SPIN JOURNAL CLUB by Miguel J. Carballido

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Long-Distance Superexchange between Semiconductor Quantum-Dot Electron Spins

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Because of their long coherence times and potential for scalability, semiconductor quantum-dot spin qubits hold great promise for quantum information processing. However, maintaining high connectivity between quantum-dot spin qubits, which favor linear arrays with nearest neighbor coupling, presents a challenge for large-scale quantum computing. In this work, we present evidence for long-distance spin-chain-mediated superexchange coupling between electron spin qubits in semiconductor quantum dots. We weakly couple two electron spins to the ends of a two-site spin chain. Depending on the spin state of the chain, we observe oscillations between the distant end spins. We resolve the dynamics of both the end spins and the chain itself, and our measurements agree with simulations. Superexchange is a promising technique to create long-distance coupling between quantum-dot spin qubits.

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OUTLINE

- Generic Intro 
- Introduce System/Device
- Proof of Principle + Data
- Introduce Adiabatic Gate Teleportation
- Conclusion

INTRO

The Heisenberg exchange is an essential feature of electron (hole?) spins.

It uses an interplay of Pauli exclusion principle & Coulomb interaction.

⊕ This electrostatic nature ⇒ exchange based gates

VERY FAST + CONTROLLABLE

⊖ Requires overlap of WF's
⇒ only couples to NEAREST NEIGHBORS

→ Efforts to overcome this limitation

● ⇝ SUPEREXCHANGE

⇒ exchange between long distance e^-, mediated by intermediary spins.

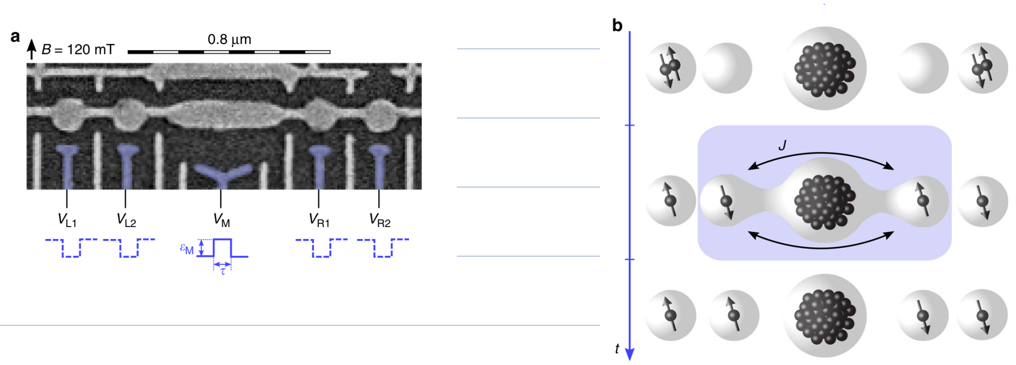
→ Applications for macro molecules (DNA/RNA)

Until now...

→ only single entities as intermediaries :

