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Article

Resonant microwave-mediated interactions between distant electron spins

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Nonlocal qubit interactions are a hallmark of advanced quantum information technologies[1–5]. The ability to transfer quantum states and generate entanglement over distances much larger than qubit length scales greatly increases connectivity and is an important step towards maximal parallelism and the implementation of two-qubit gates on arbitrary pairs of qubits[6]. Qubit-coupling schemes based on cavity quantum electrodynamics[2,7,8] also offer the possibility of using high-quality-factor resonators as quantum memories[3,9]. Extending qubit interactions beyond the nearest neighbour is particularly beneficial for spin-based quantum computing architectures, which are limited by short-range exchange interactions[10]. Despite the rapidly maturing device technology for silicon spin qubits[11–16], experimental progress towards achieving long-range spin–spin coupling has so far been restricted to interactions between individual spins and microwave photons[17–20]. Here we demonstrate resonant microwave-mediated coupling between two electron spins that are physically separated by more than four millimetres. An enhanced vacuum Rabi splitting is observed when both spins are tuned into resonance with the cavity, indicating a coherent interaction between the two spins and a cavity photon. Our results imply that microwave-frequency photons may be used to generate long-range two-qubit gates between spatially separated spins.

Key Highlights

- They have demonstrated resonant microwave-mediated coupling between two electron spins that are physically separated by more than 4mm distance.
- Shown control over the spin resonance frequencies.
- An enhanced vacuum Rabi splitting is observed when both spins are tuned into resonance with the cavity.
- $\frac{\lambda}{2}$ Nb based superconducting cavity and has a cavity centre frequency of $f_c = 6.745$ GHz and a decay rate of $\kappa/(2\pi) = 1.98$ MHz.

Two devices on Si/SiGe heterostructure

Device 1
Natural-silicon quantum well
Micromagnet tilt angle , $\theta = 15^\circ$

Device2
Enriched ^{28}Si quantum well
Micromagnet tilt angle, $\theta = 10^\circ$

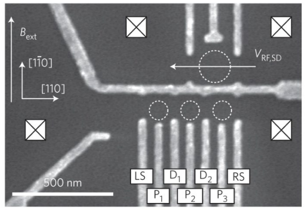
Overview of the different coupling approach

Task: coherent interactions between two spins

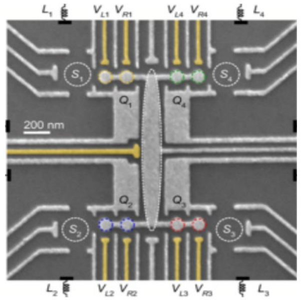
exchange interaction

- wave function overlap between charges in neighbouring dots,
- qubit separations of 100–200 nm
- million-qubit register at a 100 nm pitch will face challenges, related to the fan-out of control and readout wires.

coupling spins via an intermediate quantum dot



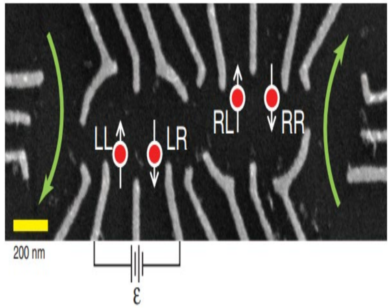
L.M.K Vandersypen group (2017)



F.Kuemmeth group (2021)

capacitive coupling

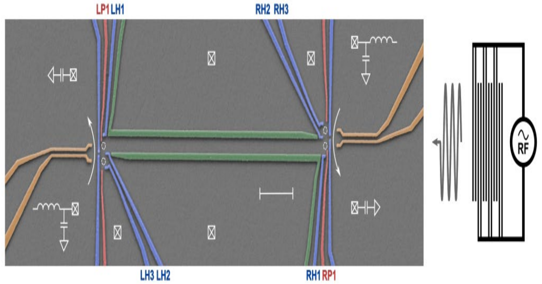
- Short range
- two adjacent S-T0 qubits such that they are capacitively coupled, but tunneling between them is suppressed



A.Yacoby group(2012)

shuttling of electrons

- limited to micrometer distance
- electrically controlled shuttling is slow in process
- via surface acoustic wave has practical obstacles



