HOPPING MODE IN PLANAR GE

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24/10/2025

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RESEARCH ARTICLE | QUANTUM COMPUTING

Operating semiconductor quantum processors with hopping spins

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SCIENCE • 25 Jul 2024 • Vol 385, Issue 6707 • pp. 447-452 • DOI: 10.1126/science.ado5915

↑ **For hopping mode**
↓ **For comparison**

Article | Published: 24 March 2021

A four-qubit germanium quantum processor

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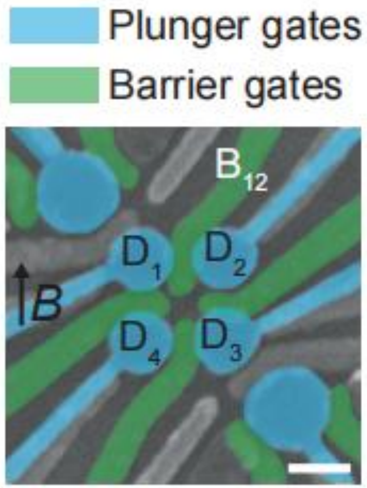
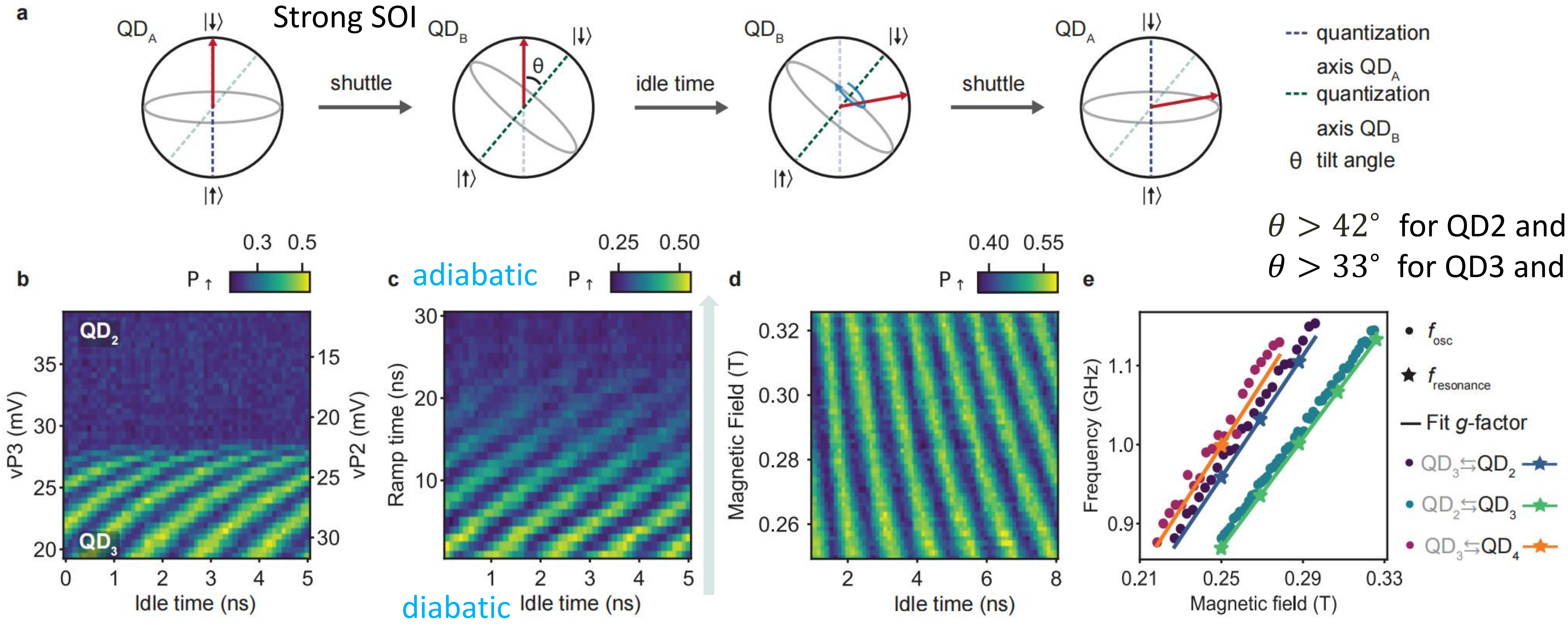
Nature **591**, 580–585 (2021) | Cite this article



SOI Induced Quantization Axis Change



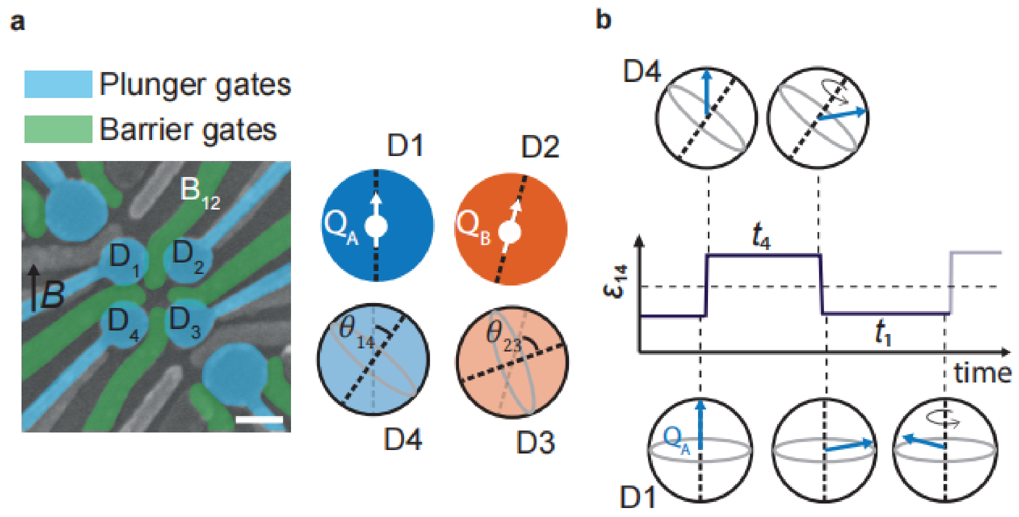
$\theta > 42^\circ$ for QD2 and QD3

$\theta > 33^\circ$ for QD3 and QD4

Shuttle in Ge is not easy: large axis angle between the neighbor QDs

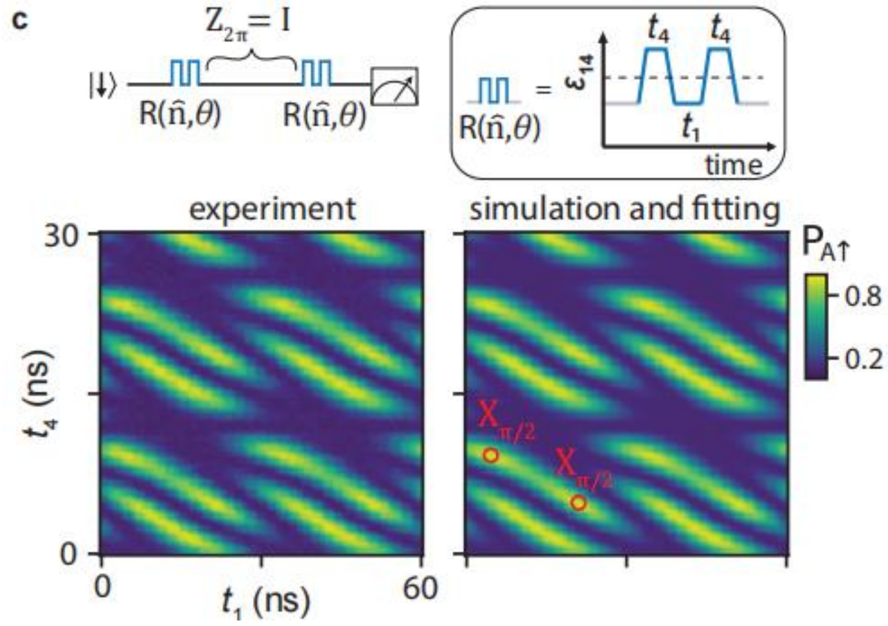
Floor van Riggelen-Doelman et al., Nat. Commun 15, 5716 (2024)