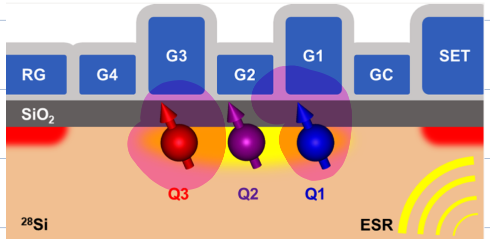
i) multy e^- mediator

Nat. Comm. 10, 1196 (2019) - C.M. Marcus



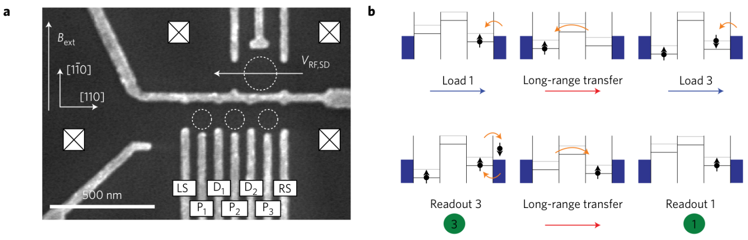
ii) single e^- mediator

Nano Lett. 21, 1517 (2021) - A.S. Dzurak



iii) empty quantum dot mediator

Nature Nano. 12, 26 (2017) - L.M.K. Vandersypen



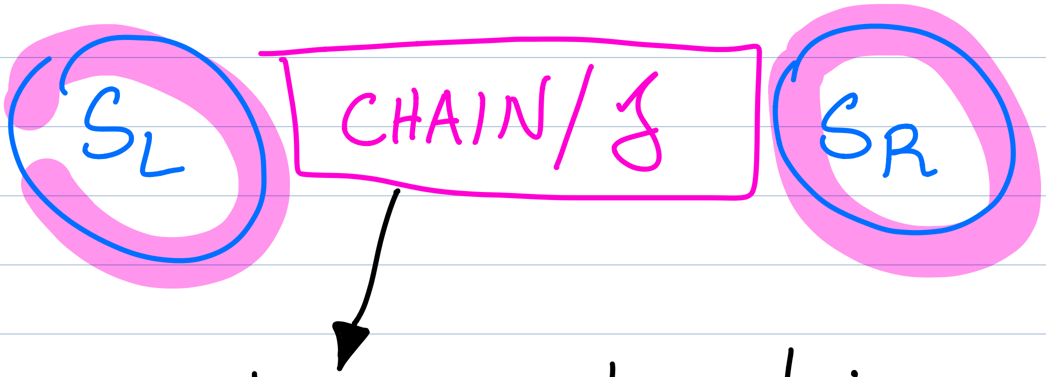
The key signature of these long-range interactions is a strong dependence on a coupling J.

MISSING:

iv) Spin-chain mediator for effective coupling between spins.

→ TODAY's JC:

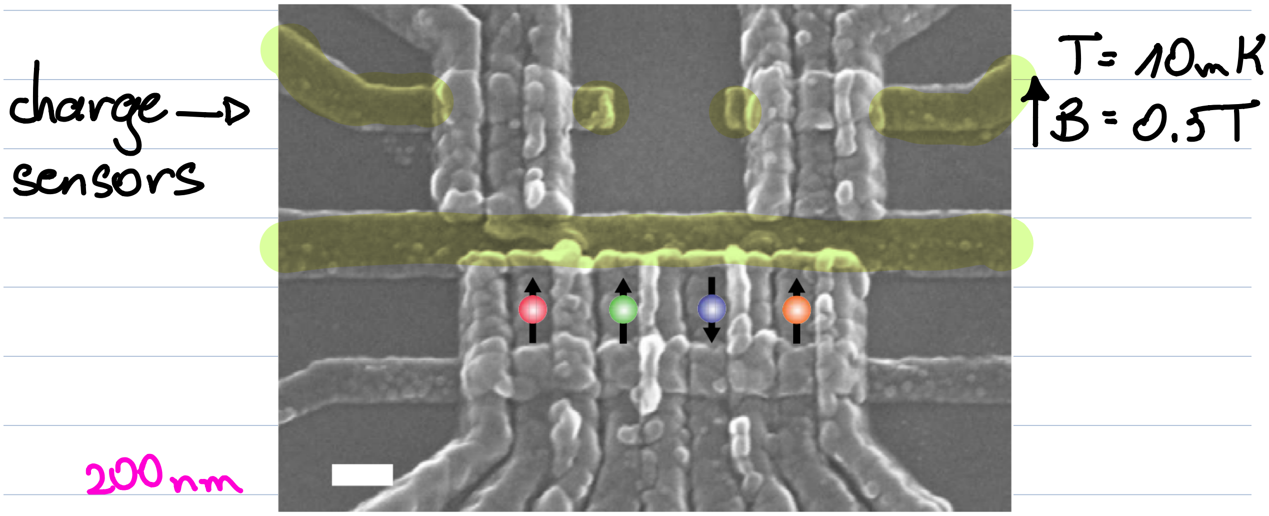
How to couple distant spins by exciting intermediary spins.



