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A dressed singlet-triplet qubit in germanium

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In semiconductor hole spin qubits, low magnetic field (B) operation extends the coherence time (T_2^*) but proportionally reduces the gate speed. In contrast, singlet-triplet (ST) qubits are primarily controlled by the exchange interaction (J) and can thus maintain high gate speeds even at low B. However, a large J introduces a significant charge component to the qubit, rendering ST qubits more vulnerable to charge noise when driven. Here, we demonstrate a highly coherent ST hole spin qubit in germanium, operating at both low B and low J. By modulating J, we achieve resonant driving of the ST qubit, obtaining an average gate fidelity of 99.68% and a coherence time of $T_2^* = 1.9\,\mu s$. Moreover, by applying the resonant drive continuously, we realize a dressed ST qubit with a tenfold increase in coherence time ($T_{2\rho}^* = 20.3\,\mu s$). Frequency modulation of the driving signal enables universal control, with an average gate fidelity of 99.63%. Our results demonstrate the potential for extending coherence times while preserving high-fidelity control of germanium-based ST qubits, paving the way for more efficient operations in semiconductor-based quantum processors.
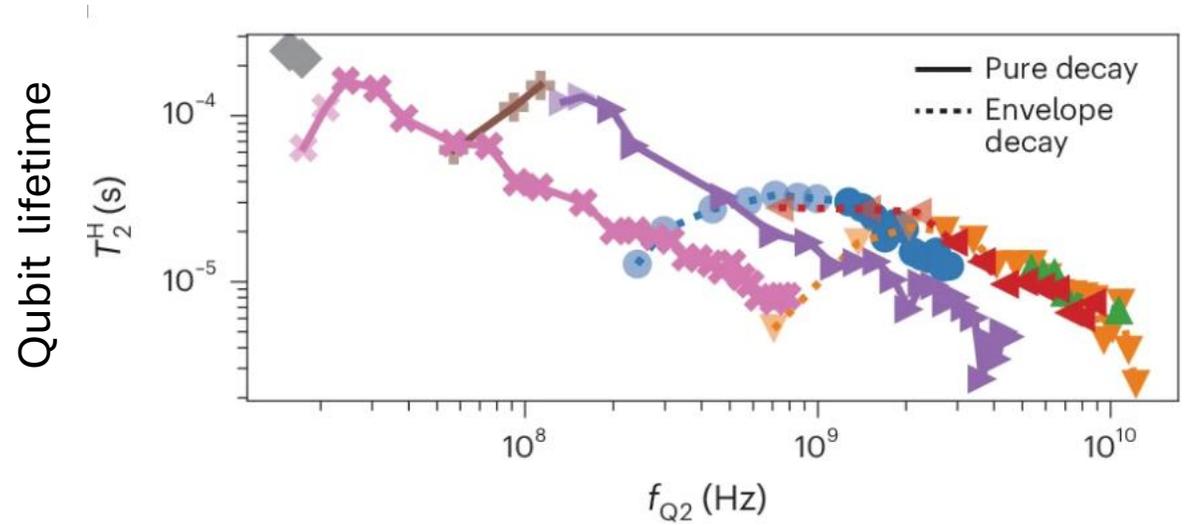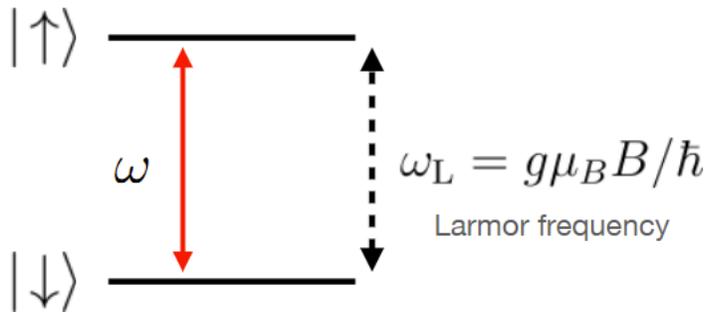
Problem addressed

Semiconductor hole spin qubits

$$\hat{H}_{\text{vacuum}} = \frac{1}{2}g\mu_B\hat{\boldsymbol{\sigma}} \cdot \boldsymbol{B}$$

g-factor

$$\hat{H}_{\text{semic.}} = \frac{1}{2}\mu_B\hat{\boldsymbol{\sigma}} \cdot \underline{\underline{g}}\boldsymbol{B}$$

g-matrix or g-tensor

$$\omega_{\text{L}} = g\mu_B B/\hbar$$

$|\uparrow\rangle$

ω

$|\downarrow\rangle$

Larmor frequency

Hendrickx et al. Nature Materials(2024)