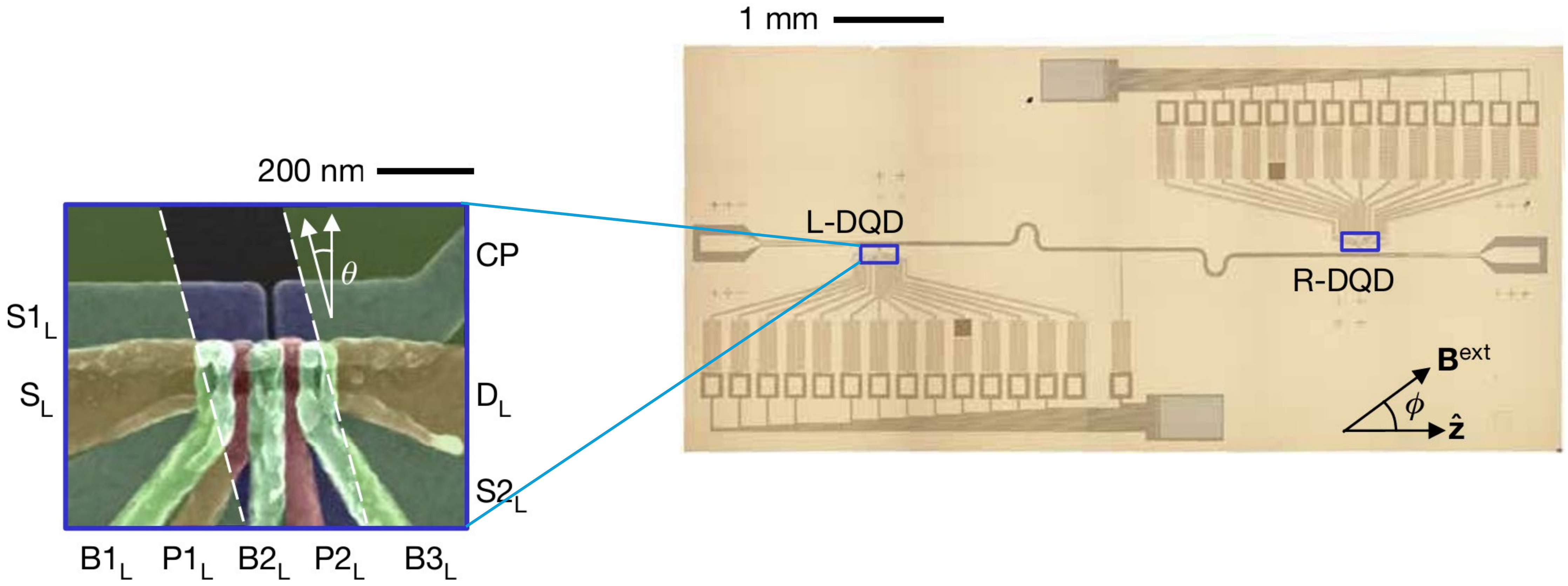
Baptiste Jadot et. al(2020)

Over 6um

on-chip superconducting resonators

- coupling distances of several hundreds of micrometres achievable.
- operations can be just as fast as those based on wavefunction overlap.

Device layout



- A double-well potential is formed beneath the plunger gates $P1_L$ and $P2_L$
- Barrier gate $B2_L$ is used to adjust interdot tunnel coupling.
- Spin–orbit coupling is induced by a Co micromagnet .
- CP, split-gate cavity coupler is galvanically connected to the central pin of the superconducting cavity
- $S1_L$, $S2_L$, S_L , D_L denote other gates used to define the DQD

Coupling scheme

Two stages of quantum-state hybridization

Charge photon coupling

a single photon mode confined within a microwave cavity hybridizes with the electron charge state through the electric-dipole interaction. $g_c \sim \boldsymbol{d} \cdot \boldsymbol{E}_{rms}$

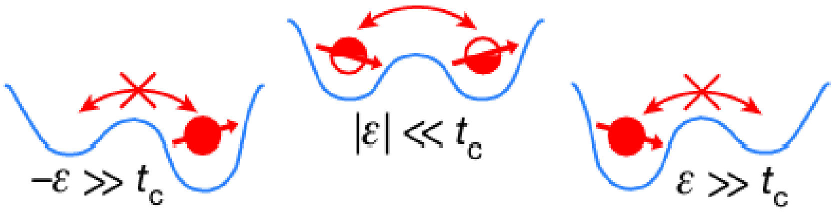
Charge-photon coupling rate , $g_c/_{2\pi} \approx 40\text{MHz}$