two spins make a chain

→ 4 spins total

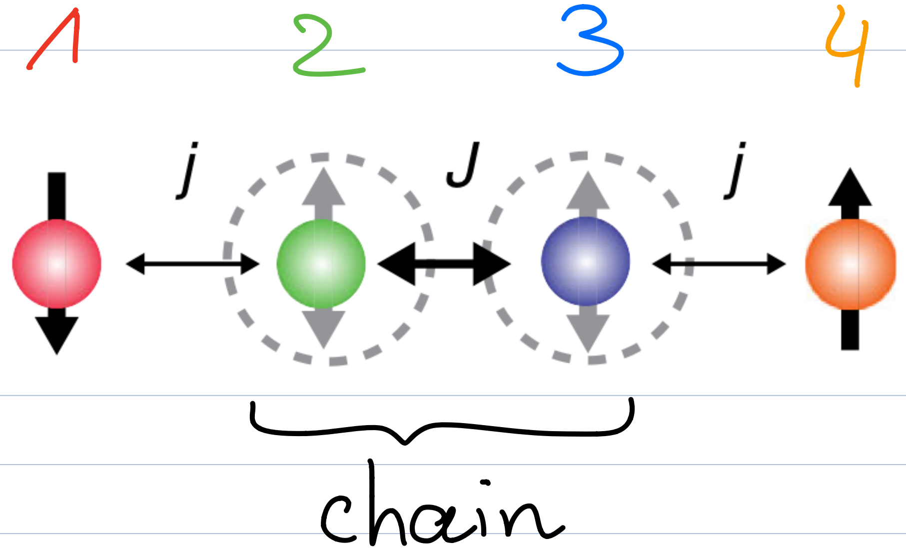
DEVICE (see suppl.)



- GaAs/AlGaAs heterostructure /w two layers of overlapping Al-confinement gates + topgate not in image (smoothes potential)

- Ohmic contacts are covered by 10 nm of Al_2O_3. Then confinement gates (↔) & (↕) and topgate (total 3 layers) are separated by native Al_2O_3.

- Apparently „the overlapping gates are essential for exchange pulses used in this work".



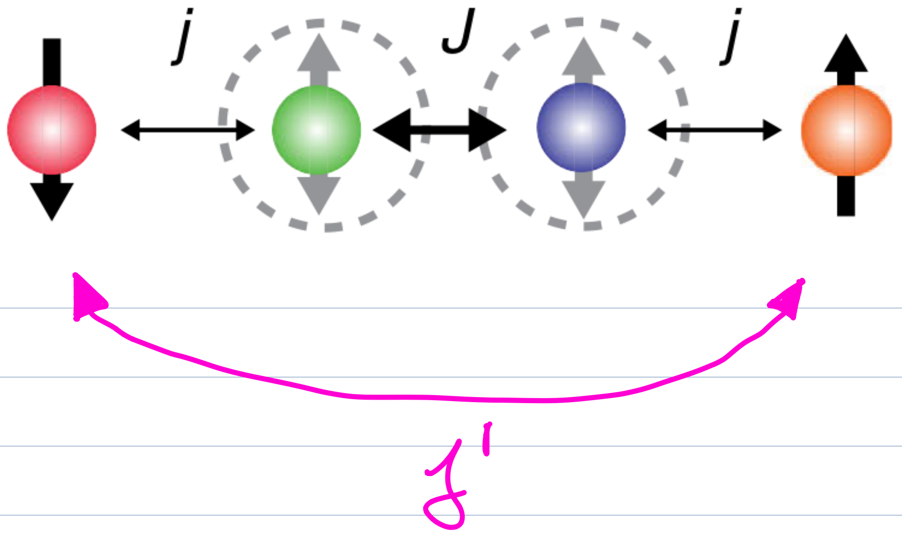
Heisenberg coupling Hamiltonian

$$\boxed{H = \frac{j}{4}\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \frac{J}{4}\boldsymbol{\sigma}_2 \cdot \boldsymbol{\sigma}_3 + \frac{j}{4}\boldsymbol{\sigma}_3 \cdot \boldsymbol{\sigma}_4.}$$

$$\boxed{\boldsymbol{\sigma}_i = \{\sigma_i^x, \sigma_i^y, \sigma_i^z\}}$$

$S_z = 0$

Superexchange can occur, when $j \ll J$ & the chain $\overset{2}{\bullet}$ $\overset{3}{\bullet}$ is configured as a singlett.



$$J' = \frac{j^2}{2J}\left(1+\frac{3j}{2J}\right) \propto j^3$$

crucial to initialise chain as singlett. If initialised in any of the triplett states, the chain will evolve between them @ scale $\propto j$ and can not be easily disentangled

