Observation of a phononic Mollow triplet in a multimode hybrid spin-nanomechanical system

B. Pigeau, S. Rohr, L. Mercier de Lépinay, A. Gloppe, V. Jacques & O. Arcizet

Reminiscent of the bound character of a qubit’s dynamics confined on the Bloch sphere, the observation of a Mollow triplet in the resonantly driven qubit fluorescence spectrum represents one of the founding signatures of quantum electrodynamics. Here we report on its observation in a hybrid spin-nanomechanical system, where a nitrogen-vacancy spin qubit is magnetically coupled to the vibrations of a silicon carbide nanowire. A resonant microwave field turns the originally parametric hybrid interaction into a resonant process, where acoustic phonons are now able to induce transitions between the dressed qubit states, leading to synchronized spin-oscillator dynamics. We further explore the vectorial character of the hybrid coupling to the bidimensional deformations of the nanowire. The demonstrated microwave assisted synchronization of the spin-oscillator dynamics opens novel perspectives for the exploration of spin-dependent forces, the key ingredient for quantum state transfer.

Institut Néel, CNRS et Université Grenoble Alpes, 38042 Grenoble, France. Laboratoire Charles Coulomb, Université de Montpellier and CNRS, 34095 Montpellier, France. Correspondence and requests for materials should be addressed to O.A. (email: olivier.arcizet@neel.cnrs.fr).
A mechanical oscillator coupled to a two-level system is a versatile basis to study the interaction between macroscopic and purely quantum objects. This unconventional combination\(^1\) is a promising route towards the generation of non-classical states of motion of macroscopic objects. Hybrid-coupling signatures have now been demonstrated between a mechanical oscillator and Bose–Einstein condensates\(^3\),\(^4\), superconducting qubits\(^5\)\(^–\)\(^7\), solid-state single spins\(^8\)\(^–\)\(^17\), molecules\(^18\) or quantum dots\(^18\)\(^–\)\(^23\).

The hybrid interaction coupling phonons and qubits is in profound analogy with quantum electrodynamics (QED) where hallmark experiments revealing the interplay between atoms and photons have permitted exploring the foundations of quantum mechanics. In particular, the appearance of a Mollow triplet in atomic fluorescence spectra\(^2\)\(^4\), characterized by the onset of sidebands appearing on each side of the pump frequency with splitting proportional to the laser field strength, is one of the characteristic signatures of the strongly driven Jaynes–Cummings interaction. Along with the Autler–Townes doublet\(^2\)\(^5\) or vacuum Rabi oscillations, it expresses the dressing of the atom with the optical photon field\(^2\)\(^6\). Since then, Mollow triplets were observed in atomic vapours\(^2\)\(^7\),\(^2\)\(^8\) single molecule\(^2\)\(^9\),\(^3\)\(^0\) single quantum dot\(^3\)\(^1\),\(^3\)\(^2\) or superconducting qubits\(^3\)\(^3\) coupled to photon fields in the optical or microwave (MW) domain.

Here we report on the observation of a phononic Mollow triplet, where the phonon field of a nanomechanical oscillator dresses a MW-dressed single spin-qubit immersed in a strong magnetic field gradient. We investigate the dynamics of the spin qubit in presence of large mechanical drive when the spin precession gets locked onto the mechanical-driving tone. We exploit the bidimensional deformations of the nanowire fundamental eigenmodes to fully investigate the vectorial character of the hybrid coupling. This also represent a novel dynamical regime for hybrid qubit-nanomechanical systems: the observed synchrononization of the spin precession onto the mechanical oscillation frequency opens new detection strategies for observing spin-dependent forces.

