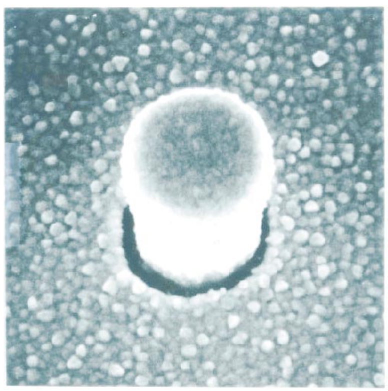
Inelastic spin relaxation in quantum dots



Toshimasa Fujisawa

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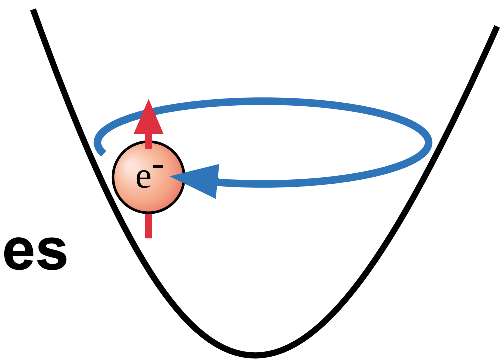

collaboration

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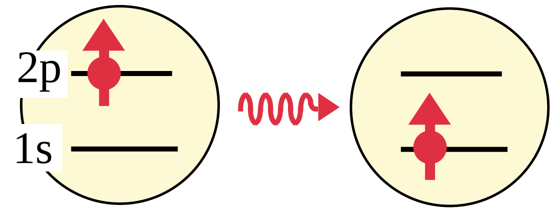
Outline

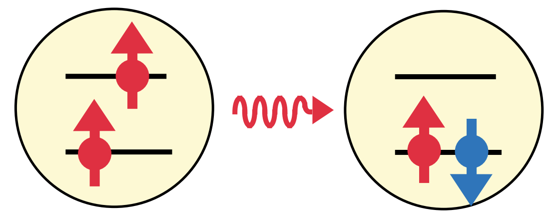
1. Introduction (energy relaxation inside a QD)

2. Momentum relaxation
   phonon emission



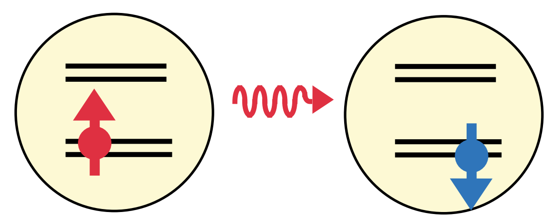
~ 10 ns (experiment)

3. Spin & momentum relaxation
   cotunneling effect
   spin-orbit interaction



~ 200 μs (experiment)