→ S.E. can not occur /w reasonable fidelity

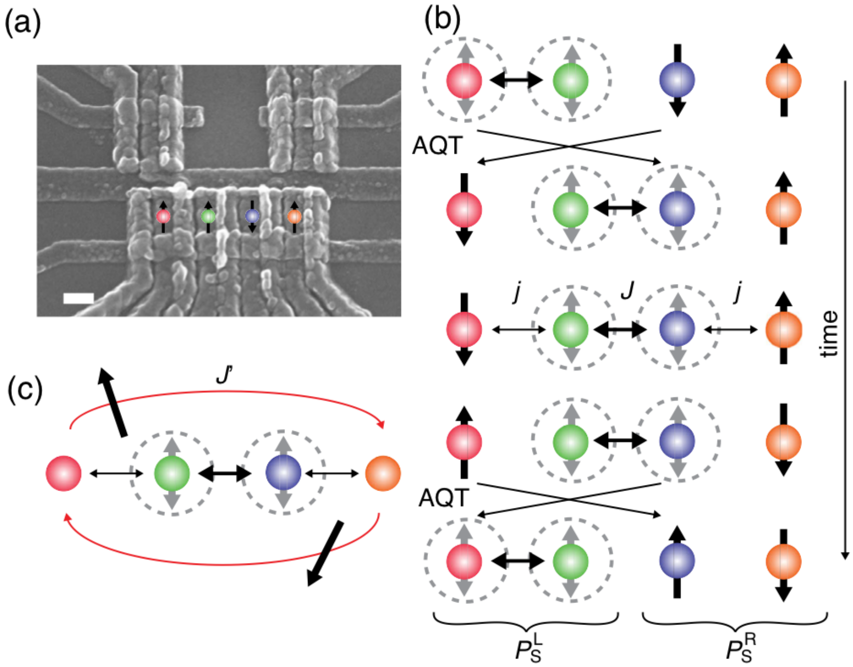
Process of Preparation

Use Adiabatic Quantum State Transfer (Adiabatic Gate Teleport.) to initialize & readout system.

(details later)

Initialize 🔴 🟢 as singlett, and 🔵 🟠 as product state with zero total spin z, $S_z = 0$.

Hence 4-spin system has $S_z = 0$.



- Load $|S\rangle$ onto ● ● & transfer $|S\rangle$ to ● ● using AQT.
- Now product state on ● ●, random individually but always opposing e.o.
- Readout by reversing AQT, provided that chain remains singlett.
- Measure P_S^L in S-T-basis, and P_S^R via adiabatic charge transfer (map $|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle$ to $|S\rangle, |T\rangle$, dep. on sign of hyperfine gradient. Then PSB meas.)

