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LETTERS

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Certified quantum non-demolition measurement of a macroscopic material system

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Quantum non-demolition (QND) measurements improve sensitivity by evading measurement back-action[1]. The technique was first proposed to detect mechanical oscillations in gravity-wave detectors[2] and demonstrated in the measurement of optical fields[3,4], which led to the development of rigorous criteria to distinguish QND from similar non-classical measurements[4]. Recent QND measurements of macroscopic material systems such as atomic ensembles[5–10] and mechanical oscillators[11–13] show some QND features, but not full QND character. Here we demonstrate certified QND measurement of the collective spin of an atomic ensemble. We observed quantum-state preparation (QSP) and information-damage trade-off (IDT) beyond their classical limits by seven and 12 standard deviations, respectively. Our techniques complement recent work with microscopic systems[14–16] and can be used for quantum metrology[6–10,17] and memory[18], the preparation[19] and detection[20] of non-Gaussian states, and proposed quantum simulation[21–23] and information[24,25] protocols. They should enable QND measurements of dynamical quantum variables[21,22,26] and the realization of QND-based quantum information protocols[19,24,25].

In a QND measurement, meter (X_m) and system (X_s) variables interact via an appropriate Hamiltonian and become entangled. Direct measurement of X_m then provides indirect information about X_s without destroying the system or altering X_s. In the formulation of Roch *et al.*[3], QND measurement of continuous variables, as used to describe systems with more than a few particles, is quantified by three figures of merit: ΔX_m^2 describes the measurement noise referred to the input, ΔX_s^2 describes the variance in X_s added by the QND interaction and $\Delta X_{s|m}^2$ describes the post-measurement conditional variance, that is, the uncertainty in X_s given the measurement outcome. Two non-classicality criteria must be met to certify QND measurement[3,4]: $\Delta X_{s|m}^2 < 1$ describes a non-classical QSP capability and $\Delta X_s^2 \Delta X_m^2 < 1$ describes a non-classical IDT. This latter inequality is usually expressed in terms of transfer coefficients $T_s \equiv 1/(1+\Delta X_s^2)$ and $T_m \equiv 1/(1+\Delta X_m^2)$ as $T_s + T_m > 1$. Similar criteria were developed for discrete-variable systems such as qubits[14–16], but are beyond the scope of this letter. Throughout, the unit of noise is the standard quantum limit of the system, in our case the spin-projection noise.

The QSP property describes the ability to generate quantum correlations between meter and output signal variables, that is, at the end point of the QND interaction. This generates (conditional) squeezing[7–10,13,17], a resource for metrology or quantum information, but does not guarantee that the system variable is measured well. In the extreme, the signal and meter could finish in a perfectly correlated state that is completely unrelated to the input signal. In contrast, the IDT property involves the ability to correlate the meter to the input system variable, that is, at the start of the QND interaction. This is valuable for any precise measurement, but does not imply measurement-induced squeezing. For example, the measurement could faithfully copy the signal onto the meter, $\Delta X_m^2 = 0$, before adding two units of quantum noise to the signal, $\Delta X_s^2 = 2$. This satisfies IDT, as $T_s + T_m \approx \frac{4}{3} > 1$, but it leaves the system in an extra-noisy state. To satisfy both QND criteria implies the generation of quantum correlations between the meter and both the input and output states of the system variable. This is important in metrological applications that involve monitoring dynamical variables, such as in quantum waveform estimation[26] or the study of how quantum correlations in degenerate quantum gases evolve[21,22]. Similarly, repeated QND measurements of the same input state that satisfy both criteria are required in various continuous-variable quantum-information applications, for example, proposals for generating non-Gaussian states[19] or protocols for quantum-information processing[24,25]. Some non-QND operations, such as filtering and optimal cloning, can satisfy one or the other criterion[4]. Recently, QND measurement of dynamical variables was placed in a more general theoretical framework by Tsang and Caves[27].

