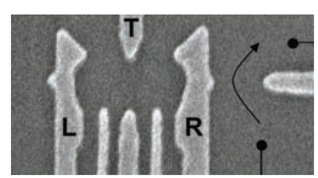
Quantum Dot Spin QuBits

Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots

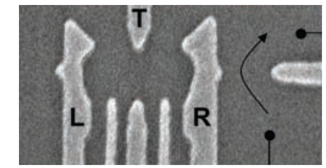
J. R. Petta,[1] A. C. Johnson,[1] J. M. Taylor,[1] E. A. Laird,[1] A. Yacoby,[2] M. D. Lukin,[1] C. M. Marcus,[1] M. P. Hanson,[3] A. C. Gossard[3]



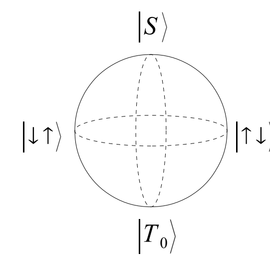
Quantum Devices for Information Technology

Outline

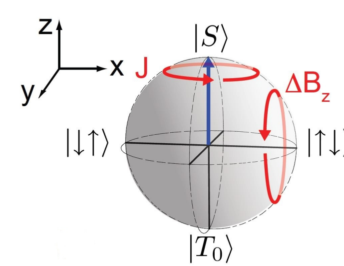
I. Double Quantum Dot



II. The Logical Qubit

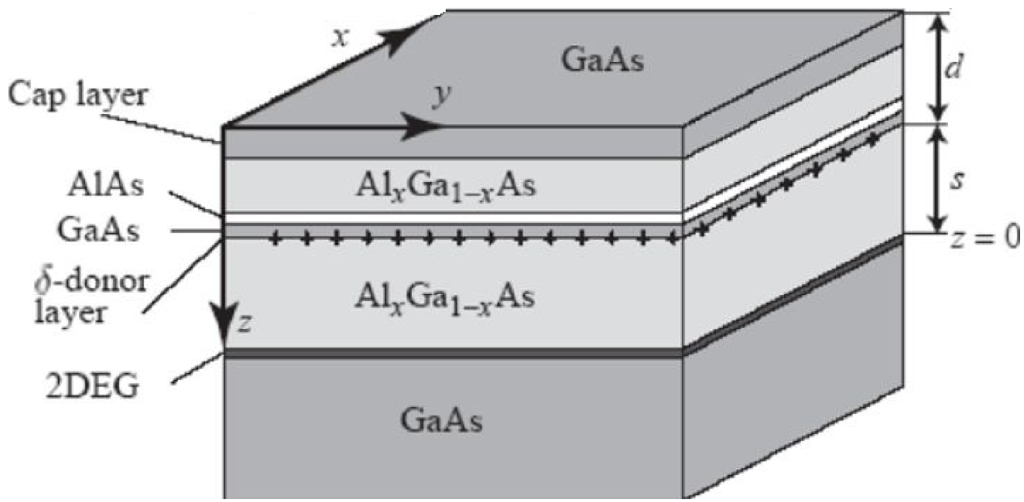


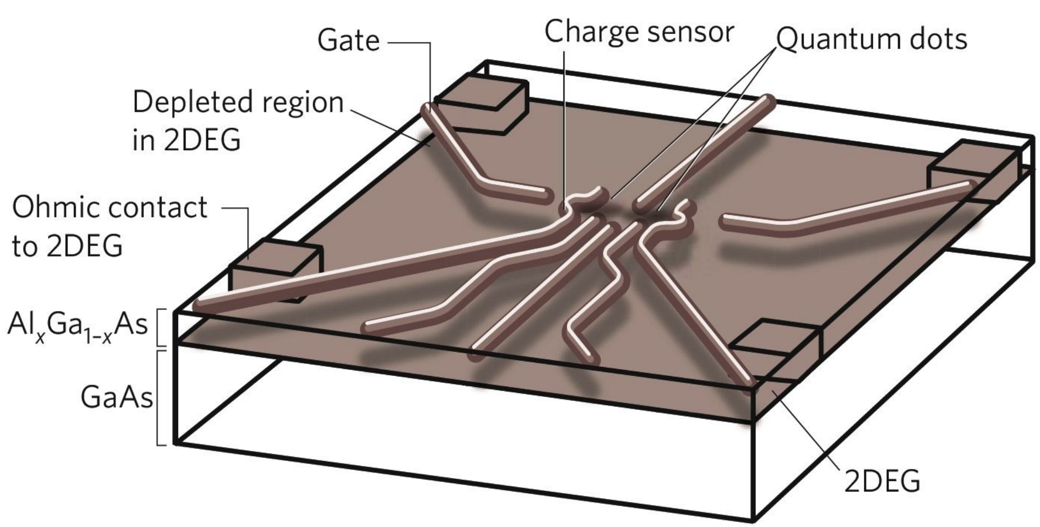
III. Experiments



1. Reminder : Quantum Dot (QD)

AlGaAs/GaAs heterostructure → 2DEG at the interface.





[1] T. Ihn, Semiconductor Nanostructures (2009), Oxford University Press.

[2] Hanson et al.,*Coherent manipulation of single spins in SC* (2008), Nature **453**, 1043

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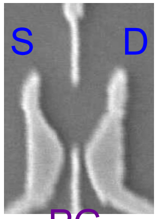
Electrically-defined island → top gates on a 2DEG
2 tunable parameters : - source and drain bias
- plunger gate voltage



Picture from:
[3] Ciorga et al.,
Phys. Rev. B **61** (2000)

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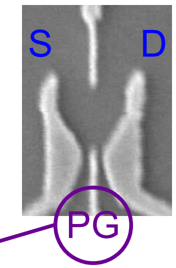

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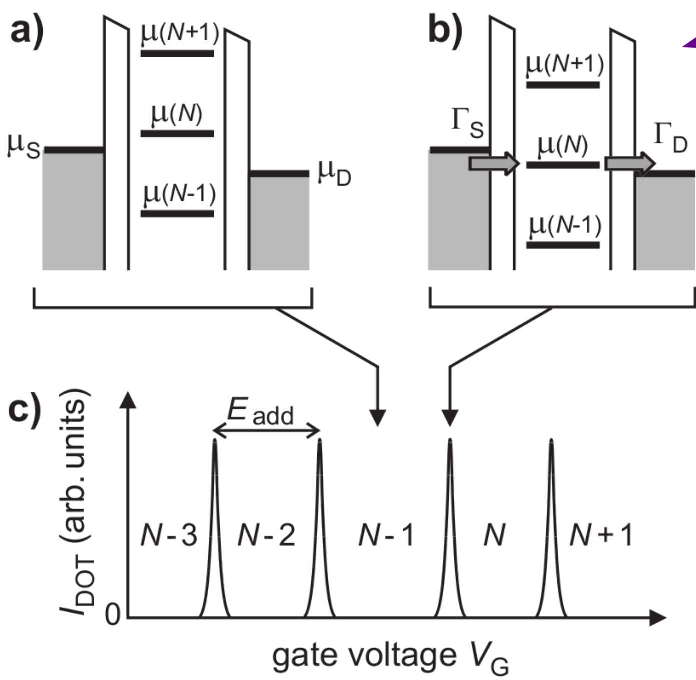

[4] Hanson et al., *Spins in few-electron QDs* (2007), Rev. Mod. Phys., Vol. **79**, No. 4

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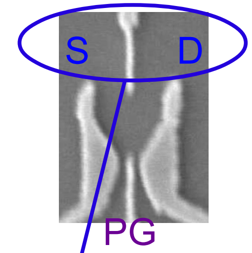

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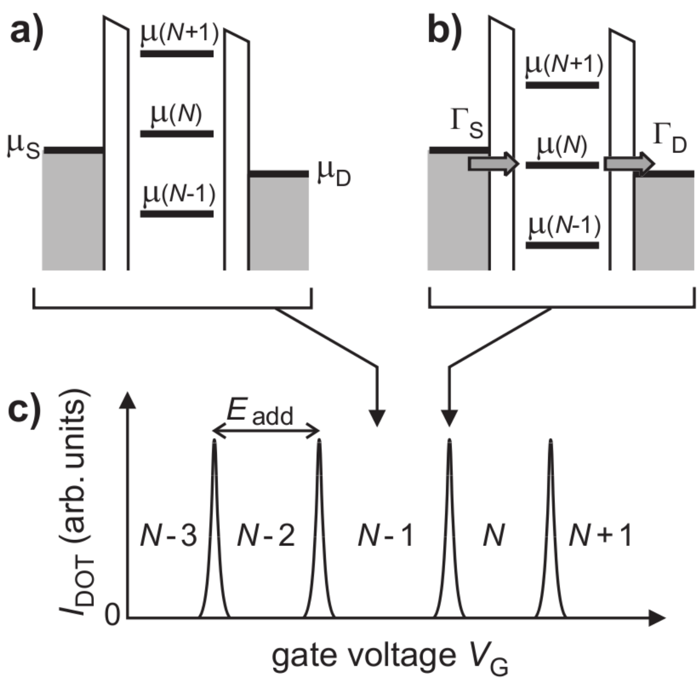

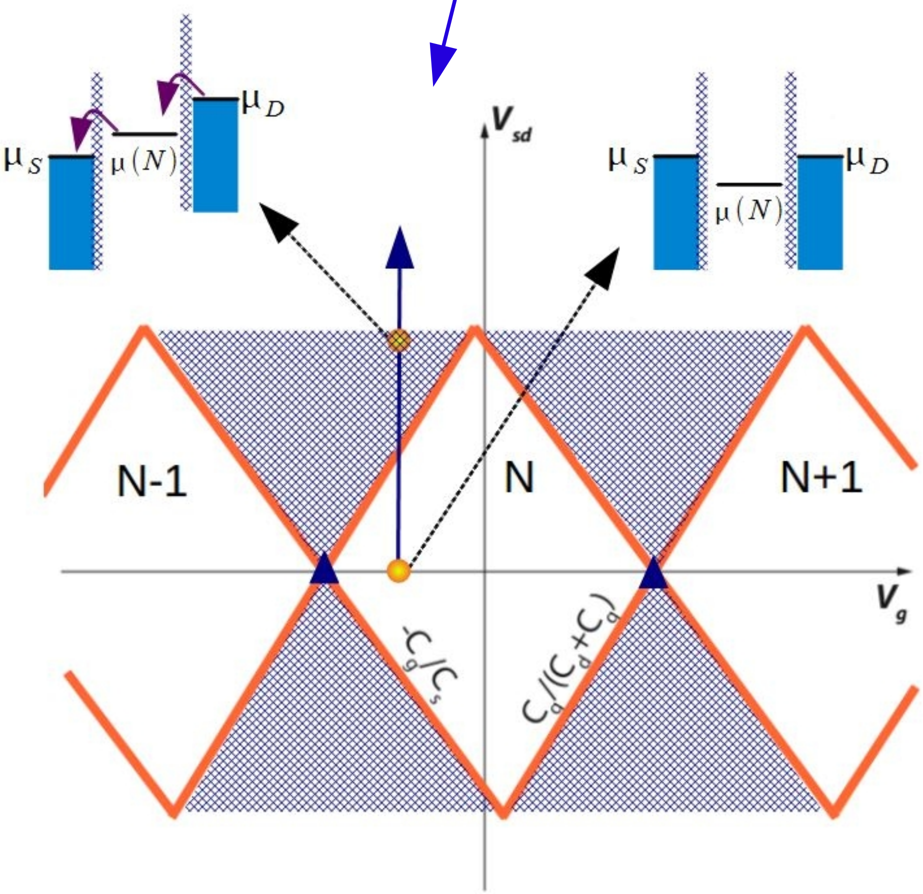

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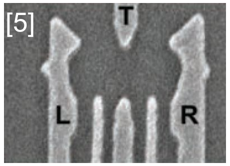
2. Double Quantum Dot