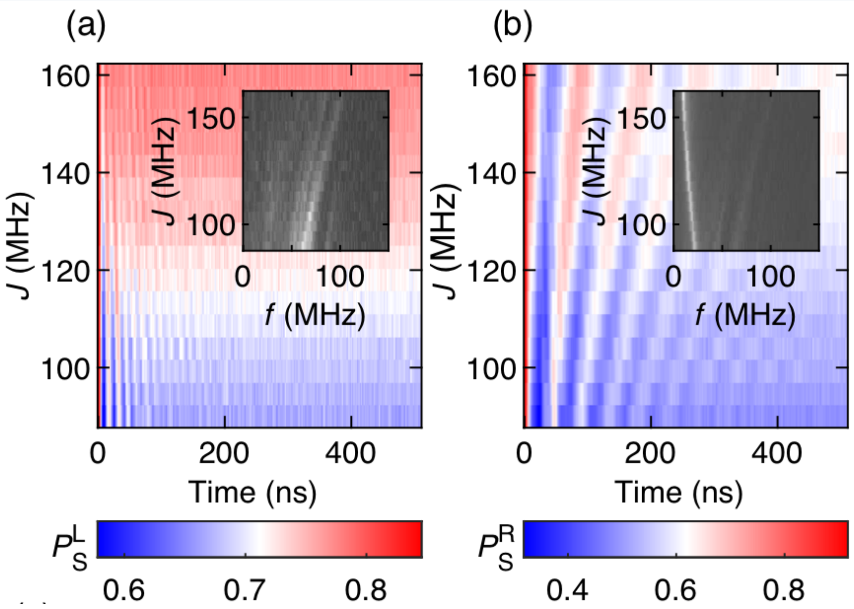
DATA

P_S^L

state of chain

small J

$j \approx J$



P_S^R

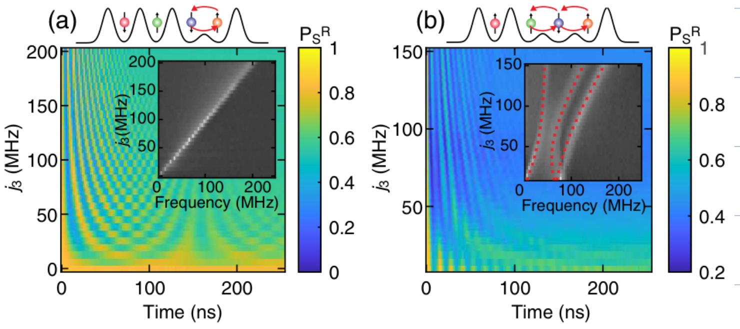
state of end spins

$j \ll J$

- set $j = 45$ MHz, sweep $J = 90$-160 MHz

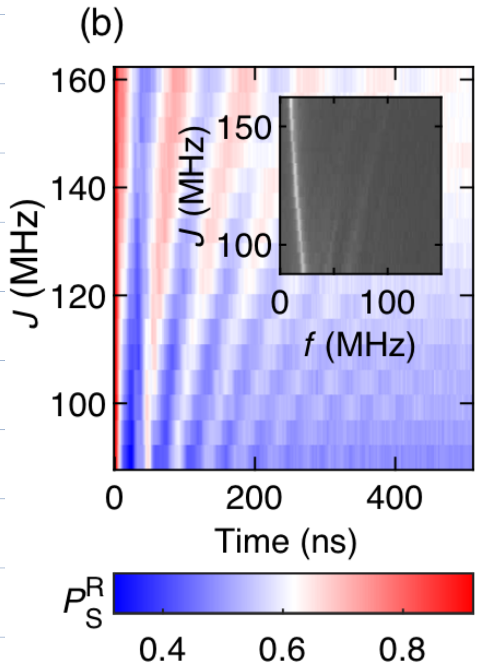
⌈ Effect of Position Shift on Exch. Coupl.

PRX 10, 031006 (2020) - J. M. Nichol

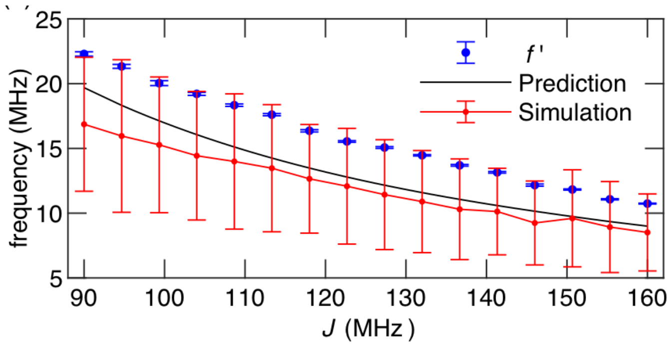


⌋

- further, oscil. freq. decreases w/ J.



- seems to all be in agreement w/ sims.