Goal : To have high coherence time(T_2^*) while maintain high gate speeds

Possible solutions

Low magnetic field operation

Extends coherence time (T_2^*)   Reduces the gate speed

Singlet-Triplet(ST) qubits: System of two spin
- ➤ controlled by exchange interaction(J)
- ➤ High gate speed at low B field
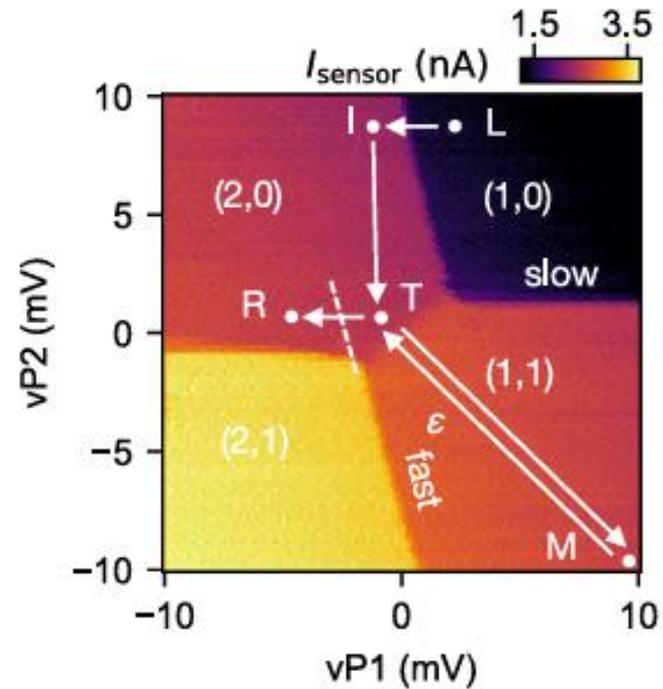- ➤ Large J exposes to charge noise when driven

This work demonstrate
- ➤ Highly coherent ST qubit in germanium at low B and low J
- ➤ Resonant driving ⟶ Modulating J ⟶ $T_2^* = 1.9\mu s$, gate fidelity = 99.68%
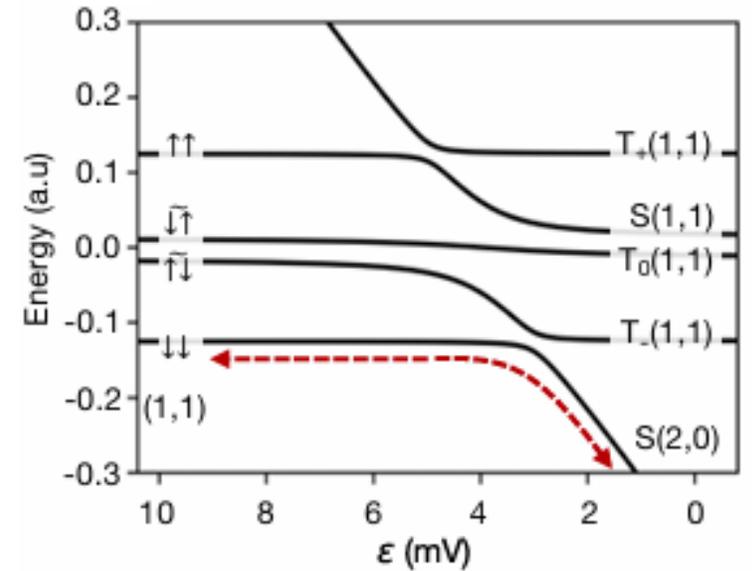- ➤ driving continuously ⟶ Dressed ST qubit ⟶ $T_2^* = 20.3\mu s$, gate fidelity = 99.63%