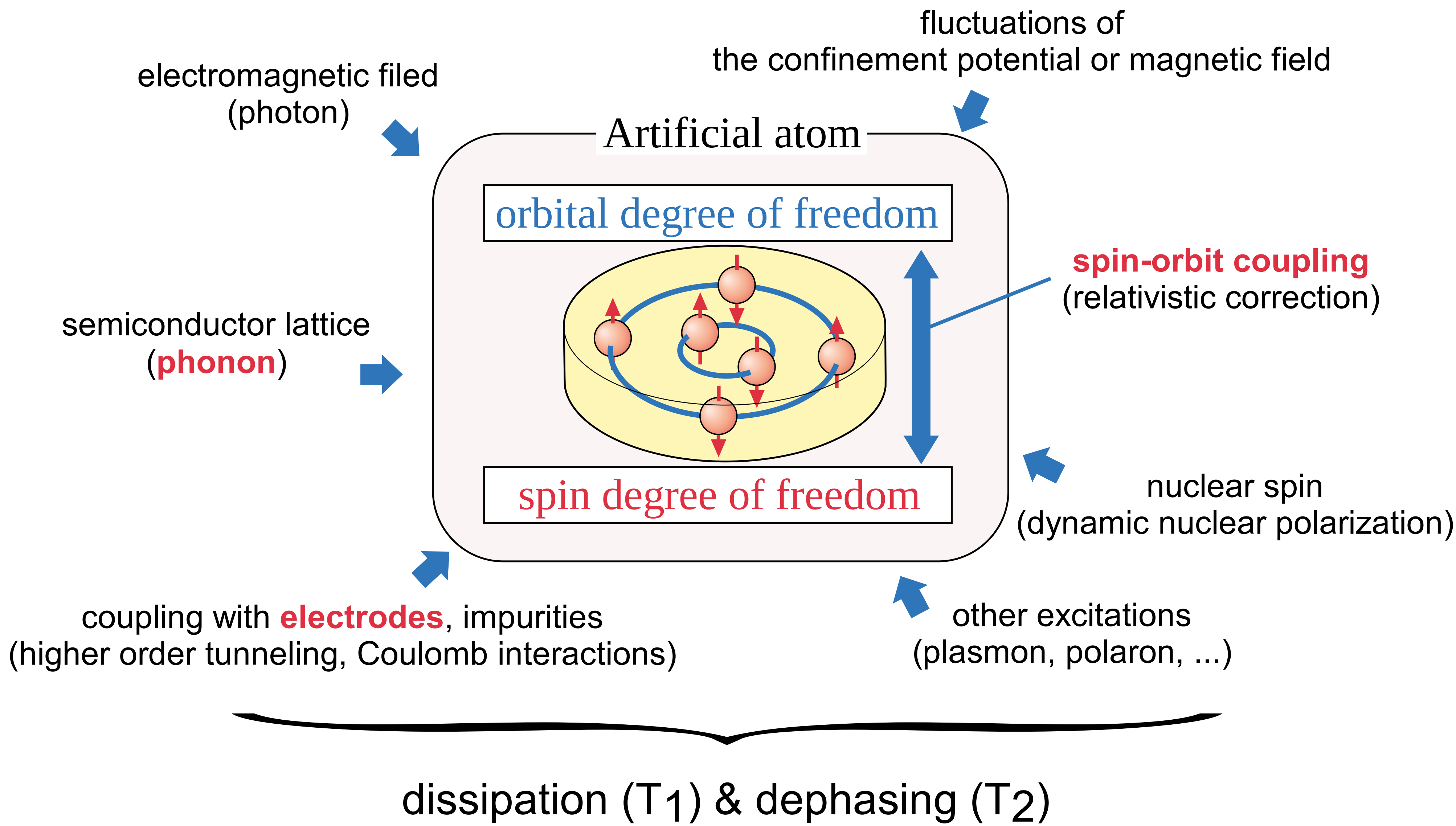
4. Spin relaxation between Zeeman sub-levels
   (spin-orbit interaction)



~ ms (estimation)

5. Summary

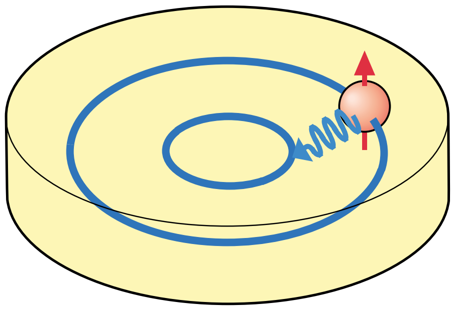
Environment surrounding a quantum dot



important characteristics for dynamics, coherence, quantum computing, ...

Energy relaxation in a quantum dot

momentum relaxation, which changes the orbital but does not change the spin



theory: electron-phonon interaction

$\tau_{e\text{-}ph} \sim 1$ ns (for GaAs QD, $\Delta \sim 1$ meV)

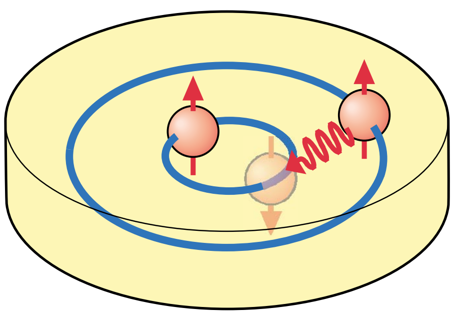
U. Bockelmann, Phys. Rev. **B50**, 17271 (1994).