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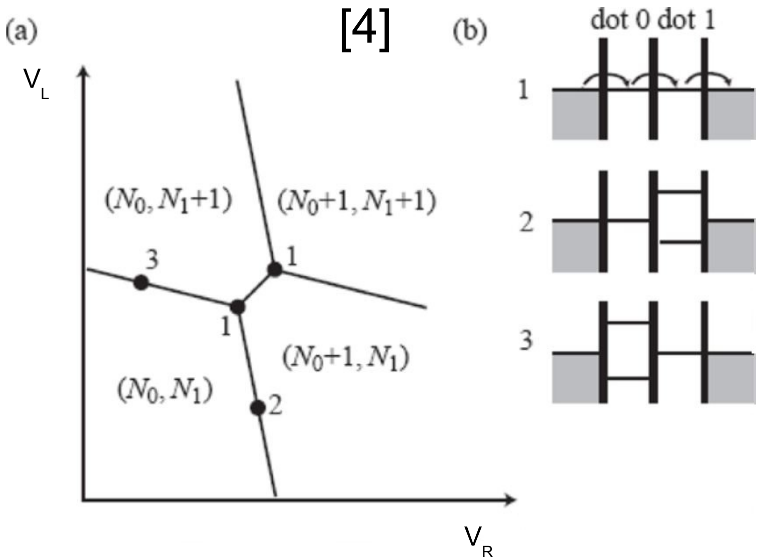

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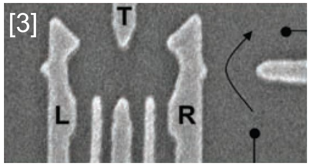
3. Two-electron regime



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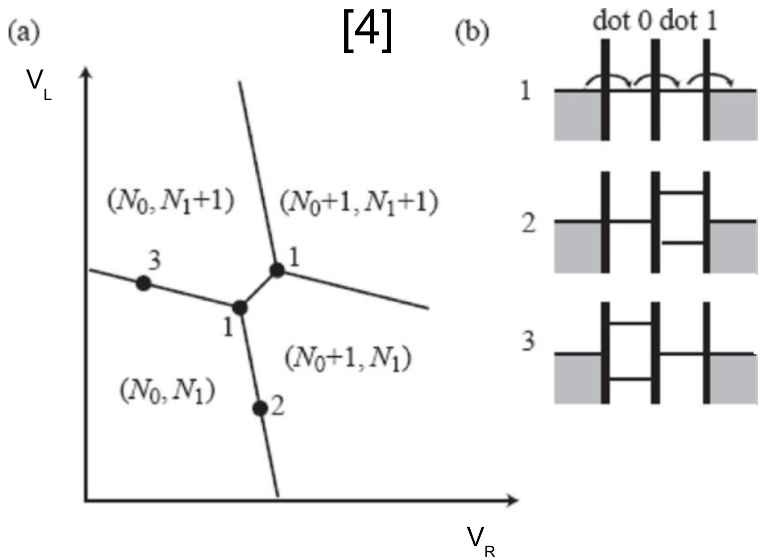
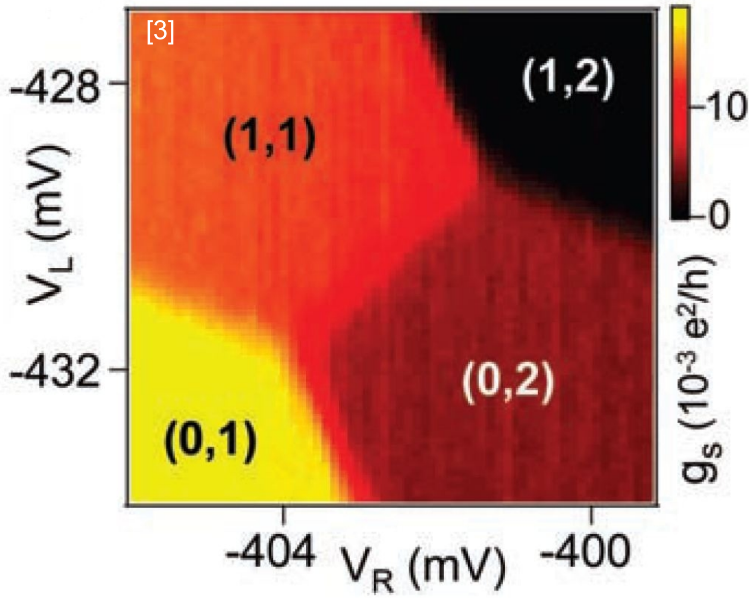
A Quantum Point Contact is used to determine the charge state in the dots.





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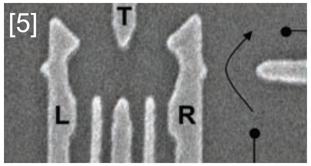

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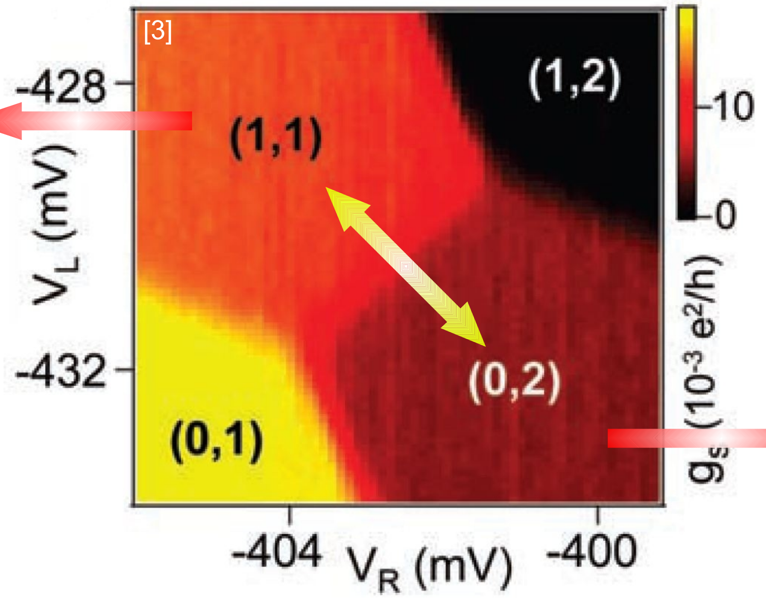
$S(1,1) = (|\uparrow_1\downarrow_2\rangle - |\downarrow_1\uparrow_2\rangle)/\sqrt{2},$

$T_+(1,1) = |\uparrow_1\uparrow_2\rangle,$

$T_0(1,1) = (|\uparrow_1\downarrow_2\rangle + |\downarrow_1\uparrow_2\rangle)/\sqrt{2},$

$T_-(1,1) = |\downarrow_1\downarrow_2\rangle.$



$S(0,2) = (|\uparrow_2\downarrow_2\rangle - |\downarrow_2\uparrow_2\rangle)/\sqrt{2},$

$T_+(0,2) = |\uparrow_2\uparrow_2\rangle,$

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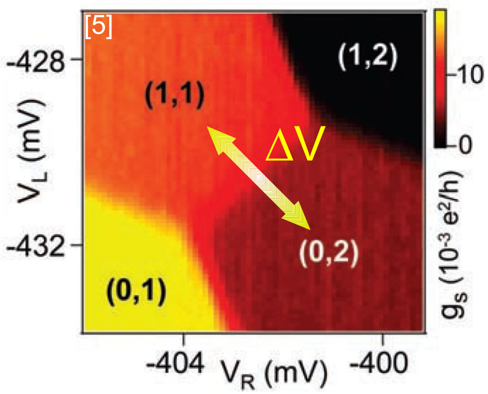
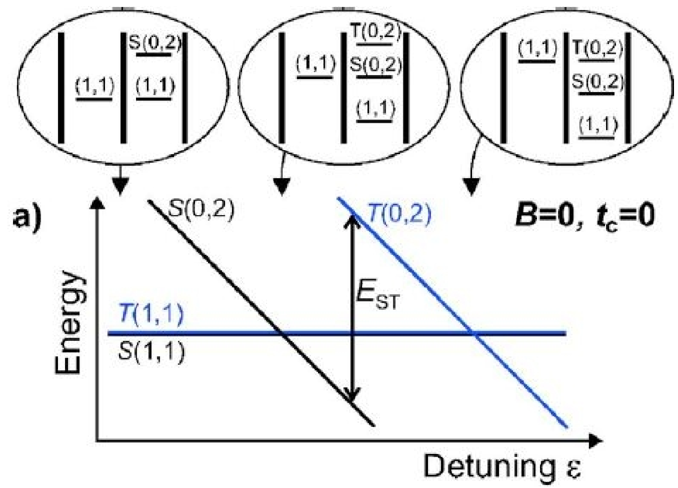
3. Two-electron regime





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$$\varepsilon = \eta \Delta V$$

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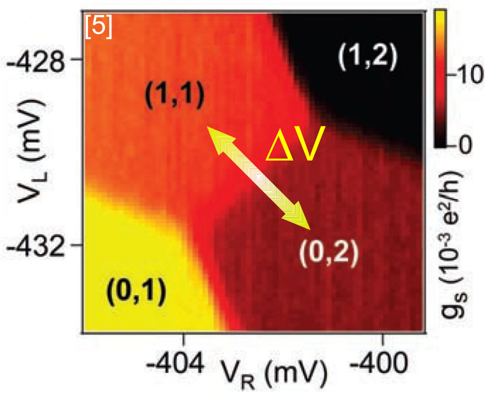

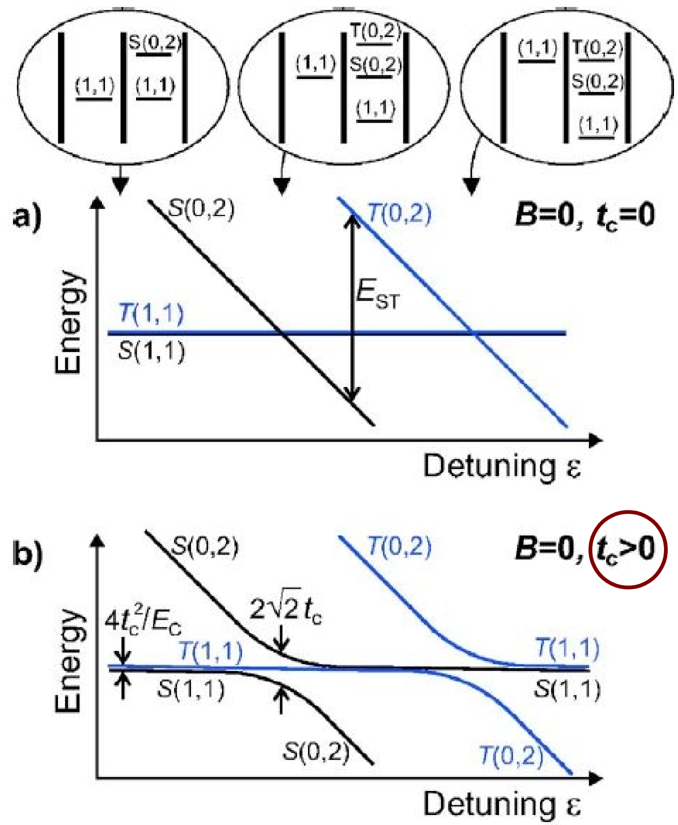

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→ (1,1) and (0,2) hybridize.