Work in details ……
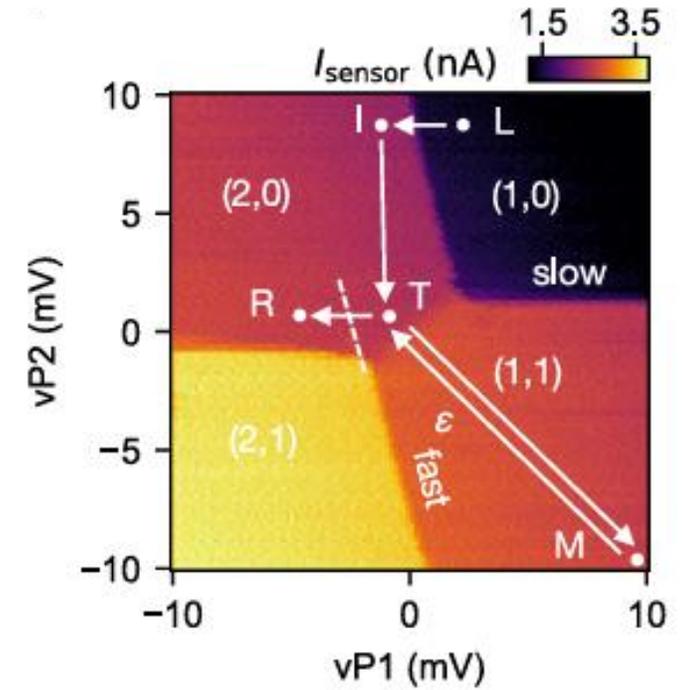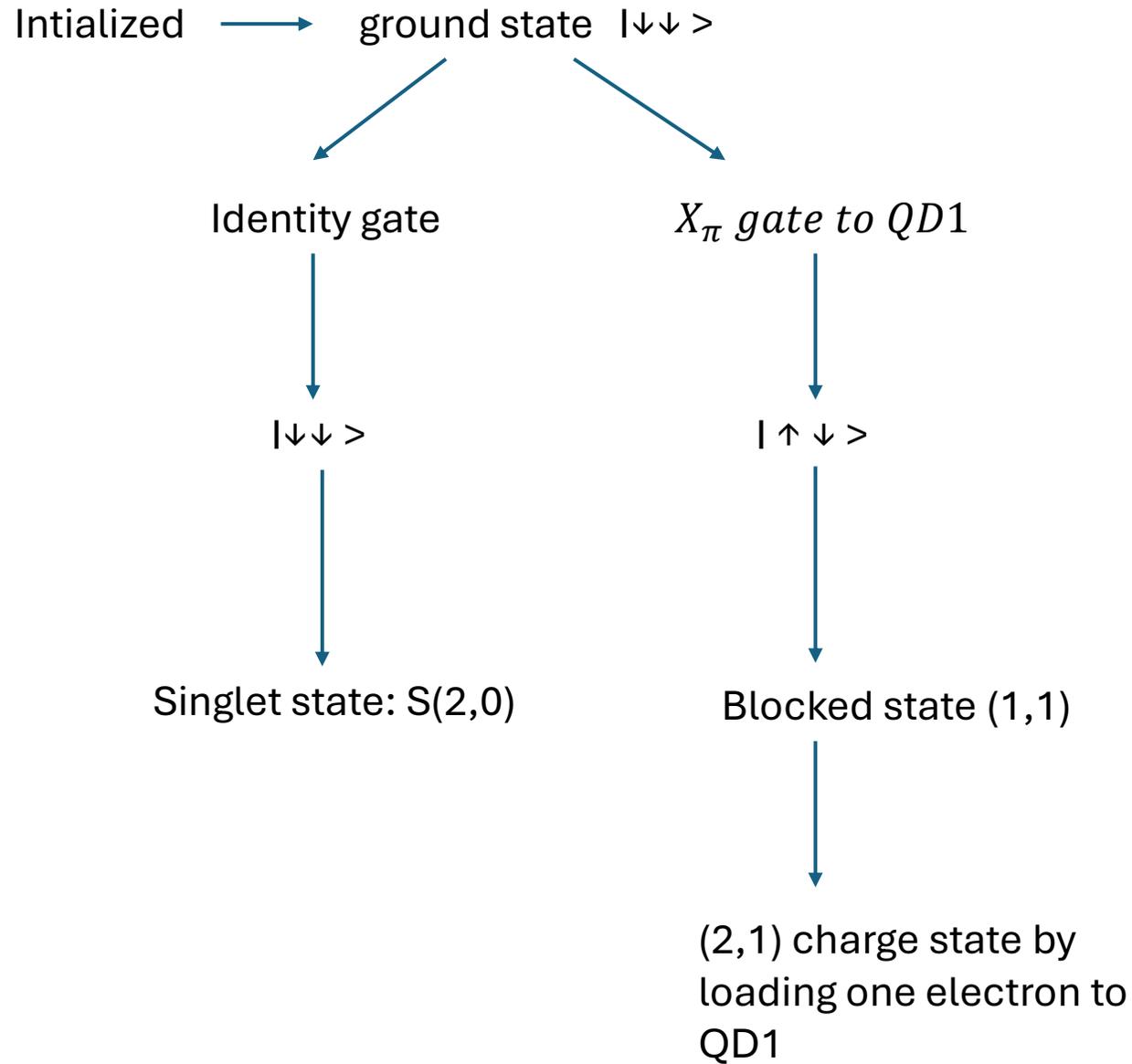
B= 20mT
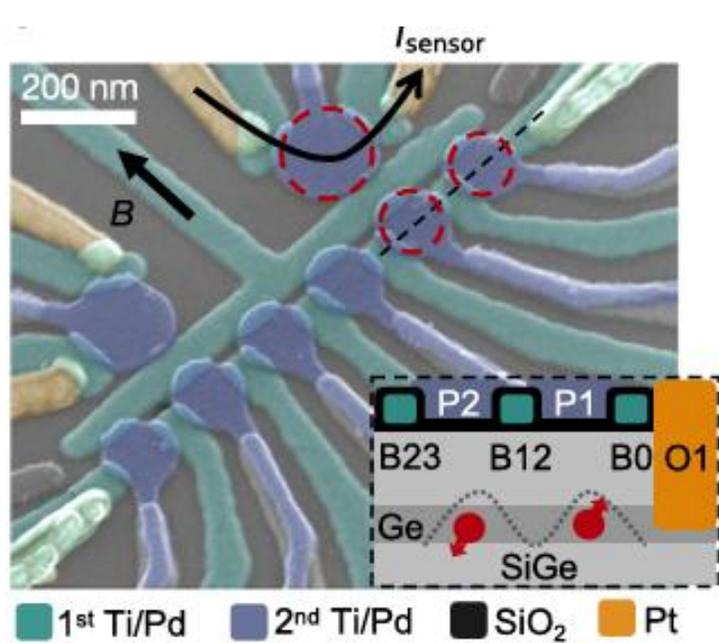
Device layout