What is hopping mode

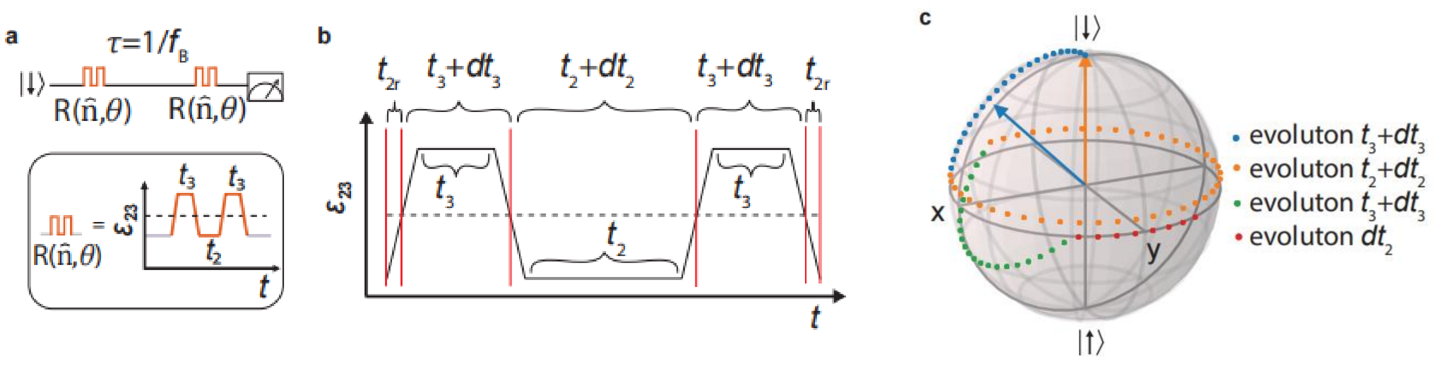


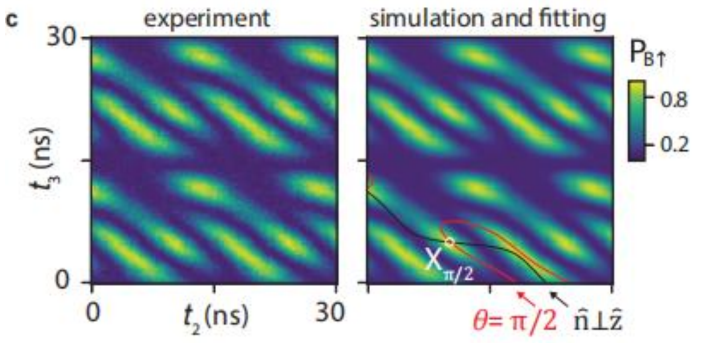
- Hopping mode: shuttle the spin between quantum dot with differences in the spin quantization axis to manipulate the qubit

- Hopping the qubit between Q1 and Q4. Measure the spin up probability with different (t1, t4)
- From simulation we can extract quantization axes angle θ_{14} , individual Larmor frequencies and the effective precession time during the ramp
- $Y_{\frac{\pi}{2}} = Z_{\frac{\pi}{2}} X_{\frac{\pi}{2}} Z_{\frac{3\pi}{2}}$, $Z_{\frac{\pi}{2}}$ gate is implemented by idling the qubit for the time defined by its precession in the lab frame



QB hopping





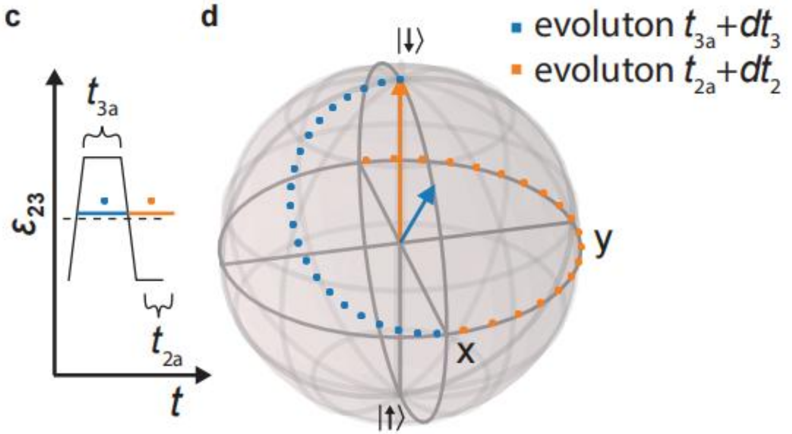
Shuttle method QB

- θ_{23} is close to 45 degree, we can get the X gate only shuttle back and forth
- Efficient qubit rotation frequency 7.1MHz, Larmor frequency 89.5 MHz
- $T_2^* \;=\; 4.5\,\mu s, T_2^{Hahn} \;= 24\,\mu s, T_2^{CPMG} \;= 1.7\,ms$
- Measured in 25mT
- Fidelity of $X_{\frac{\pi}{2},B} > 99.960\%$, $\mathrm{F_{shuttle}} = 99.992\%$

