Photon-mediated interactions between quantum emitters in a diamond nanocavity

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Photon-mediated interactions between quantum systems are essential for realizing quantum networks and scalable quantum information processing. We demonstrate such interactions between pairs of silicon-vacancy (SiV) color centers coupled to a diamond nanophotonic cavity. When the optical transitions of the two color centers are tuned into resonance, the coupling to the common cavity mode results in a coherent interaction between them, leading to spectrally resolved superradiant and subradiant states. We use the electronic spin degrees of freedom of the SiV centers to control these optically mediated interactions. Such controlled interactions will be crucial in developing cavity-mediated quantum gates between spin qubits and for realizing scalable quantum network nodes.

Photon-mediated interactions involve a quantum block of quantum information systems, enabling entanglement generation and quantum logic operations involving both stationary qubits and photons (1, 2). Progress in cavity quantum electrodynamics (QED) with trapped atoms and ions (3), superconducting qubits (4), and self-assembled quantum dots (5) has created possibilities for engineering such interactions. In particular, coherent multi-qubit interactions mediated via a cavity have been demonstrated in the microwave domain using circuit QED (6). Extending such interactions to the optical domain could enable key protocols in long-distance quantum communication (1, 7). This goal is challenging owing to the inability of achieving strong cavity coupling and individual control of multiple resonant quantum emitters. Recently, cavity-modified collective scattering has been observed in two-ion (8) and two-atom (9) systems. Signatures of cavity-mediated interactions between quantum dots have also been reported (10, 11). However, the realization of controlled, coherent optical interactions between solid-state emitters is difficult because of inhomogeneous broadening and decoherence introduced by the solid-state environment (5, 11).

We realize controllable optically mediated interactions between negatively charged silicon-vacancy (SiV) color centers coupled to a diamond photonic crystal cavity (Fig. 1A) (12). SiV centers in diamond are atom-like quantum emitters featuring nearly lifetime-limited optical linewidths with low inhomogeneous broadening, both in bulk (13) and in nanostructures (14). We integrate SiV centers into devices consisting of a onedimensional diamond waveguide with an array of holes defining a photonic crystal cavity with quality factor Q ~ 10^4 and simulated mode volume V ~ 0.5λ/λ(n = 2.4) (Fig. 1B) (15). SiV centers are positioned at a single spot in these devices with 40-nm precision by targeted implantation using a focused beam of 28Si ions, yielding around five SiV centers per device (12). The diamond waveguide is tapered and adiabatically coupled to a tapered single-mode fiber, enabling collection efficiencies from the waveguide into the fiber of more than 90% (15). These devices are placed in a dilution refrigerator with an integrated confocal microscope (16). At 85 mK, SiV centers are completely polarized into the orbital ground state (17). Here, we use optical transitions between the lowest-energy orbital states in the electronic ground and excited states. The SiV electronic spin degeneracy is lifted by applying a magnetic field up to 10 kG (17, 18). The cavity resonance frequency ω0 is tuned using gas condensation (16).

The coupling between SiV centers and the cavity is characterized by scanning the frequency of a laser incident on one side of the device from free space while monitoring the transmitted intensity in the collection fiber. The resulting transmission spectrum (Fig. 1C) reveals strong modulation of the cavity response resulting from the coupling of spectrally resolved SiV centers to the cavity mode. For instance, two SiV centers near the cavity resonance each result in almost-full extinction of the transmission through the cavity (Fig. 1C, lower spectrum) (19). By contrast, when the cavity is detuned from the SiV by several cavity linewidths (σc), the spectrum shows a narrow peak near each SiV frequency (Fig. 1D), corresponding to an atom-like dressed state of the SiV-cavity system with high transmission (6). The resonance linewidth (Γ) changes by more than an order of magnitude depending on the SiV-cavity detuning (Δ = ω0 − ωSiV). This can be understood through Purcell enhancement, which predicts Γ(Δ) = γ + 4πg^2/Q, where g is the single-photon Rabi frequency, k is the cavity energy decay rate, and γ is twice the decoherence rate due to free-space spontaneous emission and spectral diffusion. For the strongest-coupled SiV in the device used in Fig. 1, linewidths range from Γ(0) = 2π × 4.6 GHz on resonance to Γ(Δc) = 2π × 0.19 GHz = γ when the cavity is far detuned. The measured Γ(0) corresponds to an estimated lifetime of 35 ps compared to the natural SiV lifetime of 1.8 ns (12). These measurements give cavity QED parameters {g, k, γ} = 2π × {7.3, 48, 0.19} GHz, corresponding to a cooperativity (the key cavity-QED figure of merit) C = 4g^2/kγ ~ 23 (16). This order-of-magnitude improvement in SiV-cavity cooperativity over previous work (12, 20) primarily results from the decreased cavity mode volume (15).