**Results**

**Hybrid spin-nanomechanical interaction.** Our hybrid device consists of a single nitrogen-vacancy (NV) spin-qubit hosted in a diamond nanocrystal attached to the vibrating extremity of a silicon carbide (SiC) nanowire\(^1\)\(^0\). A strong magnetic field gradient couples both components through a spatially dependent Zeeman effect (Fig. 1a). Formally, the generic hybrid spin-oscillator Hamiltonian can be expressed as

\[
\hat{h}_{\text{hyb}} = \hbar \Omega_0 \sigma_z + \hbar \Omega_m(a^+ + \frac{1}{2}) + \hbar g \sigma_z (a + a^+),
\]

where \(\omega_0/2\pi\) is the qubit energy, \(\Omega_m/2\pi\) the oscillator frequency, \(a(a^+)\) the phonon creation (annihilation) operator, \(\sigma\) the Pauli matrices of the spin-qubit quantized along the \(z\) axis and \(g\) the respective coupling constants. In QED, a distinction between the transverse and parametric regimes can be made. In the first situation, described by the interaction Hamiltonian \(\hbar g \sigma_z (a + a^+)\), the mechanical oscillator and qubit can coherently exchange single excitations if they have similar frequencies. Several hybrid mechanical systems are exploring this regime, either through a direct interaction\(^6\),\(^3\)\(^4\),\(^3\)\(^5\) or mediated by a bus cavity\(^7\),\(^3\)\(^6\),\(^3\)\(^7\). In the case of parametric hybrid-coupling, the mechanical motion modulates the qubit energy according to the coupling Hamiltonian \(\hbar g \sigma_z (a + a^+\rangle\). Reciprocally, the qubit exerts a state dependent force on the oscillator which represents the key ingredient for quantum state transfer between both components. This configuration enables hybrid coupling between components with totally different excitation energies. Moreover by employing a resonant MW tone driving Rabi precession of the qubit at frequencies \(\Omega_m/2\pi\) close to the mechanical frequency, it is possible to let both components of the hybrid system evolve on similar time scales\(^1\)\(^2\),\(^1\)\(^3\)\(^8\). By doing so the parametric interaction with the original qubit is turned into a transverse coupling to the MW-dressed qubit. This configuration enables the observation of a phononic Mollow triplet, provided that the phonon field is coherently driven and that the oscillator frequency is larger than the qubit decay rate \(\Gamma_{\text{spin}}\), which corresponds to the so-called resolved sideband regime \((\Omega_m > \Gamma_{\text{spin}}\rangle\) (ref. 16) of the parametric interaction. In that situation we introduce the dynamical parametric modulation strength \(\delta \omega_m\), which denotes the classical amplitude of the mechanically driven parametric modulation (Fig. 1b).

The bidimensional vibration properties of our nanowires were described in ref. 39. First signatures of parametric coupling of a single NV spin-qubit to the vibrations of a nanowire were reported in ref. 10 in the adiabatic regime through continuous spin-qubit electron spin resonance spectroscopy. The mechanism of spin locking on a time varying RF field was first observed in ref. 15 and suggested the possibility to observe a phononic Mollow triplet in our hybrid spin-nanomechanical system. Formally, this required entering the resolved sideband regime, developing fast and stable dynamical actuation and readout capacity of the suspended spin qubit and coping with the bidimensional character of the spin-qubit trajectories in space. This permitted thereby a full exploration of the intrinsically vectorial nature of the hybrid parametric coupling.

**Experimental setup.** The experimental setup is sketched in Fig. 1a. The nanomechanical oscillator is a 6-μm-long SiC nanowire of 300 nm diameter, suspended from a sharp metallic tip. Its moving extremity is functionalized with a \(\approx 50\) nm nano-diamond hosting a single NV defect. The hybrid system is investigated with a confocal microscope apparatus (Supplementary Fig. 1) and a 532-nm laser. It serves for both measuring the vibrations of the nanowire using either the transmitted or reflected light beams and for optical polarization and readout of the qubit using spin-state dependent fluorescence detection\(^1\)\(^0\), see Supplementary Fig. 2.