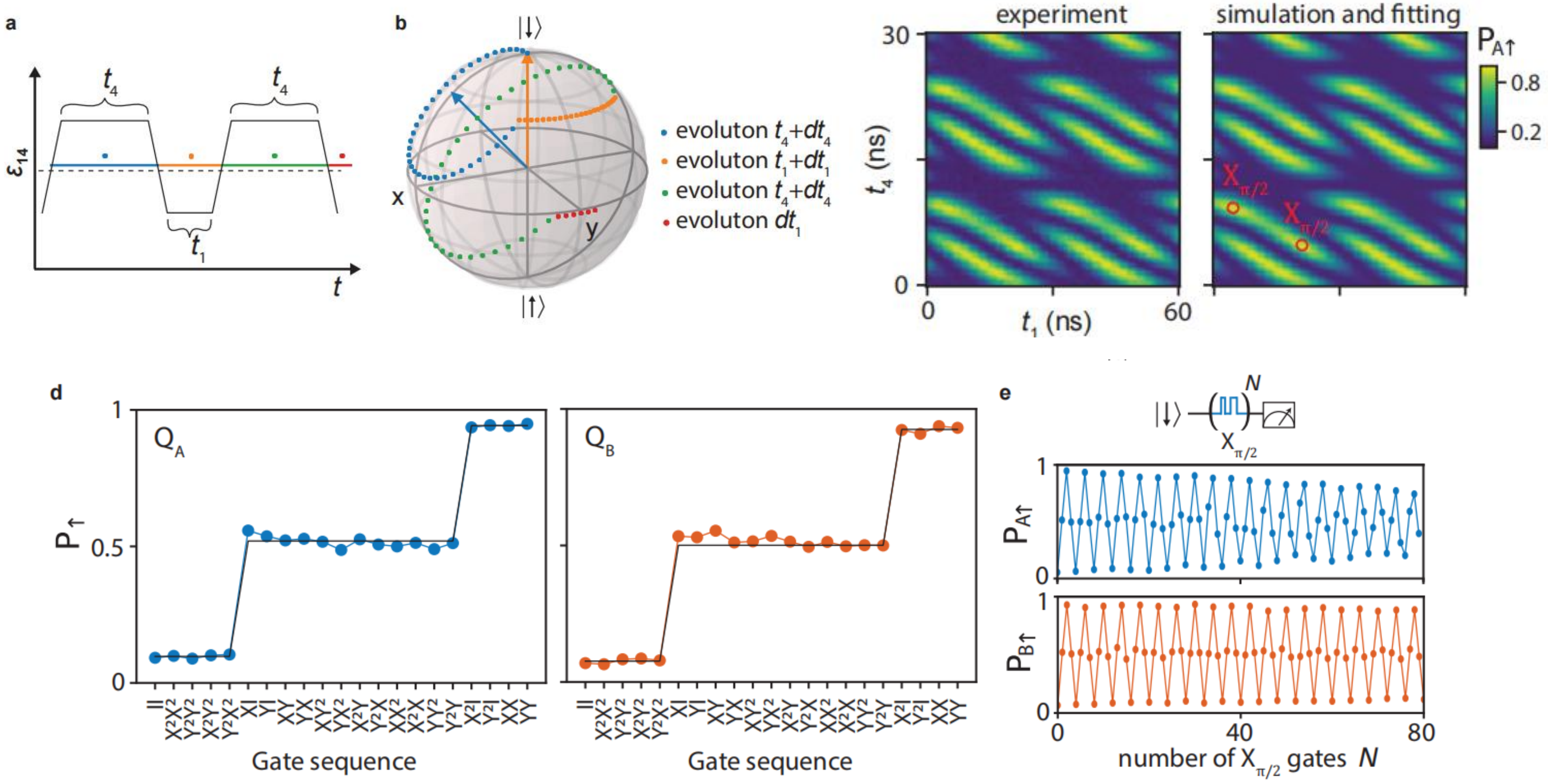
improve

EDSR method

- Measured in 1.05T
- $T_2^* \;= 146\,ns$

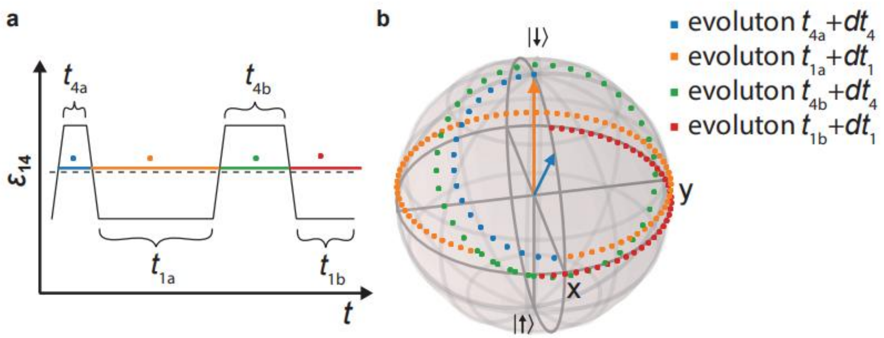


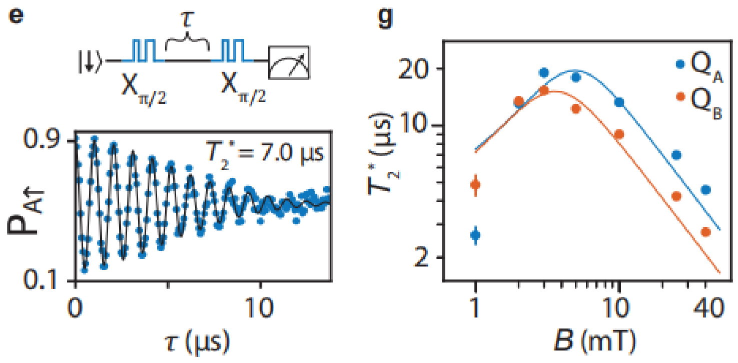
QA hopping: equal waiting time

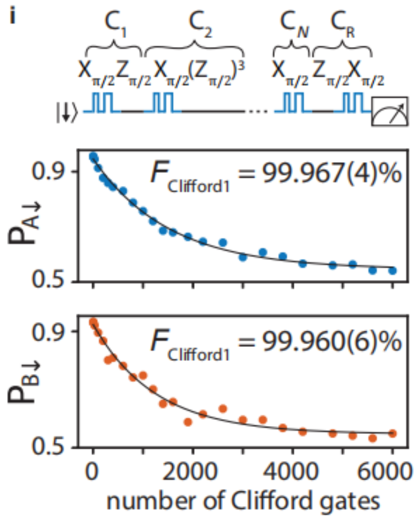


- Shuttle D1-D4-D1-D4-D1 to make a X gate of qubit A, θ_{14} ~ 65 degree
- Efficient qubit rotation frequency 2.6 MHz, Larmor frequency 42.6 MHz
- Measured in 25mT

QA hopping: unequal waiting time





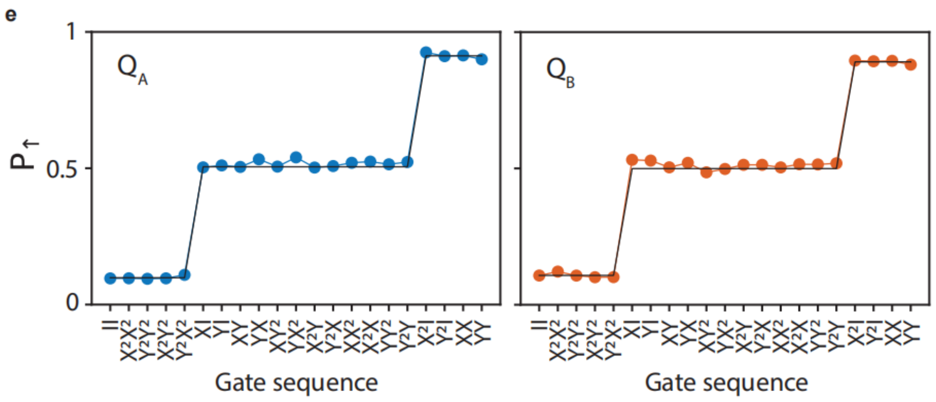


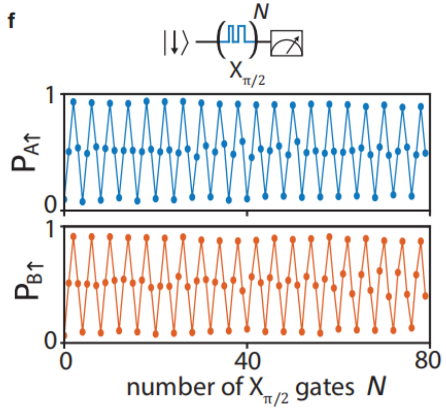
Shuttle method

- t_{4a} and t_{4b} is different. The first rotation in D4 is π and the subsequent rotations in D1 and D4 are either close to π or 2π.
- $T_2^* = 7.5\ \mu s, T_2^{Hahn} = 32\ \mu s, T_2^{CPMG} = 1.9\ ms$
- T_2^* changes with magnetic field, affected by electric noise and nuclear noise
- Fidelity of $X_{\frac{\pi}{2},A} > 99.967\%$, $\mathrm{F_{shuttle}} = 99.992\%$