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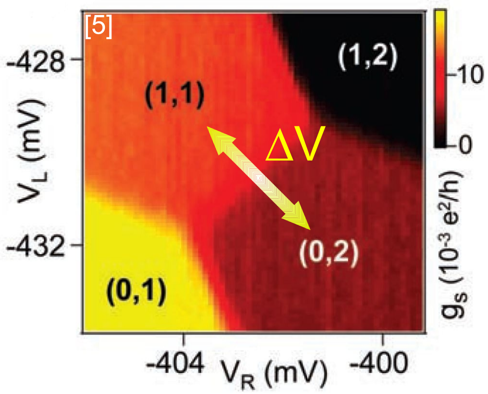

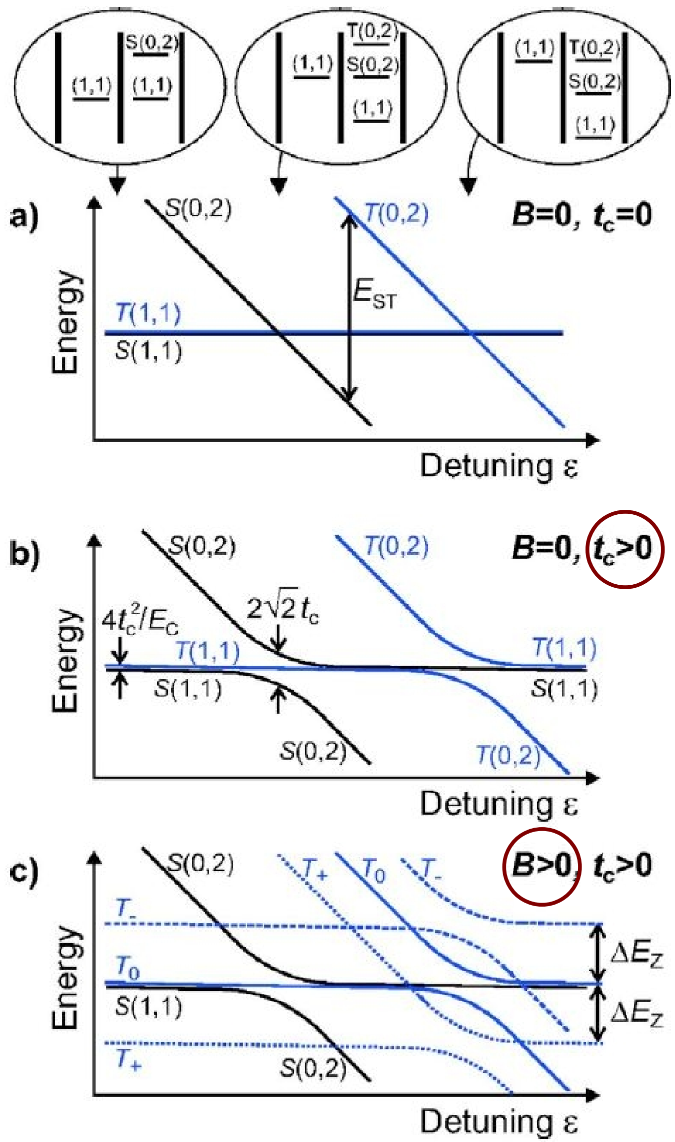

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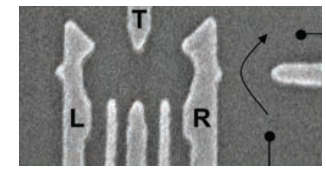
$$\varepsilon = \eta \Delta V$$

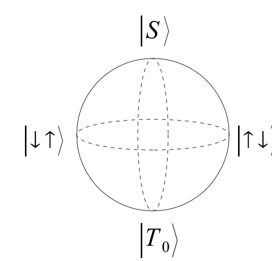
→ (1,1) and (0,2) hybridize.

→ Triplet states are split.

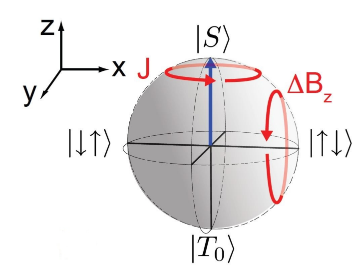
I. Double Quantum Dot



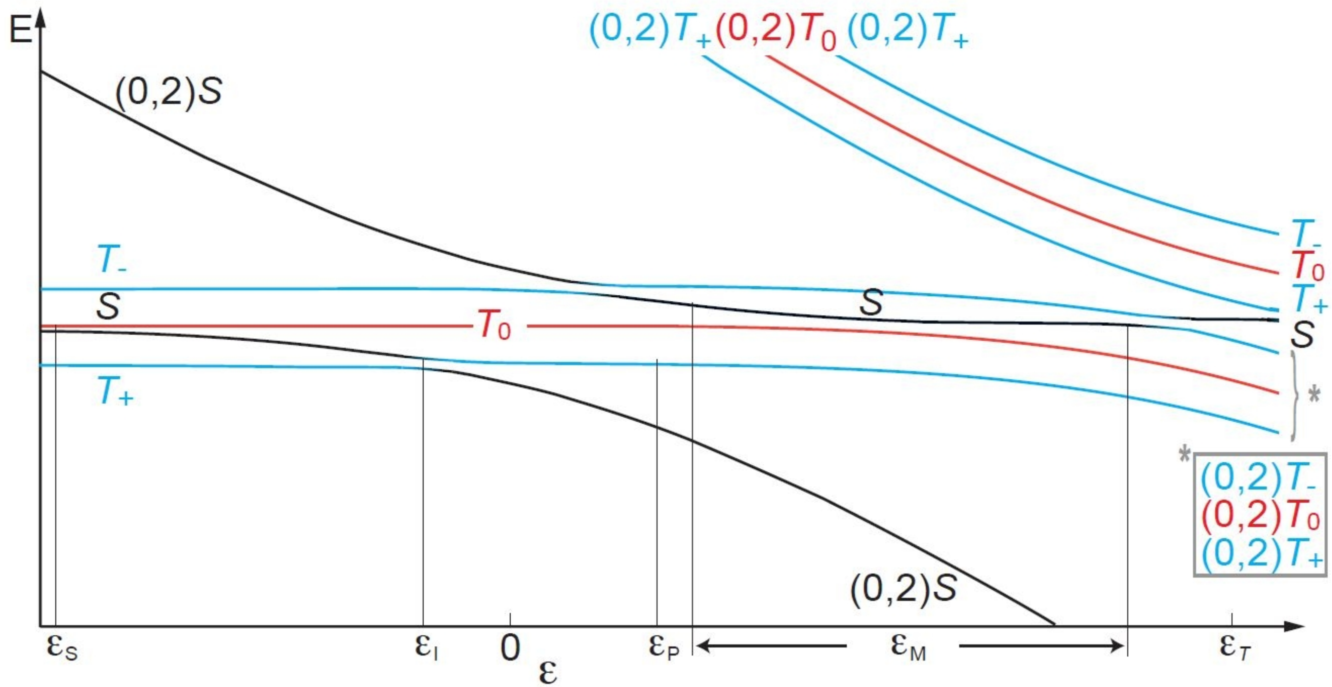
II. The Logical Qubit



III. Experiments



1. Which System ?



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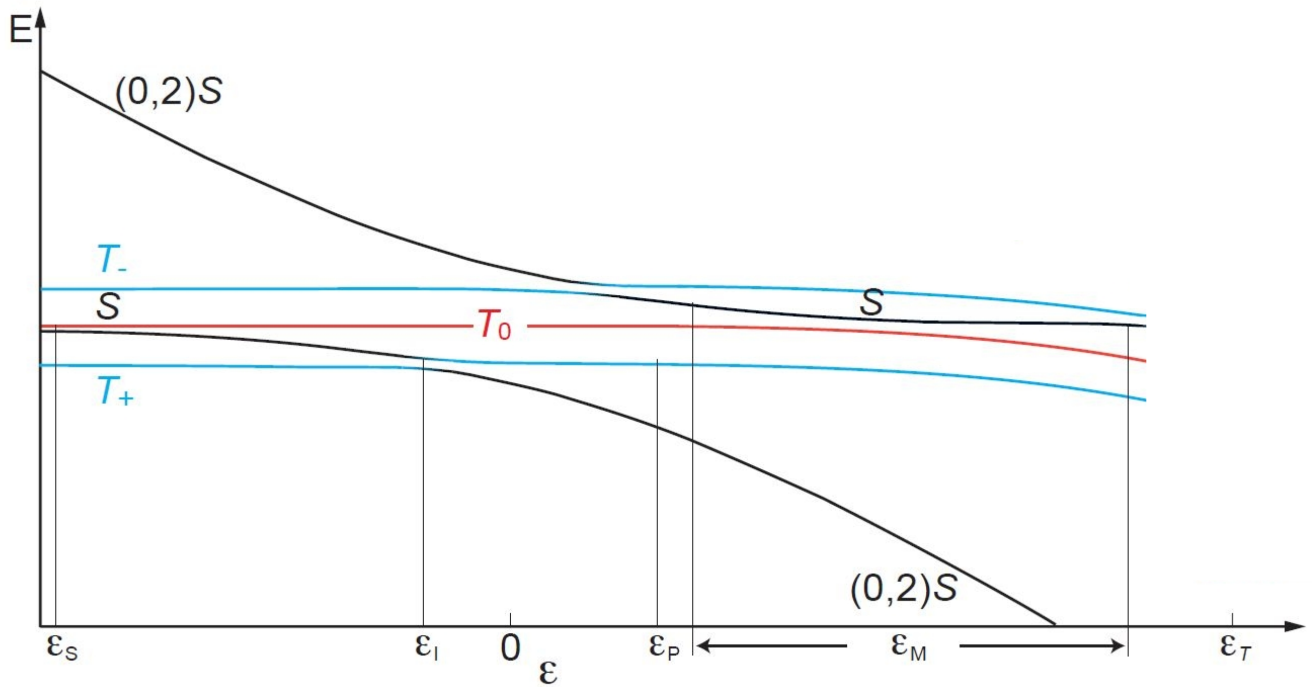