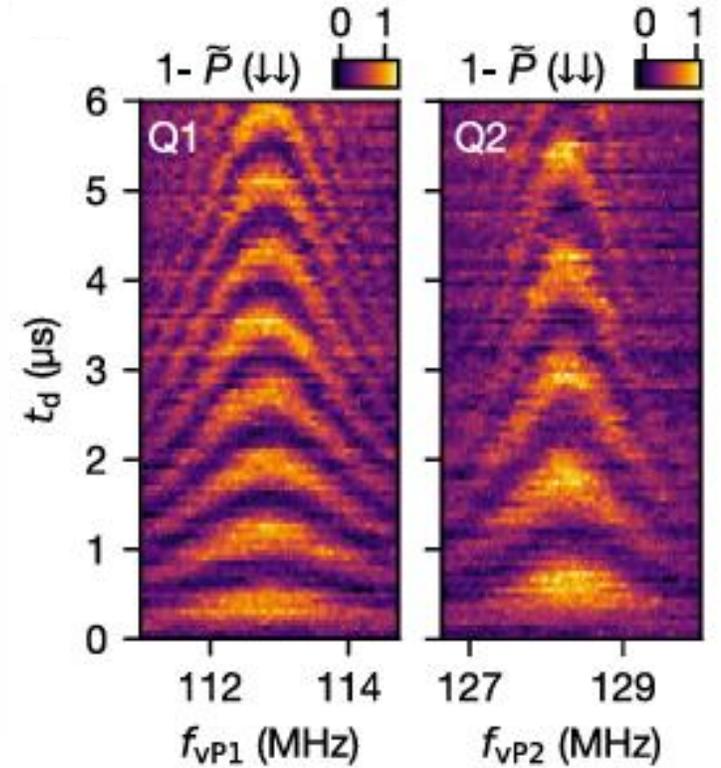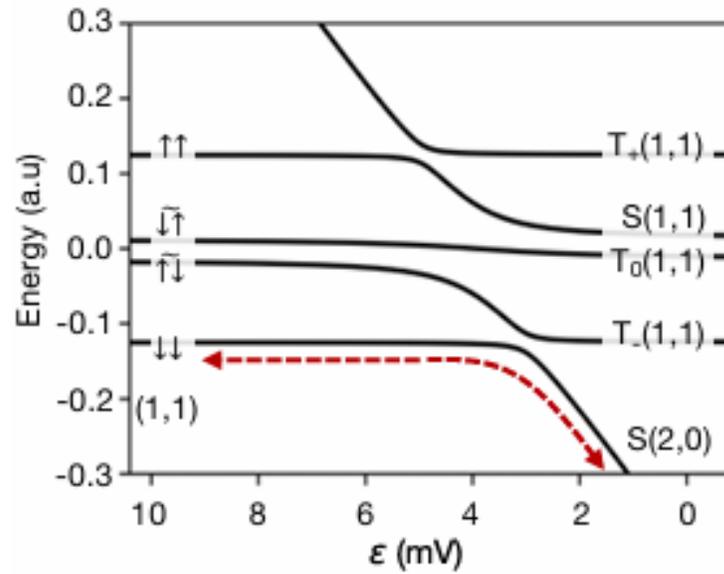Charge stability diagram
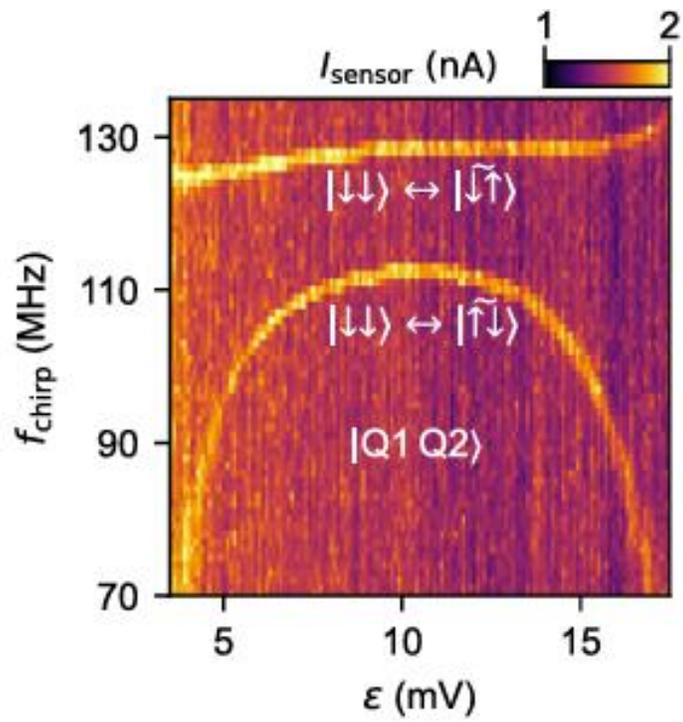