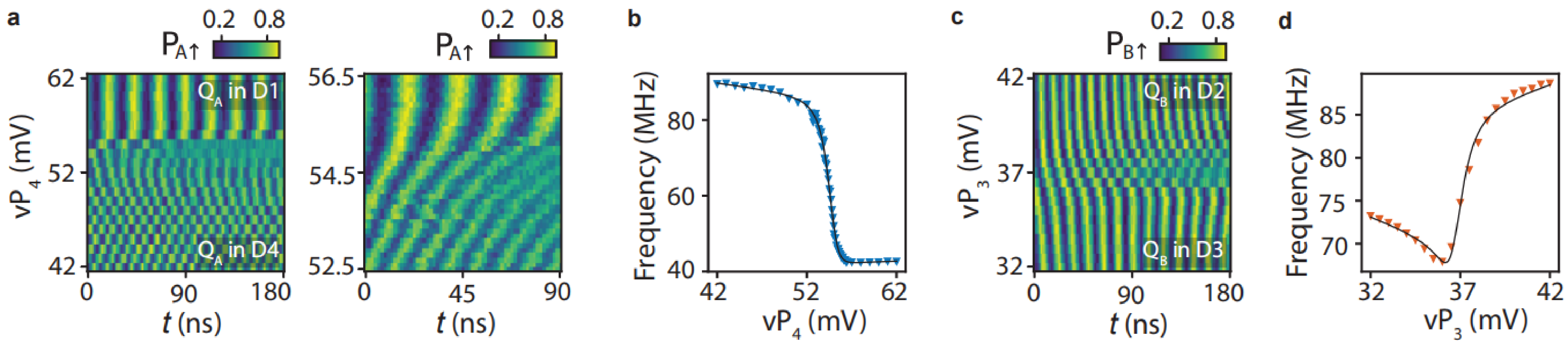
EDSR method

- Measured in 1.05T
- $T_2^* = 201\ ns$



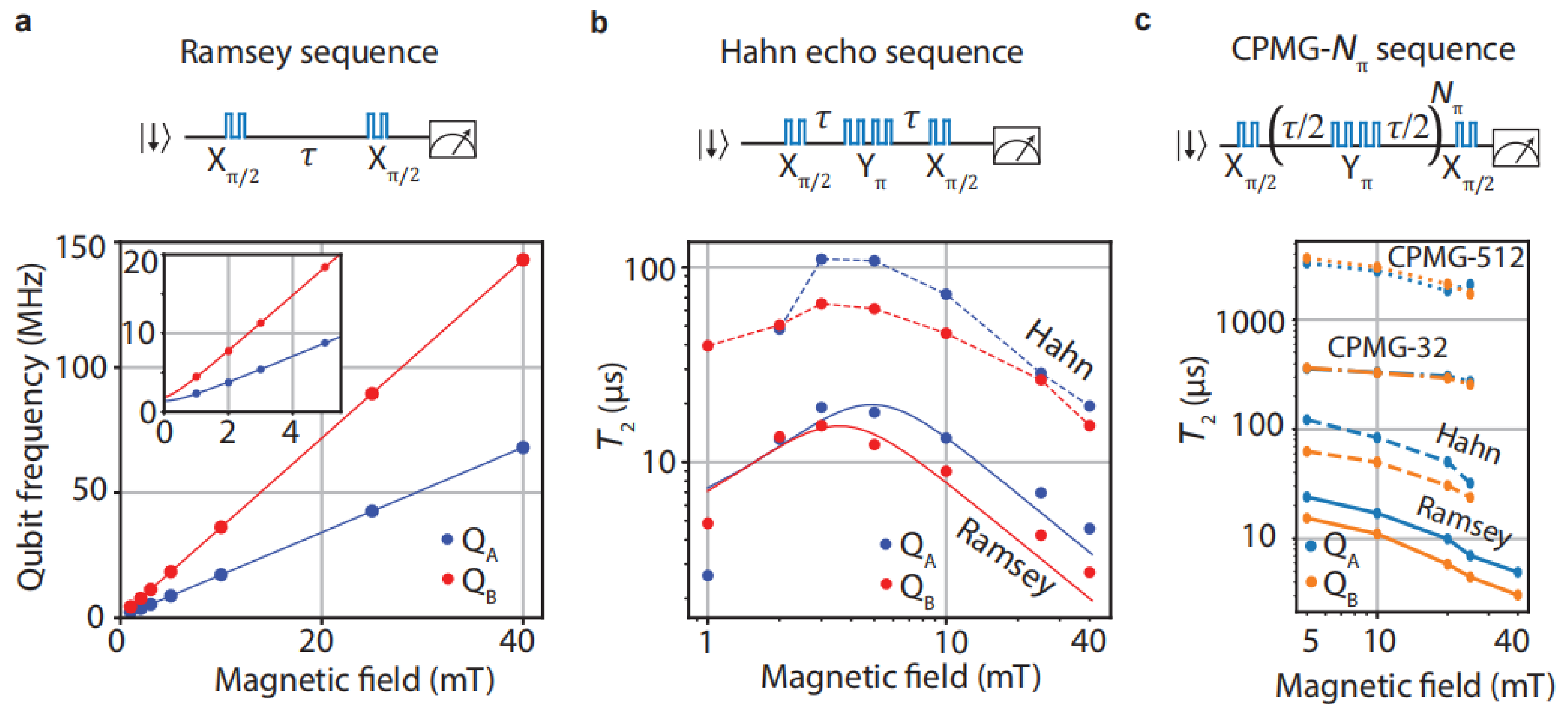


One qubit hopping



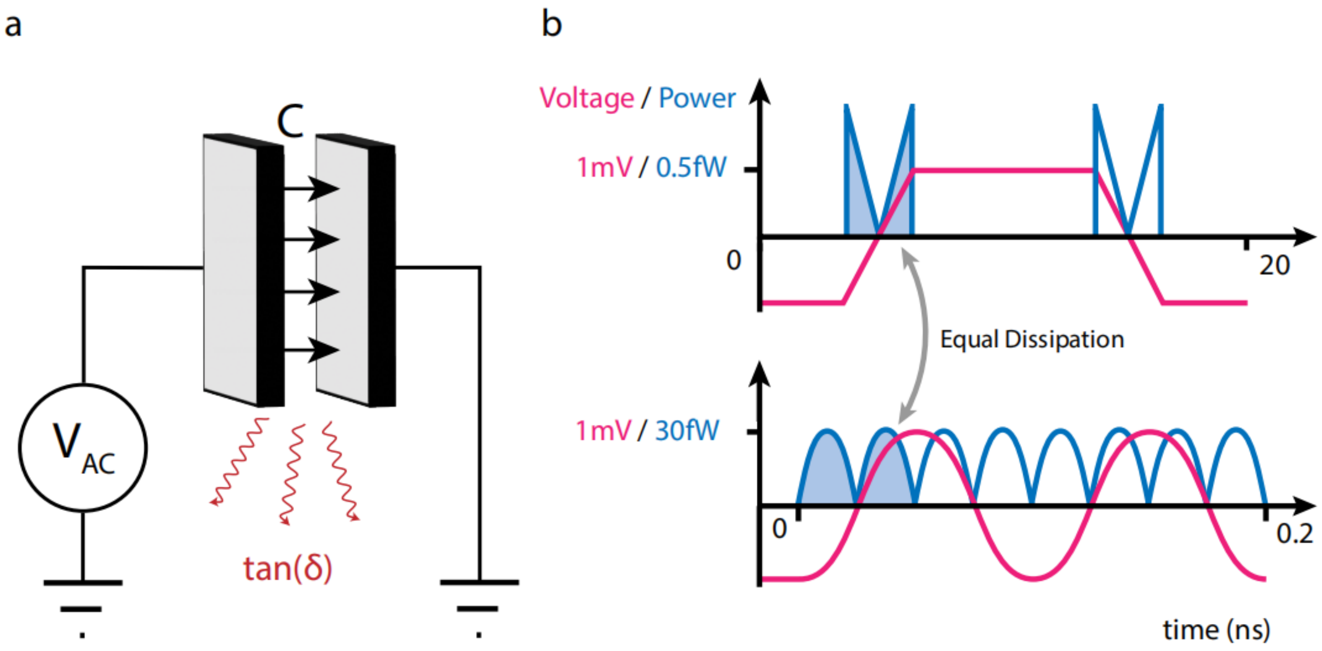
- The free evolution of QA at different detuning across D1-D4 anti-crossing. The panel on the right is the fine scan around anti-crossing
- the charge anti-crossing where the frequencies changes rapidly. The free evolution of QB at different detuning across D2-D3 charge anti-crossing