optical studies: discussions about phonon bottleneck effect

J. Urayama et al., Phys. Rev. Lett. 86, 4930 (2001).

R. Heiz et al., Phys. Rev. B 64, 241305 (2001).

spin relaxation, which changes the spin (and can changes the orbital)



theory: spin-orbit interaction
(+ electron-phonon interaction)

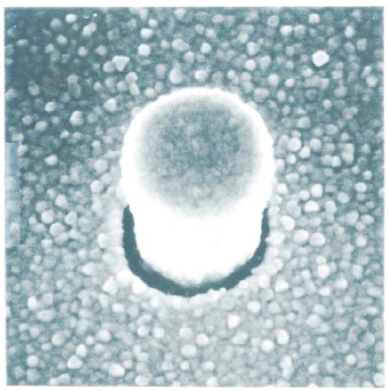
$\tau_{so} > 100$ μs (for GaAs QD, $\Delta \sim 1$ meV)

A. V. Khaetskii and Yu. V. Nazarov, Phys. Rev. **B61**, 12639 (2000)

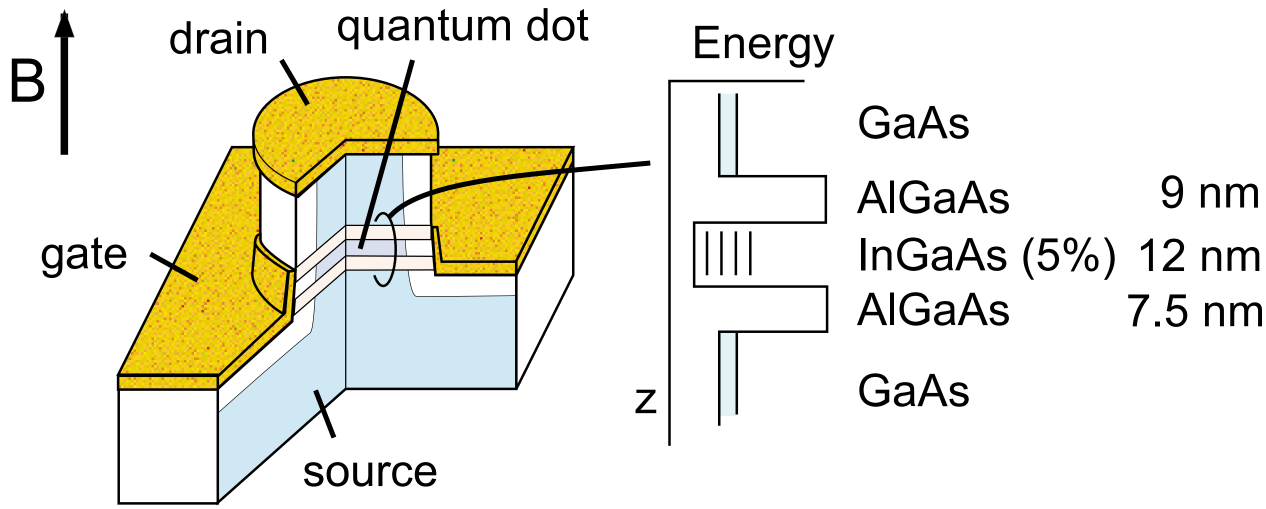
optical studies: longer than measurable range at low temperature
(>20 ns @T~10K)

M. Paillard et al., Phys. Rev. Lett. 86, 1634 (2001).

A vertical quantum dot (artificial atom)



SEM picture of mesa after gate metallization



S. Tarucha et al., Phys. Rev. Lett. **77**, 3613 (1996).
L. P. Kouwenhoven et al., Science **278**, 1788 (1997).

non-circular dot

(nominally circular, d = 0.50 μmϕ)

