Implementing gates in quantum dot spin qubits

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Source:

Petta, JR; Johnson, AC; Taylor, JM; et al.
Coherent manipulation of coupled electron spins in semiconductor quantum dots.
Science 309, 2180 (2005)

David P. DiVincenzo
Double Quantum Dot as a Quantum Bit. Science 309, 2173 (2005);

Outline

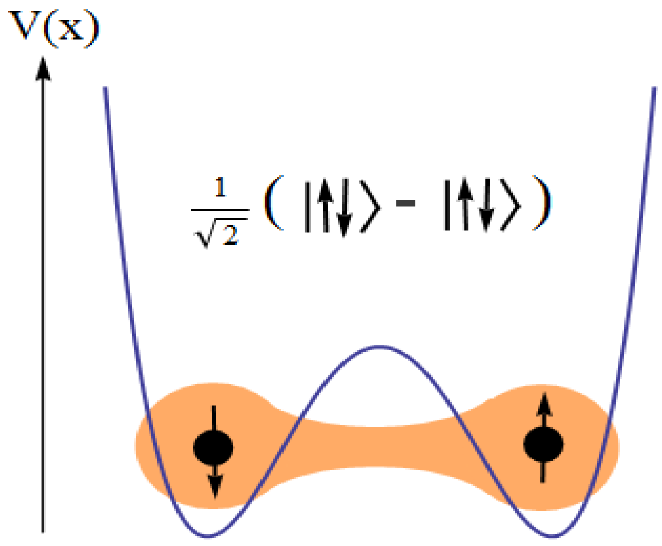
- Two electron spin qubit
- Device
- Energy levels
- Manipulation of states
    - Dephasing
    - Rabi oscillations
    - Spin echo technique

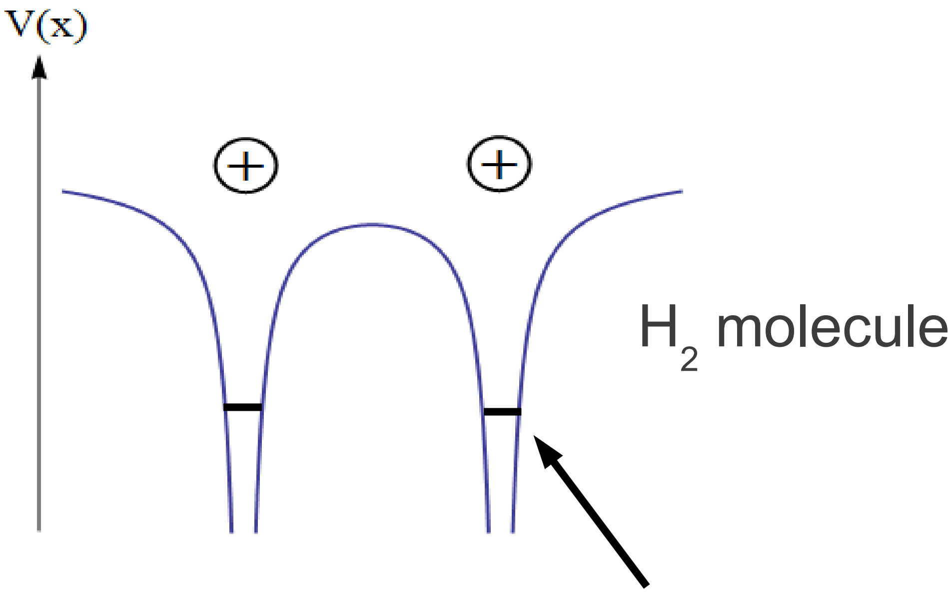
motivation

Semiconductor quantum dots:

- Engineered artificial atoms
- Long lifetime of the quantum states (T_1) compared to pulse frequency
- Short coherence lifetime T_2 -> spin echo

Two electron spin qubit



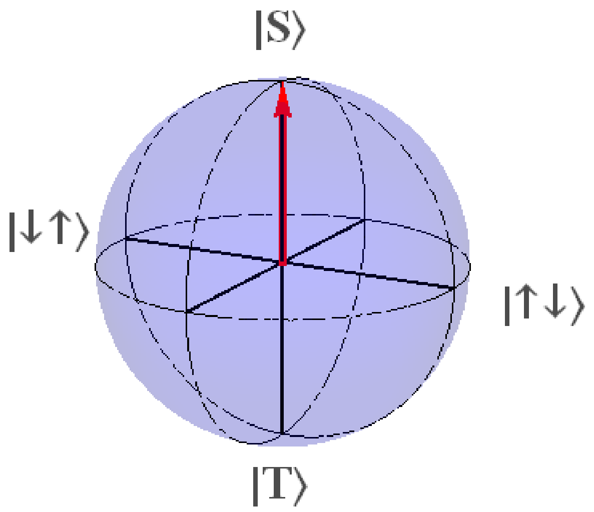


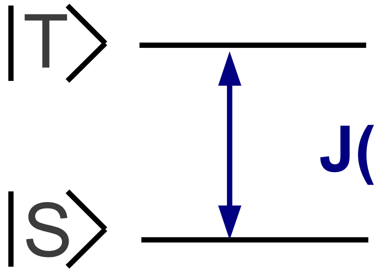
H_2 molecule

Ground state of H atom

- Double-well potential = H_2 molecule
- ground state = Singlet
  excited state = Triplet
- Difference: Spin coupled to 10^6 spins of host crystal nuclei