Measurements of the nanowire Brownian motion permit determining the mechanical properties of the fundamental flexural eigenmodes\(^3\)\(^9\). These are aligned along two perpendicular directions \(e_{1,2}\) (see Fig. 1f, tilted by \(\approx 10^\circ\) with respect to the optical axis, at frequencies \(\Omega_m/2\pi\) (\(m = 1\) or 2) of 5.99 and 6.29 MHz respectively, with mechanical damping rates \(\Gamma_{m}/2\pi\) of 180 (190) kHz in air, limited by acoustic emission. The measured effective masses of \(M_m \approx 10^{-15}\) kg correspond to a spatial spreading of their Brownian motion over \(\Delta x_m = (k_BT/M_m\Omega_m^2)^{1/2}\) \(\approx 52\) pm with zero-point fluctuations of \(\Delta x_m \approx 36\) fm. Using a resonant force actuation \(\delta F\), either piezoelectric or electrostatic, it is possible to drive vibrations of the the nanowire around its rest position \(r_0\). Its vectorial deflection \(\delta r(t)\) can thus be expressed in frequency space as:

\[
\delta r(\Omega) = \sum_{m=1,2} \chi_m(\Omega) \left( \delta F^{\text{r.m.}}(\Omega) + \delta F(\Omega) \cdot e_m \right) e_m,
\]

using the mechanical susceptibilities \(1/\chi_m(\Omega) \equiv M_m(\Omega_m^2 - \Omega^2 - i\Omega \Gamma_m)\) and the independent Langevin forces \(\delta F^{\text{r.m.}}(\Omega)\). By adjusting the drive frequency as well as the orientation \(e_{\text{ph}}\) of the force vector with respect to the nanowire eigenmodes it is thus possible to generate different trajectories in the oscillation plane. This will permit exploring the vectorial character of the magnetic hybrid interaction.

The backscattered fluorescence of the NV defect is collected by avalanche photodiodes arranged in a Hanbury Brown and Twiss
Figure 1 | A hybrid spin-qubit-nanomechanical system. (a) A single NV spin-qubit hosted in a diamond nanocrystal is attached at the oscillating extremity of a suspended SiC nanowire. A strong magnetic field gradient source is micro-positioned in the vicinity of the hybrid system to magnetically couple the spin state to the vibrations of the nanoresonator through the Zeeman effect. (b) In the parametric coupling regime, the mechanical motion modulates the qubit energy with an amplitude \( \delta \omega_0 \). E/\( 2\pi \) is the MW driven Rabi frequency \( \omega_0 \). (c) Scanning fluorescence image of the hybrid device (1 \( \mu \)m scale bar). (d) Autocorrelation function of the NV spin-qubit fluorescence revealing the presence of a single defect. (e) ESR spectroscopy of the suspended spin qubit in a weak magnetic field, highlighting the spin-state dependence of the average emitted fluorescence (FWHM \( \approx 4 \) MHz). (f) Brownian motion of the nanowire measured in reflection (below) revealing the two fundamental eigenmodes, which can be coherently driven through electrostatic or piezo actuations. The response curve (above) permits to determine the local orientation \( \mathbf{e}_r \) of the force vector as well as its magnitude.49.

Determination of the vectorial parametric coupling strength

To determine the vector parametric coupling strength, the spatial dependence of the spin-qubit energy \( \omega_0(t) \) was measured by collecting the NV fluorescence while scanning the position of the micromagnet in presence of a continuous MW tone. Typical fluorescence maps are shown in Fig. 2d for varying MW frequencies. The projections of the qubit iso-energy surfaces on the oscillation plane, see Fig. 2d, appear as dark resonant slices. In addition, a global fluorescence quenching which indicates regions with a strong off-axis magnetic field. Reproducing this measurement for varying MW frequencies permits determination of \( \omega_0(t) \) (Fig. 2f). When moving in those strong magnetic field gradients, the suspended spin qubit undergoes a dynamical parametric energy modulation of \( \delta \omega_0(t) = \delta \mathbf{r}(t) \cdot \nabla \omega_0(t) \), which is determined by evaluating the gradient of the iso-energy map in the \( \mathbf{e}_1, \mathbf{e}_2 \) oscillating plane. The mapping of the vectorial coupling strength \( \lambda \equiv \mathbf{r} \mathbf{e}_1 \) measured in a 10 \( \times \) 2.5 \( \mu \)m² horizontal area in front of the magnetic bead is reproduced in Fig. 2f. Inherent to the dipolar structure of the microbead magnetic stray field, it strongly varies in magnitude and in orientation \( \mathbf{e}_2 \) which permits a fine adjustment of the vectorial coupling strength with respect to the eigenmodes orientations by properly nano-positioning the micromagnet. Furthermore analysis of the fluorescence quenching in this imaging procedure also permits a direct identification of the locations where the B field is properly aligned with the NV quantization axis (Fig. 2c, d), which
is a key requirement to ensure efficient optical spin-state readout. Finally, the triple requirement of avoiding fluorescence quenching, polarizing the nitrogen atom spin and operating with a large parametric coupling strength compete in determining the best location in space where to operate the experiment.