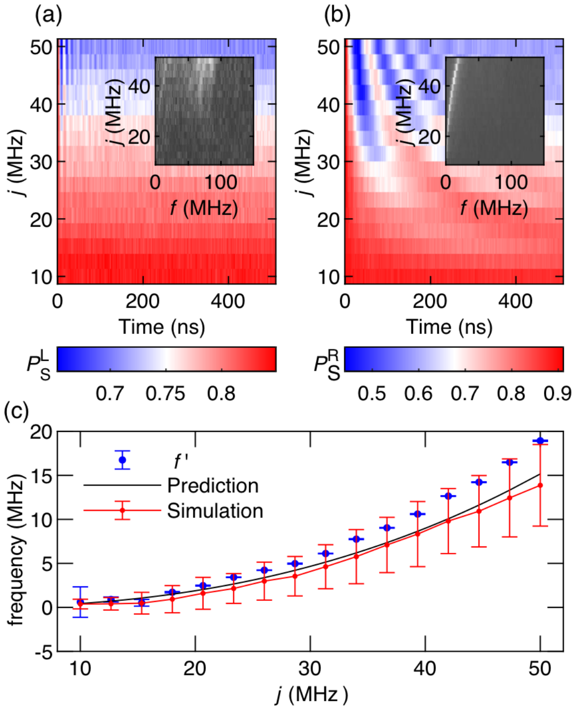
systematic ~~over~~ estimation

„imperfect calibration of j, J which is accurate within 10 MHz".

→ modelling e^--WF during gate pulses based on meas. of indiv. couplings. (underest.)

- if $J = 130$ MHz, $j = 10 - 50$ MHz

chain P_S^L



end spin P_S^R

?

- In even no. chains, the ground state of the chain is non degenerate (→ ideal for S.E.)

- For a 2-spin chain → g.s. is $|S\rangle$

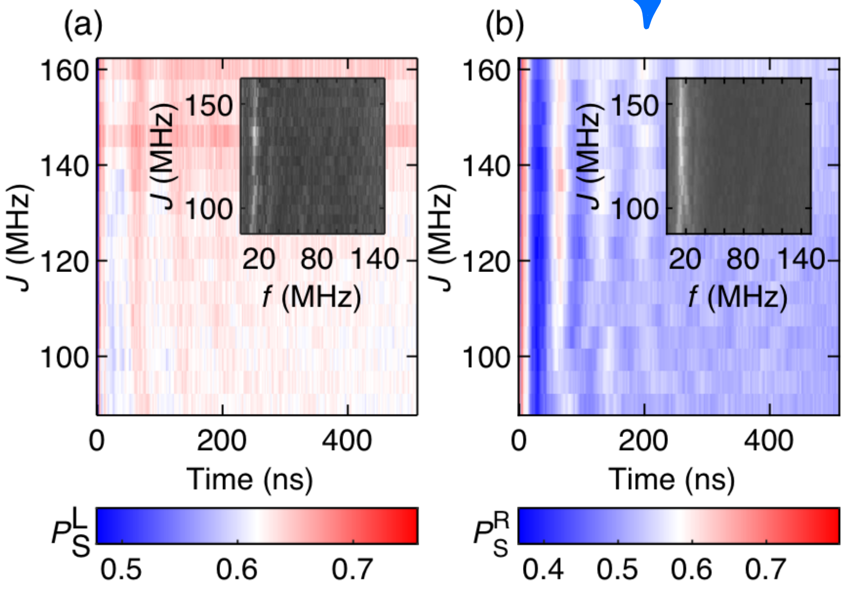
→ to test this initialize chain in $|T_0\rangle$ and see what happens...

(↳ details page 3)

- set $j = 45$ MHz, sweep f

→ observe oscillations with both, chain & end spins.
(short-lived & decay after 200ns)

chain P_S^L



end P_S^R

- small oscill. amplitude & weak dependence on f.

→ attributed to rapid mixing between triplets, not S.E.

DISCUSSION

- Ranges of J & j only marginally satisfy $j \ll J$.

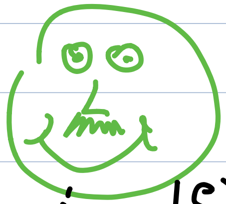
  Large pulse amplitudes to induce exchange between 1&2, limit J_{MAX}.

  → defect near 1&2? since 2-3, 3-4 not badly affected.

- Have presented evidence for long-dist. SUPEREXCHANGE between e^--spins. FUTURE: 2-qubit coupling.

- Work is directly applicable to Ge/Si where reduced hyperfine leads to extended coherence.

  → EXCITING



- hyperfine needed for forming $|S\rangle, |T\rangle$ qubit can be replaced by g-factor anisotr.