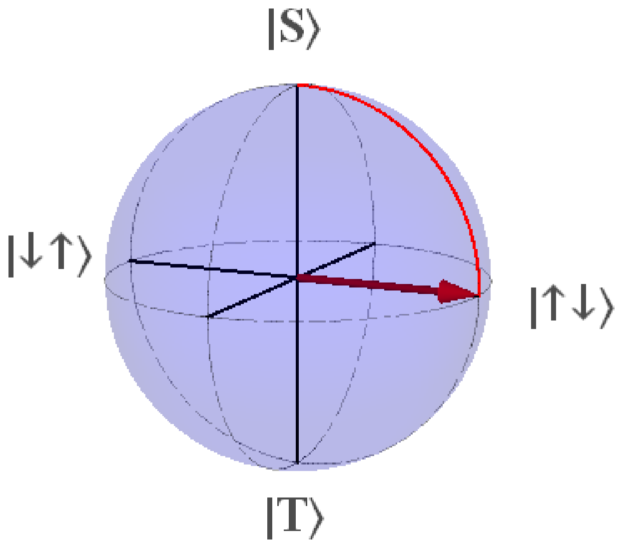
Bloch sphere representation

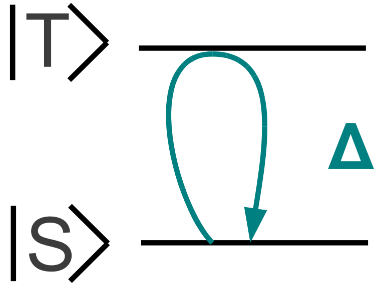




J(ε) exchange interaction

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

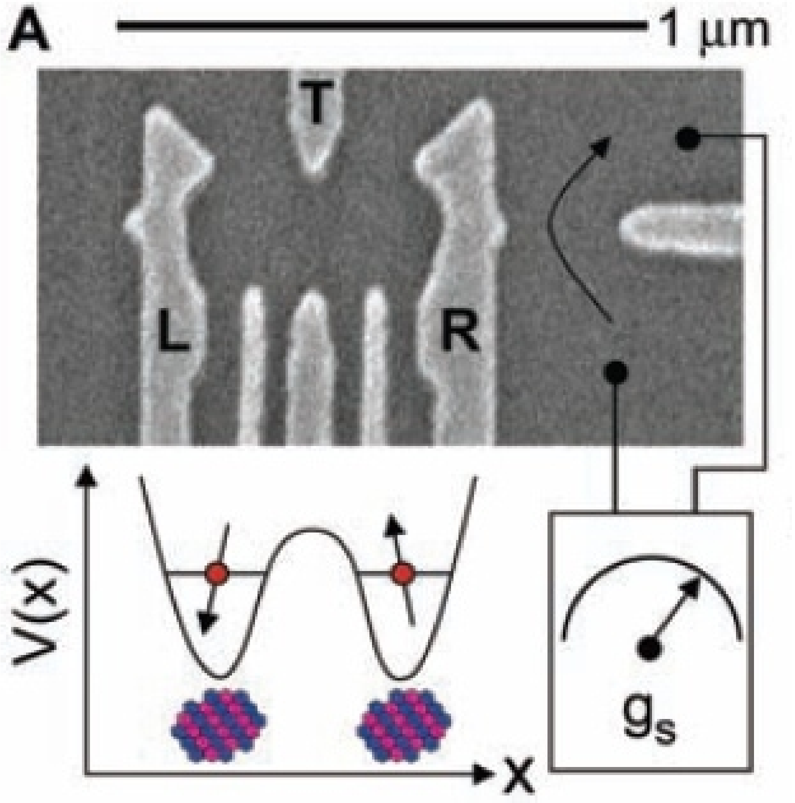




$\mathbf{\Delta B^{z}_{nuc}}$ hyperfine interactions

Device

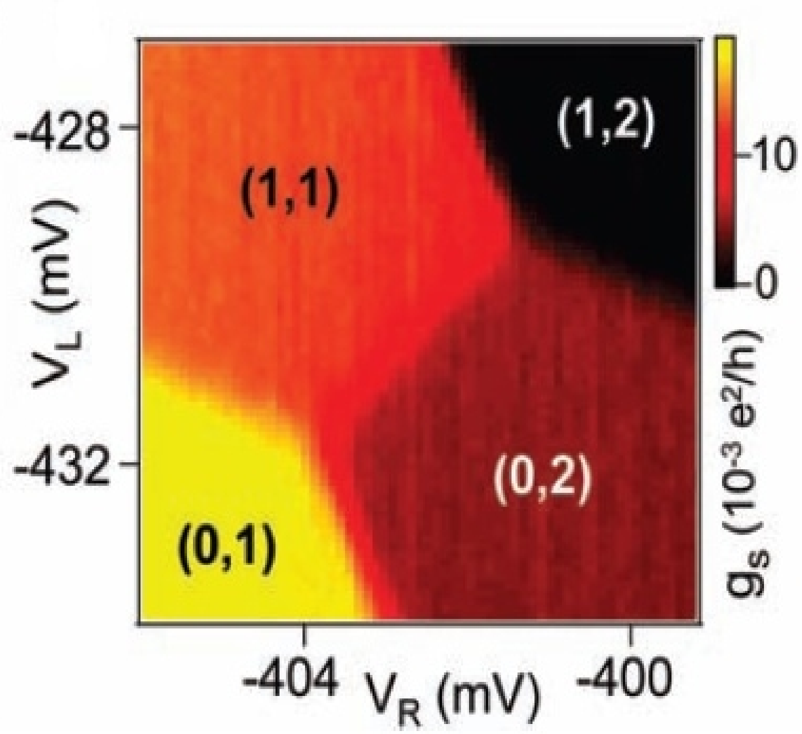
- Quantum Dots (QDs) confined in 2DEG (GaAs/AlGaAs interface) with split gate technique
- The voltage V_L, V_R controls charge in QDs
- V_T tunes interdot tunneling
- Single electrons can be detected by measuring the conductance gs over the quantum point contact (QPC)



Charge state depent QPC conductance

- (m,n) = electrons in (left, right) dot
- Additional electrons reduce the conductance *discretely*

- QPC is more sensitive to the right dot
  -> difference between (0,2) and (1,1)
- V_L also affects right dot
  -> honeycomb shape