As is evident from Fig. 1C, SiV centers are subject to inhomogeneous broadening, resulting predominantly from strain within the device (14, 21). This broadening is smaller than that of other solid-state emitters compared to their lifetime-limited linewidths (5, 10, 11). Indeed, the frequencies of some SiV centers within the same devices are nearly identical. We study the cavity-mediated interaction between a pair (SiV 1 and SiV 2 in Fig. 1) of such nearly- resonant SiV centers (SiV-SiV detuning δ = 2π × 0.6 GHz) coupled to the cavity in the dispersive regime, that is, with large SiV-cavity detuning (Δ = 2π × 79 GHz > κ, Fig. 2A). To identify resonances associated with individual SiV centers, we selectively ionize either SiV into an optically inactive charge state by applying a resonant laser at powers orders of magnitude higher than those used to probe the system (16). This allows measurement of each of the SiV centers’ spectra individually, with the other parameters (such as Δ) fixed (Fig. 2A, gray data).

When both SiV centers are in the optically active charge state, the splitting between the resonances increases. The new resonances (Fig. 2A, black data) also display different amplitudes compared with the single-SiV resonances and are labeled as bright (|S⟩) and dark (|D⟩) states. The linewidths of |S⟩ (|D⟩) are also enhanced (suppressed) compared to those of the individual SiV centers (Fig. 2B, inset). At a cavity detuning of the opposite sign (Δ = 2π × −55 GHz), the sign of the energy splitting δSD between |S⟩ and |D⟩ is reversed (Fig. 2B). The observation that Δ affects δSD indicates that this effect arises from the cavity.

To understand these observations, we describe the system of two SiV centers coupled to a cavity mode using the Hamiltonian (6, 22):

$$H / h = \omega_0 \hat{a}^\dagger \hat{a} + \omega_0 \sum_{i=1}^{2} \sigma_{i} + \omega_0 \sigma_{1} \sigma_{2} + \sum_{i=1}^{2} \sigma_{i} \hat{a}^\dagger (\hat{g}_{1} \sigma_{1} + \hat{g}_{2} \sigma_{2}) + \hat{a}^\dagger (\hat{g}_{1}^\dagger \sigma_{1} + \hat{g}_{2}^\dagger \sigma_{2})$$
where $\omega_0$ is the frequency of the $i$th SiV center and $\delta$ and $\sigma_i$ are the cavity photon annihilation and $i$th SiV center’s electronic state lowering operators. Coherent evolution under $\hat{H}$ is modified by cavity ($\kappa$) and SiV ($\gamma$) decay and decoherence ($\gamma_D$). In the dispersive regime, $\hat{H}$ yields an effective Hamiltonian for two resonant ($\delta = 0$) SiV centers (6,22): $\hat{H}_{ij}/h = J(\sigma_i^{\dagger} \sigma_j \pm \sigma_j^{\dagger} \sigma_i)$ where $J = \omega_0^2/(\kappa g_j^2)$. Thus, the two SiV centers undergo a flip-flop interaction at rate $J$ mediated by the exchange of cavity photons (Fig. 2C). This interaction hybridizes the two SiV centers, forming collective eigenstates from the SiV ground ($|g\rangle$) and excited ($|e\rangle$) states which, for $\delta = 0$, are $|S\rangle = 1/2(|eg\rangle + |ge\rangle)$ and $|D\rangle = 1/\sqrt{2}(|eg\rangle - |ge\rangle)$ and are split by $2J$ (Fig. 2D) (6). The symmetric superradiant state $|S\rangle$ has an enhanced coupling to the cavity of $\sqrt{2}g$ (making it “bright” in transmission) and an energy shift of $2J = 2g^2/\Delta$, whereas the antisymmetric combination $|D\rangle$ is completely decoupled from the cavity (“dark” in transmission) and has zero energy shift ($\delta/I \ll J$). As $\delta/I$ increases, $|D\rangle$ becomes visible and the individual SiV eigenstates are eventually recovered. The energy shift of state $|S\rangle$ is away from the cavity resonance, explaining the reversed energy difference $\delta_{SD}$ upon changing the sign of $\Delta$ (Fig. 2B). By comparing the data in Fig. 2 to theory accounting for finite $\delta$ (Fig. 2, solid curves), the SiV-SiV interaction strength $J = 2\times0.6$ GHz is extracted. The splitting $\delta_{SD}$ (which is at least 2$\delta$) is larger than the measured linewidths (for a single SiV, $\Gamma(\Delta = 79$ GHz) $= 2 \times 0.4$ GHz), allowing these states to be spectrally resolved.