- NEW primitive: Adiabatic Gate Teleportation (AGT)
  PRL 103, 120504 (2009)

Setup uses 3 qubits $Q_1, \underset{\uparrow \text{ mediator}}{Q_2}, Q_3$

state we would like to swap to

i) ground state:

$$Q_1 \quad \underbrace{Q_2 \quad Q_3}_{\text{Bell Pair (e.g. Singlet)}}$$

$|\phi\rangle$

adiabatically drag system

ii) new ground state

$$\underbrace{Q_1 \quad Q_2}_{\text{Bell Pair}} \quad Q_3$$

$|\phi\rangle$

→ throughout evolution, the lowest energy level remains twofold degenerate → used for encoding

„Teleportation"

not the usual

transfer state of qubit A → B via initial shared entangled state (+ 2 classic bits)

aside of using a Bell state, nothing in common

Adiabatic QC

$$H(s) = \omega (1-s) H_i + \omega s H_f$$

$$s : 0 \to 1$$

\+ Adiabatic Gate Preparation (AGP)

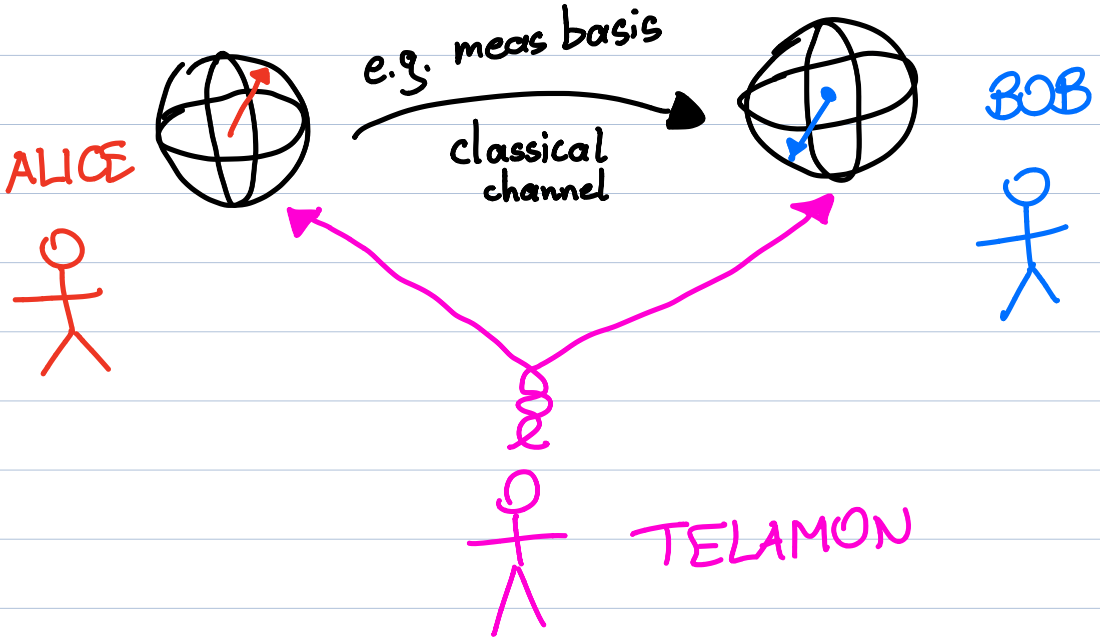
$$H_i' = U H_i U^\dagger$$

gap $\sqrt{2}\,\omega$ between $|\Psi_{eig}\rangle$ remains, since spectrum unchanged under U.

AGT

Side Note „Teleportation"

- Simple Quantum Teleportation Protocol (requires a third party „Telamon")



- Here: use three qubits Q_1 Q_2 Q_3

construct ground state /w Bell pair $|\phi\rangle$ on Q_2 & Q_3

$\downarrow$ adiabatically drag system from $H_i \to H_f$

new Hamiltonian whose ground state has a Bell pair on Q_1 & Q_2

$\to$ H_i & H_f are degenerate, hence we can store a qubit of information into degeneracy

$$\left(\begin{array}{ll} \text{Basis } H_i & |0\rangle \otimes |\phi\rangle, |1\rangle \otimes |\phi\rangle \\ \text{Basis } H_f & |\phi\rangle \otimes |0\rangle, |\phi\rangle \otimes |1\rangle \end{array}\right)$$

$\to H(s) = \omega(1-s) H_i + \omega s H_f$

is diagonal in both basis, H_i & H_f.