In optics, direct measurement of X_s and X_m can be compared against the QND criteria. With the macroscopic material systems used to date, X_s is not directly measurable with quantum-limited precision. Nevertheless, the statistics of X_m from two repeated QND measurements, for example conditional variances, were used to demonstrate QSP[7–10]. However, the statistics of only two pulses are insufficient to verify the non-classical IDT criterion. Moreover, these experiments used independent measurements of the system coherence before and after the QND measurement to characterize damage done to the initial state and establish the reference quantum noise for verifying QSP. Such measurements are required to establish metrological gain in spin-squeezing experiments, but are not possible in many proposed QND applications, for example with unpolarized atomic ensembles[21–23,28]. As shown by Mitchell *et al.*[29], statistics of three successive QND measurements are sufficient, both to find T_s and T_m and to quantify damage to the measured variable, and thus verify both the QSP and the IDT criteria.

Here, we demonstrate certified QNDs of atomic spins via paramagnetic Faraday rotation in a quantum atom–light interface[30]. In our apparatus, described in detail in Kubasik *et al.*[31] and illustrated in Fig. 1a, we work with an ensemble of $f = 1$ atoms held in an optical dipole trap and interacting with pulses of near-resonant light propagating along the z-axis. The interaction between the atoms and each pulse of light is characterized by an effective Hamiltonian

$$\tau \hat{H} = \kappa \hat{S}_z \hat{J}_z \tag{1}$$

which describes a QND measurement of $\hat{J}_z$ via paramagnetic

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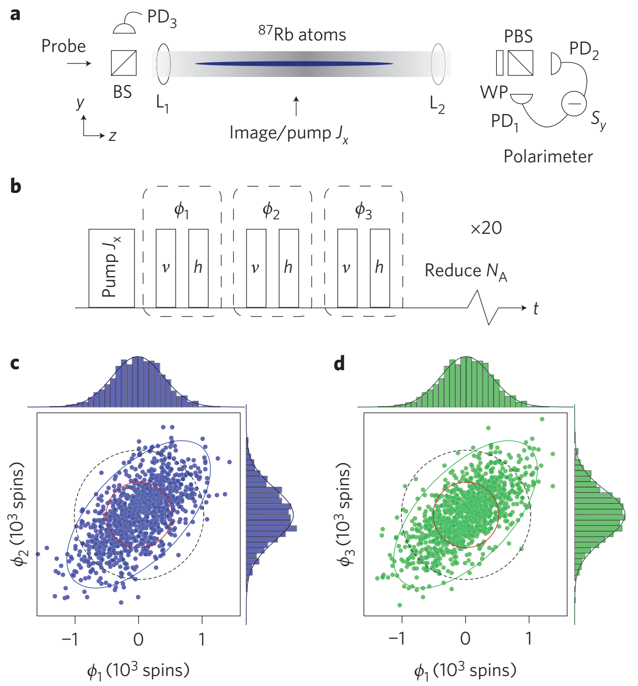

Figure 1 | Experimental set-up and measurement pulse sequence used to verify QND measurement of atomic spins. a, Experimental geometry. PD, photodiode; L, lens; WP, waveplate; BS, beam splitter; PBS, polarizing beam splitter. **b**, Measurement pulse sequence (see text for details). **c**,**d**, Also shown are the correlations between the first two QND measurements (**c**) and the first and third QND measurements (**d**), with $N_A = 8.5 \times 10^5$ atoms. The black dashed circles indicate the projection noise of the input CSS and the red solid circles indicate the measurement read-out noise (due to light shot noise). The ratio of these gives the signal-to-noise of the QND measurement, a measure of the information transfer between the atomic system and meter variable. The difference between the variance of consecutive measurements gives information about the noise introduced into the system variable by the QND measurement. Damage to the system variable $\hat{J}_z$ is quantified by comparing the covariance between the first and third measurements to that between the first and second measurements.