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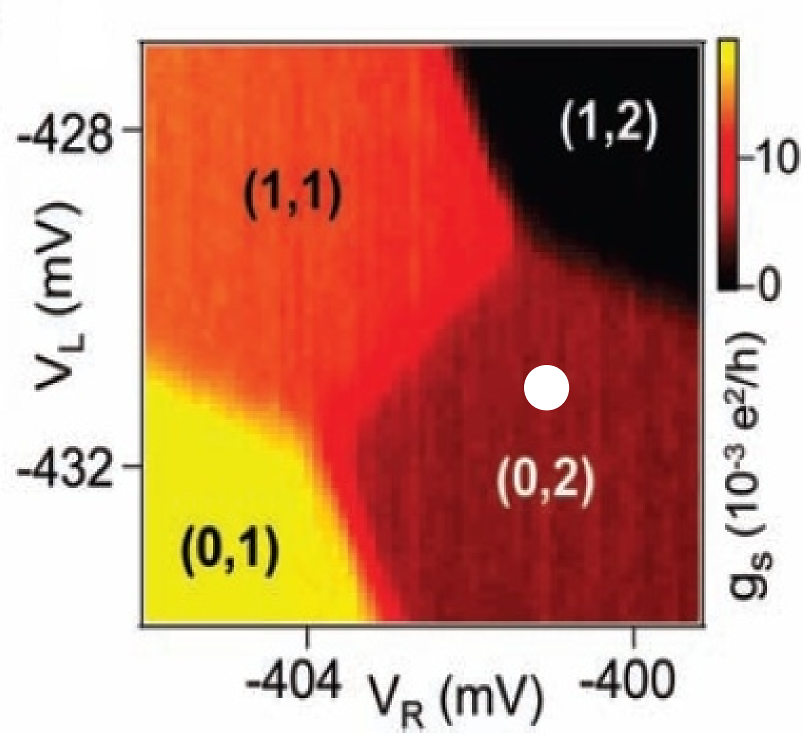

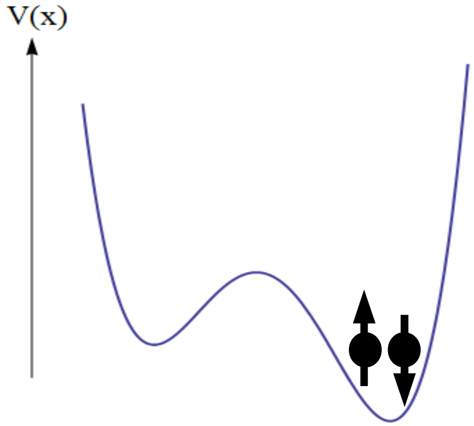

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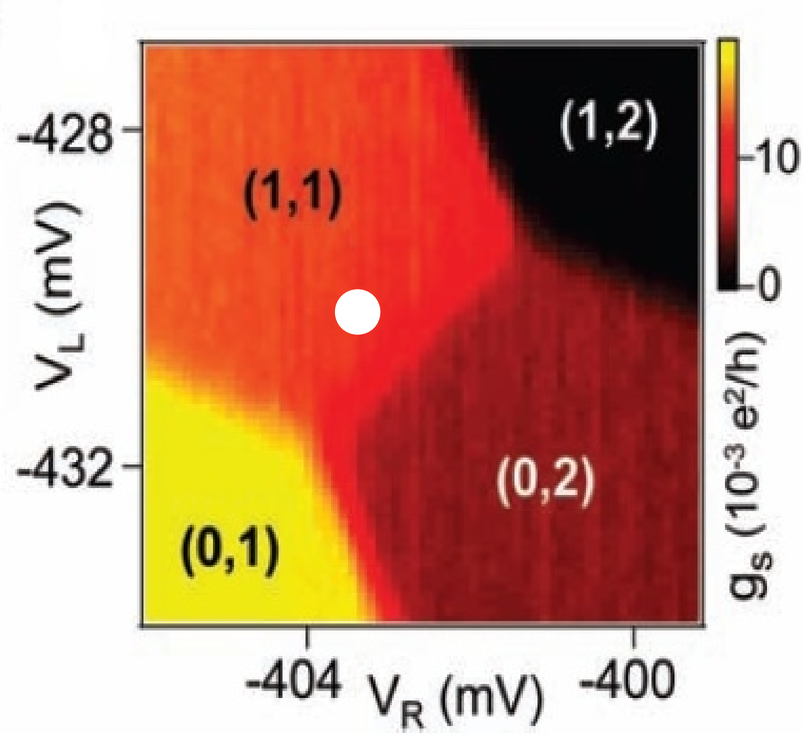

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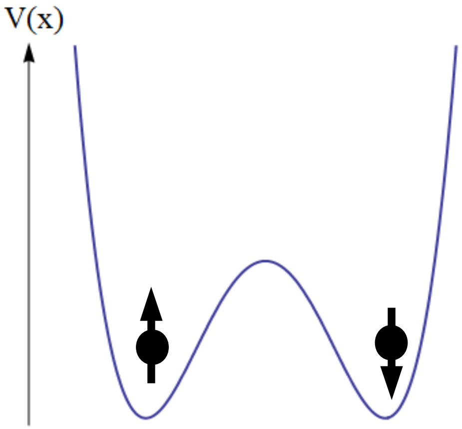
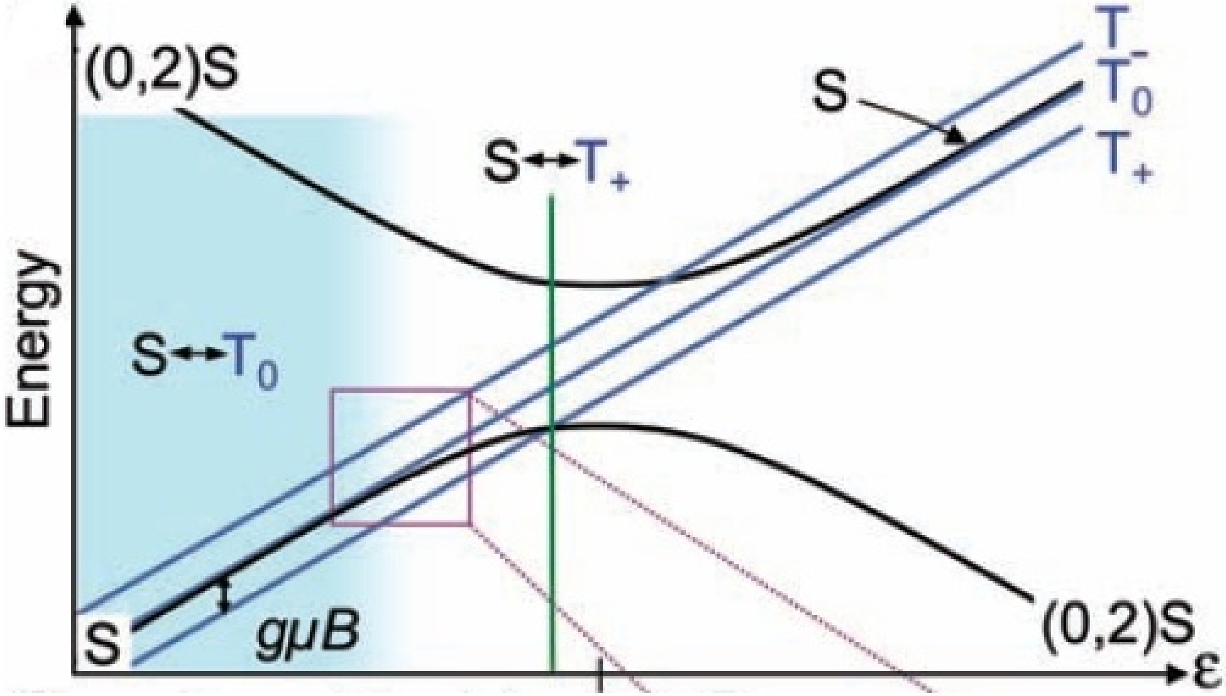


