Single-Shot Nondestructive Detection of Rydberg-Atom Ensembles by Transmission Measurement of a Microwave Cavity

Journal Article**Author(s):**

Garcia, S.; Stammeier, Mathias; Deiglmayr, Johannes; Merkt, Frédéric; Wallraff, Andreas

Publication date:

2019-11-08

Permanent link:

<https://doi.org/10.3929/ethz-b-000378857>

Rights / license:

In Copyright - Non-Commercial Use Permitted

Originally published in:

Physical Review Letters 123(19), <https://doi.org/10.1103/PhysRevLett.123.193201>

This article may be downloaded for personal use only. Any other use requires prior permission of the author and The American Physical Society (APS).

The following article appeared in *Phys. Rev. Lett.* **123**, 193201 (2019) and may be found at <https://doi.org/10.1103/PhysRevLett.123.193201>.

Single-Shot Nondestructive Detection of Rydberg-Atom Ensembles by Transmission Measurement of a Microwave Cavity

S. Garcia^{1,*}, M. Stammeier¹, J. Deiglmayr^{2,†}, F. Merkt², and A. Wallraff¹

¹*Department of Physics, ETH Zürich, CH-8093 Zürich, Switzerland*

²*Laboratorium für Physikalische Chemie, ETH Zürich, CH-8093 Zürich, Switzerland*

(Received 21 January 2019; published 8 November 2019)

We present an experimental realization of single-shot nondestructive detection of ensembles of helium Rydberg atoms. We use the dispersive frequency shift of a superconducting microwave cavity interacting with the ensemble. By probing the transmission of the cavity, we determine the number of Rydberg atoms or the populations of Rydberg quantum states when the ensemble is prepared in a superposition. At the optimal microwave probe power, determined by the critical photon number, we reach single-shot detection of the atom number with 13% relative precision for ensembles of about 500 Rydberg atoms with a measurement backaction characterized by approximately 2% population transfer.

DOI: [10.1103/PhysRevLett.123.193201](https://doi.org/10.1103/PhysRevLett.123.193201)

Rydberg atoms have extreme properties [1,2] which are used in many experiments investigating quantum computation [2–4], quantum simulation [5–7], quantum optics [8–12], or chemical reaction dynamics [13–15]. The standard technique for the detection of Rydberg atoms relies on field ionization followed by the counting of ions or electrons using an avalanche detector [1]. More recently, experiments with arrays of trapped single atoms [5–7] detect Rydberg excitations by ground-state atom loss with fluorescence imaging. Both methods are efficient but destructive. Nondestructive detection offers tools for quantum-state engineering, in particular with characterization of the initial state, measurement-induced multipartite entanglement [16,17], quantum Zeno effect [18,19] and quantum feedback [20,21]. Rydberg atoms can be detected non-destructively with optical photons using electromagnetically induced transparency [22–24]. However, this technique relies on the change of the optical response of a dense gas of ground-state atoms within the Rydberg-blockade volume surrounding a Rydberg atom. Thus, it remains impractical for spatially extended ensembles of Rydberg atoms such as atomic beams or large single-atom arrays.

Cavity-quantum-electrodynamics (QED) techniques allow efficient single-shot nondestructive measurements for many different systems including atoms [25] and superconducting qubits [26,27]. In this context, Rydberg atoms have been used to probe nondestructively microwave photons confined in a cavity [8,28]. This detection relies on the photon-number-dependent dispersive shift of the Rydberg levels induced by the nonresonant atom-photon interaction, which also leads to a dispersive shift of the cavity frequency induced by the atoms. The latter effect was used in Ref. [29] to determine the Rydberg-atom number or state, but the presented method required extremely long-lived cavity photons, measured with

additional destructively detected Rydberg atoms. In contrast, cavity-transmission measurements, used in optical cavity QED and circuit QED, offer direct detection.

In this Letter, we present experiments in which we reach the single-shot detection regime, where the uncertainty [30] of a single measurement becomes much smaller than the signal, for Rydberg-atom ensembles by measuring microwaves transmitted through a cavity. To this end, we combine a cavity offering a high sensitivity to the dispersive shift with an optimized signal-to-noise ratio (SNR) of the detection. By using a superconducting cavity with a high internal quality factor of 1.7×10^6 , we obtain an increase in sensitivity to the Rydberg-atom number by a factor of 20 over our previous results [31]. We demonstrate that transmission measurements enable the detection of the populations of Rydberg quantum states coupled to the cavity when the ensemble is prepared in a superposition state. By optimizing the SNR with a microwave probe power corresponding to the critical photon number, we achieve single-shot detection with a relative precision of 13% (statistical standard deviation) for Rydberg ensembles of about 500 atoms. This presents an opportunity for applications in experiments with ensembles of Rydberg atoms, in particular for detection of Rydberg atoms in cold-collision experiments or for quantum-state engineering in atomic-array experiments.