Faraday rotation: pulses of light with an input polarization $\hat{S}_x$ and pulse duration τ experience a polarization rotation $\hat{\varphi}^{(\mathrm{out})} = \hat{\varphi}^{(\mathrm{in})} + \kappa \hat{J}_z^{(\mathrm{in})}$ proportional to the collective atomic spin, with the spin variable left unchanged, $\hat{J}_z^{(\mathrm{out})} = \hat{J}_z^{(\mathrm{in})}$ (see Methods). For multilevel alkali atoms, this effective Hamiltonian can be synthesized using multicolour or dynamical-decoupling probing techniques[7,32].

For convenience, we define a scaled rotation angle $\hat{\phi} \equiv \hat{\varphi}/\kappa$, so that $\hat{\phi}^{(\mathrm{out})} = \hat{\phi}_{\mathrm{RO}} + \hat{J}_z^{(\mathrm{in})}$, where $\hat{\phi}_{\mathrm{RO}} = \hat{S}_y^{(\mathrm{in})}/(\kappa \hat{S}_x^{(\mathrm{in})})$ is the (scaled) input polarization angle. In our experiment the coupling constant κ was calibrated from independent measurements (see Methods), but it can also be extracted from the noise scaling of a known input state[33]. Fluctuations of $\hat{\phi}_{\mathrm{RO}}$ gave the read-out noise $\mathrm{var}(\hat{\phi}_{\mathrm{RO}})$, which is directly observable by measuring without atoms in the trap.

To quantify the QND measurement variances we made three consecutive measurements, $\hat{\phi}_{\{1,2,3\}}$, of $\hat{J}_z$ (see Fig. 1b). The conditional noise reduction was quantified using the first two measurements, $\mathrm{var}(\hat{J}_z|\hat{\phi}_1) \equiv \mathrm{var}(\hat{\phi}_1 - \chi\hat{\phi}_2) - \mathrm{var}(\hat{\phi}_{\mathrm{RO}})$, where $\chi \equiv \mathrm{cov}(\hat{\phi}_1, \hat{\phi}_2)/\mathrm{var}(\hat{\phi}_1)$ (ref. 10). The normalized conditional variance is then[29]

$$\Delta X_{\mathrm{s|m}}^2 \equiv \frac{\mathrm{var}(\hat{J}_z|\hat{\phi}_1)}{r_A J_0} \tag{2}$$

where $J_0 \equiv \langle \hat{J}_x \rangle /2 = N_A/4$ is the projection noise of the input atomic state, established from an independent measurement of the atom number N_A, and r_A is the fraction of atoms that remain in the input state after the interaction.

To quantify the damage r_A to the $\hat{J}_z$ variable because of the QND measurement without resorting to auxiliary measurements requires a comparison of the correlations among all three measurements (see Fig. 1c,d). In Mitchell *et al.*[29] it is shown that $r_A \equiv \widetilde{\mathrm{cov}}(\hat{\phi}_1, \hat{\phi}_3)/\widetilde{\mathrm{cov}}(\hat{\phi}_1, \hat{\phi}_2)$, where the notation $\widetilde{\mathrm{var}}(X) \equiv \mathrm{var}(X) - \mathrm{var}(X_{\mathrm{RO}})$ and $\widetilde{\mathrm{cov}}(X, Y) \equiv \mathrm{cov}(X, Y) - \mathrm{cov}(X_{\mathrm{RO}}, Y_{\mathrm{RO}})$ is introduced for variances and covariances.