Next, the SiV center’s long-lived electronic spin degree of freedom (18) is used to control the SiV-cavity transmission and two-SiV interaction. We apply a magnetic field to lift the degeneracy of the spin sublevels in the ground ($\sigma_\uparrow$ and $\sigma_\downarrow$) and excited ($\sigma_\uparrow'$ and $\sigma_\downarrow'$) states. Thus, the two SiV centers form collective eigenstates from the SiV ground ($|g\rangle$) and excited ($|e\rangle$) states which, for $\delta = 0$, are $|S\rangle = 1/2(|eg\rangle + |ge\rangle)$ and $|D\rangle = 1/\sqrt{2}(|eg\rangle - |ge\rangle)$ and are split by $2J$ (Fig. 2D) (6). The symmetric superradiant state $|S\rangle$ has an enhanced coupling to the cavity (making it “bright” in transmission) and an energy shift of $2J = 2g^2/\Delta$, whereas the antisymmetric combination $|D\rangle$ is completely decoupled from the cavity (“dark” in transmission) and has zero energy shift ($\delta/I \ll J$). As $\delta/I$ increases, $|D\rangle$ becomes visible and the individual SiV eigenstates are eventually recovered. The energy shift of state $|S\rangle$ is away from the cavity resonance, explaining the reversed energy difference $\delta_{SD}$ upon changing the sign of $\Delta$ (Fig. 2B). By comparing the data in Fig. 2 to theory accounting for finite $\delta$ (Fig. 2, solid curves), the SiV-SiV interaction strength $J = 2\times0.6$ GHz is extracted. The splitting $\delta_{SD}$ (which is at least 2$\delta$) is larger than the measured linewidths (for a single SiV, $\Gamma(\Delta = 79$ GHz) $= 2 \times 0.4$ GHz), allowing these states to be spectrally resolved.

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Fig. 1. High cooperativity SiV-photon interface. (A) Schematic of a diamond nanocavity containing two SiV centers. (B) Scanning electron micrograph of a nanocavity. (C) Transmission spectrum of the coupled SiV-cavity system (blue). The broad Lorentzian response of an empty cavity (dashed) is modulated by cavity-coupled SiVs. Near the cavity resonance (lower panel), two SiVs each result in greater than 95% extinction in transmission and are broadened by the Purcell effect [Γ(Δ = 0) = 2 × 4.6 GHz]. (D) In the dispersive regime (Δ = 2π × 79 GHz − 2π), SiVs appear as narrow peaks in transmission Γ(Δ = 2π × 0.5 GHz). The solid lines in (D) and the lower panel of (C) are fits to a model (16).

We also perform this experiment in the resonant-cavity regime and observe spin-dependent transmission switching with 80% contrast (16).