Our experimental setup, schematically shown in Fig. 1(a), combines a nondestructive detection by measurement of the microwave-cavity transmission with a subsequent destructive detection by ionization. The experiment uses an atomic beam pulsed with a repetition rate of 25 Hz. We start each measurement cycle by creating a cloud of metastable ($1s^1 2s^1 3S_1$) helium atoms, which propagates at a mean velocity $v = 950(20) \text{ m s}^{-1}$ through a cryogenic

FIG. 1. (a) Experimental setup combining the generation of an ensemble of He Rydberg atoms, its nondestructive detection by transmission measurement of a microwave cavity and its destructive detection by field ionization followed by a measurement of the number of extracted electrons on a MCP. (b) Energy-level diagram of the Rydberg atom and the cavity, with dashed arrows marking the coupled transitions and dotted arrows indicating the atom-cavity detunings $\Delta_{\pm 1}$. (c) Single-atom-cavity coupling strength g (thick curve, right axis) and measured phase change for a microwave probe frequency on resonance with the cavity (data points and fitted model, left axis) versus the elapsed time since the atoms entered the cavity t_c and equivalently versus their position $z_c = t_c v$. The data are averaged over 5.5×10^4 repetitions and error bars indicate $\pm$ the standard uncertainty. Vertical full and dashed lines indicate the time t_{cen} at which the atoms reach the cavity center and $t_{max} = t_{cen} + 2/\kappa$, respectively.

environment at 3K [31,32]. We prepare a small cloud of atoms in the triplet $42s, M_S = 1$ Rydberg state, by two-photon excitation via the 3^3P_0 state in a magnetic field of ~ 5 G. At this field strength, the atomic structure is in the Paschen-Back regime, with approximate quantum numbers M_S and m_l . The atoms then interact with the microwave photons confined in a superconducting rectangular 3D cavity [33]. We measure the change of the complex transmission (amplitude and phase) of a microwave probe tone through the cavity, which results from the dispersive shift χ of the cavity frequency induced by the Rydberg atoms. The transmitted microwave tone is amplified and down-converted to a 25-MHz intermediate frequency and recorded using a field-programmable-gate-array-based device [31]. After the cloud has interacted with the cavity, we perform a state-selective destructive detection by pulsed-field ionization followed by detection of the extracted electrons on a microchannel plate detector (MCP), see Supplemental Material A [34].

The cavity-atom interaction is characterized by (i) the single atom-photon coupling strength g , which is proportional to the microwave electric field and reaches $g_{max}/2\pi \simeq 14.3$ kHz at the cavity center [see Fig. 1(c)], (ii) the number N of Rydberg atoms, and (iii) the detunings $\Delta_{\pm 1} = \omega_{\pm 1} - \omega_c$ between the cavity frequency ($\omega_c/2\pi \simeq 20.5583$ GHz) and the frequencies ($\omega_{\pm 1}/2\pi$) of the transitions to the $42p, M_S = 1, m_l = \pm 1$ levels [see Fig. 1(b)]. Because the cavity microwave electric field is orthogonal to the magnetic quantization field, the transition to the $p, m_l = 0$ state is not coupled to the cavity mode. The detunings are determined by the strength of the applied magnetic field [33] and are measured *in situ* using microwave spectroscopy [$\Delta_{+1}/2\pi \simeq -8$ MHz and $\Delta_{-1}/2\pi \simeq -26$ MHz for the data in Fig. 1(c)]. The detunings are much larger than the collective coupling [$\max(g\sqrt{N})/(2\pi) \sim 0.4$ MHz], and therefore the interaction leads to a dispersive shift χ of the cavity frequency. By calculating the eigenvalues of the Tavis-Cummings Hamiltonian [39], extended to a three-level-atom ensemble and a single-mode cavity, up to second order in $g\sqrt{N}/\Delta_{\pm 1}$ [with $g\sqrt{N} \ll (\Delta_{+1} - \Delta_{-1})$], the cavity dispersive shift

$$\chi = g^2 N \left(\frac{1}{\Delta_{+1}} (P_{p,+1} - P_s) + \frac{1}{\Delta_{-1}} (P_{p,-1} - P_s) \right) \quad (1)$$

is the sum of two terms linked to two atomic transitions (with identical coupling g), where P_s and $P_{p,\pm 1}$ are the fraction of atoms in the $42s$ and the $42p$ $m_l = \pm 1$ states, respectively.