Qubit dynamics in presence of coherent mechanical motion. Having thus fully characterized the static properties of the system, we now investigate the qubit dynamics in presence of coherent mechanical motion, generated by a modulated piezoelectric-driving force. We first restrict our analysis to one single mechanical mode \((m = 2)\) by positioning the gradient source at a location allowing a large parametric coupling strength along the \(e_2\) orientation and tuning the external drive frequency \(\Omega_d/2\pi\) to the resonance of the second eigenmode (6.29 MHz). The qubit is initialized in its ground state with laser illumination while the MW power is adjusted so that \(\Omega_d/2\pi\) exceeds the spin decay rate. It can be estimated to \(\Gamma_{\text{spin}} \approx 100\text{KHz}\) from the decay time of Rabi oscillations in the vibrating case.

**Figure 3** | A phononic Mollow triplet. (a) Evolution of the spin population when the spin qubit is at rest (top) and oscillating in space (bottom) with a piezo driven 5 nm amplitude along \(e_2\). (b) Magnitude of the corresponding Fourier transforms. A characteristic triplet structure is observed when the spin is oscillating at \(\Omega_d \approx \Omega_b\). (c) Triplet separation as a function of the oscillation amplitude. The fit corresponds to a parametric coupling strength of 0.5 MHz nm\(^{-1}\). (d) Dependence of the triplet structure on the Rabi frequency \(\Omega_d/2\pi\) detuning. (e) The phonon field is dressing the MW-dressed qubit (see text). The measured Rabi oscillations represent a time-resolved measurement of the dipole of the dressed qubit, whose spectrum reflects the allowed transitions between the phonon-dressed multiplicities. The Mollow triplet appears when the oscillation amplitude is large enough to create a parametric energy modulation \(\delta\Omega\) that exceeds the spin decay rate. It can be estimated to \(\Gamma_{\text{spin}} \approx 100\text{KHz}\) from the decay time of Rabi oscillations in the vibrating case.
A doubly dressed spin qubit. These observations can be explained by a double dressing of the spin qubit with MW photon and acoustic phonon fields as follows. The resonant interaction of the MW pump field with the qubit can be described in the dressed states basis $|\pm N\rangle$, see Fig. 3e, parameterized by the number of excitations $N$ shared between the qubit and the MW pump field. Under intense coherent excitation, the dynamics of the spin-MW (polariton-like) subsystem can be formally described by a pseudo qubit ($|\pm\rangle$), see Supplementary Note 4, quantized along the MW polarization axis with a characteristic energy splitting of $\Omega_d/2\pi$ (ref. 49). As a consequence of this rotation of perspective in the Bloch sphere, the respective roles of the $\sigma_y$, $\sigma_z$ operators are consequently exchanged. Therefore, the phonon field parametrically coupled to the spin qubit ($\propto (a + a^\dagger)\sigma_z$) is now able to resonantly drive the pseudo qubit, if the resonance condition $\Omega_\delta \approx \Omega_d$ is met. This second interaction can similarly be described by a second dressing of the pseudo qubit by the phonon field. This gives rise to a ladder of phonon dressed states, see Fig. 3e, with eigenstates $|\pm M\rangle$ parameterized by the number $M$ of phononic and dressed qubit excitations. The energy splitting within multiplicities can be expressed as (Supplementary Note 4) $\Delta_{Mollow} = \left(\Omega_d - \Omega_\delta\right)/2 + \delta\omega_0|\Omega_d|/4\lambda^2$, which simplifies to $\delta\omega_0|\Omega_d|/2 = |\delta\Omega_\delta|/2\lambda$ when the phononic dressing field frequency $\Omega_d/2\pi$ is resonant with the dressed qubit energy splitting $\Omega_\delta/2\pi$. As a consequence the spectrum of Rabi oscillations is peaked at frequencies corresponding to the allowed transitions for the $\sigma_z$ operator (Fig. 3e and Supplementary Fig. 3).