Coherence times of the individual qubits



- The frequencies of qubits QA and QB as a function of external magnetic field
- The T_2^* and T_2^{Hahn} ~ $f(B_{ext})$ when the magnet is at the driven mode
- The coherence time ~ $f(B_{ext})$ above 5 mT when magnet is in the normal operation mode. The longest coherence time is obtained at 5 mT, $T_2^* = 24.1\ \mu s, T_2^{Hahn} = 122\ \mu s, T_2^{CPMG} > 3\ ms$

Power dissipation model



- EDSR power dissipation:

$$E_{Loss} = N_{cycle} \tan(\delta)\, CV_{AC}^2$$

$$N_{cycle,EDSR} = \frac{2f_{Larmor}}{f_{rabi}} = \frac{2 \times 2MHZ}{12\ GHz}$$

$$E_{Loss} = 0.075 \tan(\delta)\, C$$

- Shuttling power dissipation:

$$N_{cycle,shuttle} = 4$$

$$E_{Loss} = 2 \times 0.0016 \tan(\delta)\, C = 0.0032 \tan(\delta)\, C$$

CZ gate and phase calibrated DCZ gate

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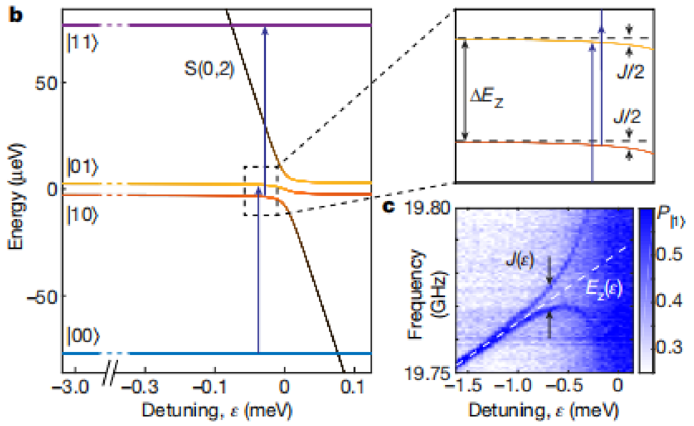
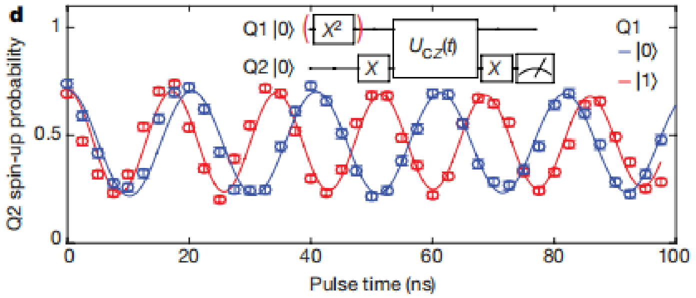


- Energy-level diagram of 2 qubit. At $\epsilon = 0$, the energy levels of the anti-parallel spin states shift by half the exchange energy J
- J changes with qubit frequency and detuning
- The spin-up probability of Q2 after applying the Ramsey sequence in which the duration of the detuning pulse is varied between two X gates on Q2

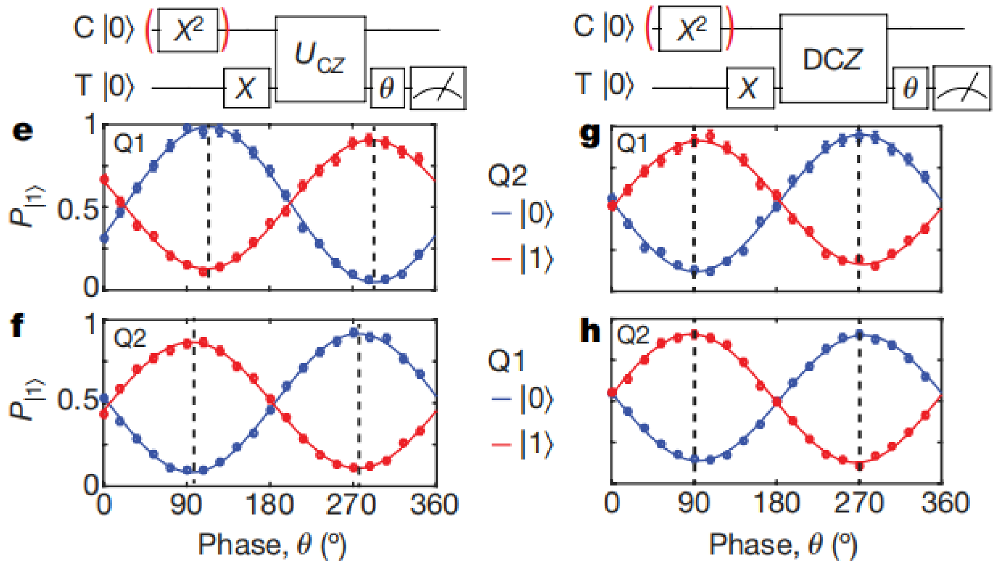


$$\mathrm{CZ} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

- $Q_1 = |0\rangle$, keep Q_2 the same
- $Q_1 = |1\rangle$, flip Q_2

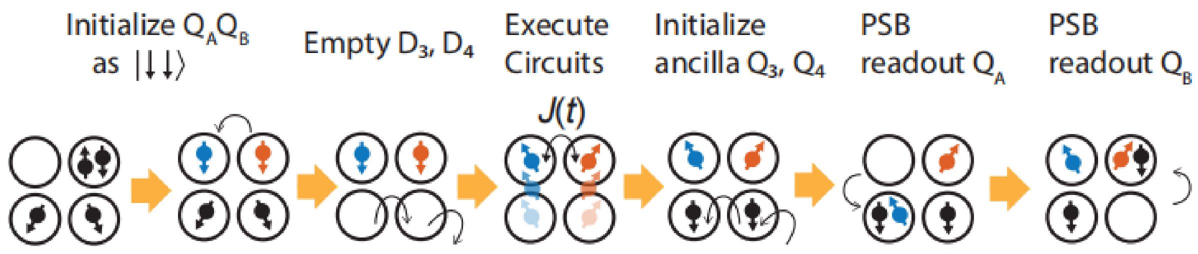
- CZ gate and decoupled CZ gate (DCZ). DCZ gate adds an refocusing pulse to remove unconditional z rotations due to the detuning dependence of $E_Z(\varepsilon)$.