Measuring the phase change $\delta\phi$ on resonance provides the best sensitivity $d\delta\phi/d\chi$ to detect a dispersive shift. Indeed, the phase change induced by a constant dispersive shift χ on a resonant microwave probe tone is given by $\delta\phi = -\arctan(2\chi/\kappa)$, where $\kappa/2\pi = 236(1)$ kHz is the cavity linewidth. Thus, $\delta\phi$ is approximately linear in χ for small shifts. A resonant microwave probe frequency also maximizes the transmitted power and consequently the precision of the phase detection.

We observe the average phase change of the cavity transmission when a cloud of $42s$ -state atoms ($P_s = 1$, $P_{p,\pm 1} = 0$) propagates through the cavity, see Fig. 1(c). The change of the coupling strength along the cloud's path induces a variation of the dispersive shift, because $\chi \propto g^2$. The cavity field reacts to this variation with a response function characterized by the time constant $\tau_c = 2/\kappa \simeq 1.35$ μ s. Thus, we observe a shift between the time t_{cen} , at which the atoms reach the cavity center, and the time of the maximum phase change at approximately $t_{max} = t_{cen} + \tau_c$. With the calculated coupling and the measured detunings, we fit the measured cavity transmission using input-output theory [40] (details in Supplemental Material B [34]). We extract the average atom number [$N = 261(1)$] in the center of the cavity from

FIG. 2. (a) Phase change $\delta\phi$ at $t_{\max}$ (black, averaged over $1\ \mu\text{s}$ and 3.8×10^4 repetitions) and extracted atom number N (red squares, from fit of transmission data) versus MCP signal S when varying the Rydberg-atom number produced by laser excitation. The linear fit (red line) emphasizes the proportionality between S and N . (b) Phase change at $t_{\max}$ (black, averaged over $1\ \mu\text{s}$ and 4.3×10^4 repetitions) and p -state occupation (blue) as a function of the normalized Rabi frequency of the microwave excitation from the s state to the $p, m_l = +1$ state. The dotted curve is the expected Rabi oscillation of the p -state occupation. The dashed curve is the phase change calculated for an atom cloud in a pure $p, m_l = +1$ state in the cavity. The full curve shows the calculation including the independently measured intracavity populations of p -state sublevels with uncertainty depicted by the shaded region. Error bars indicate $\pm$ the standard uncertainty.

the fit showing excellent agreement with the data [see Fig. 1(c)].

To characterize the sensitivity $d\delta\phi/dN$ of the cavity detection to the number of Rydberg atoms, we generate 42 s atom clouds with different average numbers of Rydberg atoms by changing the duration of the 389-nm-laser pulse from 0 to $1.1\ \mu\text{s}$. In Fig. 2(a), we present the correlation between the integrated field-ionization signal S of the MCP and both the phase change $\delta\phi$ on resonance at $t_{\max}$ and the extracted number of atoms N . Because the dispersive shift χ is smaller than the cavity linewidth κ , the phase change is proportional to the dispersive shift and thus to the atom number. Our cavity Rydberg-atom detector has a phase sensitivity $d\delta\phi/dN = 1.44(1) \times 10^{-2}$ deg/atom. This 20-fold improvement over previously published results [31] originates from the smaller linewidth of the superconducting cavity. The cavity linewidth is limited by the external coupling to maximize the SNR and to avoid a cavity-induced averaging timescale τ_c longer than the interaction time, which would reduce the sensitivity.

The MCP signal S is proportional to the number of atoms. We independently determined the MCP sensitivity $dS/dN = 2.07(4) \times 10^{-2}$ V ns/atom from the measured single-electron response and the known MCP detection efficiency ($\eta \simeq 55\%$). When accounting for the radiative decay of the Rydberg atoms between the cavity center and the ionization region, the fitted linear relation between the

MCP signal and the number of atoms detected with the cavity measurement [see Fig. 2(a)] also provides a calibration of the MCP sensitivity of $2.12(1) \times 10^{-2}$ V ns/atom. From the difference between the two independent calibrations, we deduce the trueness of the atom-number detection by the cavity, characterized by a relative systematic error of $-2.3(1.8)\%$, consistent with a $-2.4(0.8)\%$ estimate from the approximations of the model (see Supplemental Material C [34], which includes Refs. [35–38]). We conclude that the cavity measurement provides an accurate nondestructive detection of the number of Rydberg atoms.