Energy diagram

Operate device in (1,1) charge configuration and initialize the spins in their ground state $|\downarrow\downarrow\rangle$

At point R. Readout performed it distinguish other excited spin states $|\uparrow\uparrow\rangle$, $|\downarrow\uparrow\rangle$ $|\uparrow\downarrow\rangle$

If $|\downarrow\downarrow\rangle$ then slowing ramp of the detuning into S(2,0)

Read out : Spin to charge conversion

Intialized → ground state $|\downarrow\downarrow>$

Identity gate

X_π gate to QD1

$|\downarrow\downarrow>$

$|\uparrow\downarrow>$

Singlet state: S(2,0)

Blocked state (1,1)

(2,1) charge state by loading one electron to QD1

Spin flip transition frequencies

Applied broadband (chirped) voltage drive to vP2 around frequency f_{chirp}

Obtained symmetric point at $\varepsilon = 10mV$, less sensitive to the detuning

At this point, spin transition frequencies of the spin as $f_{Q1} = 112.9\ MHz$ ($g = 0.41$)
$f_{Q2} = 128.3\ MHz$ ($g = 0.44$)
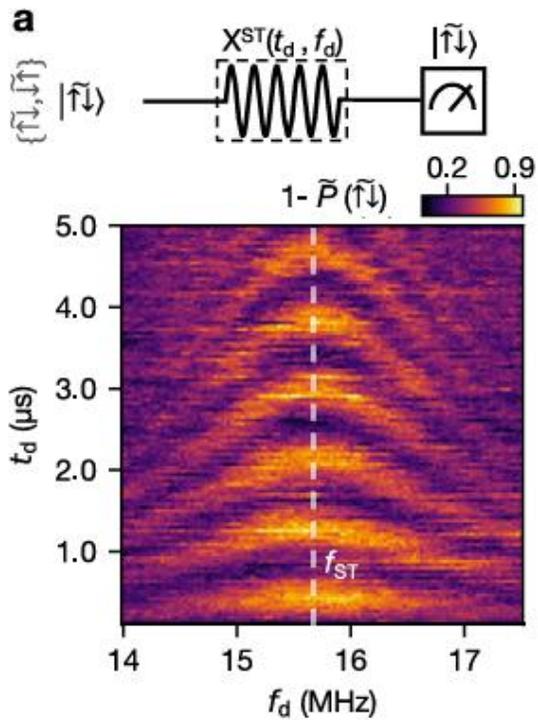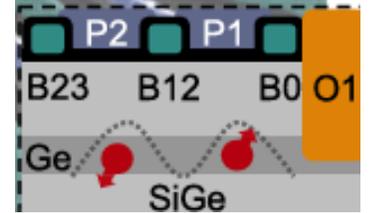
Rabi chevron pattern

First approach : Modulating the exchange interaction (J) $\longrightarrow$ resonantly driven ST qubit