Measuring the temporal evolution of the spin-qubit population $\langle \sigma_z(t) \rangle$ indeed permits to record the temporal evolution of the dipole of the MW-dressed qubit ($|\pm\sigma\rangle$) (ref. 49), see Supplementary Note 4. This dipole governs the dressed qubit emission (in analogy with the atomic case), whose spectrum (Fig. 3b) reflects the cascade among phononic dressed states. This situation is precisely the one permitting the observation of a Mollow triplet in QED when the atomic fluorescence spectrum under intense illumination was measured. An important distinction is that here the time resolved evolution of the ‘atomic’ dipole (the dressed qubit) is accessible.

Multimode phononic Mollow triplet. To fully explore the vectorial character of the parametric interaction, we now sweep the drive tone across both the mechanical eigenfrequencies. This permits moving the qubit in both directions in the $(e_x, e_y)$ oscillating plane. For each drive frequency, the MW power is adjusted to reach the resonant condition $\Omega_\delta \approx \Omega_d$. The measured Mollow triplet spectra are acquired and shown in Fig. 4a. The central component of the triplets is locked onto the drive frequency $\Omega_d$, while the splitting of the Mollow triplet presents two maxima, corresponding to the response of each eigenmode. To properly understand the observed signature, it is necessary to precisely determine the spatial trajectories followed by the moving spin-qubit. To do so, an optical measurement similar to the one shown in Fig. 1c permits establishing the local orientation of $e_\delta$ and magnitude $|\delta F|$ of the electrostatic-driving force field and determining the driven trajectories $\delta r(t) = Re\{i|\delta F|e^{-i\Omega_d t}\}$ using equation (1). The slight spectral overlap between the eigenmodes leads to elliptical trajectories (Fig. 4b) which explore the oscillation plane and the magnetic field gradient over nanometric distances. Finally, the Mollow triplet’s motional splitting can be adjusted with, see Supplementary Note 2:

$$\delta\omega_0[\Omega] = \sum_{m=-1,2} x_m[\Omega] \langle \delta F [\Omega] \cdot e_m | e_m \cdot \lambda \rangle .$$

both the deduced magnitude $(|\lambda|/2\pi = 0.5 \text{ MHz nm}^{-1})$ and the orientation $(e_x$ reported in Fig. 4b) of the vectorial coupling constant $\lambda$ are in good agreement with the static measurements described above, at the position marked in Fig. 2f. Geometrically, the magnitude of the parametric coupling strength corresponds to the length of the projection of the ellipses on the $e_x$ axis. Pursuing this geometrical approach, it is possible to introduce a characteristic length, $\delta_{Mollow} = \Gamma_{\text{spin}}/|\nabla\omega_0| \approx 200 \text{ pm}$, here

$$\delta_{Mollow} \equiv \Gamma_{\text{spin}}/|\nabla\omega_0|$$

the Mollow triplet structure. This is precisely the one permitting the observation of a Mollow triplet in QED when the atomic fluorescence spectrum under intense illumination was measured. An important distinction is that here the time resolved evolution of the ‘atomic’ dipole (the dressed qubit) is accessible.