Cavity-transmission measurements also provide a non-destructive detection of the populations of quantum states for atoms in optical cavities [25] or superconducting qubits in microwave cavities [41], for example. To measure the state populations of a Rydberg ensemble in the microwave cavity, we prepare the ensemble in different superpositions of the s and $p, m_l = +1$ states before the atoms enter the cavity, by applying a microwave drive pulse with amplitude characterized by the Rabi frequency Ω . The p -state occupation, detected with state-selective ionization after the cavity [Fig. 2(b)], follows the expected Rabi oscillation, which indicates that the cavity-measurement backaction is limited to the projection onto the eigenstates of the p -state occupation. The observed phase change reflects this sinusoidal variation of the populations. It reaches minimal values when the ensemble is prepared in the p state with a π pulse ($\Omega = \Omega_\pi = \pi/\delta t$ with $\delta t = 0.4\ \mu\text{s}$ the pulse duration), because this state induces a dispersive shift opposite to that of the s state. However, the amplitude of the phase change is reduced as compared to the initial s -state ensemble, because only one transition contributes to the dispersive shift for $p, m_l = +1$ [see Eq. (1), dashed line]. Additionally, a depolarization of the ensemble, occurring between the location of the state preparation and the cavity, transfers a part of the p -state population from $m_l = +1$ to $m_l = 0$ and $m_l = -1$. We attribute this depolarization to stray electric fields at the cavity entrance hole, which could be avoided with an improved cavity design. Using *in situ* microwave spectroscopy, we determined the resulting populations of the p -state sublevels to be $P_{p,+1} = 0.61(3)$ and $P_{p,-1} = 0.20(3)$ (see Supplemental Material D [34]). The corresponding calculated response (red) agrees with the observed phase change. Thus, the microwave-cavity-transmission measurement enables the nondestructive detection of the state populations of a Rydberg ensemble.

The main interest of nondestructive detection lies in its single-shot-measurement abilities. In order to reach the single-shot regime for the detection of the Rydberg-atom number, additionally to the high sensitivity presented above, we optimized the SNR. The power SNR of the microwave detection $R_{S/N} = n_c \kappa_{\text{out}} \tau_i / n_{\text{noise}}$ depends on the number of photons in the cavity n_c (proportional to the microwave probe power, calculated using input-output

theory), the coupling of the output port $\kappa_{\text{out}}/2\pi \simeq 150$ kHz, the integration time τ_i and the effective noise photon number $n_{\text{noise}} \simeq 23$ of the detection, which is dominated by the noise of the first amplifier. Thus, increasing n_c reduces the phase-detection precision $\sigma_\phi = 1/\sqrt{R_{S/N}}$. However, simultaneously the dispersive shift decreases as $\chi(n_c) = \chi_0/\sqrt{1 + n_c/n_{\text{crit}}}$ where the critical photon number $n_{\text{crit}} = \Delta^2/(4g^2)$ characterizes the threshold of the validity of the dispersive approximation [42] and χ_0 is the dispersive shift for $n_c \ll n_{\text{crit}}$ given by Eq. (1) [31]. In Fig. 3(a), we present measurements of the dependence of

FIG. 3. (a) Phase change $\delta\phi$ (at t_{max} averaged over $\tau_i = 6.2 \mu\text{s}$ and 3×10^4 repetitions) as a function of the number of cavity photons n_c for the indicated average numbers of Rydberg atoms. The global fit (solid lines) determines the critical photon number (dashed vertical line). The dotted vertical line indicates the photon number used in the measurements presented in Fig. 2(b). (b) Probability of excitation to p state as a function of n_c , measured using the MCP. Error bars are dominated by systematic uncertainties. The solid line is a fit of the data to the model presented in the text. (c) Single-shot measurements (dots) of the phase change $\delta\phi$, and deduced Rydberg-atom number N , vs the MCP signal S . The average number of Rydberg-atoms is controlled during the preparation by the pulse duration of the laser excitation (0 to $1 \mu\text{s}$ in $0.1 \mu\text{s}$ steps). The shaded region indicates the standard deviation $\sigma_N \simeq 65$ of the atom number extracted from the transmission measurement.