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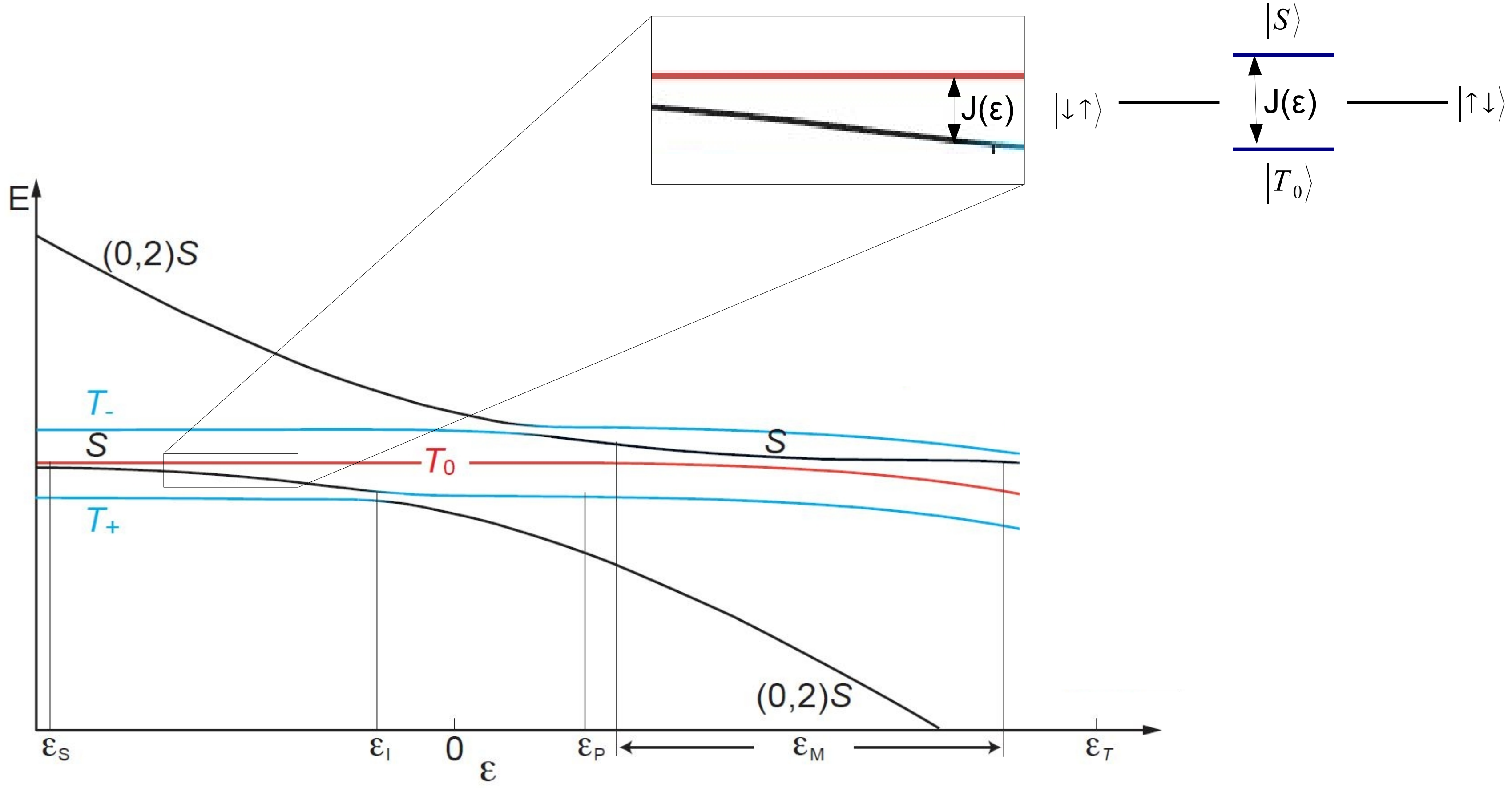

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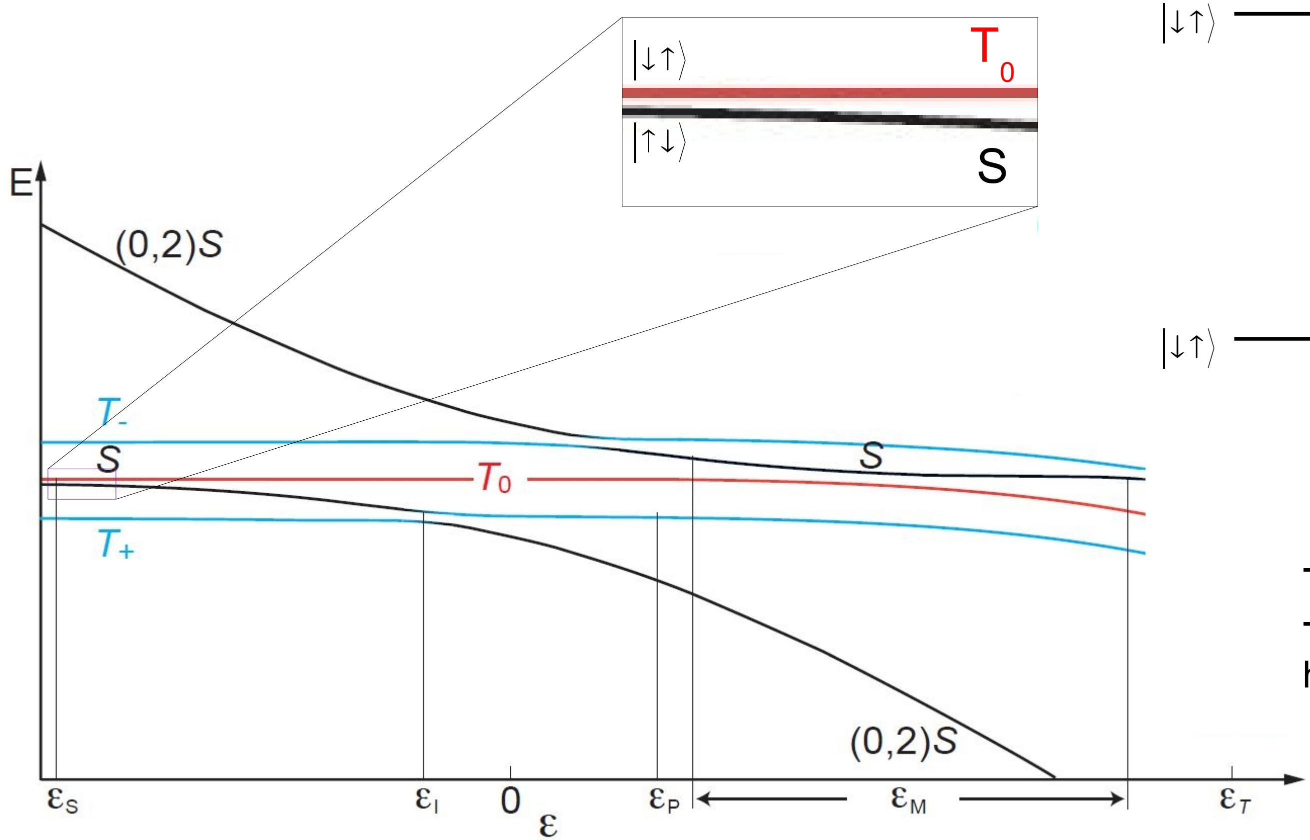
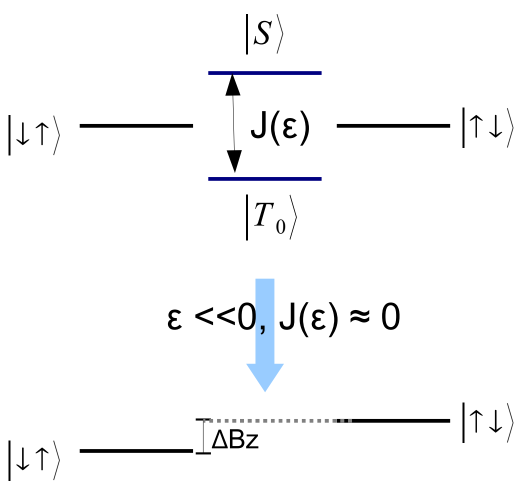
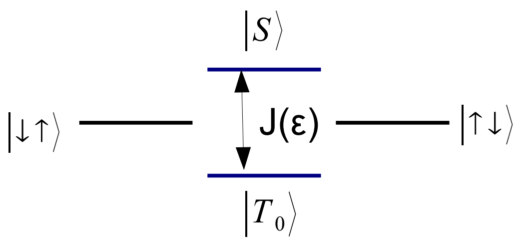


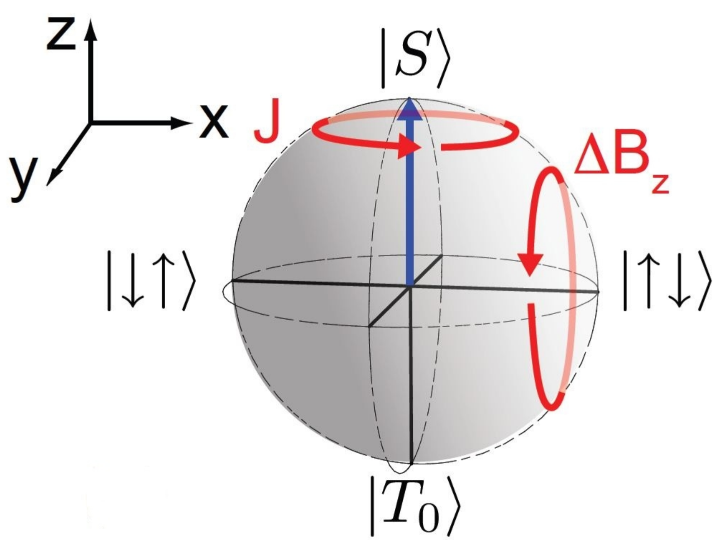


- ΔB_z between the dots.
- S and T_0 are mixed by hyperfine field.