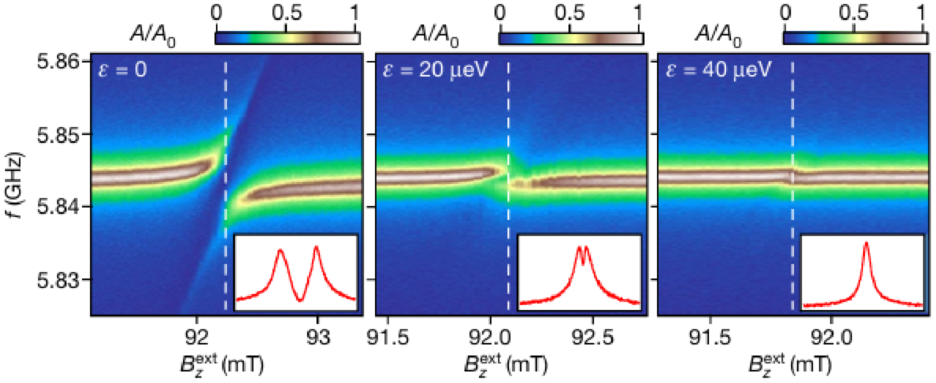
Hybridization of spin and charge degree of freedom

Micromagnet placed over the DQD hybridizes electron charge and spin by producing an inhomogeneous magnetic field.

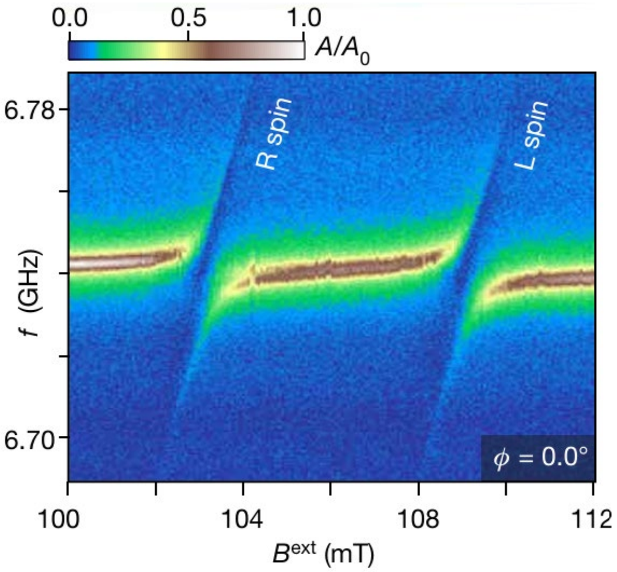
The combination of the electric-dipole interaction and spin–charge hybridization gives rise to a large effective spin–photon coupling rate.

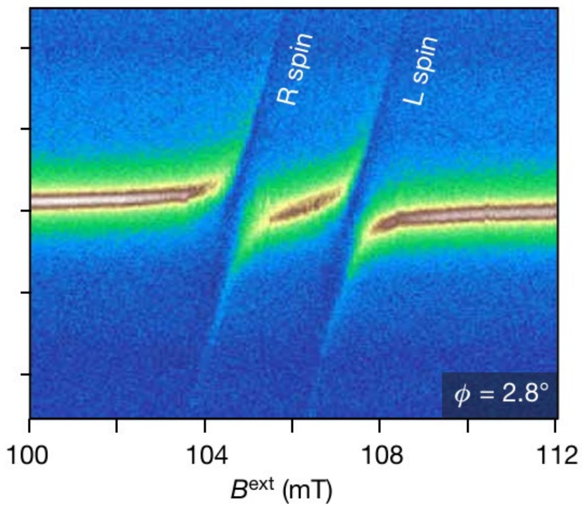
Detuning of qubit-photon interaction





Control over the spin-resonance frequency





Total magnetic field, $B_T = B_{ext} + B_M$

Susceptibility of micromagnet, $\varkappa$~ 0.6

$$\Delta f = \frac{g\mu_B B_T}{h} = 268MHz$$

spin-cavity coupling rate , ${}^{g_{s,L}}/_{2\pi} \approx 10.7 \pm 0.1\mathrm{MHz}$