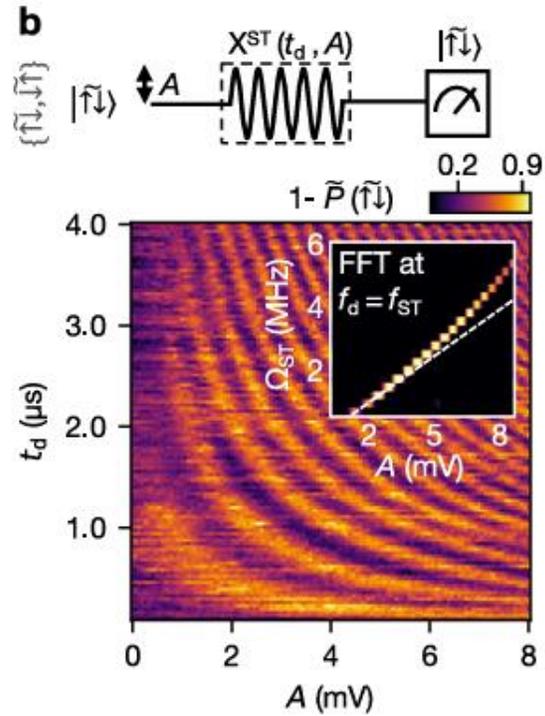$$Hamiltonian, \frac{H_{res}^{ST}}{h} = \frac{1}{2}(f_{ST}\sigma_Z + J_{AC}(t)\sigma_X)$$

$$J_{AC}(t) = A_J \cos(2\pi f_d t)$$

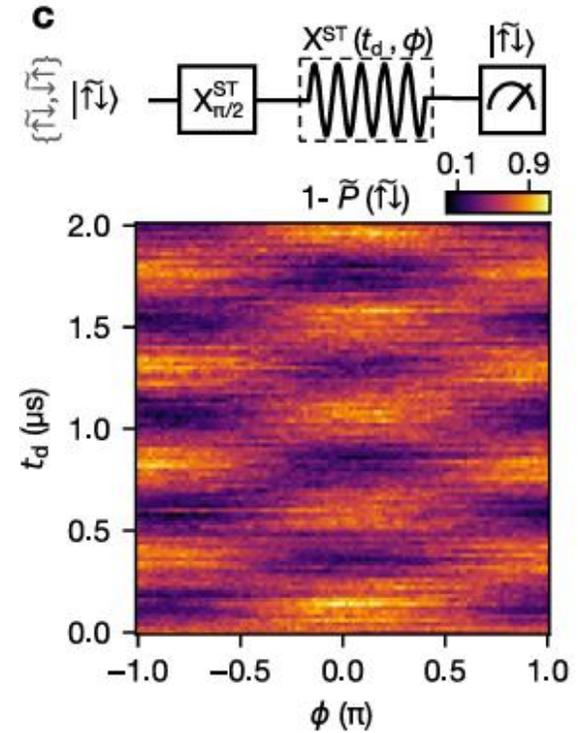$$f_{ST} = \sqrt{(\frac{\Delta E_Z}{h})^2 + (J_{DC})^2} = 15.65 MHz$$
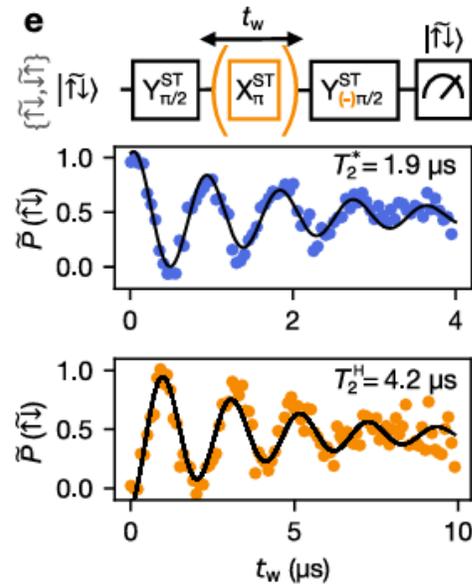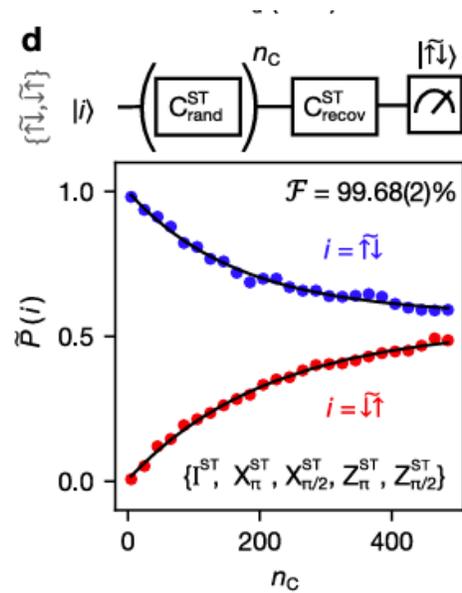
Drive tone applied to vB12

Rabi chevron pattern

Exponential dependence
of the Rabi oscillation $J_{AC} \propto \exp(vB12) \sim \exp(A\sin(2\pi f_d t))$

Qubit lifetime and Gate fidelity

Single-Qubit gate fidelity

Performed Randomized benchmarking using Clifford gate set.