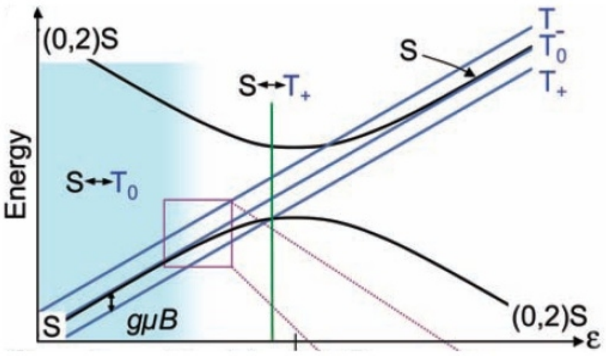
Energy depending on detuning

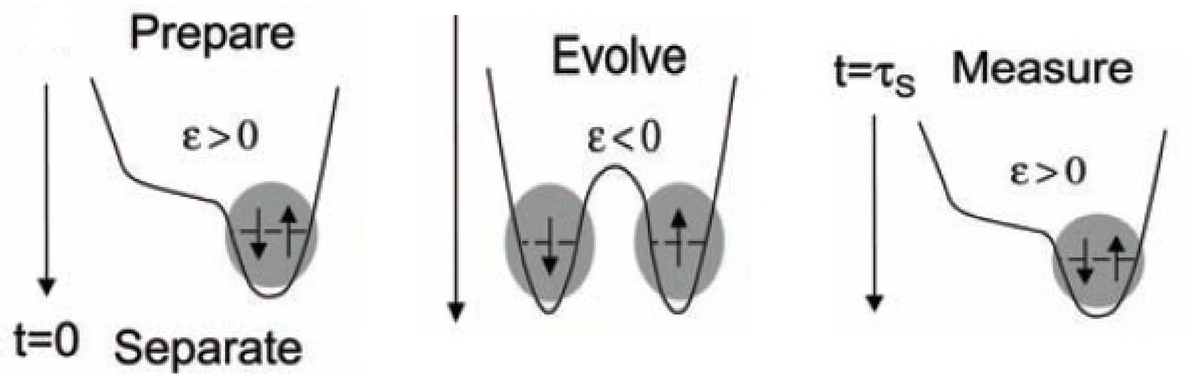
- The triplet states (m = -1,0,+1) are split off by a 100mT external magnetic field
- Detuning parameter ε ~ $(V_R - V_L)$
- Only states with similar energies can mix (consider $S=T_0$, $S=T_+$)



Gerneral method for propagation and readout

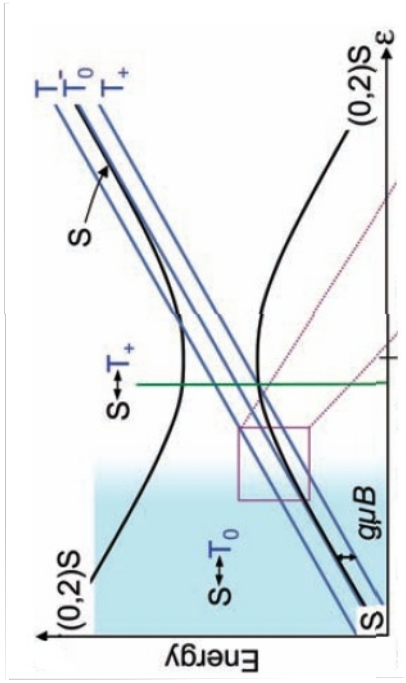
- Initialize in (0,2)S
- Pulse transferes (0,2)S into the spatially separated (1,1)S state
- (1,1)S and (1,1)T form a two level system
- The (1,1)S state is manipulated
- The state is projected back onto (0,2)S if the final state was (1,1)S and measured with the QPC. Tripplet state is blocked