${}^{g_{s,R}}/_{2\pi} \approx 12.0 \pm 0.2\mathrm{MHz}$

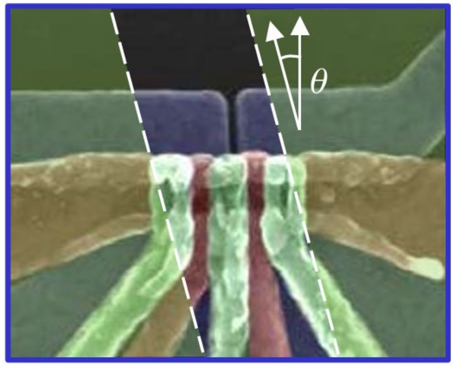
cavity decay rate, ${}^{\kappa}/_{2\pi} \approx 1.98\mathrm{MHz}$

${}^{\gamma_{s,R}}/_{2\pi} \approx 5.3\mathrm{MHz}$

spin decoherence rate, ${}^{\gamma_{s,L}}/_{2\pi} \approx 4.7\mathrm{MHz}$

at $B_{ext} = 109.1\mathrm{mT}$

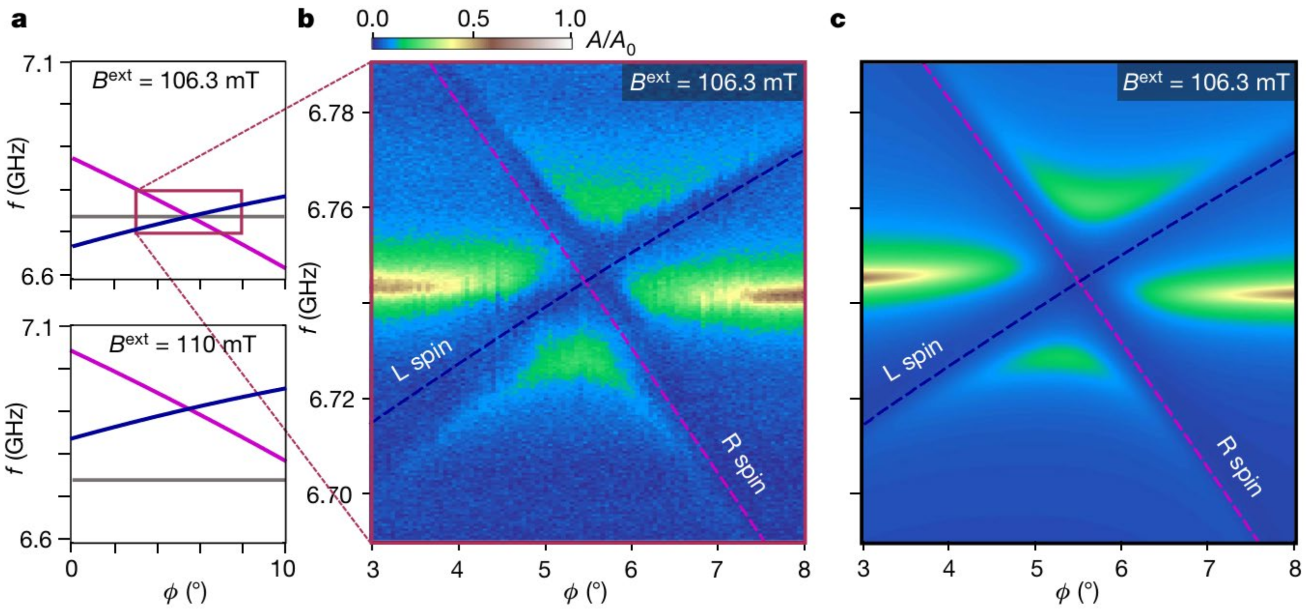
at $B_{ext} = 103.1\mathrm{mT}$



To overcome this local difference in the magnetic field , they tilted the micromagnet by 15°
Angle ,ϕ as an additional degree of freedom.