the phase change on the photon number for three different average atom numbers. The global fit of the three data sets confirms that the measured power dependence is not influenced by the atom number and yields a critical photon number of $n_{\text{crit}} \simeq 4.4 \times 10^4$, consistent with the value calculated from the detuning Δ_{+1} and coupling g averaged over the integration time. Because of the power dependences of the SNR and the dispersive shift, for $n_c \gg n_{\text{crit}}$, both the phase detection precision ($\sigma_\phi = 1/\sqrt{R_{S/N}}$) and the phase change ($\delta\phi \propto \chi$) scale as $1/\sqrt{n_c}$. Thus, the atom-number precision only significantly improves with increasing power up to n_{crit} .

Large photon numbers also induce a residual excitation of the atomic ensemble after the interaction with the cavity, which we measure with the MCP [see Fig. 3(b)]. Such backaction is commonly observed in dispersive readout and arises from relaxation and dephasing [43] during the interaction with the microwave probe field which mixes the atomic states. The atomic excitation of the system eigenstate in the cavity is $P_e = \sin^2\{\arctan[\sqrt{(n_c + 1)/n_{\text{crit}}}]\}$ [27,44,45]. As shown by the fitted curve, the residual excitation is proportional to P_e up to n_{crit} . At larger microwave probe powers, the dispersive approximation breaks down and ac Stark shifts induced by couplings to other Rydberg states become significant; these effects hinder predictions of the residual excitation beyond n_{crit} . The residual excitation remains below $\sim 2\%$ up to n_{crit} , so that the detection can still be considered nondestructive.

To achieve high precision with limited backaction, we perform single-shot measurements of the Rydberg-atom number with a cavity photon number ($n_c \simeq 5.9 \times 10^4$) close to the critical photon number. We integrate the signal over $\tau_i = 6.2 \mu\text{s}$, which corresponds to the time span over which $g \geq 0.8g_{\text{max}}$. We observe the expected linear relationship between the single-shot results of the destructive detection by ionization and the nondestructive detection by measuring the phase change of the cavity transmission for different average Rydberg-atom numbers, see Fig. 3(c). The scatter of the data points around the average response (full line) is caused by the precisions of the two detection methods. The precision of the phase detection limits the precision of the atom-number determination to a statistical standard deviation $\sigma_N \simeq 65$. Our nondestructive detector thus reaches a single-shot relative precision $\sigma_{N,\text{rel}} = \sigma_N/N \simeq 13\%$ for ensembles of about 500 atoms, which is on the same order of precision as the ionization detection (see Supplemental Material E [34]).

The cavity-transmission detection has potential for significant improvement. For example, the noise of the microwave detection could be reduced to an effective noise photon number $n_{\text{noise}} \sim 1$ by using a quantum-limited amplifier [46,47], leading to a relative precision of 4.8% for 500 atoms. The same improvement could be reached by increasing the integration time up to $\tau_i \sim 0.1$ ms, which could be obtained by decelerating the Rydberg-atom cloud [48].

In conclusion, we demonstrated nondestructive detection of atom number and atomic-state populations of Rydberg atom ensembles by microwave cavity transmission. Single-shot detection is achieved with small backaction of the measurement. The presented detection scheme opens up new perspectives for experiments with Rydberg ensembles. In particular, we anticipate that single-atom precision could be obtained with integration times on the order of 10 ms in experiments with trapped circular Rydberg atoms [49].

We thank Tobias Thiele for his contributions to the initial phase of the experiment. This work was supported by the European Union H2020 FET Proactive project RySQ (Grant No. 640378) and by the National Centre of Competence in Research “Quantum Science and Technology” (NCCR QSIT), a research instrument of the SNSF.

*sebastien.garcia@college-de-france.fr

[†]Present address: Institute of Physics, Collège de France, Paris, France.

[‡]Present address: University of Leipzig, Felix-Bloch Institut, Leipzig, Germany.