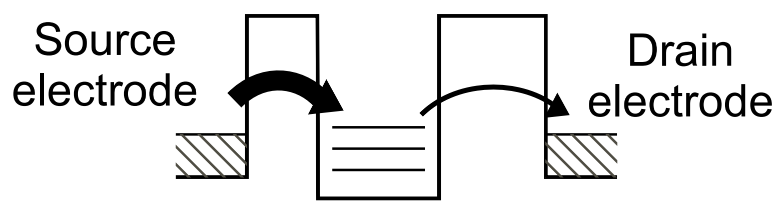
no orbital degeneracy

2p’ —— ($2p_y$)

2p —— ($2p_x$)

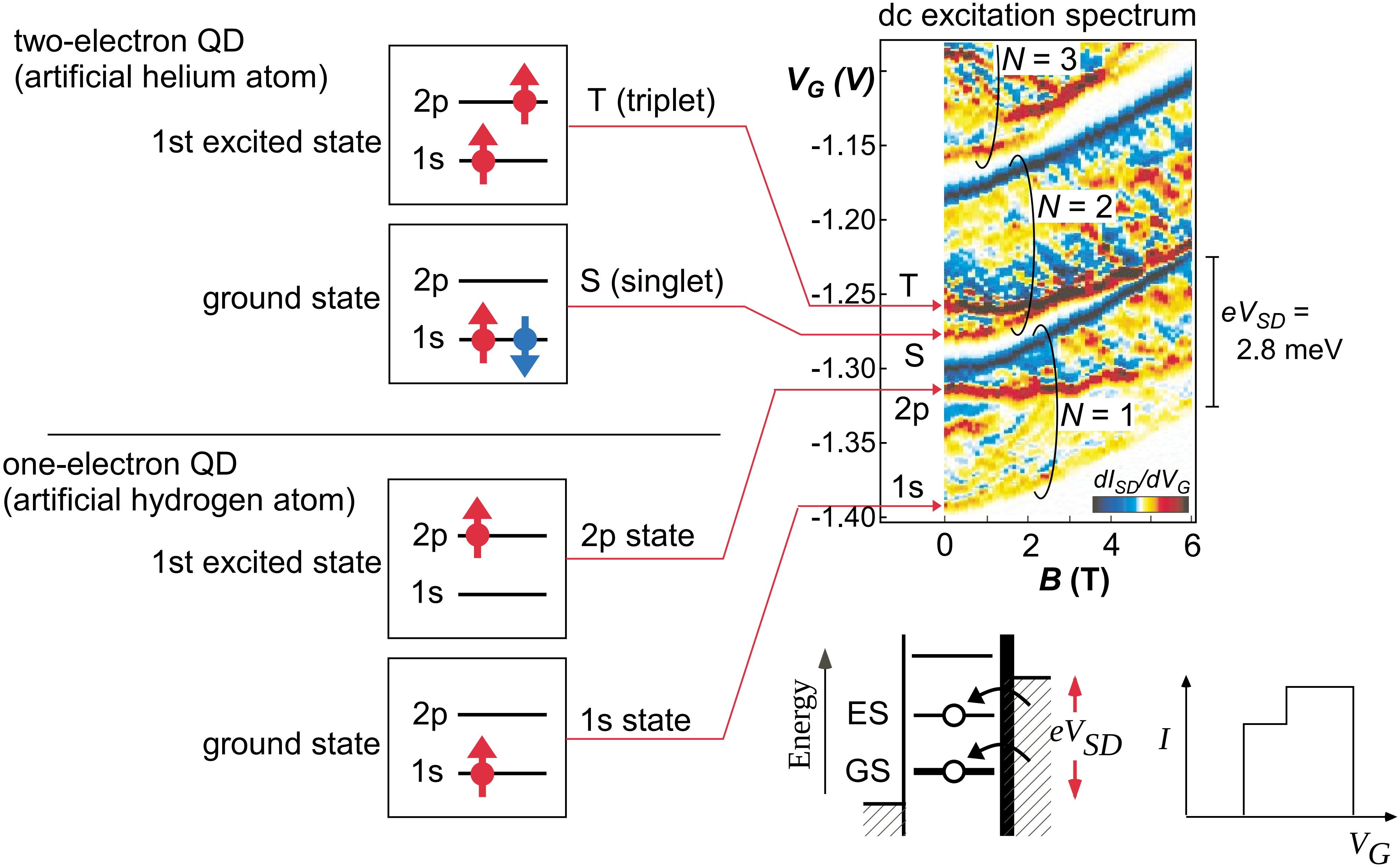
1s ——

$\Gamma_S \sim (3\ \mathrm{ns})^{-1}$ $\Gamma_D \sim (100\ \mathrm{ns})^{-1}$

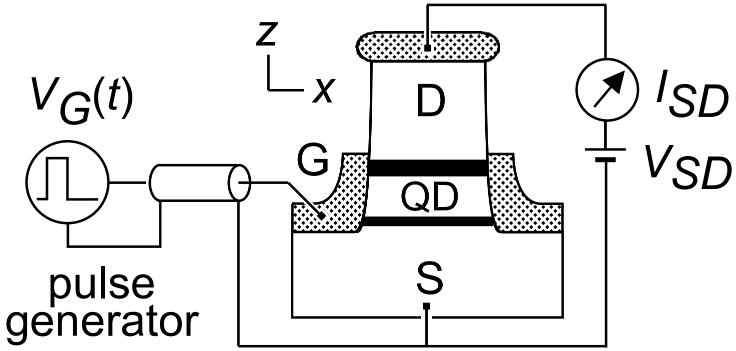


measured at B = 0 - 8 T and T = 0.05 - 1 K