The normalized meter and system variances can be written as[29]

$$\Delta X_{\mathrm{m}}^2 \equiv \frac{\mathrm{var}(\hat{\phi}_1) - J_0}{J_0} \tag{3}$$

$$\Delta X_{\mathrm{s}}^2 \equiv \frac{\widetilde{\mathrm{var}}(\hat{\phi}_2) - \widetilde{\mathrm{var}}(\hat{\phi}_1)}{r_A J_0} \tag{4}$$

and can be quantified similarly from the statistics of the three successive measurements. The meter variance ΔX_{m}^2 is a measure of the information transfer between the atomic system and meter variable; $\mathrm{var}(\hat{\phi}_1)$ includes quantum noise from the system variable (atomic projection noise) and a contribution (light shot noise) from the meter variable that should be small to ensure that the system variable is measured with good precision. The system variance ΔX_{s}^2 is a measure of the perturbation to the system variable because of the QND measurement.

We gain insight into the expected behaviour with a simple model of an ideal QND measurement. As described in Hammerer *et al.*[30] and de Echaniz *et al.*[34], we expect a conditional noise reduction by a factor $1/(1 + d_0\eta) + 2\eta$, where $d_0 = (\sigma_0/A)N_A$ is the on-resonance optical depth of the atomic ensemble with σ_0 the on-resonance scattering cross-section and A an effective interaction area, and η is the probability that any given atom suffers decoherence caused by spontaneous scattering from the probe beam. $d_0\eta = \kappa^2 N_A N_L/2$ is the ratio of atomic projection noise $\mathrm{var}(J_z)$ to read-out noise $\mathrm{var}(\hat{\phi}_{\mathrm{RO}})$ at the standard quantum limit, that is, it is the signal-to-noise ratio when a spin-coherent state is measured.

The conditional variance can then be expressed as

$$\Delta X_{\mathrm{s|m}}^2 = \frac{1}{(1 + d_0\eta)(1 - \eta)} + \frac{2\eta}{1 - \eta} \tag{5}$$

Similarly, the measurement noise referred to the input is just the inverse of the signal-to-noise ratio, $\Delta X_{\mathrm{m}}^2 = 1/d_0\eta$, and if we define $\delta J_{\mathrm{s}} \equiv (\widetilde{\mathrm{var}}(\hat{\phi}_2) - \widetilde{\mathrm{var}}(\hat{\phi}_1))/J_0$ (in units of the atomic projection noise) so that $\Delta X_{\mathrm{s}}^2 = \delta J_{\mathrm{s}}/(1 - \eta)$, then we have

$$\Delta X_{\mathrm{m}}^2 \Delta X_{\mathrm{s}}^2 = \frac{\delta J_{\mathrm{s}}}{d_0\eta(1 - \eta)} \tag{6}$$

Equations (5) and (6) have different dependences on d_0 and η, with the result that some conditions satisfy QSP but not IDT and vice versa. As shown in Fig. 2, for sufficient d_0, low η gives QSP, high η gives IDT and intermediate η can give both, that is, QND.

In our experiment we trapped between 3.9×10^4 and 8.5×10^5 ^{87}Rb atoms in a weakly focused single-beam optical dipole trap. We probed the atoms with 2 μs duration pulses of light propagated along the z-axis, with on average 2×10^8 photons per pulse and 0.6 GHz detuned from the D_2 line. The trap geometry produces a large atom–light interaction for light propagating along the trap axis, characterized by the effective on-resonance optical depth d_0. Dynamical-decoupling techniques allow us to

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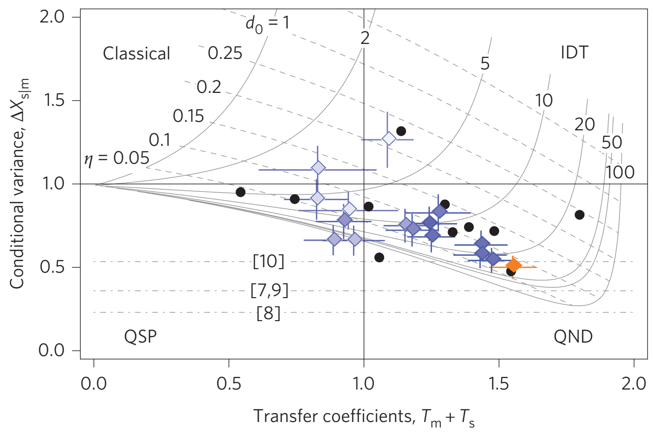