- [1] T. F. Gallagher, *Rydberg Atoms* (Cambridge University Press, Cambridge, England, 1994).
- [2] M. Saffman, T. G. Walker, and K. Mølmer, *Rev. Mod. Phys.* **82**, 2313 (2010).
- [3] D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin, *Phys. Rev. Lett.* **85**, 2208 (2000).
- [4] L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson, T. G. Walker, and M. Saffman, *Phys. Rev. Lett.* **104**, 010503 (2010).
- [5] P. Schauß, J. Zeiher, T. Fukuhara, S. Hild, M. Cheneau, T. Macrì, T. Pohl, I. Bloch, and C. Gross, *Science* **347**, 1455 (2015).
- [6] H. Labuhn, D. Barredo, S. Ravets, T. L. Sylvain de Léséleuc, Tommaso Macrì, and A. Browaeys, *Nature (London)* **534**, 667 (2016).
- [7] H. Bernien, S. Schwartz, A. Keesling, H. Levine, A. Omran, H. Pichler, S. Choi, A. S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M. D. Lukin, *Nature (London)* **551**, 579 (2017).
- [8] S. Haroche, *Rev. Mod. Phys.* **85**, 1083 (2013).
- [9] T. Peyronel, O. Firstenberg, Q.-Y. Liang, S. Hofferberth, A. V. Gorshkov, T. Pohl, M. D. Lukin, and V. Vuletić, *Nature (London)* **488**, 57 (2012).
- [10] D. Maxwell, D. J. Szwer, D. Paredes-Barato, H. Busche, J. D. Pritchard, A. Gauguier, K. J. Weatherill, M. P. A. Jones, and C. S. Adams, *Phys. Rev. Lett.* **110**, 103001 (2013).
- [11] S. Baur, D. Tiarks, G. Rempe, and S. Dürr, *Phys. Rev. Lett.* **112**, 073901 (2014).
- [12] Q.-Y. Liang, A. V. Venkatramani, S. H. Cantu, T. L. Nicholson, M. J. Gullans, A. V. Gorshkov, J. D. Thompson, C. Chin, M. D. Lukin, and V. Vuletić, *Science* **359**, 783 (2018).
- [13] V. Bendkowsky, B. Butscher, J. Nipper, J. P. Shaffer, R. Low, and T. Pfau, *Nature (London)* **458**, 1005 (2009).
- [14] M. Schlagmüller, T. C. Liebisch, F. Engel, K. S. Kleinbach, F. Böttcher, U. Hermann, K. M. Westphal, A. Gaj, R. Löw, S. Hofferberth, T. Pfau, J. Pérez-Ríos, and C. H. Greene, *Phys. Rev. X* **6**, 031020 (2016).
- [15] P. Allmendinger, J. Deiglmaier, K. Höveler, O. Schullian, and F. Merkt, *J. Chem. Phys.* **145**, 244316 (2016).
- [16] M. H. Schleier-Smith, I. D. Leroux, and V. Vuletić, *Phys. Rev. Lett.* **104**, 073604 (2010).
- [17] F. Haas, J. Volz, R. Gher, J. Reichel, and J. Estève, *Science* **344**, 180 (2014).
- [18] J. Bernu, S. Deléglise, C. Sayrin, S. Kuhr, I. Dotsenko, M. Brune, J. M. Raimond, and S. Haroche, *Phys. Rev. Lett.* **101**, 180402 (2008).
- [19] G. Barontini, L. Hohmann, F. Haas, J. Estève, and J. Reichel, *Science* **349**, 1317 (2015).
- [20] C. Sayrin, I. Dotsenko, X. Zhou, B. Peaudecerf, T. Rybarczyk, S. Gleyzes, P. Rouchon, M. Mirrahimi, H. Amini, M. Brune, J.-M. Raimond, and S. Haroche, *Nature (London)* **477**, 73 (2011).
- [21] R. Vijay, C. Macklin, D. H. Slichter, S. J. Weber, K. W. Murch, R. Naik, A. N. Korotkov, and I. Siddiqi, *Nature (London)* **490**, 77 (2012).
- [22] G. Günter, M. Robert-de-Saint-Vincent, H. Schempp, C. S. Hofmann, S. Whitlock, and M. Weidemüller, *Phys. Rev. Lett.* **108**, 013002 (2012).
- [23] G. Günter, H. Schempp, M. Robert-de-Saint-Vincent, V. Gavryusev, S. Helmrich, C. S. Hofmann, S. Whitlock, and M. Weidemüller, *Science* **342**, 954 (2013).
- [24] H. Gorniaczyk, C. Tresp, J. Schmidt, H. Fedder, and S. Hofferberth, *Phys. Rev. Lett.* **113**, 053601 (2014).
- [25] J. Volz, R. Gehr, G. Dubois, J. Estève, and J. Reichel, *Nature (London)* **475**, 210 (2011).
- [26] E. Jeffrey, D. Sank, J. Y. Mutus, T. C. White, J. Kelly, R. Barends, Y. Chen, Z. Chen, B. Chiaro, A. Dunsworth, A. Megrant, P. J. J. O’Malley, C. Neill, P. Roushan, A. Vainsencher, J. Wenner, A. N. Cleland, and J. M. Martinis, *Phys. Rev. Lett.* **112**, 190504 (2014).
- [27] T. Walter, P. Kurpiers, S. Gasparinetti, P. Magnard, A. Potočnik, Y. Salathé, M. Pechal, M. Mondal, M. Oppliger, C. Eichler, and A. Wallraff, *Phys. Rev. Applied* **7**, 054020 (2017).
- [28] G. Nogues, A. Rauschenbeutel, S. Osnaghi, M. Brune, J. M. Raimond, and S. Haroche, *Nature (London)* **400**, 239 (1999).
- [29] P. Maioli, T. Meunier, S. Gleyzes, A. Auffèves, G. Nogues, M. Brune, J. M. Raimond, and S. Haroche, *Phys. Rev. Lett.* **94**, 113601 (2005).
- [30] In this Letter, we use the definitions of words related to measurement (uncertainty, precision, trueness, sensitivity, etc.) as given by the International Bureau of Weights and Measures in International Vocabulary of Metrology, 3rd ed. (Sevres, France, 2012).
- [31] M. Stammeier, S. Garcia, T. Thiele, J. Deiglmaier, J. A. Agner, H. Schmutz, F. Merkt, and A. Wallraff, *Phys. Rev. A* **95**, 053855 (2017).
- [32] T. Thiele, S. Filipp, J. A. Agner, H. Schmutz, J. Deiglmaier, M. Stammeier, P. Allmendinger, F. Merkt, and A. Wallraff, *Phys. Rev. A* **90**, 013414 (2014).
- [33] M. Stammeier, S. Garcia, and A. Wallraff, *Quantum Sci. Technol.* **3**, 045007 (2018).
- [34] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.123.193201> for details