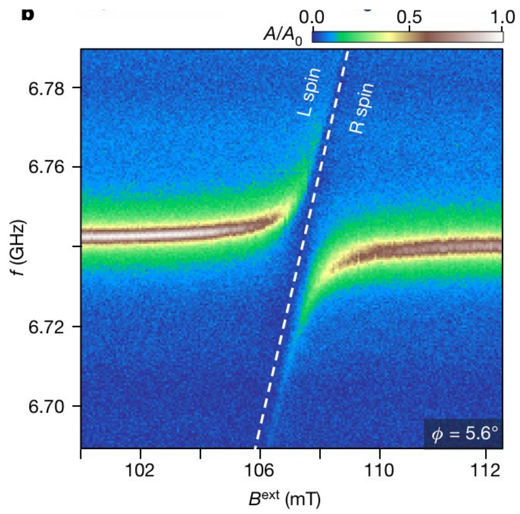
Tuning two spatially separated spins into resonance

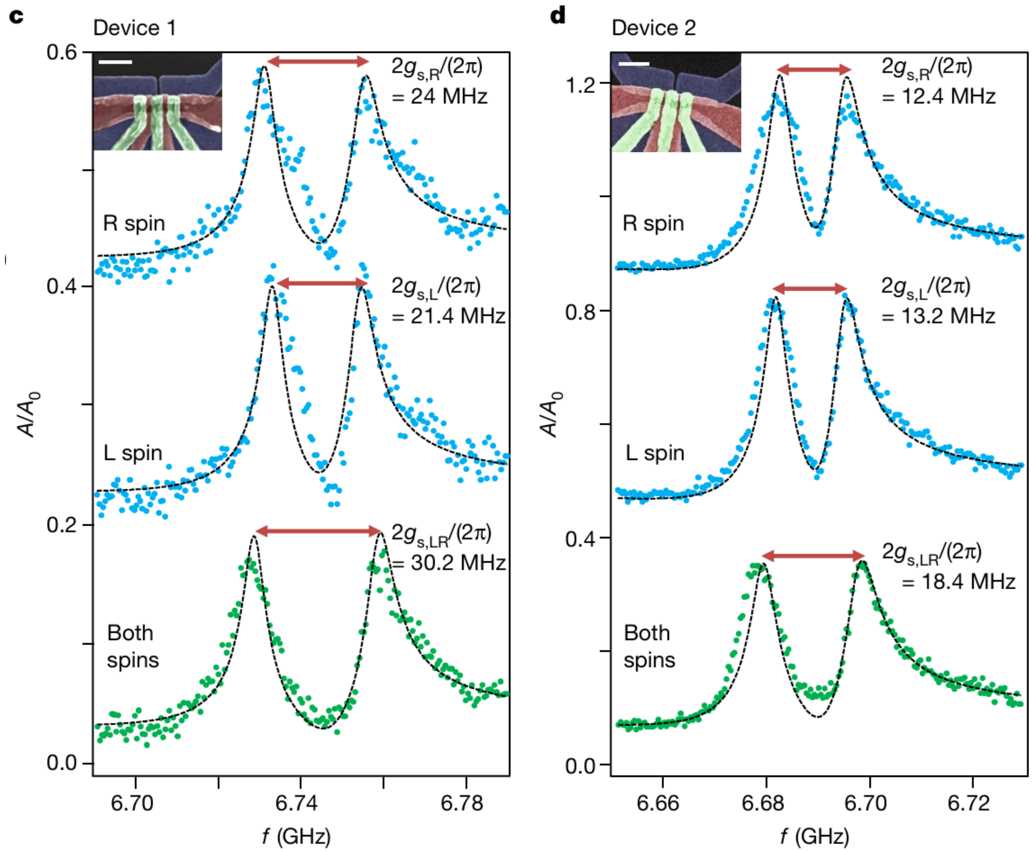
Microwave spectroscopy measurements of spins , $\phi = 6^{\circ}$ and $B_{ext} = 106.3mT$



ϕ allows control over the spin frequencies with respect to each other.
B_{ext} brings both spins into resonance with the cavity.