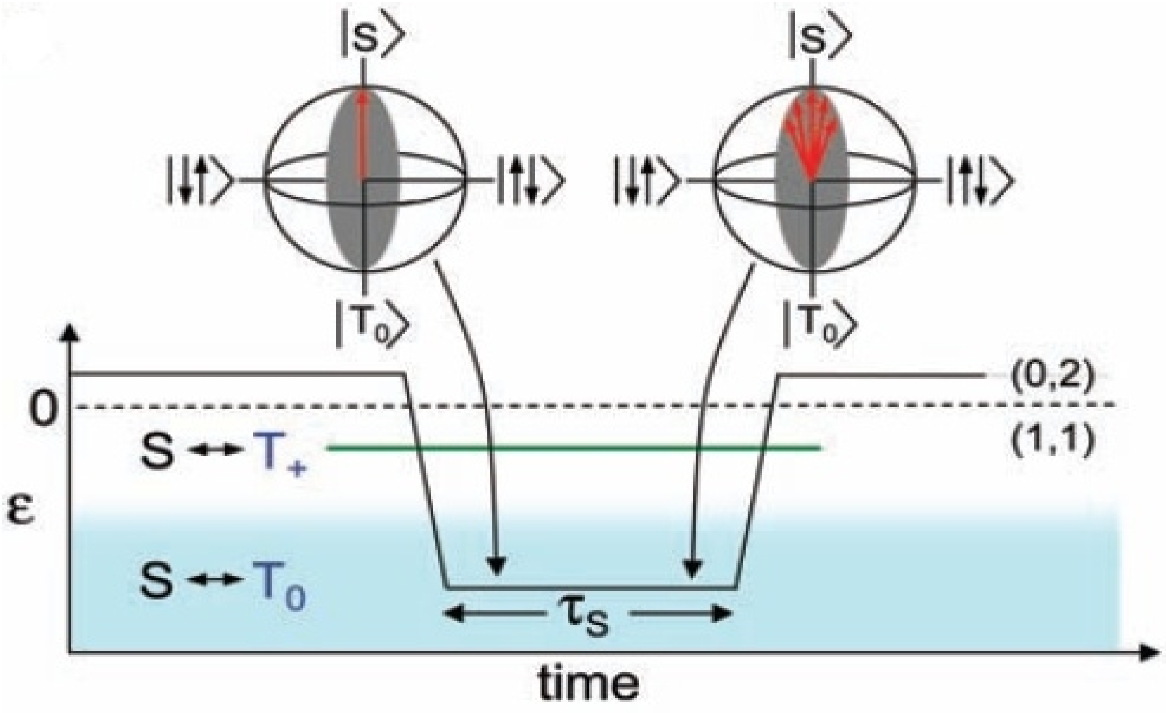




Manipulation of states, dephasing

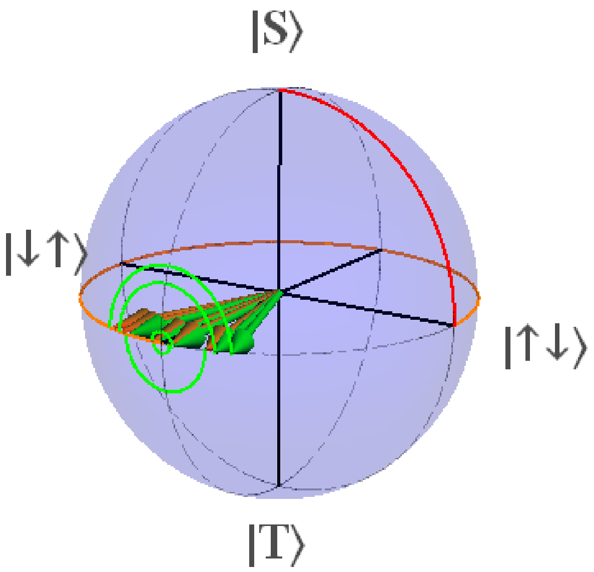
- Short voltage pulse to large detuning suppresses exchange interaction of separated spins
- Due to different hyperfine interactions caused by the GaAs nuclei in the QDs, different rotations occur
- -> dephasing





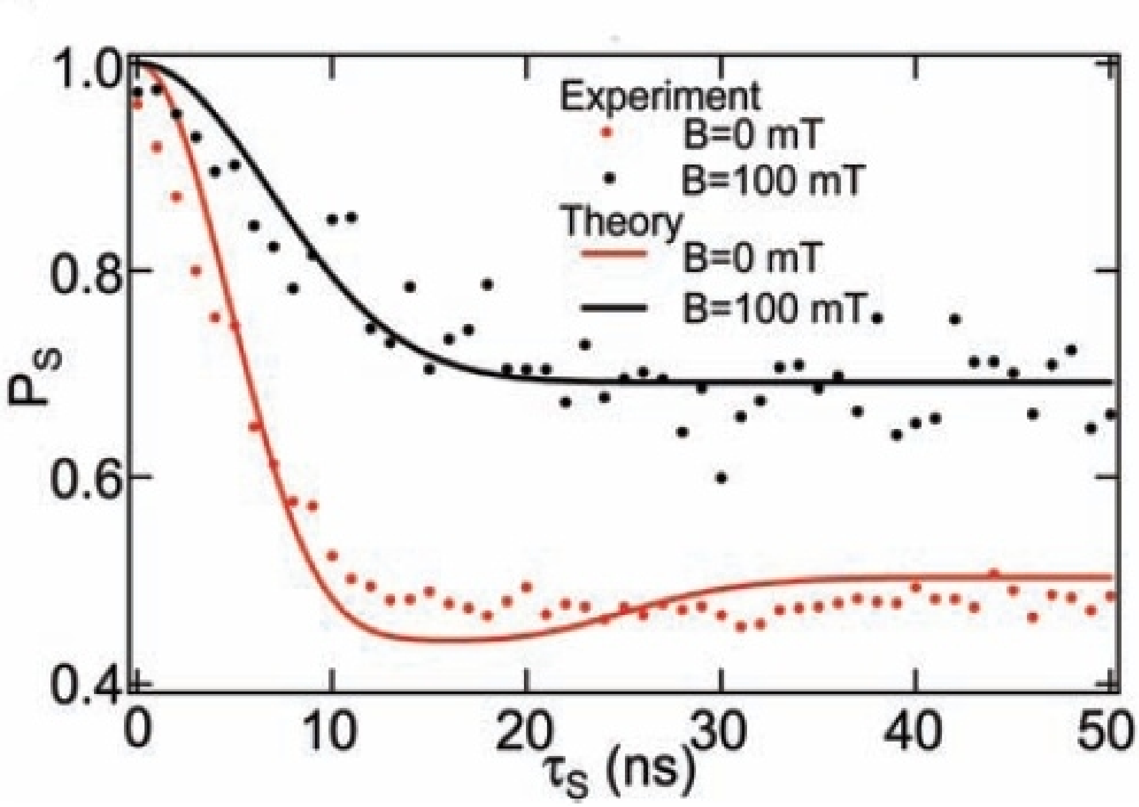
Limits of the coherence

- Weak interaction with ~10^6 other GaAs atoms
- Fluctuations of the magnetic field of 1-5mT, chaning at arround 10µs



Experimental results of dephasing

- Correlation of the states decays gaussian
- With B-field of 100mT, S state can only mix with the T_0 state and thus S has a higher probability than with B=0mT