Picture from:
[6] C. Barthel, PhD Thesis (2010)

2. Singlet-Triplet QuBit





$$H = \begin{pmatrix} J(\varepsilon) & \Delta B^{z}_{\mathrm{nuc}} \\ \Delta B^{z}_{\mathrm{nuc}} & 0 \end{pmatrix}$$

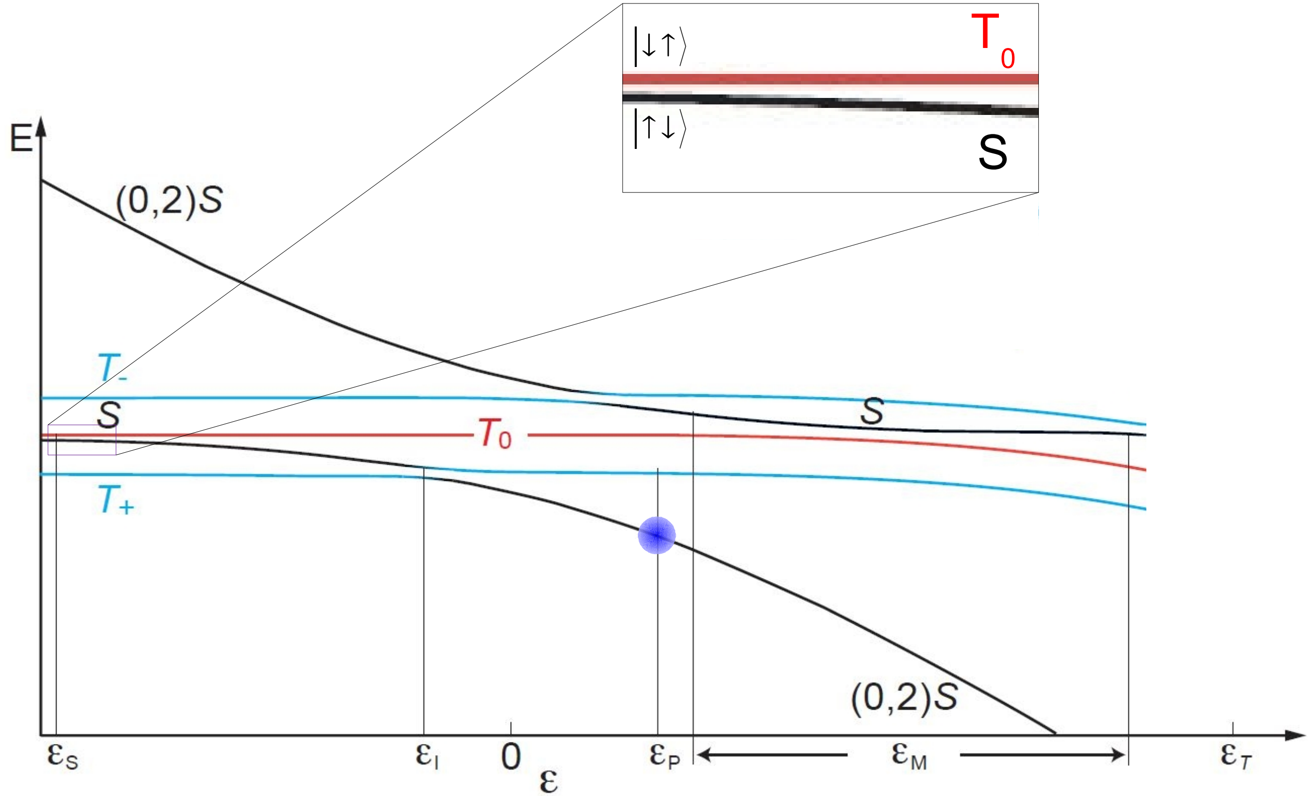
J = exchange energy between singlet and triplet
→ rotation around the z-axis.

ΔB_{Znuc} = difference in B-field seen by the two electrons
→ rotation around x-axis

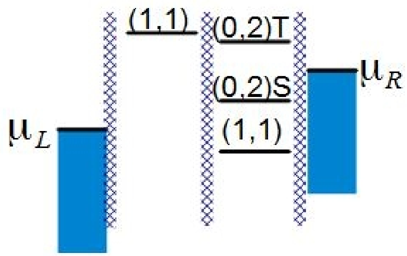
Picture from:
[6] C. Barthel, PhD Thesis (2010)

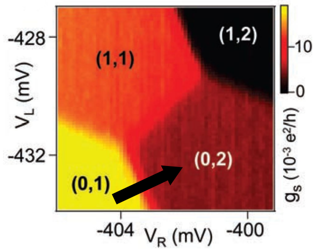
3. Manipulation

Source [6]



1. Initialization





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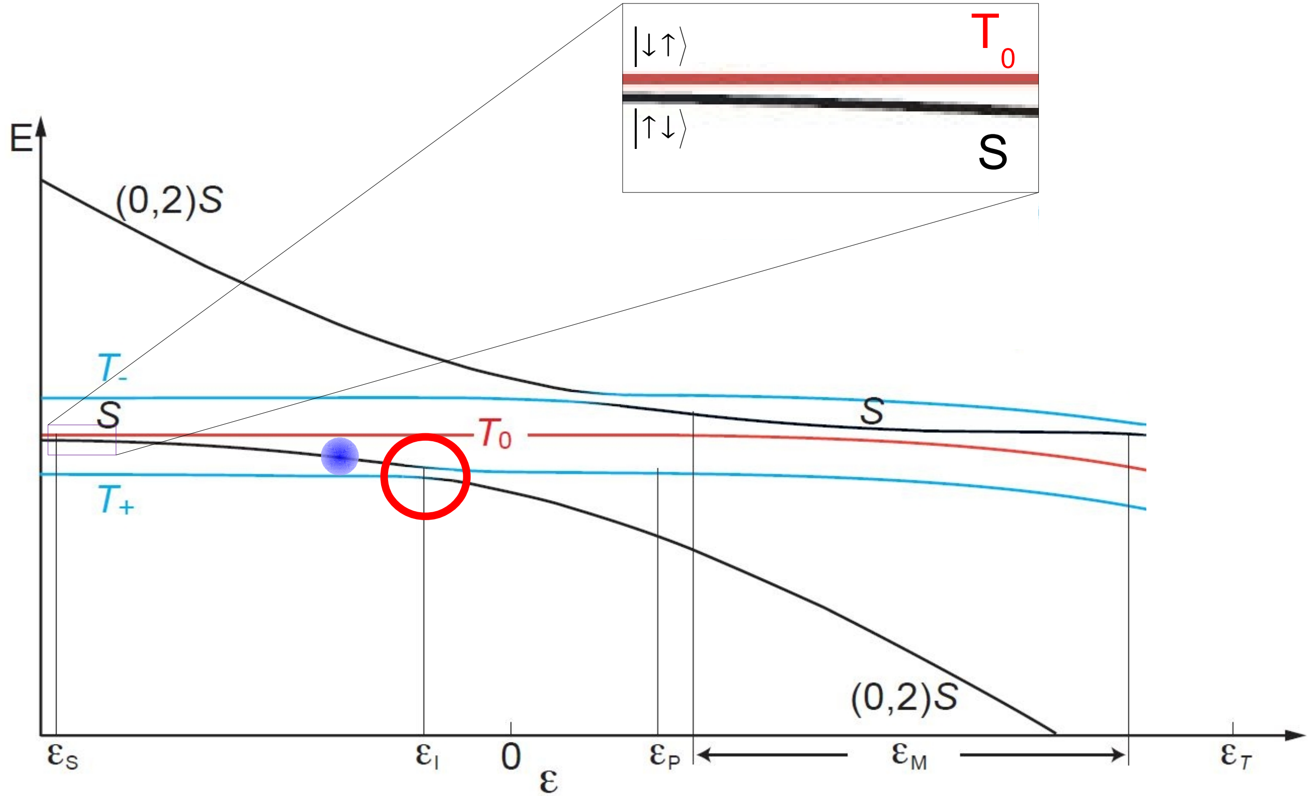
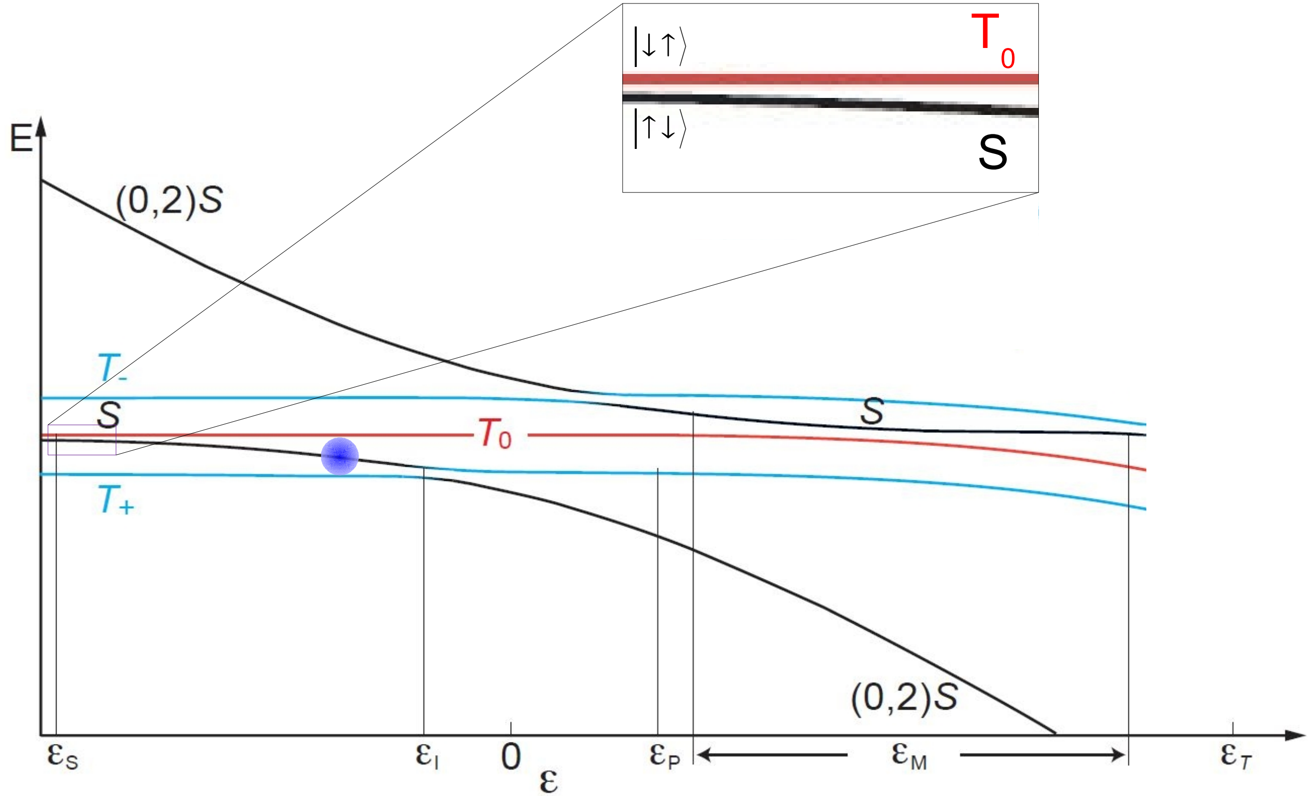