Upto 485 Clifford gates and 100 randomizations

Dressed ST qubit: continuous application of resonant exchange drive

$$Hamiltonian, \frac{H^{ST}_{dressed}}{h} = \frac{1}{2}(\Omega_{ST}\tau_Z + \Delta v\,(t)\tau_X)$$

Approach 1: two- tone drive

Pump tone : $f_{pump} = f_{ST}$, A_{pump} varying, ⟶ Dressing of ST qubit

Weaker probe tone : $A_{probe} = 0.3mV$, f_{probe} varying ⟶ Induces transitions in dressed qubit

$$\Delta f = f_{probe} - f_{ST}$$

$$Drive\ term, \Delta v(t) \sim A_{probe}\cos(2\pi\Delta f t)$$

Rabi oscillation with three prominent features where the oscilations are perturbed

$\Delta f = 0$, increase in effective Rabi drive amplitude

$\Delta f = \pm\Omega_{ST}$, resonant driving in the dressed qubit subspace takes place.

This effect is called 'Mollow triplet'
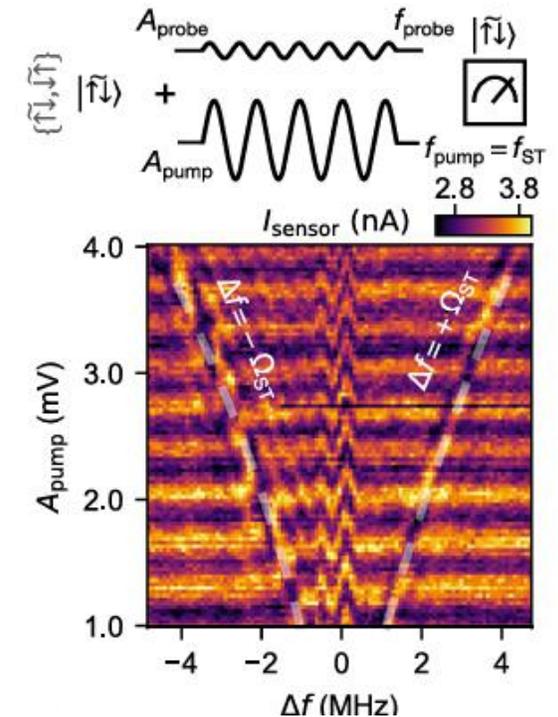
Dressed ST qubit
Approach 2: Frequency modulation

periodically modulate $f_d(t)$ around f_{ST}

Drive term , $\Delta\nu(t)\sim \Delta\nu_{FM}\cos(2\pi f_{FM}t + \phi_{FM})$

When f_{FM} scanned around Ω_{ST} ,
rabi chevron pattern is observed with Rabi freq.
of $\Omega_{ST}^{FM} = 0.75MHz$ for $\Delta\nu_{FM} = 1.5MHz$
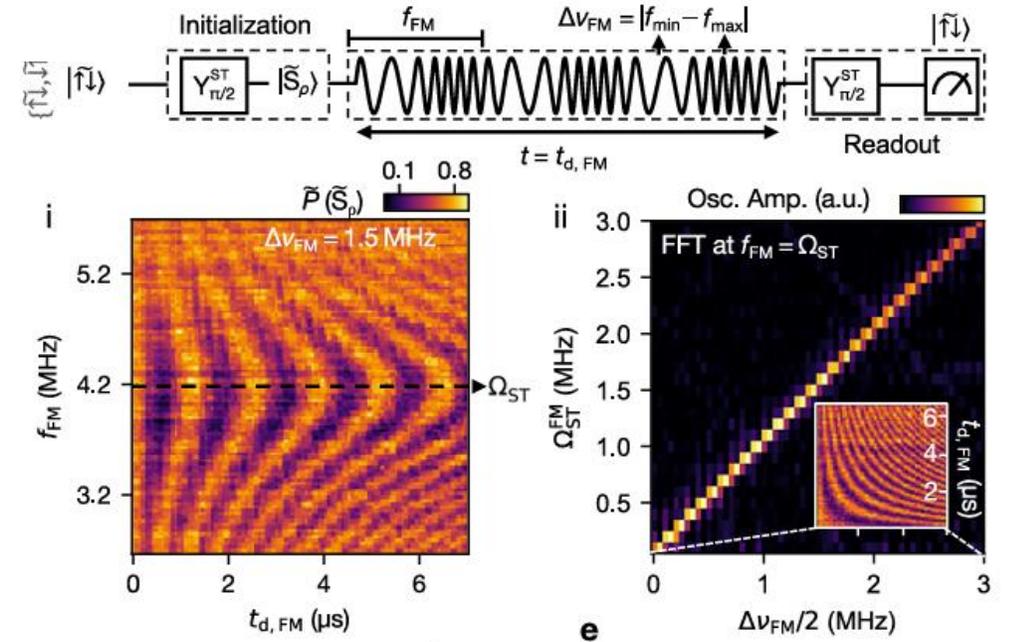
Dressed ST qubit lifetime and gate fidelity
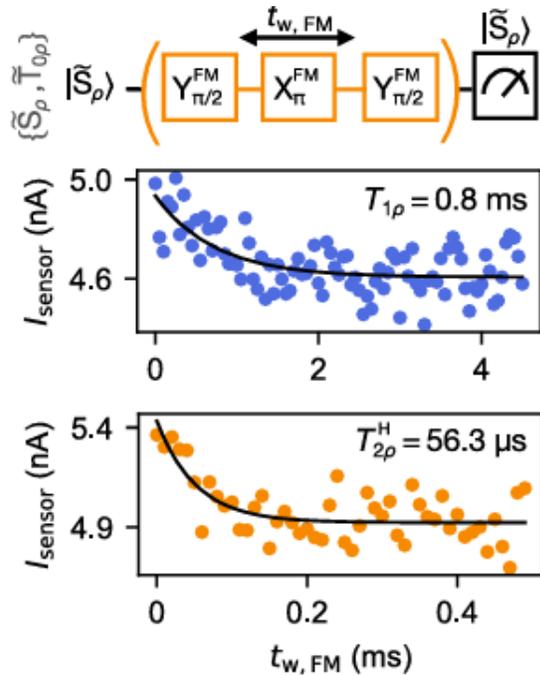
Qubit lifetime