Multimode phononic Mollow triplet. To fully explore the vectorial character of the parametric interaction, we now sweep the drive tone across both the mechanical eigenfrequencies. This permits moving the qubit in both directions in the $(e_x, e_y)$ oscillating plane. For each drive frequency, the MW power is adjusted to reach the resonant condition $\Omega_\delta \approx \Omega_d$. The measured Mollow triplet spectra are acquired and shown in Fig. 4a. The central component of the triplets is locked onto the drive frequency $\Omega_d$, while the splitting of the Mollow triplet presents two maxima, corresponding to the response of each eigenmode. To properly understand the observed signature, it is necessary to precisely determine the spatial trajectories followed by the moving spin-qubit. To do so, an optical measurement similar to the one shown in Fig. 1c permits establishing the local orientation of $e_\delta$ and magnitude $|\delta F|$ of the electrostatic-driving force field and determining the driven trajectories $\delta r(t) = Re\{i|\delta F|e^{-i\Omega_d t}\}$ using equation (1). The slight spectral overlap between the eigenmodes leads to elliptical trajectories (Fig. 4b) which explore the oscillation plane and the magnetic field gradient over nanometric distances. Finally, the Mollow triplet’s motional splitting can be adjusted with, see Supplementary Note 2:

$$\delta\omega_0[\Omega] = \sum_{m=-1,2} x_m[\Omega] \langle \delta F [\Omega] \cdot e_m | e_m \cdot \lambda \rangle .$$

both the deduced magnitude $(|\lambda|/2\pi = 0.5 \text{ MHz nm}^{-1})$ and the orientation $(e_x$ reported in Fig. 4b) of the vectorial coupling constant $\lambda$ are in good agreement with the static measurements described above, at the position marked in Fig. 2f. Geometrically, the magnitude of the parametric coupling strength corresponds to the length of the projection of the ellipses on the $e_x$ axis. Pursuing this geometrical approach, it is possible to introduce a characteristic length, $\delta_{Mollow} = \Gamma_{\text{spin}}/|\nabla\omega_0| \approx 200 \text{ pm}$, here...
(reported in Fig. 4b), which represents the minimum oscillation amplitude along $e_i$ necessary to resolve the phononic Mollow triplet. It is interesting to point out that this quantity is comparable to the spatial spreading of the nanowire Brownian motion of $\approx 52 \text{ pm}$, responsible for an equivalent incoherent parametric modulation of $\Delta o_0^{\text{inh}} = \Delta \omega_0 \approx 2 \times 25 \text{ kHz}$, which could alter the Mollow triplet structure in larger magnetic field gradients. Understanding the coherence properties of the dressed qubit and the contribution of Brownian motion will be the subject of future investigation.

Discussion

We have demonstrated the observation of a phononic Mollow triplet in a spin-nanomechanical hybrid system, reproducing with phonons and a spin qubit one of the founding signatures of QED based on photons and atoms. The observed signatures also demonstrate the synchronization of the spin precession onto the mechanical oscillation frequency. This opens the road towards demonstrating the synchronization of the spin precession onto the triplet in a spin-nanomechanical hybrid system, reproducing with photons and atoms. The observed signatures also show the direct mechanism for creating single phonons sources through cascaded phonon emission within the dressed state ladder.