2. Spin separation

Fast sweep rate

3. Manipulation

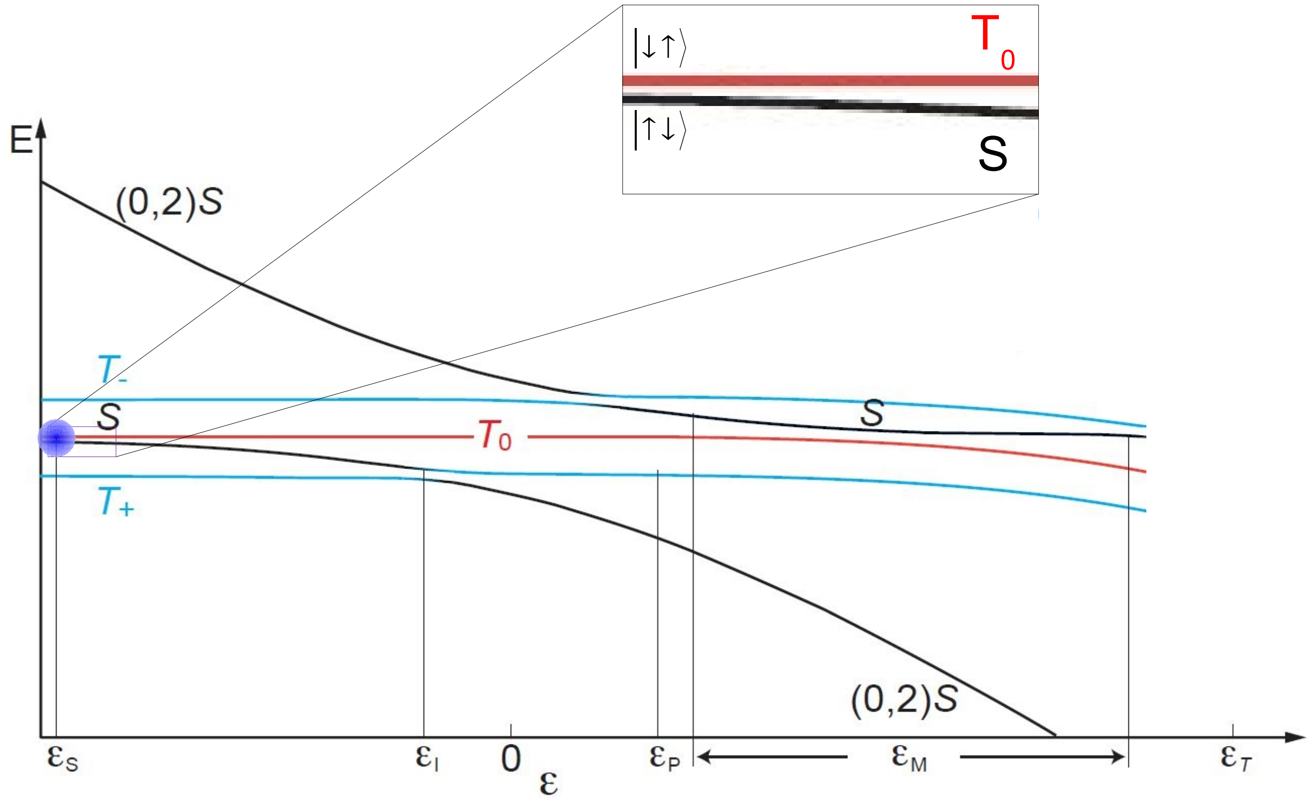
Source [6]



3. Adiabatic sweep

3. Manipulation

Source [6]



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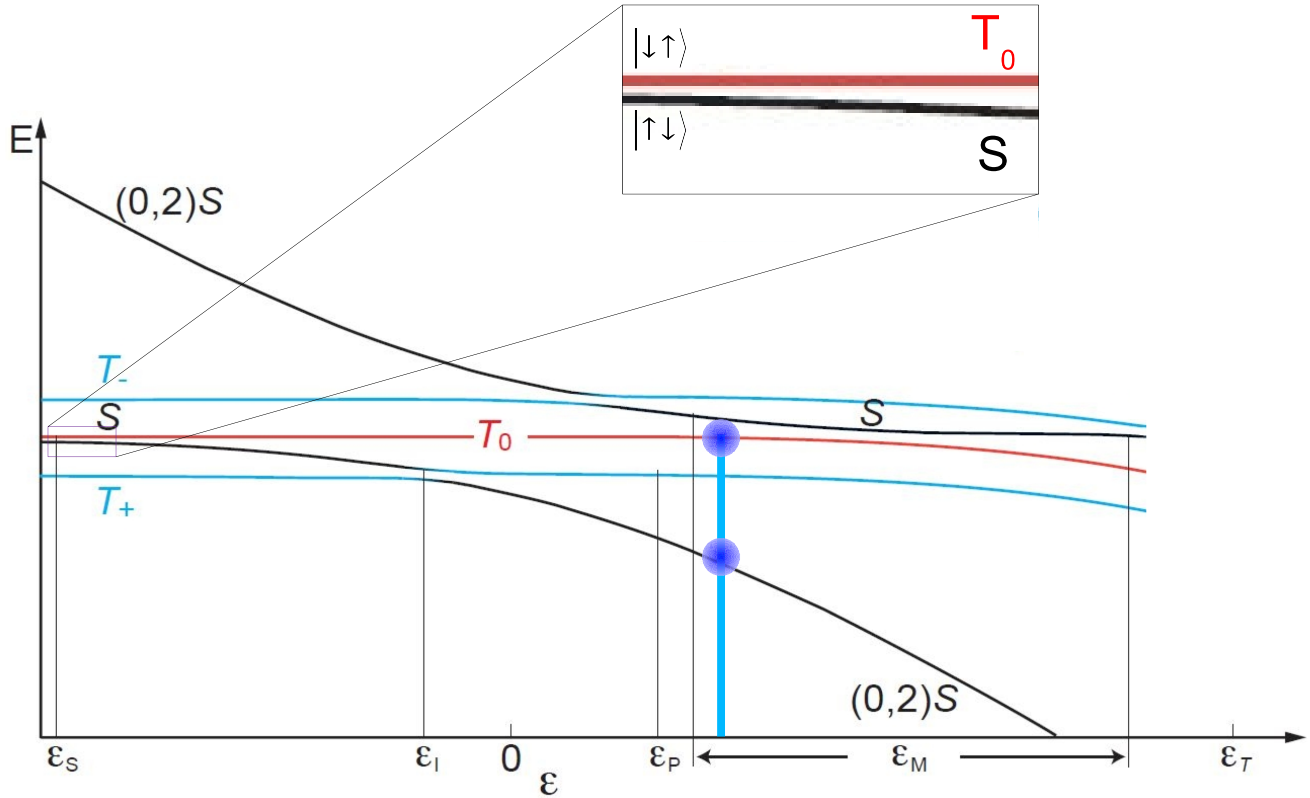
3. Manipulation

Source [6]



5. Read-out

Determination of the charge state via QPC

→ measurement of P_s

Outline

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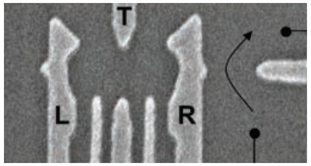

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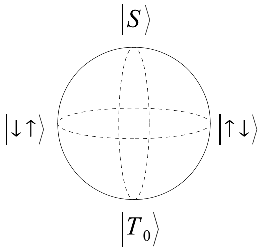

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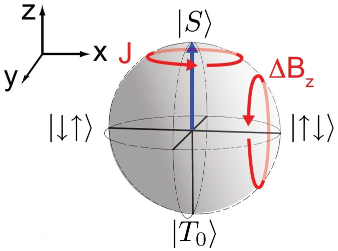
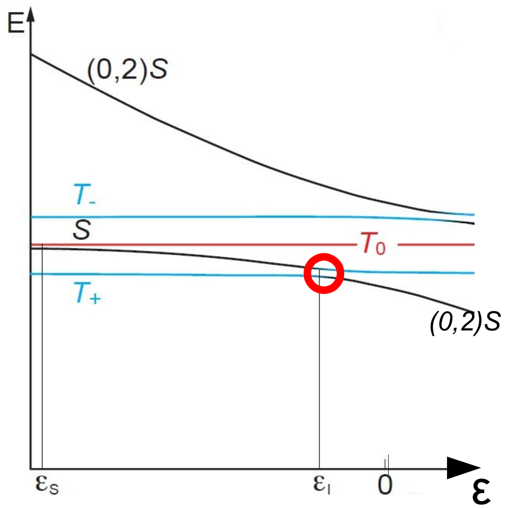
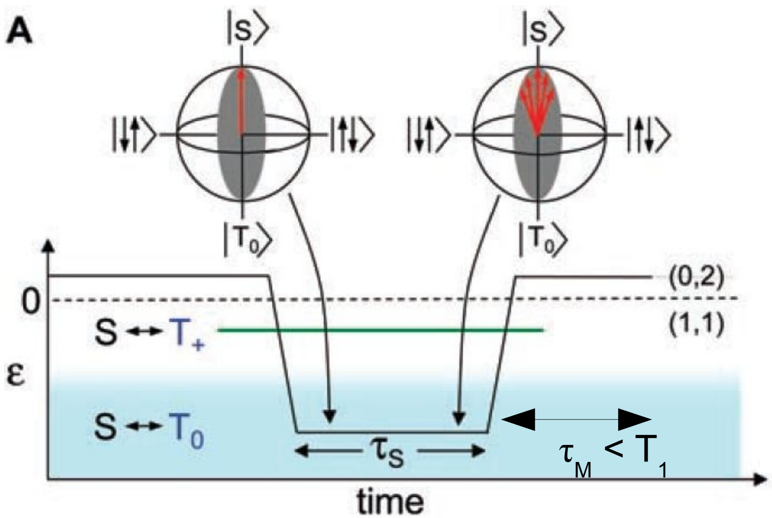


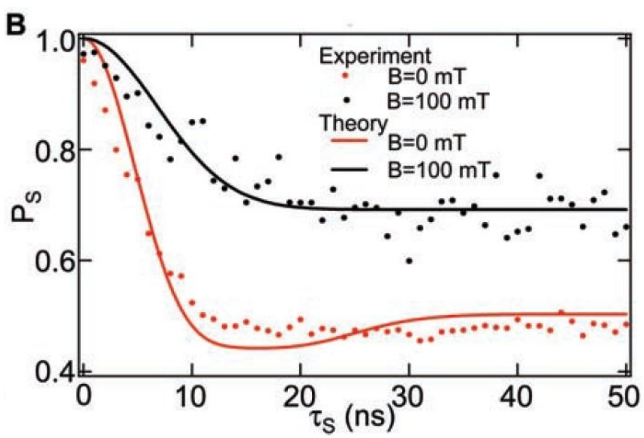
1. Coherence

How long do two spatially separated electrons retain coherence ?
→ Measurement of the dephasing time of S(1,1)