Figure 2 | Experimental verification of QSP and non-classical IDT in a QND measurement of atomic spins. The blue diamonds show the conditional variance and transfer coefficients quantified via three successive QND measurements. The shading represents a change in N_A from 3.9×10^4 (light blue) to 8.5×10 (dark blue). Error bars indicate $\pm 1\sigma$ statistical errors. Orange diamonds show the best-observed QND measurement with $\Delta X^2_{s|m} = 0.64(5)$, $T_m + T_s = 1.72(4)$ and $N_A = 8.5 \times 10^5$. Contours show the simple model described in equations (5) and (6) using the measured disturbance parameter $\delta J_s = 0.3(2)$; solid curves show contours of increasing on-resonant optical depth d_0, and dashed curves show increasing η. For comparison, we also show QND measurements of optical fields (black circles) reviewed in Grangier *et al.*[4] and indicate the demonstrated QSP from spin-squeezing results reported in Sewell *et al.*[10] ([10]), Appel *et al.*[7] ([7]), Chen *et al.*[9] ([9]) and Schleier-Smith *et al.*[8] ([8]) with dot-dashed lines (the transfer coefficients are unknown for these results). We do not include results from Kuzmich *et al.*[5] and Takano *et al.*[6] for lack of an estimate of the damage to the measured state.

make projection-noise-limited measurements of the spin-1 atoms using pairs of alternately h- and v-polarized pulses[32] with a demonstrated spin read-out noise of $(515\ \text{spins})^2$ (ref. 33). From independent measurements, we estimate a maximum optical depth $d_0 = 43.5$ and the probability of damage to any given atom's state because of scattering $\eta = 0.093$ (ref. 10).

The results of the measurement as a function of increasing atom number N_A are shown as blue diamonds in Fig. 2. A conditional variance $\Delta X^2_{s|m} < 1$ indicates successful QSP and results in a spin-squeezed atomic state[10]. With $N_A = 8.5 \times 10^5$ atoms, we measured $\Delta X^2_{s|m} = 0.64(5)$, with a fraction of atoms remaining in the initial state, $r_A = 0.76(4)$. The normalized meter and system variances with the same number of atoms were $\Delta X^2_m = 0.11(5)$ and $\Delta X^2_s = 0.23(1)$, to give $T_m + T_s = 1.72(4) > 1$, which demonstrates a non-classical IDT and thus fulfils both criteria for a certified QND measurement. For comparison, with our parameters the simple model of equations (5) and (6) gives a QSP parameter $\Delta X^2_{s|m} = 0.42(2)$ and IDT parameters $\Delta X^2_m = 0.25(3)$ and $\Delta X^2_s = 0.3(2)$, or $T_m + T_s = 1.6(1)$.

QND measurement techniques play an increasingly important role in diverse applications, from quantum metrology[7–10,17] and quantum memory[18] to proposals for producing[19] and detecting[20] non-Gaussian states, for protocols for continuous-variable quantum-information processing[24,25] and for hybrid quantum devices[35]. The pulsed-measurement techniques demonstrated here can be applied to QND measurements of any continuous variable material system, and complement similar criteria established for discrete-variable experiments[14–16]. They may be particularly useful in experiments in which auxiliary measurements of system coherence are not possible, such as applications that require unpolarized atomic ensembles[23,28]. Also, pulsed QND measurement techniques were used recently to demonstrate ponderomotive squeezing, measurement-induced cooling and quantum-state tomography in nanomechanical oscillators[13]. To verify that both the QSP and IDT criteria of QND measurement are satisfied will be important in applications that require multiple repeated measurements of the same system, such as in monitoring dynamical quantum variables[21,22,26,27] and in some continuous-variable quantum-information protocols[19,24,25].