References

1. Schwab, K. & Roukes, M. Putting mechanics into quantum mechanics. Phys. Today 58, 36–42 (2005).
2. Trehuilem, P., Genes, C., Hamaker, K., Poggio, M. & Ralph, P. Hybrid Mechanical Systems (Springer, 2011).
3. Camerer, S. et al. Optical force microscopy. Phys. Rev. Lett. 107, 223001 (2011).
4. Jochel, A. et al. Sympathetic cooling of a molecular oscillator in a hybrid mechanical-atomic system. Nat. Nanotechnol. 10, 55–59 (2015).
5. LaHaye, M. D., Suh, J., Echtner, P. M. Schwab, K. C. & Roukes, M. L. Nanomechanical measurements of a superconducting qubit. Nature 459, 960–964 (2009).
6. O’Connell, A. D. et al. Quantum ground state and single-photon control of a mechanical resonator. Nature 464, 697–703 (2010).
7. Girakalinen, J. M. et al. Hybrid circuit cavity quantum electrodynamics with a nanomechanical resonator. Nature 494, 211–215 (2013).
8. Rugar, D., Budakian, R., Mamin, H. J. & Chui, B. W. Single spin detection by magnetic resonance force microscopy. Nature 430, 329–332 (2004).
9. Rabl, P. et al. Strong magnetic coupling between and electronic spin qubit and a mechanical oscillator. Phys. Rev. B 79, 041302 (2009).
10. Arcizet, O. et al. A single nitrogen-vacancy defect coupled to a nanomechanical oscillator. Phys. Rev. Lett. 111, 023601 (2013).
11. Kolkowitz, S. et al. Coherent sensing of a mechanical resonator with a single-spin qubit. Science 335, 1603–1606 (2012).
12. Bennett, S. D. et al. Measuring mechanical motion with a single spin. New. J. Phys. 14, 125004 (2012).
13. Hong, S. et al. Coherent mechanical control of a single electronic spin. Nano Lett. 12, 3920–3924 (2012).
14. Ganzhorn, M. et al. Strong spin-phonon coupling between a single-molecule magnet and a carbon nanotube nanoelectromechanical system. Nat. Nanotechnol. 8, 165 (2013).
15. Rohr, S. et al. Synchronizing the dynamics of a single nitrogen vacancy spin qubit on a parametrically coupled radio-frequency field through microwave dressing. Phys. Rev. Lett. 112, 016802 (2014).
16. Teissier, J., Barfuss, A., Appel, P.-E. & Maitlinsky, P. Strain coupling of a nitrogen-vacancy center spin to a diamond mechanical oscillator. Phys. Rev. Lett. 113, 020503 (2014).
17. Ovartchaiyapong, P., Lee, K. W., Myers, B. A. & Jayich, A. C. Dynamic strain-mediated coupling of a single diamond spin to a mechanical resonator. Nat. Commun. 5, 4429 (2014).
18. Tian, Y., Navarro, P. & Orrit, M. A single molecule as a local acoustic detector for mechanical oscillators. Phys. Rev. Lett. 113, 135505 (2014).
19. Lasagni, B. et al. Coupling mechanics to charge transport in carbon nanotube mechanical resonators. Science 325, 1107–1110 (2009).
20. Steele, G. et al. Strong coupling between single-electron tunneling and nanomechanical motion. Science 325, 1103–1107 (2009).
21. Salen, G. et al. Exciton dynamics of a single atomic quantum dot embedded in a nanowire. Phys. Rev. B 80, 053310 (2009).
22. Bennett, S., Cockins, L., Miyahara, Y., Grutter, P. & Clerk, A. Strong electromechanical coupling of an atomic force microscope cantilever to a quantum dot. Phys. Rev. Lett. 104, 017203 (2010).
23. Yo, I. et al. Spin-mediated coupling in a quantum dot-mechanical oscillator hybrid system. Nat. Nanotechnol. 9, 106–110 (2014).
24. Mollow, B. Power spectrum of light scattered by two-level systems. Phys. Rev. 188, 1969 (1969).
25. O’Connell, A. D. & Townes, C. Stark effect in rapidly varying fields. Phys. Rev. 100, 705 (1955).
26. Hounsfield, J. & Raimond, J. M. Exploring the Quantum (Oxford University Press, 2006).
27. Wu, F. Y., Grove, R. E. & Ezekiel, S. Investigation of the spectrum of resonance fluorescence induced by a monochromatic field. Phys. Rev. Lett. 35, 1426 (1975).
28. Schabert, A., Keil, R. & Toschek, P. Dynamic stark effect of an optical line observed by cross-saturated absorption. Appl. Phys. 6, 181–184 (1975).