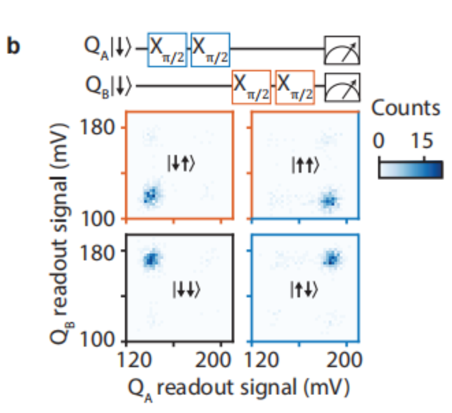
$$DCZ = U_{CZ}\left(\frac{\pi\hbar}{2J}\right) X_1^2 X_2^2 U_{CZ}\left(\frac{\pi\hbar}{2J}\right)$$

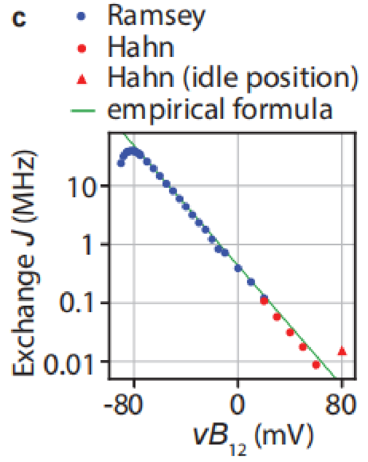


Watson et al., Nature 555, 633–637 (2018)

High fidelity 2-qubit exchange gate

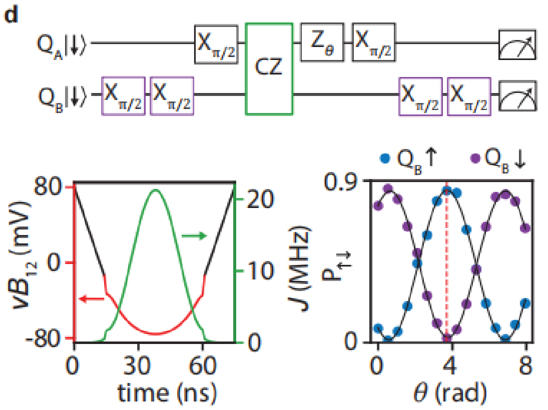


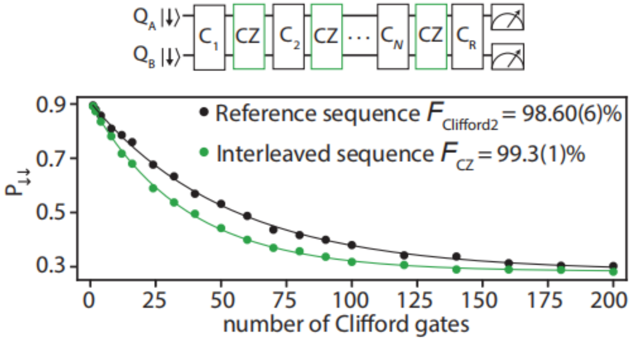




- CZ gate: pulsing the barrier gate between quantum dots D1-D2 to accumulate two-qubit phases resulting from the exchange coupling $J(t)$.
- vB12 can change exchange coupling J from 10 kHz to 40 MHz

- Sensor signals for four different two-qubit states
- $J(vB_{12}) = J_0 \exp(-\kappa\, vB_{12})$





- Use vB12 to tune the exchange $J(t)$ with Hamming window pulse
- The CZ gate calibration circuit for single-qubit phases
- Gate sequence and measurement result of two-qubit interleaved RB

J controls qubit frequencies and coherence time

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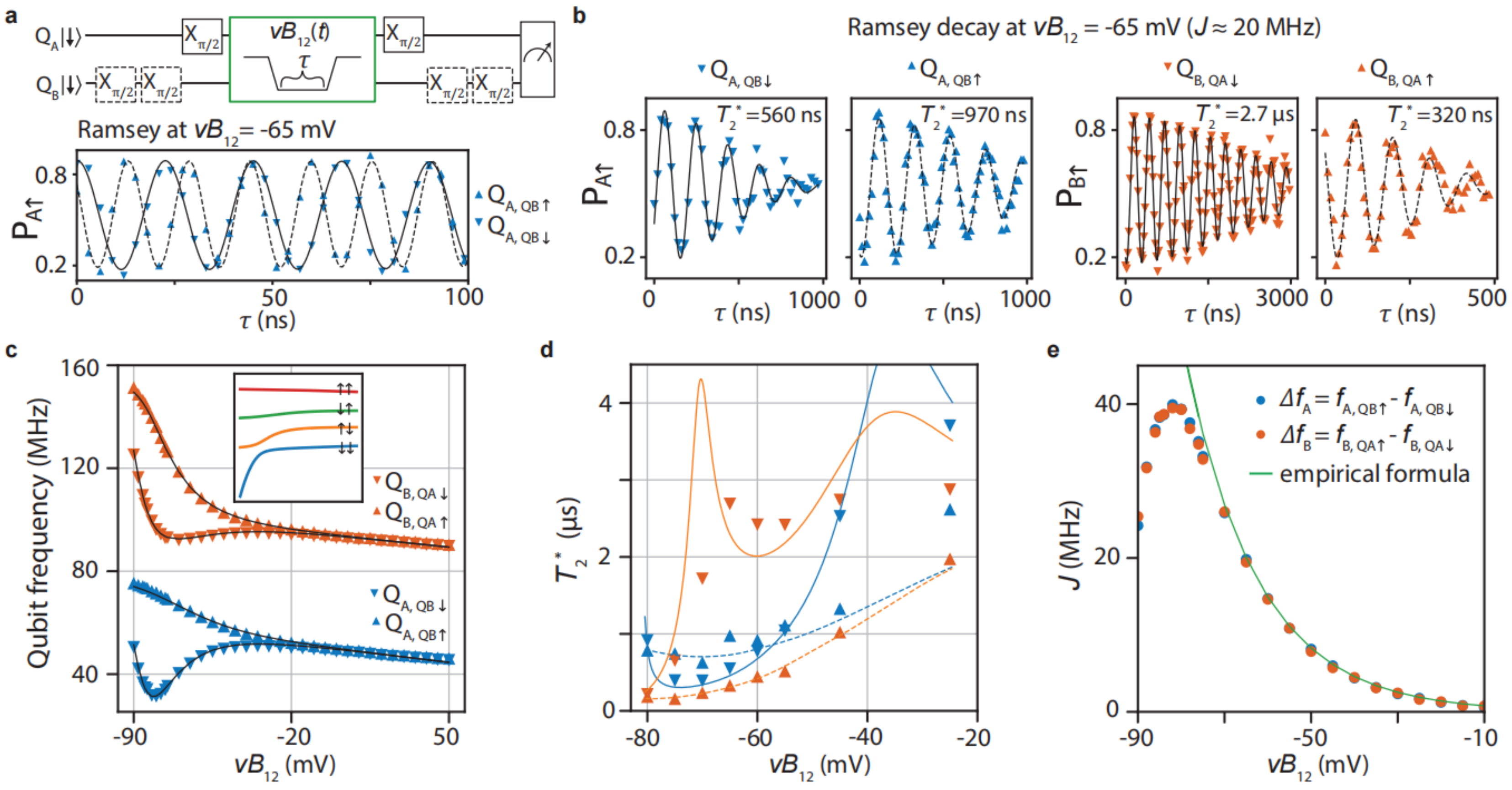

- T_2^* changes with virtual barrier gate voltage vB12
- T_2^* with different spin configuration
- The state-dependent qubit frequencies
- Exchange couplings $J = \Delta f_{A(B)}$. We fit the curve as $J(vB_{12}) = J_0 \exp(-\kappa\, vB_{12})$