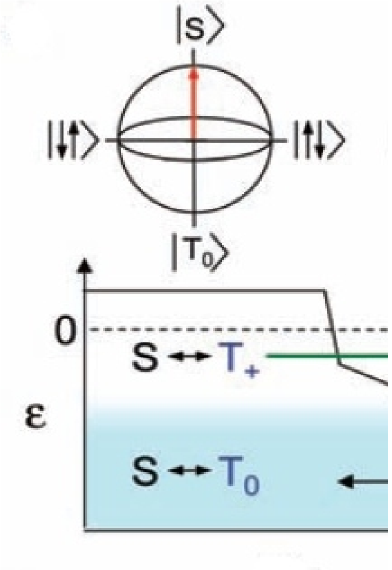


SWAP

- The four states can be maped on the bloch sphere
- At an energy of slightly below ε the state rotates between the states l > and l >
- After a time τ_E the state changes from l > to l > or vice versa, this is called $\sqrt{SWAP}$

Rabi oscillations

- By a slow decrease of ε the state gets initialized in the |↑↓> state
- Small detuning leads to a rotation around the z-axis due to large exchange interaction
- Depending on τ the state is in a superposition of |↑↓>, |↓↑>
- The slow increase of ε leads either to (1,1)S or (1,1)T state



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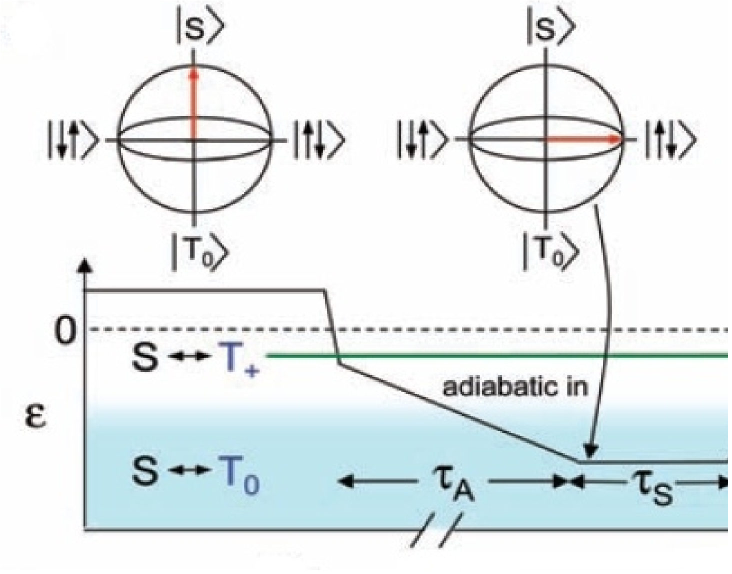

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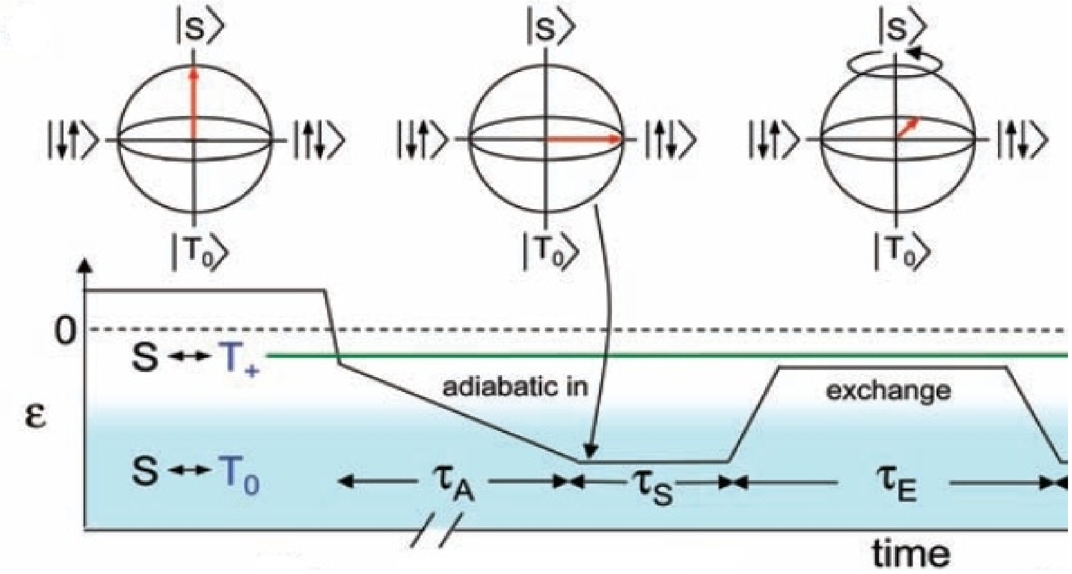

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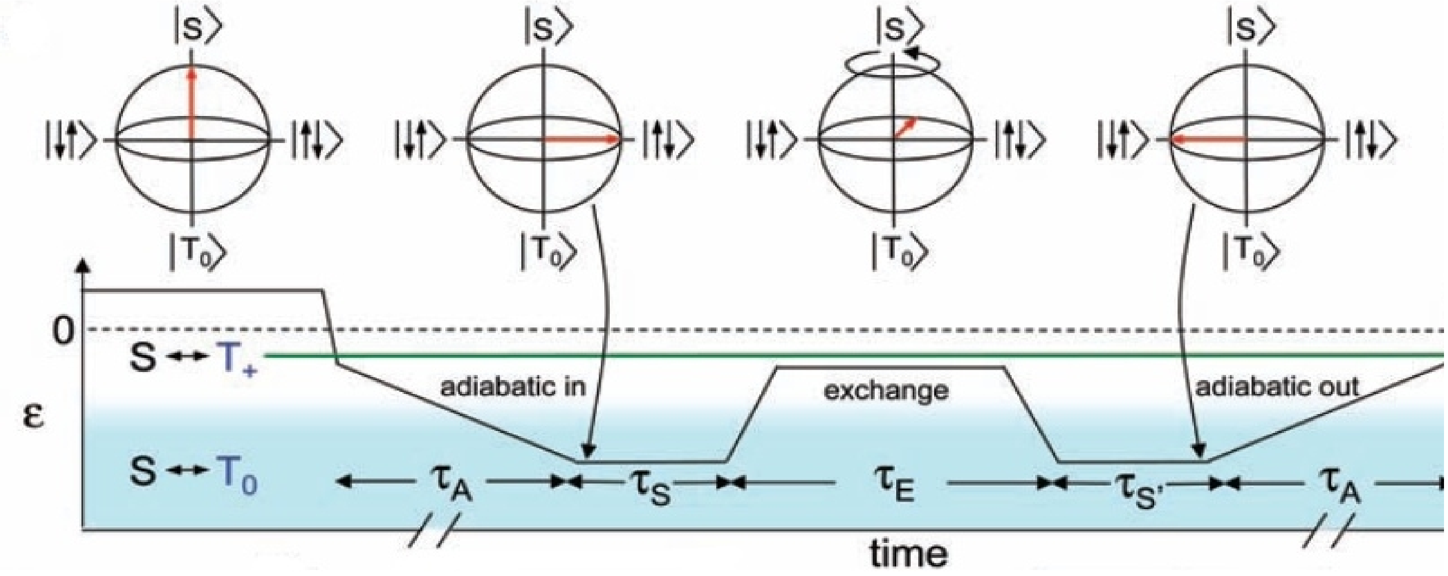