- on calibration measurements, data analysis and measurement uncertainty, which includes Refs. [35–38].
- [35] M. L. Zimmerman, M. G. Littman, M. M. Kash, and D. Kleppner, *Phys. Rev. A* **20**, 2251 (1979).
 - [36] G. W. F. Drake, *Phys. Scr.* **T83**, 83 (1999).
 - [37] D. M. Pozar, *Microwave Engineering*, 4th ed. (John Wiley & Sons, Inc., New York, 2011).
 - [38] V. Zhelyazkova, R. Jirschik, and S. D. Hogan, *Phys. Rev. A* **94**, 053418 (2016).
 - [39] M. Tavis and F. W. Cummings, *Phys. Rev.* **170**, 379 (1968).
 - [40] C. W. Gardiner and M. J. Collett, *Phys. Rev. A* **31**, 3761 (1985).
 - [41] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **95**, 060501 (2005).
 - [42] A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *Phys. Rev. A* **69**, 062320 (2004).
 - [43] M. Boissonneault, J. M. Gambetta, and A. Blais, *Phys. Rev. A* **79**, 013819 (2009).
 - [44] L. M. Narducci, M. Orszag, and R. A. Tuft, *Phys. Rev. A* **8**, 1892 (1973).
 - [45] B. M. Garraway, *Phil. Trans. R. Soc. A* **369**, 1137 (2011).
 - [46] B. Yurke, M. L. Roukes, R. Movshovich, and A. N. Pargellis, *Appl. Phys. Lett.* **69**, 3078 (1996).
 - [47] M. A. Castellanos-Beltran, K. D. Irwin, G. C. Hilton, L. R. Vale, and K. W. Lehnert, *Nat. Phys.* **4**, 929 (2008).
 - [48] S. D. Hogan, P. Allmendinger, H. Saßmannshausen, H. Schmutz, and F. Merkt, *Phys. Rev. Lett.* **108**, 063008 (2012).
 - [49] T. L. Nguyen, J. M. Raimond, C. Sayrin, R. Cortiñas, T. Cantat-Moltrecht, F. Assemat, I. Dotsenko, S. Gleyzes, S. Haroche, G. Roux, T. Jolicœur, and M. Brune, *Phys. Rev. X* **8**, 011032 (2018).