Hopping spins in 10 QD

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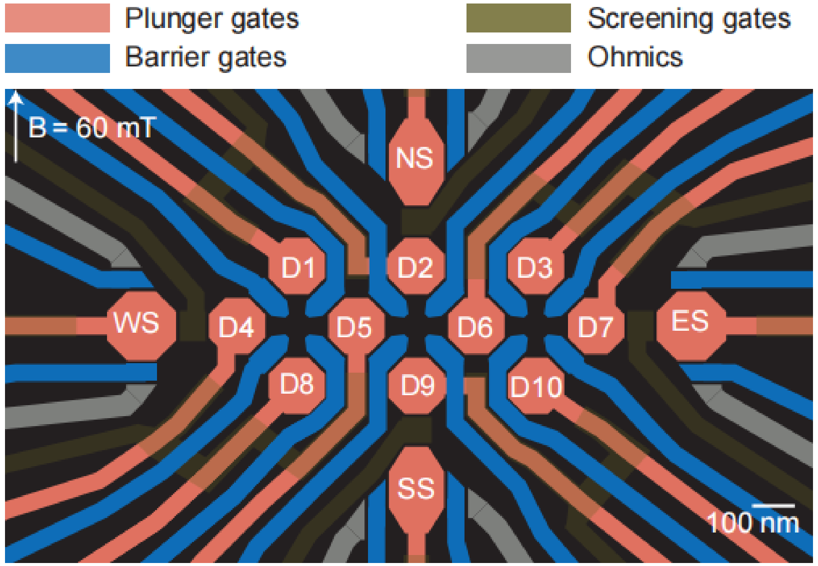
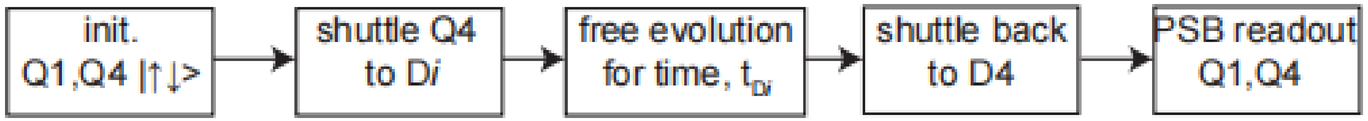
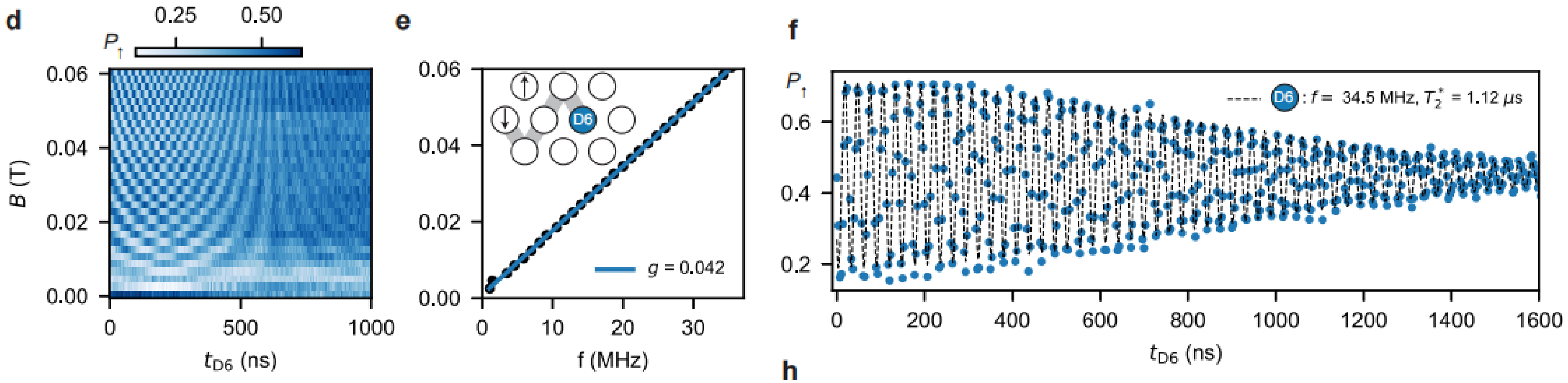




1. initialize the D1, D4 double quantum dot system in the ↑↓
2. shuttle the Q4 to target Qdi.
3. wait in target QD for a varying free-precession time
4. pulse back to the anticrossing point, and to the (1,0) setpoint
5. readout the spin via PSB

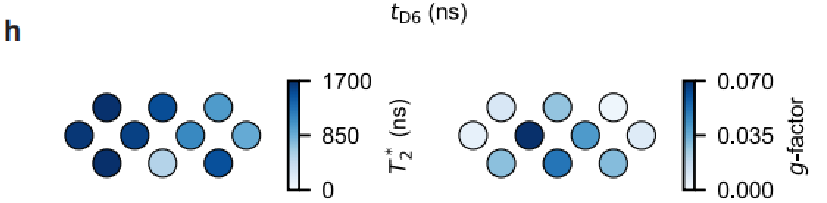
Shuttle D4 - D6:

- Qubit rotations – idle time in Q6 and B
- D6 Larmor frequency and g factor
- Time evolution in D6 at 41.4mT



g

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
g-factor	0.011	0.028	0.0030	0.0056	0.070	0.042	0.009	0.029	0.051	0.030
T_2^* (μs)	1.69	1.51	0.99	1.65	1.59	1.12	0.88	1.70	0.52	1.49