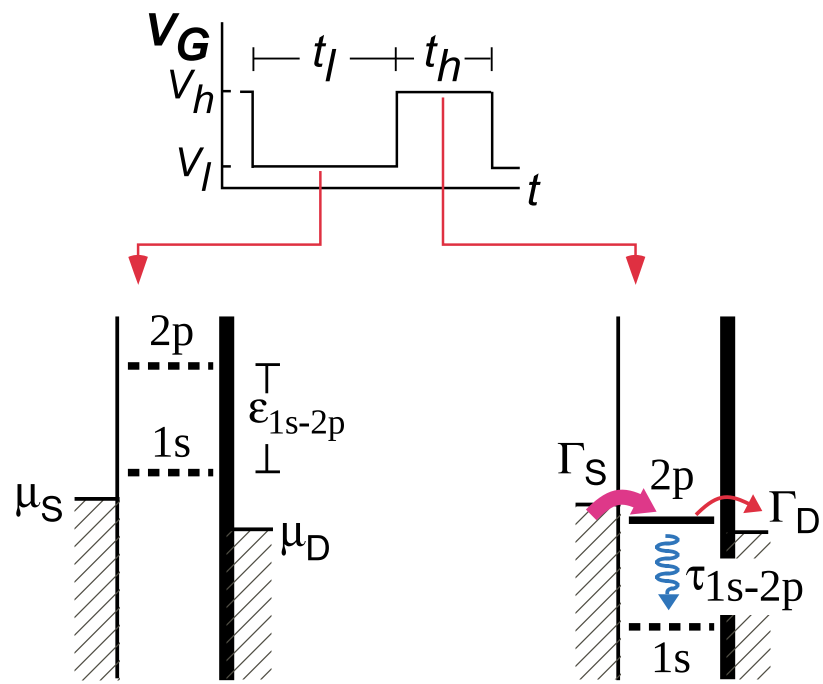
Energy spectrum of one- and two-electron QD



Electrical pump-and-probe experiment I (one-electron QD)



rise time of the pulse: ~ 0.7 ns



empty QD (N = 0)

pump into 2p state (~ 2 ns), and **probe** by drain current (max. ~100 ns)