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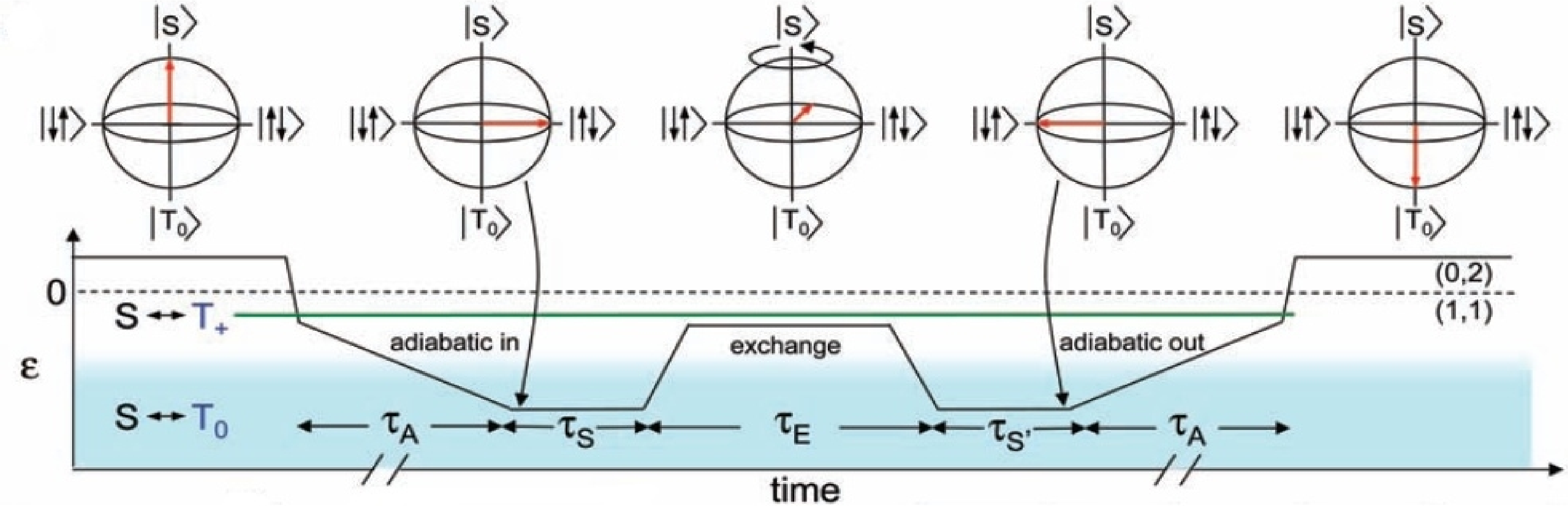
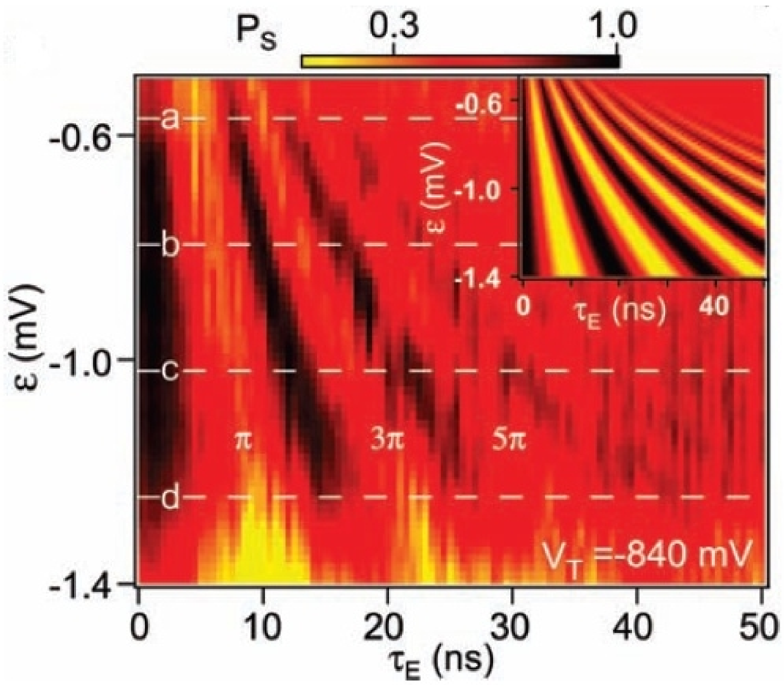
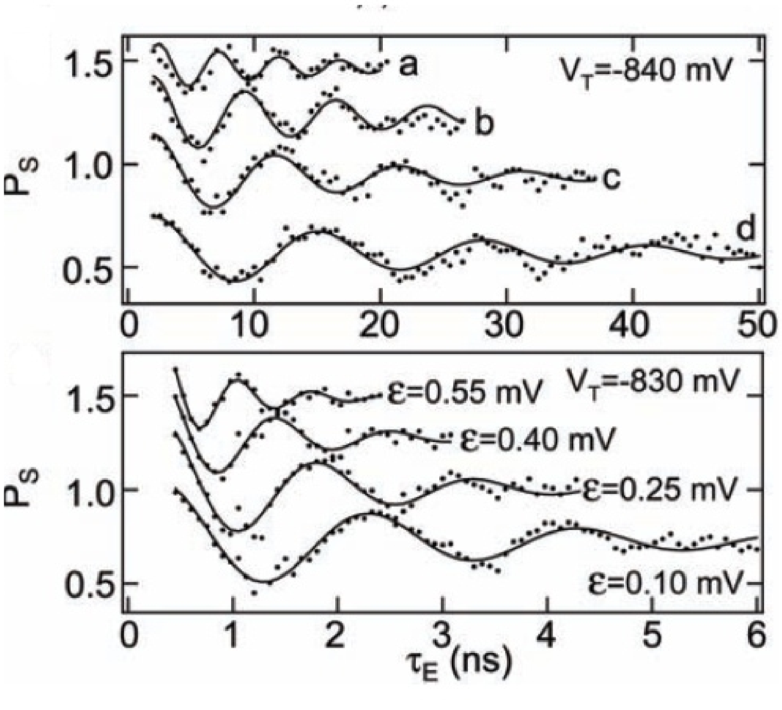