29. Wrigge, C., Gerhardt, I., Hwang, J., Zamolet, G. & Sandoghdar, V. Efficient coupling of photons to a single molecule and the observation of its resonance fluorescence. Nature 4, 60–66 (2008).
30. Tamarat, P. et al. Pump-probe experiments with a single molecule: ac-stark effect and nonlinear optical response. Phys. Rev. Lett. 75, 1514–1517 (1995).
31. Nick Vamvakas, A., Zhao, Y., Lu, C. Y. & Nature, M. Spin resolved quantum-dot resonance fluorescence. Nat. Phys. 5, 198–202 (2009).
32. Flagg, E. B. et al. Resonantly driven coherent oscillations in a single-state quantum emitter. Nat. Phys. 5, 203–207 (2009).
33. Baur, M. et al. Measurement of aturer-towns and mellow transitions in a strongly driven superconducting qubit. Phys. Rev. Lett. 102, 243602 (2009).
34. Schaller, D. et al. Resonant coupling of a bose-einstein condensate to a microelectromechanical oscillator. Phys. Rev. Lett. 104, 143002 (2010).
35. MacQuarrie, E. R., Gosavi, T. A., Jungwirth, N. R., Bhaye, S. A. & Fuchs, G. D. Mechanical spin control of nitrogen-vacancy centers in diamond. Phys. Rev. Lett. 111, 227602 (2013).
36. Lecocq, F., Teufel, J. D., Aumentado, J. & Simmons, R. W. Relaxing vacuum fluctuations of micromechanical motion using a phonon. Nat. Phys. 11, 635–639 (2015).
37. Restrepo, J. C., Ciuti, C. & Farrow, I. Single-polariton optomechanics. Phys. Rev. Lett. 112, 013601 (2014).
38. Saiko, A. P., Fedaruk, R. & Markevich, S. A. Relaxation, decoherence, and steady-state population inversion in qubits doubly dressed by microwave and radiofrequency fields. J. Phys. B: At. Mol. Opt. Phys. 47, 155304 (2014).
39. Gloppe, A. et al. Bidimensional nano-optomechanics and topological backaction in a non-conservative radiation force field. Nat. Nanotechnol. 9, 920–926 (2014).
40. Jelezko, F., Gaebel, T., Popa, I., Gruber, A. & Wrachtrup, J. Observation of coherent oscillations in a single electron spin. Phys. Rev. Lett. 92, 076401 (2004).
41. Mercier de Lépinay, L. et al. Nanooptomechanical measurements in the photon counting regime. Preprint at http://arxiv.org/abs/1503.03200 (2015).
42. Jacques, V. et al. Dynamic polarization of single nuclear spins by optical pumping of nitrogen-vacancy color centers in diamond at room temperature. Phys. Rev. Lett. 102, 057403 (2009).
43. Møller, B., McIntyre, J. & Childress, L. Robust control of individual nuclear spins in diamond. Phys. Rev. A. 80, 050302 (2009).
44. Balasubramanian, G. et al. Nanoscale imaging magnetometry with diamond spins under ambient conditions. Nature 455, 648 (2008).
45. Degen, C. L. et al. Nanoscale magnetic resonance imaging. Proc. Natl Acad. Sci. 106, 1313–1317 (2009).
46. Malinowski, P. et al. A robust scanning diamond sensor for nanoscale imaging with single nitrogen-vacancy centres. Nat. Nanotechnol. 7, 320–324 (2012).
47. Rondin, L. et al. Magnetometry with nitrogen-vacancy defects in diamond. Rep. Prog. Phys. 77, 056503 (2014).
Acknowledgements
We thank C. Fabre, G. Nogues, O. Buisson, J.-F. Roch, J.-P. Poizat, P. Vincent, P. Poncharal, A. Auffeves, A. Kuhn, P. Verlot, E. Dupont-Ferrier, C. Hoarau, D. Lepoittevin and E. Eyraud for theoretical, experimental and technical assistance. This work was supported by the Agence Nationale de la Recherche (RPDoc-2010, FOCUS 2013), Lanef (CryOptics) and the European Research Council (ERC-StG-2012, HQ-NOM). S.R. acknowledges funding from the Nanoscience Foundation.

Author contributions
All authors contributed to all aspects of the work.

Additional information
Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing financial interests: The authors declare no competing financial interests.

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/

How to cite this article: Pigeau, B. et al. Observation of a phononic Mollow triplet in a multimode hybrid spin-nanomechanical system. Nat. Commun. 6:8603 doi: 10.1038/ncomms9603 (2015).

This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/