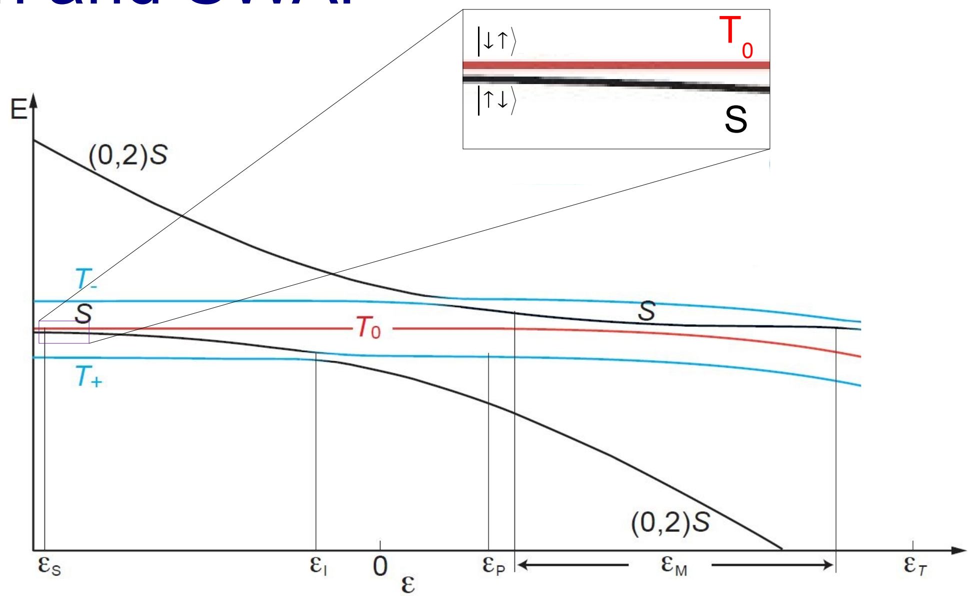
Determination of the spin state using the calibrated QPC charge sensor



→ Estimation of T_2^* ~10ns

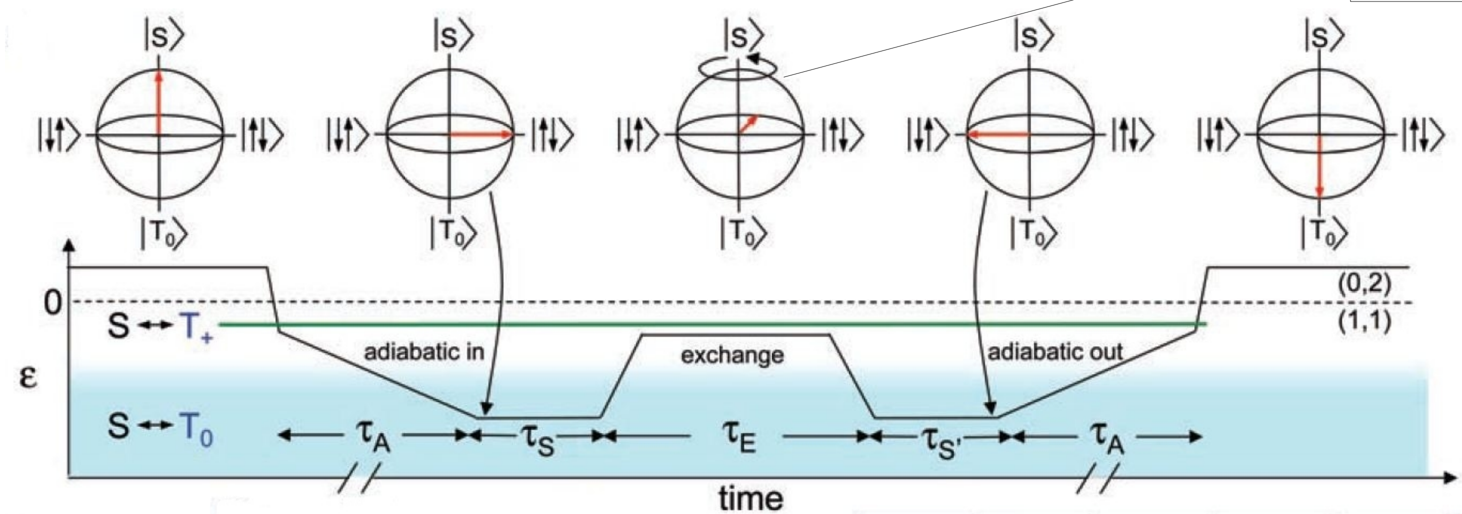
2. Manipulation and SWAP

Source [6]



$$\phi = \frac{J(\epsilon)\tau_E}{\hbar}$$

If $\phi = \pi$: Swap !



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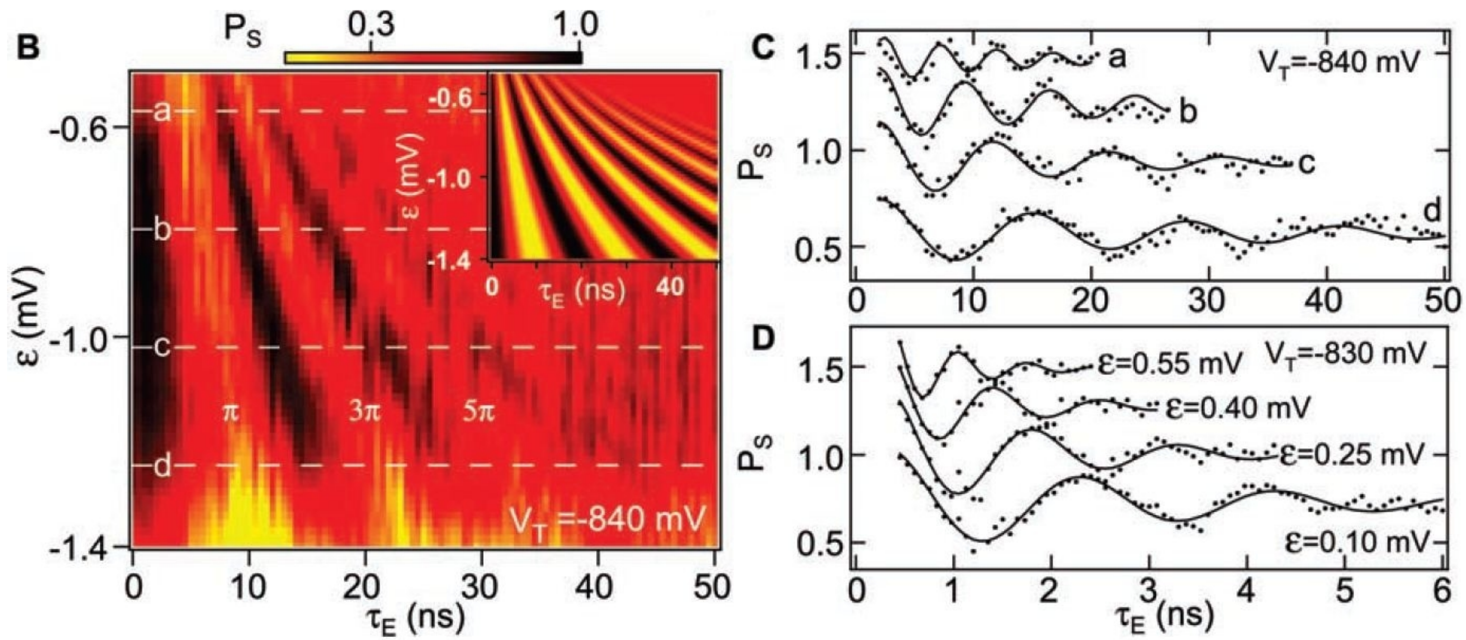

→ 180ps

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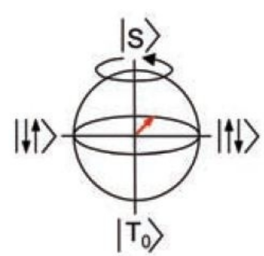
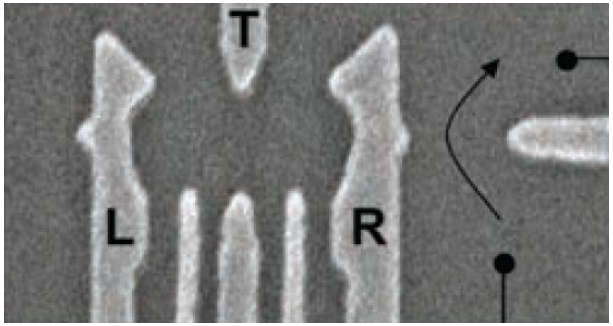
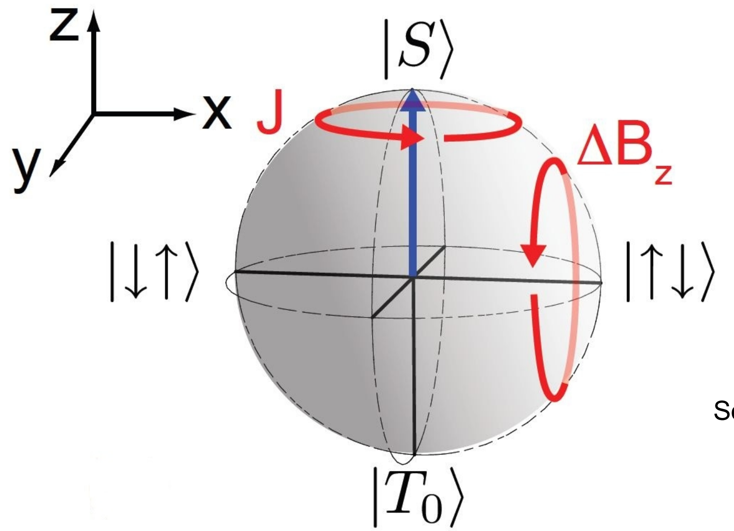
If $\phi = \pi$: Swap !



Conclusion





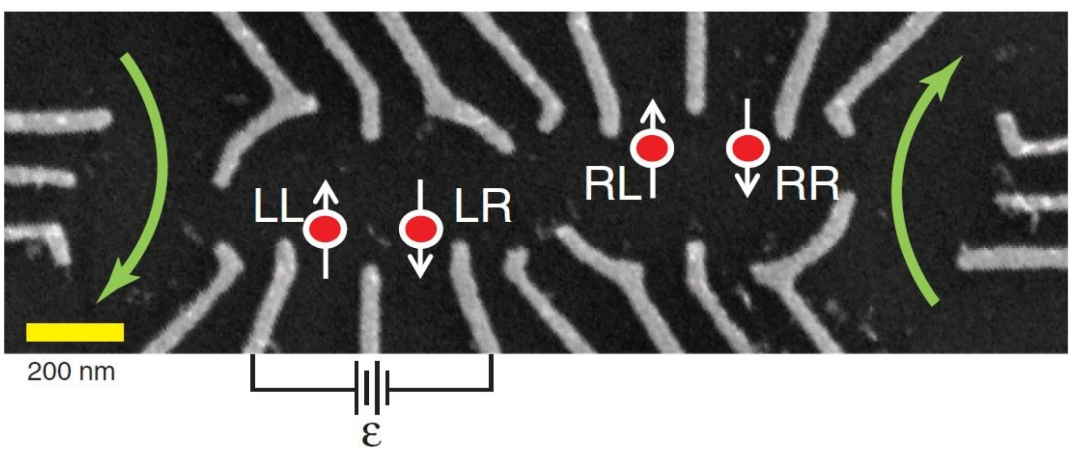
Source [6]