Methods

Atom–light interaction. The atoms are described by collective spin $\hat{\mathbf{J}} \equiv \sum_n \hat{\mathbf{j}}^{(n)}$ where $\hat{\mathbf{j}}$ is a pseudo-spin-1/2 operator on the $|f=1, m_f = \pm 1\rangle$ subspace and the sum runs over the N_A atoms in the ensemble. The light pulse, with N_L photons on average, is described by the Stokes operator $\hat{S}_i \equiv \frac{1}{2}(a^\dagger_L, a^\dagger_R)\sigma_i(a_L, a_R)^T$ where $a_{L,R}$ are annihilation operators for the left- and right-circular polarizations and σ_i are the Pauli matrices. The input pulses are polarized with $\langle \hat{S}_x \rangle = N_L/2$. To the lowest order in the atom–light coupling constant κ (which depends on the trap and probe-beam geometry, excited-state linewidth, laser detuning and the hyperfine structure of the atom) the interaction described by equation (1) produces a rotation of the state $\hat{O}^{(\text{out})} = \hat{O}^{(\text{in})} - i\tau[\hat{O}^{(\text{in})}, \hat{H}]$. For an input atomic polarization $\langle \hat{J}_x \rangle = N_A/2$, which corresponds to a coherent spin state (CSS), this imprints information about the system variable $\hat{J}_z$ onto the measurement variable $\hat{S}_y$ without changing $\hat{J}_z$

$$\hat{S}^{(\text{out})}_y = \hat{S}^{(\text{in})}_y + \kappa \hat{S}^{(\text{in})}_x \hat{J}^{(\text{in})}_z \tag{7}$$

$$\hat{J}^{(\text{out})}_z = \hat{J}^{(\text{in})}_z \tag{8}$$

which describe a QND measurement of the collective atomic spin $\hat{J}_z$. The parameter $\kappa \hat{S}_x$ parametrizes the strength of the coupling between the atoms and light; however, increasing $\kappa \hat{S}_x$ also increases damage to the atomic state via spontaneous scattering[30].

Measurement cycle. In each experimental cycle we prepared a CSS $\langle \hat{J}_x \rangle = N_A/2$ via optical pumping and made three successive QND measurements using a train of pulses of light with alternating h and v polarization, at a detuning of 600 MHz to the red of the $f = 1 \rightarrow f' = 0$ transition on the D_2 line, detected by a shot-noise-limited polarimeter. We synthesized the interaction described in equation (1) by combining the measurement results of consecutive pulses with orthogonal polarization[10,32]. We varied the number of atoms, N_A, from 3.9×10^4 and 8.5×10^5 by briefly switching off the optical dipole trap for 100 μs after each measurement, which reduced the atom number by ~15%, and repeating the sequence 20 times per trap-loading cycle. At the end of each cycle the measurement was repeated without atoms in the trap. To collect statistics, the entire cycle was repeated ~1,000 times.

Calibration. The coupling constant $\kappa = 1.47 \times 10^{-7}$ radians per spin is calibrated against a measurement of the atom number made by absorption imaging[33]. To account for the spatial variation in the coupling between the probe beam and the trapped atoms, we defined an effective atom number such that the parametric Faraday rotation signal was proportional to the total number of atoms, and the expected variance of the measurement variable was $\text{var}(\hat{J}_z) \equiv N_A/4$ (refs 7–9). For our trap and probe geometry $N_A = 0.9 N_A^{(\text{total})}$ (ref. 10).

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Author contributions

R.J.S. and M.W.M. conceived and designed the project; R.J.S., M.N., N.B. and G.C. performed the experiment; R.J.S. performed the data analysis; R.J.S. and M.W.M. co-wrote the manuscript with feedback from all the authors.

Additional information

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Competing financial interests

The authors declare no competing financial interests.

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