The combination of spin control, high-cooperativity coupling, and a small inhomogeneous distribution of SiVs enables controllable optically mediated interactions between multiple SiV centers. We focus on two SiV centers (SiV 1 and SiV 2 in Fig. 1) in the dispersive...
regime ($\Delta = 2\pi \times 109$ GHz) with $g_1 = g_2$, $\kappa_1 = \gamma_1 = \gamma_2 = 2\pi \times (7.3, 39, 0.5)$ GHz ($C = 1$) and an initial two-SiV detuning $\delta = 2\pi \times 5$ GHz (16). We sweep the magnitude of a magnetic field oriented almost orthogonal to the SiV symmetry axis and tune transitions $|1\rangle \rightarrow |1\rangle$ and $|2\rangle \rightarrow |2\rangle$ (which have opposite Zeeman shifts) in and out of resonance (Fig. 4A). At each magnetic field, a continuous field $\Omega_1$ or $\Omega_2$ is used to optically pump either SiV 1 or SiV 2 into the spin state resonant with a weak probe field $\Omega_3$ measuring the transmission spectrum of the system, thus enabling control measurements where only one spin is addressed by $\Omega_3$ at a time (Fig. 4B, gray). The single-spin transmission spectra at each field are summed to form a composite spectrum of the two-SiV system (Fig. 4C), which displays an energy level crossing of the two SiV transitions characteristic of noninteracting systems.

Measurements were then made in the interacting regime by preparing the spins into $|1\rangle |2\rangle$ by simultaneously applying $\Omega_1$ and $\Omega_2$. The two-SiV transmission spectrum demonstrates the formation of superradiant and subradiant states (Fig. 4B, black) that exist only for this combination of superradiant and subradiant states of light (30), which are useful in, for example, measurement-based quantum computing. On-chip integration and GHz-level bandwidths make our system well-suited for exploring potential applications in quantum networking, including the implementation of efficient quantum repeaters (26) and distributed quantum computing.
16. Materials and methods are available as supplementary materials online.

ACKNOWLEDGMENTS

We thank D. Twitchen and M. Markham from Element Six for substrates, J. Borregaard and K. De Greve for discussions, and D. Perry for implantation assistance. **Funding:** Support was provided by the NSF, CUA, DoD/ARO DURIP, AFOSR MURI, ONR MURI, ARL, Vannevar Bush Faculty Fellowship, DoD NDSEG (M. K. B.), and NSF GRFP (B. M. and G. Z.). Devices were fabricated at the Harvard CNS (NSF ECCS-1541959). Implantation was performed at Sandia National Laboratories through the Center for Integrated Nanotechnologies, operated for the DOE-SC (contract DE-NA-0003525) by Sandia Corporation, a Honeywell subsidiary. **Author contributions:** R.E., M.K.B., D.S., C.N., and A.S. performed experiments and analyzed data. M.J.B. and B.M. designed and fabricated nanocavities. A.Z. and G.Z. assisted with experiments. E.B. performed implantation. H.P., M.L., and M.D.L. supervised experiments and analysis. All authors contributed to analysis and manuscript preparation. **Competing interests:** The authors declare no competing interests. The views expressed here do not necessarily represent the DOE or U.S. Government. **Data and materials availability:** All data are available in the manuscript or supplementary materials.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/362/6415/662/suppl/DC1

Materials and Methods

Figs. S1 to S9

References (32–36)

26 June 2018; accepted 3 September 2018

Published online 20 September 2018

10.1126/science.aau4691
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Science 362 (6415), 662-665.
DOI: 10.1126/science.aau4691 originally published online September 20, 2018

Inducing interactions between quantum emitters

The development of scalable quantum systems will require the ability to control the interactions between the individual quantum building blocks of the system. Evans et al. used a pair of silicon vacancy centers embedded in a diamond nanocavity to show that interactions between the quantum emitters can be mediated optically (see the Perspective by Lodahl). Such optical control provides a speed advantage as well as the potential to develop an integrated platform for future quantum communication and quantum networking.

Science, this issue p. 662; see also p. 646