Resonant coupling of the two spins via a cavity photon





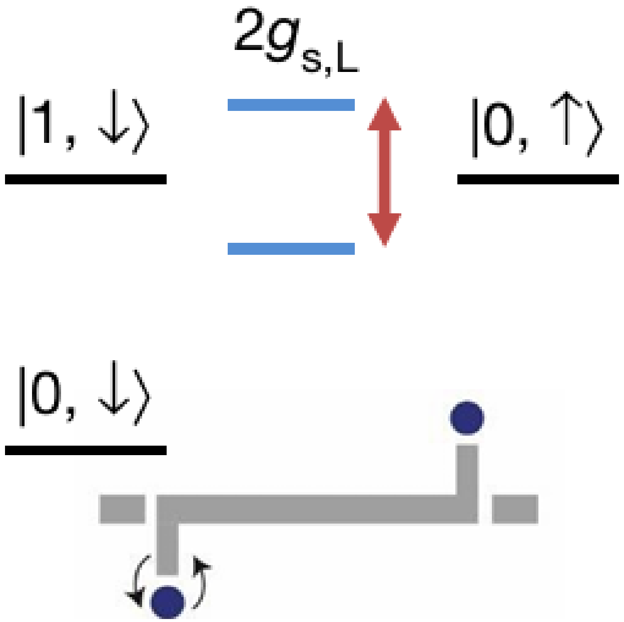
At 5.6 degree , Both experiences the same magnetic field hence have equal spin resonance frequency.

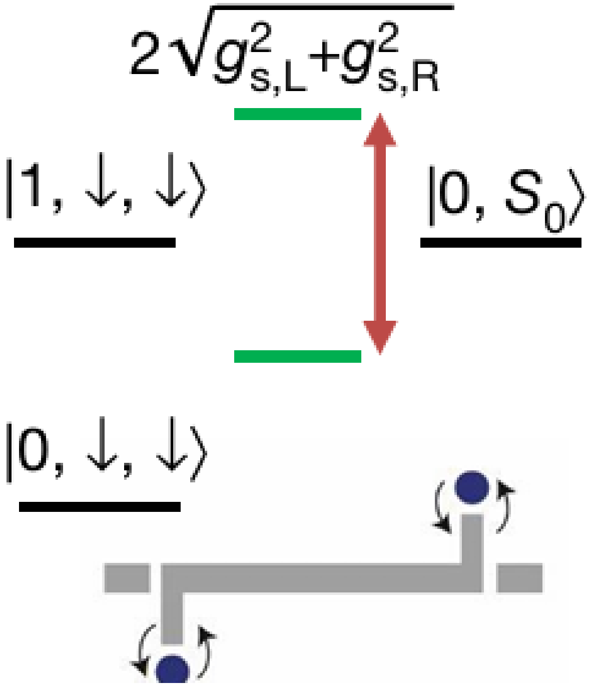
Enhanced Rabi splitting is observed

Vacuum rabi splitting

For N identical spins, Jaynes-Cummings model predicts a collective $\sqrt{N}$ enhancement of the coupling rate
Hence there will be factor of $\sqrt{2}$ enhancement will be seen.
With theoretical predictions they have 6% of deviation.

Jaynes-Cumming Model





Jaynes–Cummings model for a single spin and a single photon in the cavity.

With the L spin tuned into resonance with the cavity, the spin and cavity photon hybridize, leading to a vacuum Rabi splitting of magnitude 2gs,L in the cavity transmission.