Experimental results of Rabi oscillations

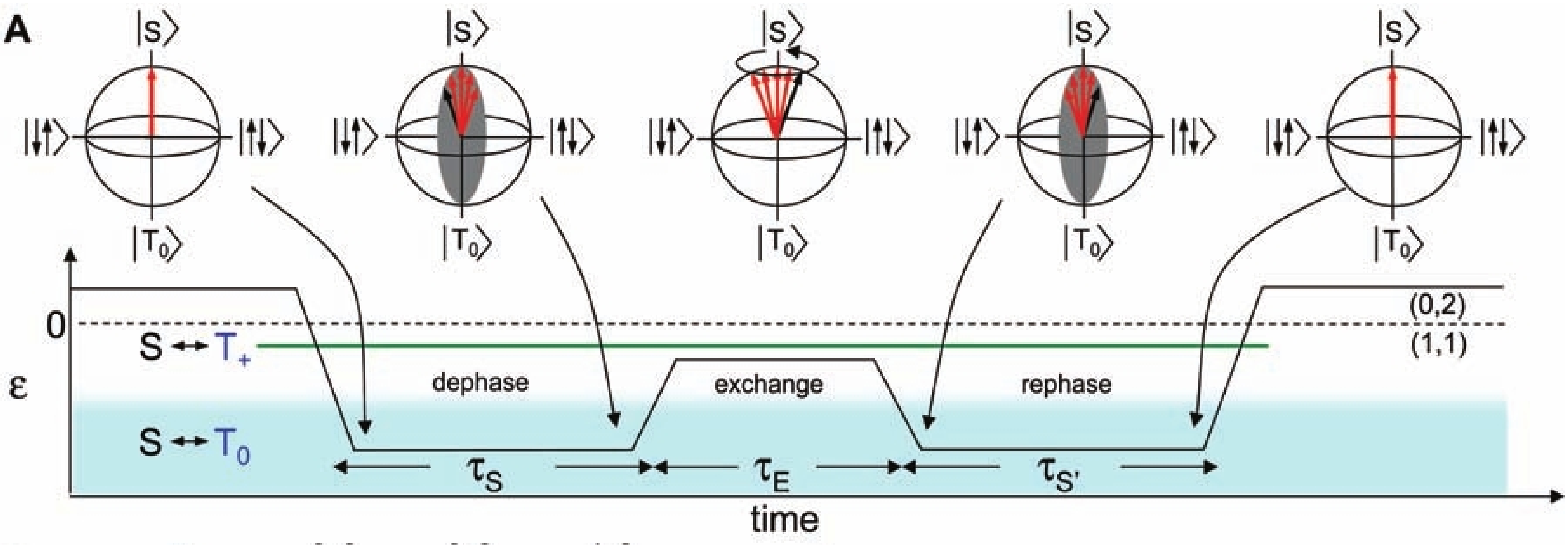
- Rotations about the x-axis leads to oscillations on the singlet probability
- The decaytime is proportional to the frequency
- Small detuning leads to higher exchange and therefore to faster rotations





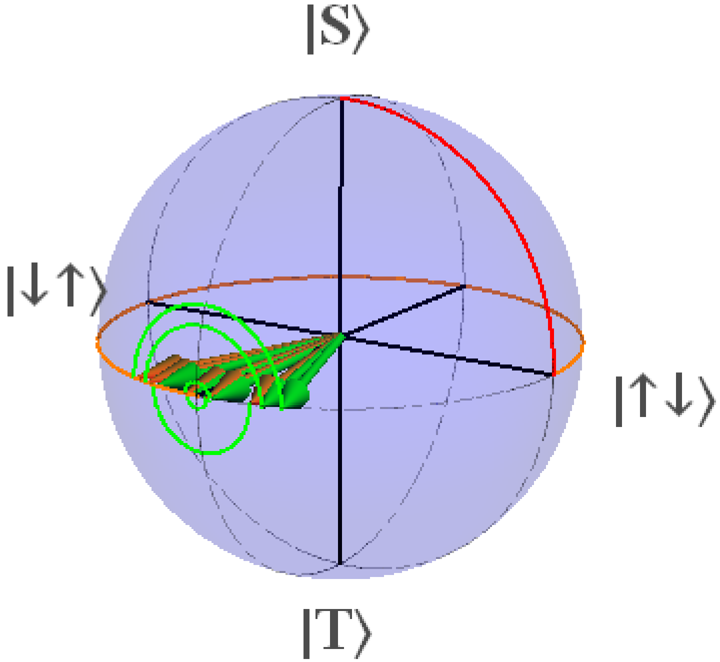
Spin echos

- **Idea:** reduce the dephasing by using rabi oscillations
- rotation by (2n+1)=π about z-axis
- Let system evolve for the same time $\tau_S = \tau_{S'}$
- dephasing is interfering destructively



Conclusion

- Coherent control of a logical qubit based on two-electron spin states
- Electrostatic gate control only
- Rabi oscillations and SWAP operation were demonstrated
- Spin echo technique reduces the decoherence caused by B-field fluctuations
  -> enhanced coherent spin-lifetime of 1µs


|S⟩
|↓↑⟩
|↑↓⟩
|T⟩