non-demolition measurements and squeezing, Europhys. Lett. **42**, 481 (1998).

[60] A. Kuzmich, L. Mandel, and N. P. Bigelow, Generation of spin squeezing via continuous quantum nondemolition measurement, Phys. Rev. Lett. **85**, 1594 (2000).

[61] W. Wasilewski, K. Jensen, H. Krauter, J. J. Renema, M. V. Balabas, and E. S. Polzik, Quantum noise limited and entanglement-assisted magnetometry, Phys. Rev. Lett. **104**, 133601 (2010).

[62] L. Pezzè and A. Smerzi, Heisenberg-limited noisy atomic clock using a hybrid coherent and squeezed state protocol, Phys. Rev. Lett. **125**, 210503 (2020).

[63] C. A. Muschik, E. S. Polzik, and J. I. Cirac, Dissipatively driven entanglement of two macroscopic atomic ensembles, Phys. Rev. A **83**, 052312 (2011).

[64] W. Zheng, H. Wang, R. Schmieg, A. Oesterle, and E. S. Polzik, Entanglement-enhanced magnetic induction tomography, Phys. Rev. Lett. **130**, 203602 (2023).

[65] M. Takeuchi, S. Ichihara, T. Takano, M. Kumakura, T. Yabuzaki, and Y. Takahashi, Spin squeezing via one-axis twisting with coherent light, Phys. Rev. Lett. **94**, 023003 (2005).

[66] M. V. Balabas, T. Karaulanov, M. P. Ledbetter, and D. Budker, Polarized alkali-metal vapor with minute-long transverse spin-relaxation time, Phys. Rev. Lett. **105**, 070801 (2010).

[67] S. J. Seltzer and M. V. Romalis, High-temperature alkali vapor cells with antirelaxation surface coatings, J. Appl. Phys. **106**, 114905 (2009).

[68] K. A. Gilmore, M. Affolter, R. J. Lewis-Swan, D. Barberena, E. Jordan, A. M. Rey, and J. J. Bollinger, Quantum-enhanced sensing of displacements and electric fields with two-dimensional trapped-ion crystals, Science **373**, 673 (2021).

[69] J. Fiurášek, J. Sherson, T. Opatrný, and E. S. Polzik, Single-passage readout of atomic quantum memory, Phys. Rev. A **73**, 022331 (2006).

[70] N. Didier, A. Kamal, W. D. Oliver, A. Blais, and A. A. Clerk, Heisenberg-limited qubit read-out with two-mode squeezed light, Phys. Rev. Lett. **115**, 093604 (2015).

[71] H. J. Kimble, The quantum internet, Nature (London) **453**, 1023 (2008).

[72] T. Fernholz, H. Krauter, K. Jensen, J. F. Sherson, A. S. Sørensen, and E. S. Polzik, Spin squeezing of atomic ensembles via nuclear-electronic spin entanglement, Phys. Rev. Lett. **101**, 073601 (2008).

[73] C. A. Muschik, K. Hammerer, E. S. Polzik, and J. I. Cirac, Efficient quantum memory and entanglement between light and an atomic ensemble using magnetic fields, Phys. Rev. A **73**, 062329 (2006).

[74] D. Schrader, I. Dotsenko, M. Khudaverdyan, Y. Miroshnychenko, A. Rauschenbeutel, and D. Meschede, Neutral atom quantum register, Phys. Rev. Lett. **93**, 150501 (2004).