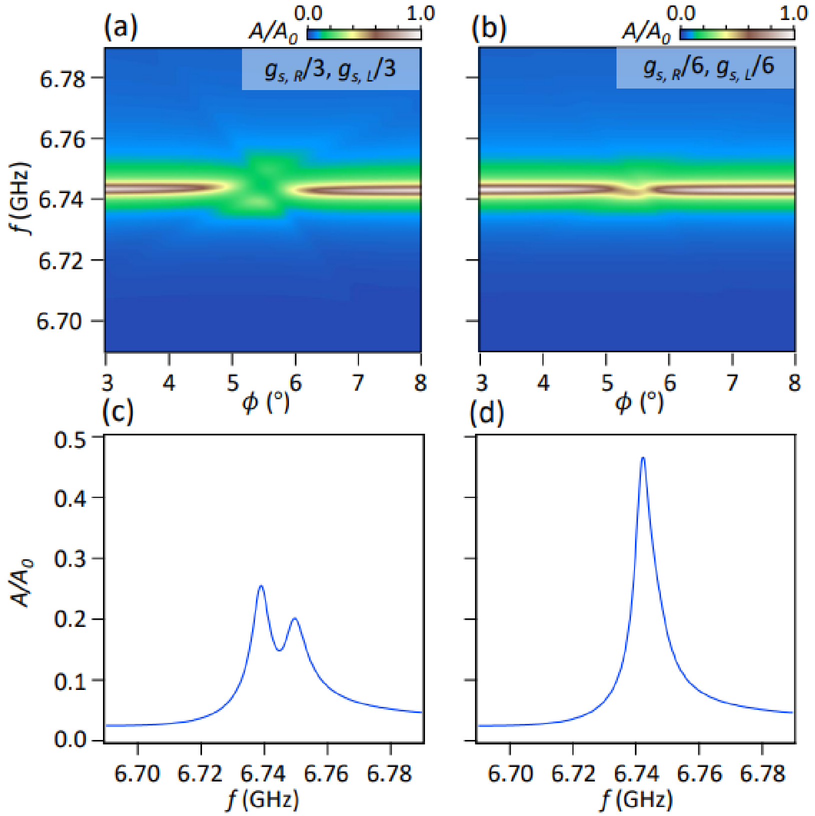
when both spins are simultaneously tuned into resonance with the cavity, the excited-state spectrum splits into dark state given here by spin triplet state and two bright states.

Bright states are hybridization between the singlet state and the state with single photon.

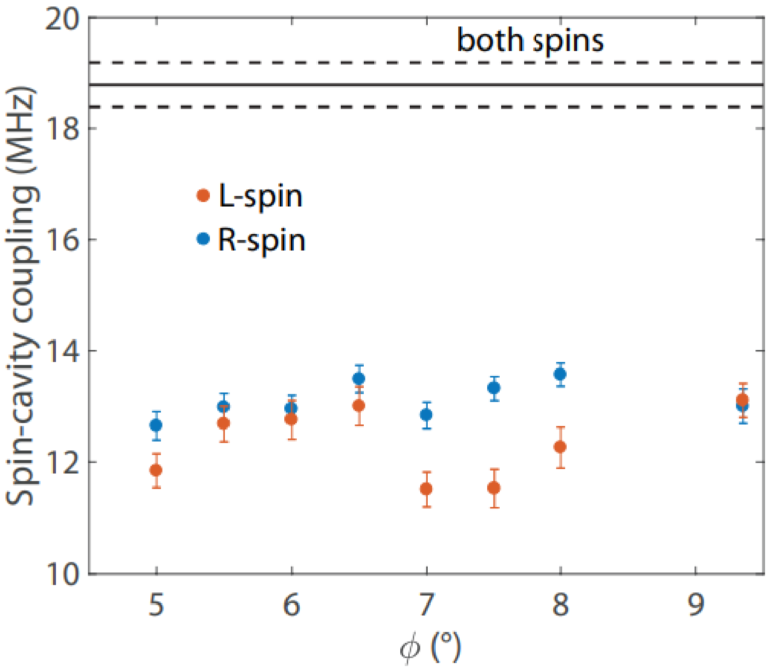
which are separated in energy by $2g_{sLR} = 2\sqrt{g_{s,L}^2 + g_{s,R}^2}$

Information from supplementary

Simulation results to calibrate the strength of the coupling rates



Angular dependence of spin-cavity coupling



Deviation due to slight changes in the electrostatic tuning of the DQD

Summary

Resonant coupling has been demonstrated which involves the real cavity photon and spins interaction.

Coupling strength,$g_c \sim g_s \sim \sqrt{Z_r}$, since $Z_r = 200\Omega$ they couldn't reach the dispersive regime

Coupling rate between the two spins in the dispersive regime is given as $J = \frac{g_s^2}{\Delta}$ where $\Delta = f_c - f_s$

Observation of dispersive regime requires $\frac{J}{\gamma_s} > 1$, in this work the ≈ 0.4- 0.5

Implementation of high impedence resonator will results to higher coupling strength into dispersive regime.