Gate fidelity

Initial in dressed singlet state
Drive the system for a time $t_{w,FM}$
Readout of the dressed singlet population
Fit to the exponential decay gives the T1 time
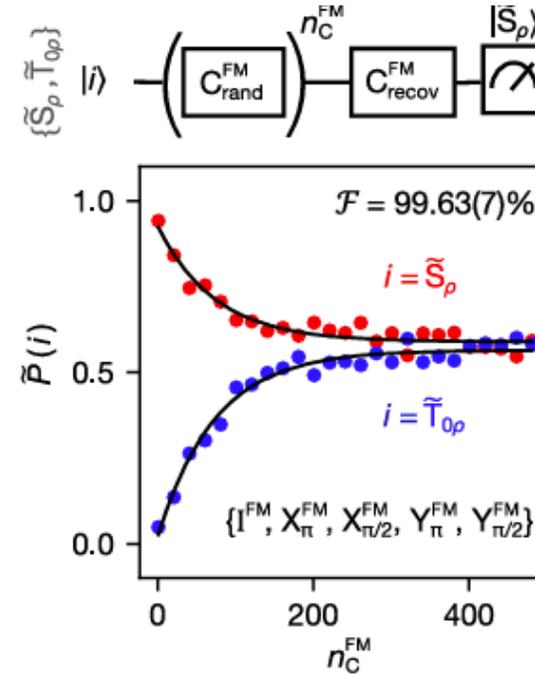
For T2 Hahn ,
X_π^{FM} echo pulse is inserted in between the initialization and readout .
This leads to refocus the state and $T_2^H = 56us$

Conclusion

Comparison of Metrics

	Resonant ST	Dressed ST
T_1	> 5 ms	0.8 ms
T_2^R	20.3 µs	–
T_2^*	1.9 µs	20.3 µs
T_2^H	4.2 µs	56.3 µs
$\mathcal{F}$	99.68(2)%	99.63(7)%
Ω_{ST}	1.5 MHz	1 MHz

e *Lab frame*

i $|\tilde{\uparrow\downarrow}\rangle$

f_{ST}

$|\tilde{S}\rangle$ $|\tilde{T}_0\rangle$

$J_{AC}(t)$

$|\tilde{\downarrow\uparrow}\rangle$

z, x, y

1st RWA

Rotating frame

ii $|\tilde{\uparrow\downarrow}\rangle = |\tilde{\uparrow\downarrow}_R\rangle$

$|\tilde{S}_R\rangle$ $|\tilde{T}_{0R}\rangle$

Ω_{ST}

$|\tilde{\downarrow\uparrow}\rangle = |\tilde{\downarrow\uparrow}_R\rangle$

iii *change of basis*

Rotating frame new basis

$|\tilde{S}_R\rangle$

$|\tilde{\downarrow\uparrow}_R\rangle$ Ω_{ST} $|\tilde{\uparrow\downarrow}_R\rangle$

$\Delta\nu(t)$

$|\tilde{T}_{0R}\rangle$

2nd RWA

Dressed frame

iv $|\tilde{S}_R\rangle = |\tilde{S}_\rho\rangle$

$|\tilde{\downarrow\uparrow}_\rho\rangle$ Ω_{ST}^ρ $|\tilde{\uparrow\downarrow}_\rho\rangle$

$|\tilde{T}_{0R}\rangle = |\tilde{T}_\rho\rangle$