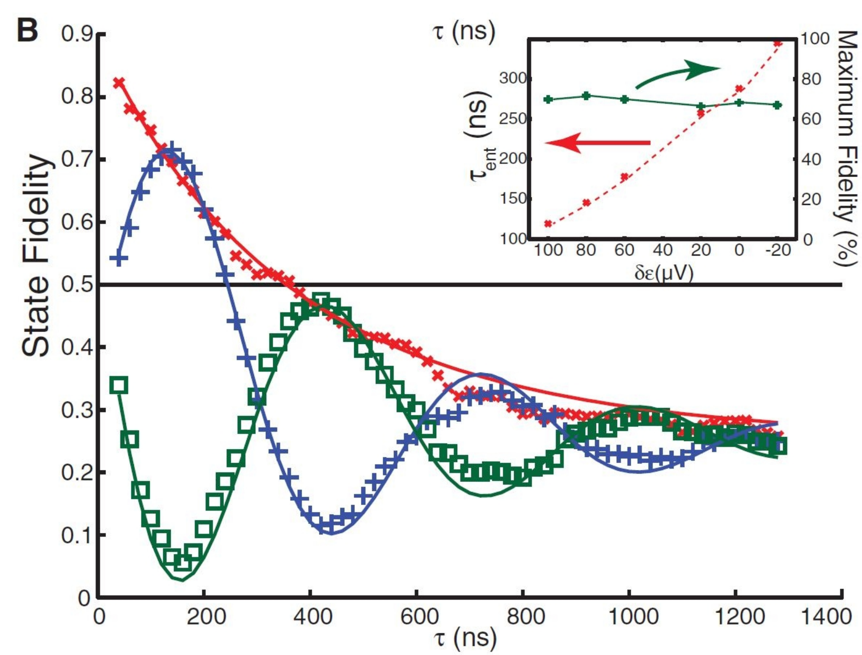
- *Coherent control of a logical QuBit*
- *T_2* was measured*
- *Rabi Oscillations were observed*
- *√SWAP operation-time ~ 180ps.*

Demonstration of Entanglement of Electrostatically Coupled Singlet-Triplet Qubits

M. D. Shulman,[1*] O. E. Dial,[1*] S. P. Harvey,[1] H. Bluhm,[1†] V. Umansky,[2] A. Yacoby[1‡]

3 weeks ago...





End of the presentation

Thank you for your attention !

And many thanks to Arkady.

Questions ?

References

[1] T. Ihn, *Semiconductor Nanostructures* (2009), Oxford University Press.

[2] Hanson et al.,*Coherent manipulation of single spins in SC* (2008), Nature **453**, 1043 .

[3] Ciorga et al., Phys. Rev. B **61** (2000).

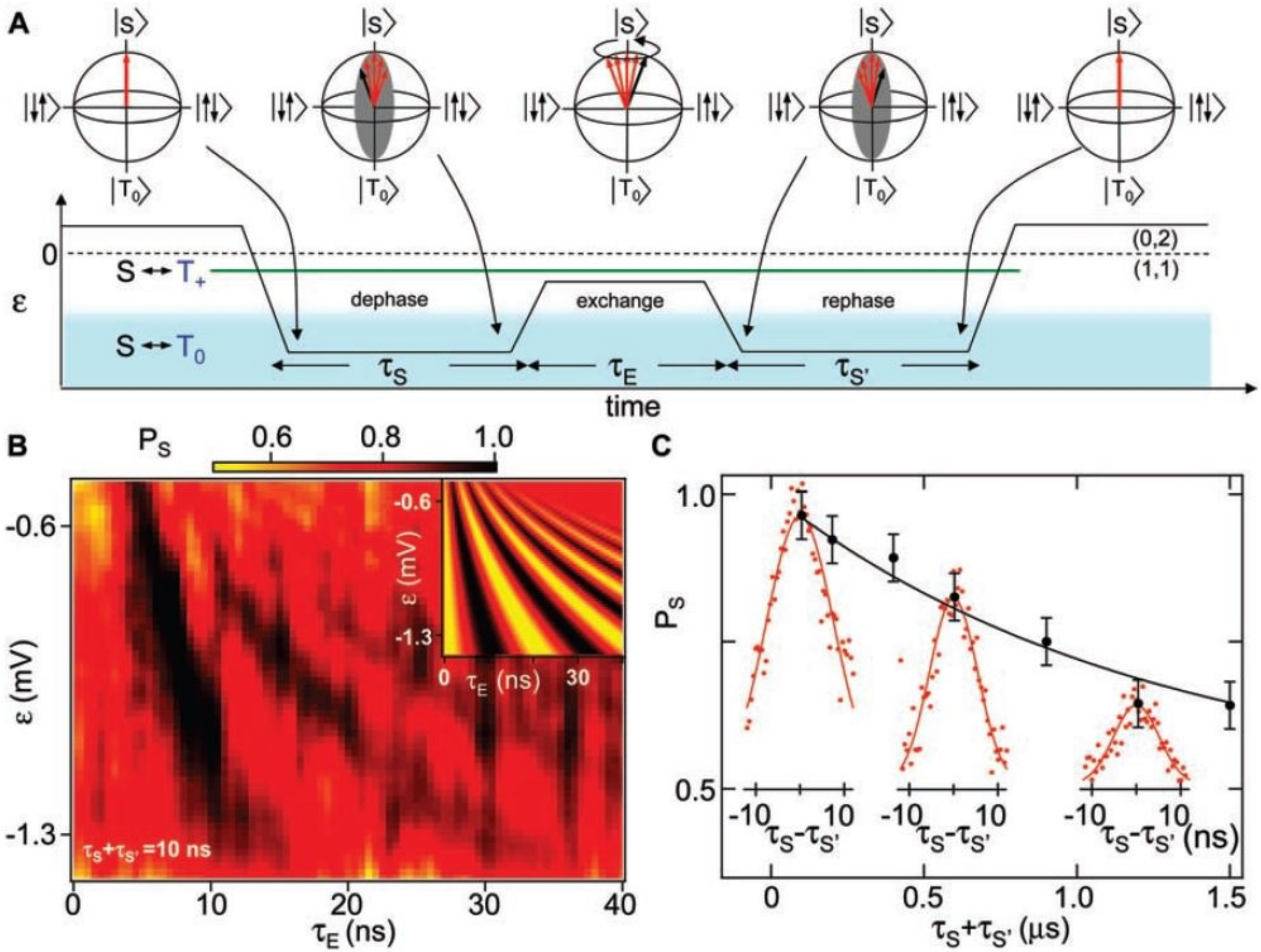
[4] Hanson et al., *Spins in few-electron QDs* (2007), Rev. Mod. Phys., Vol. **79**, No. 4

[5] Petta et al., *Coherent Manipulation of coupled electron spins in SC Qds*, Science **309** (2005)

[6] C. Barthel PhD Thesis, *Control and Fast Measurement of Spin Qubits* (2010).

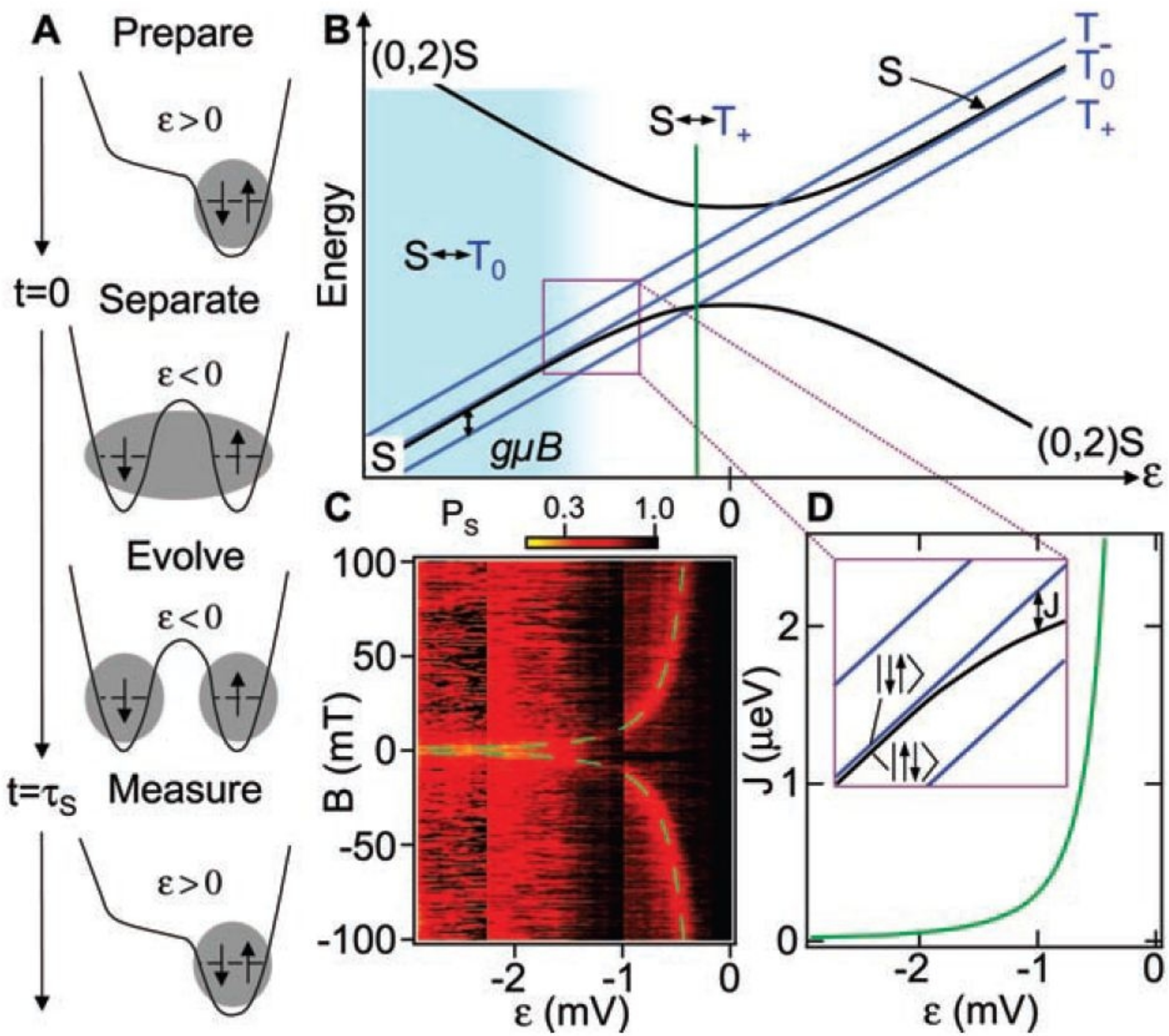
[7] Shulman et al., *Demonstration of Entanglement of Electrostatically Coupled S-T QuBits,* Science **336** (2012).

3. Spin Echo



A
dephase
exchange
rephase
time
(0,2)
(1,1)
B
C
τE (ns)
τS+τS' =10 ns
τS+τS' (μs)
τS-τS' (ns)

Appendix



A
Prepare
ε>0
t=0
Separate
ε<0
Evolve
ε<0
t=τS
Measure
ε>0
B
(0,2)S
S
T-
T0
T+
S↔T+
Energy
S↔T0
S
gμB
(0,2)S
ε
0
C
PS
0.3
1.0
100
50
0
-50
-100
B (mT)
-2
-1
0
ε (mV)
D
J
|↓↑⟩
|↑↓⟩
2
1
0
J (μeV)
-2
-1
0
ε (mV)