Detuning and barrier dependence

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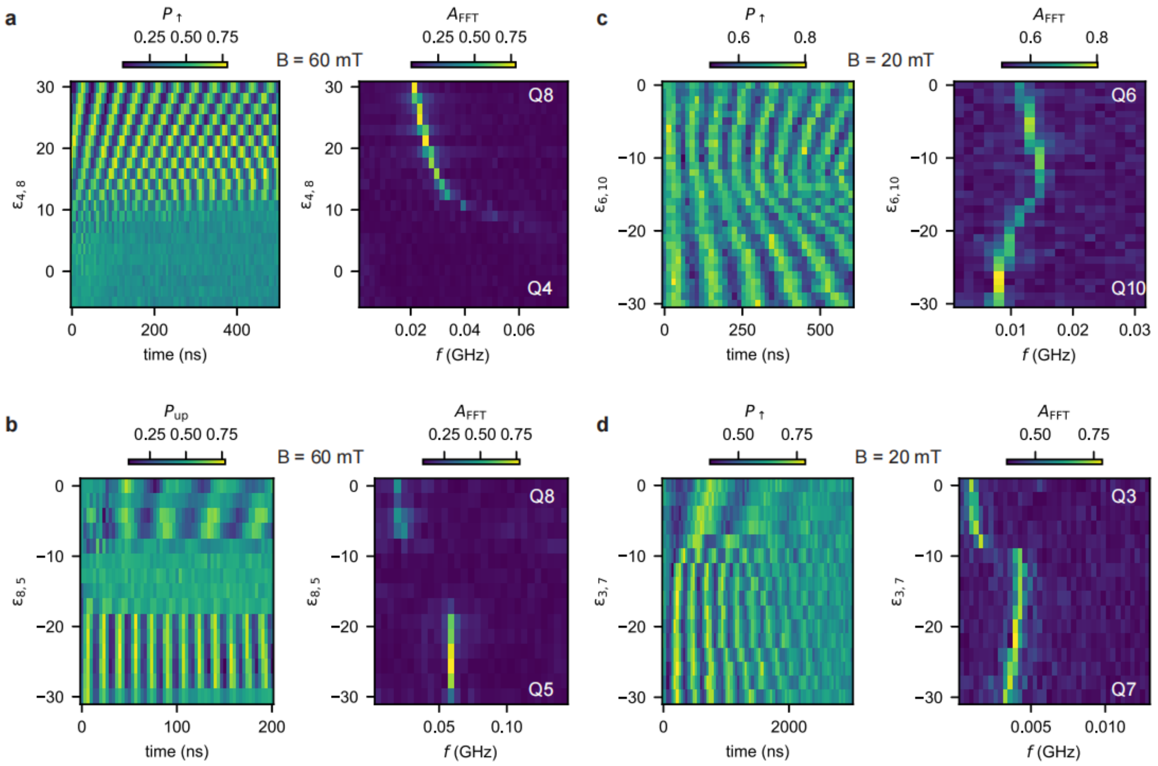
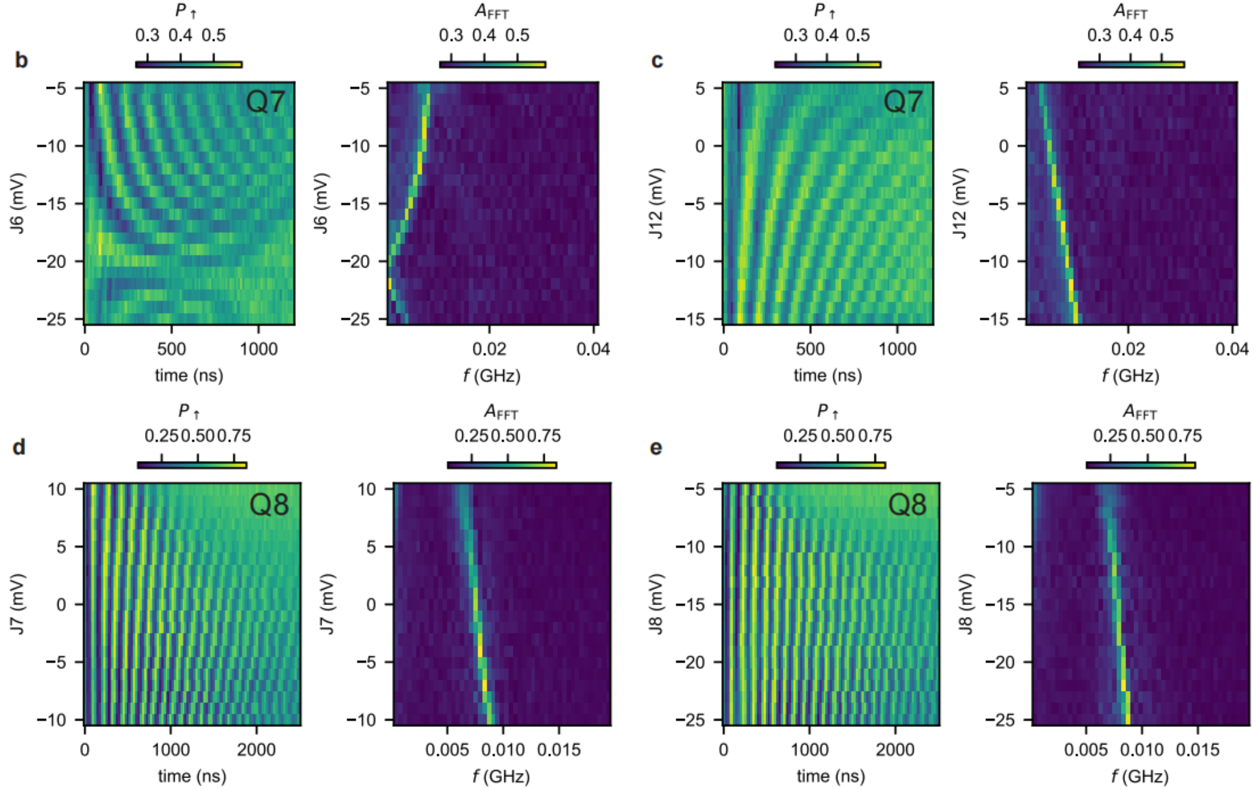


- Detuning don’t change qubit frequencies except for the region around the charge anti-crossing



- Barrier gates affect qubit frequencies strongly
- Mostly shift linearly the D7 Larmor frequency crosses zero as a function of J6, suggesting a change of sign in the g-factor of the qubit

Hopping in occupied dots

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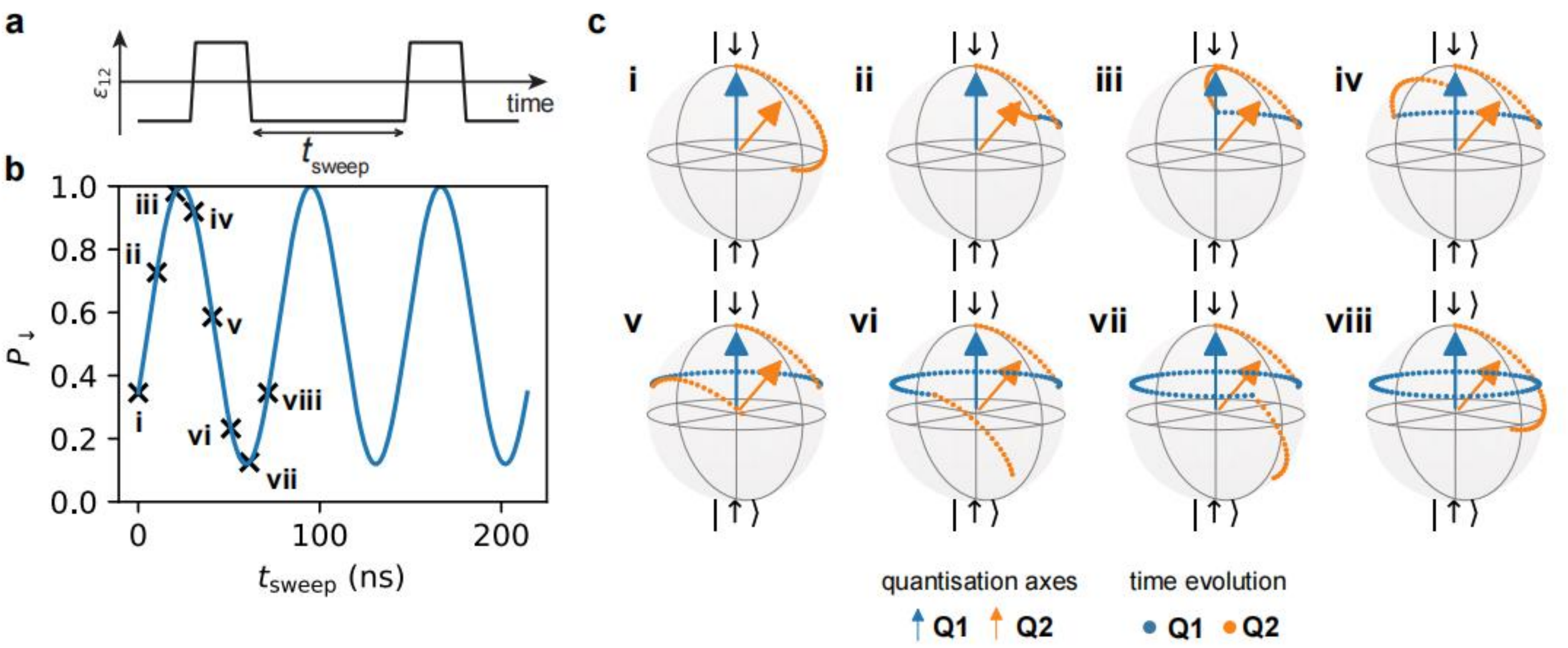

- Shuttling sequence that moves Q1 from D1 → D2 → D1 → D2 → D1. t_{sweep} is the evolution time in Q1. This protocol enables to convert the free evolution in D1 around the z axis to a rotation around a different axis of the D1 Bloch sphere.
- Calculated spin down probability as a function of sweep time in D1.
- State evolution during the shuttling sequence for different waiting times in D1

Conclusion:

- Utilize the angle between neighboring QDs to achieve high fidelity 1-qubit gate and 2-qubit gate
- Single-qubit gate fidelities of 99.97%, coherent shuttling fidelities of 99.992%, and two-qubit gates fidelities of 99.3%
- Utilize shuttling to map the g-tensor
- Low energy dissipation: 5% of EDSR method
- Manipulate the qubit in small magnetic field ~40mT (1.05T in EDSR control in same sample)[1] , allows high fidelity in qubit manipulation

[1] N Hendrickx et al., Nature 591, 580–585 (2021)