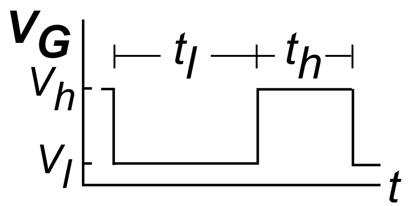
average number of tunneling electrons during one pulse

$$\boxed{\langle n_t \rangle \sim \Gamma_D \tau_{1s\text{-}2p}[1 - \exp(-t_h/\tau_{1s\text{-}2p})]}$$

$$\underbrace{\Gamma_S^{-1}}_{\sim 2\text{ ns}} < \tau_{1s\text{-}2p} < \underbrace{\Gamma_D^{-1}}_{\sim 100\text{ ns}}$$

T. Fujisawa et al., Phys. Rev. B 63, 081304(R) (2001).

Pump-and-probe current I



$V_G = V_{g,static} + V_p(t)$

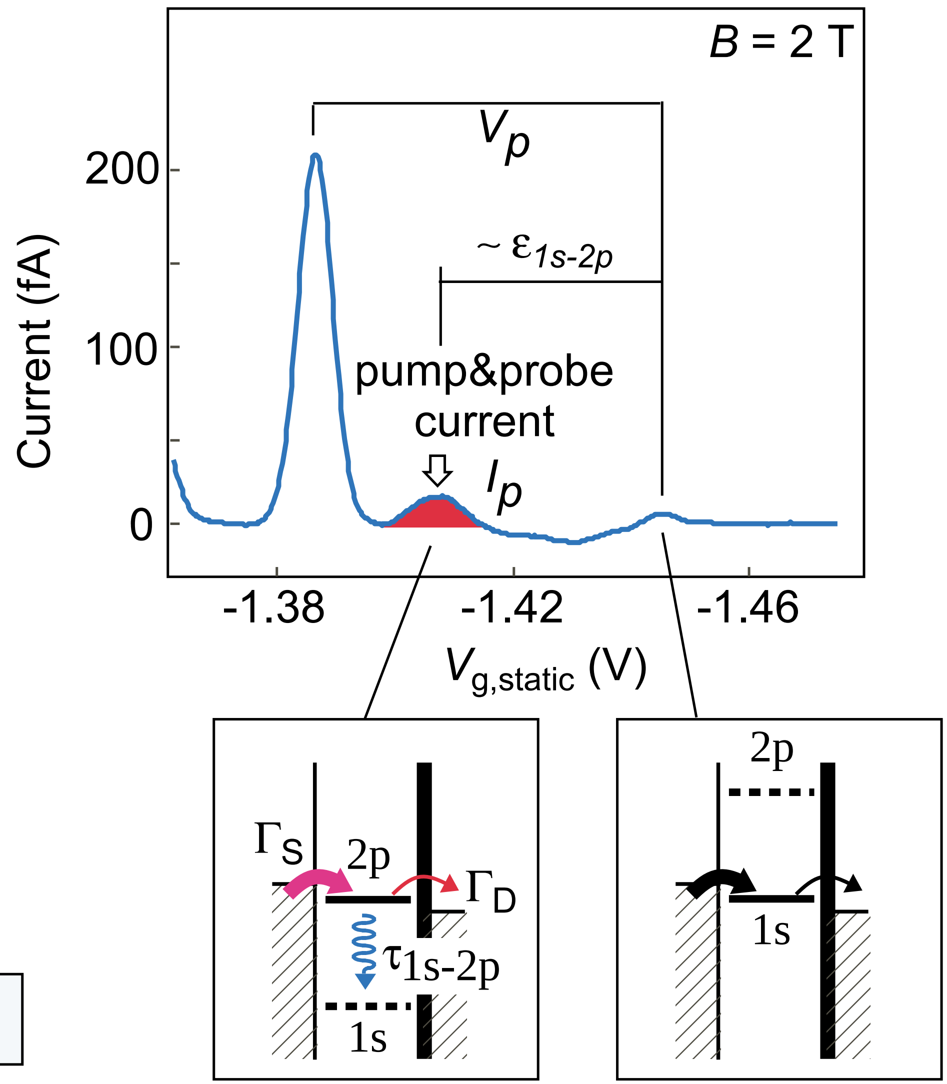
$V_{SD} = 0.2$ mV

$V_p = V_h - V_l \sim 60$ mV

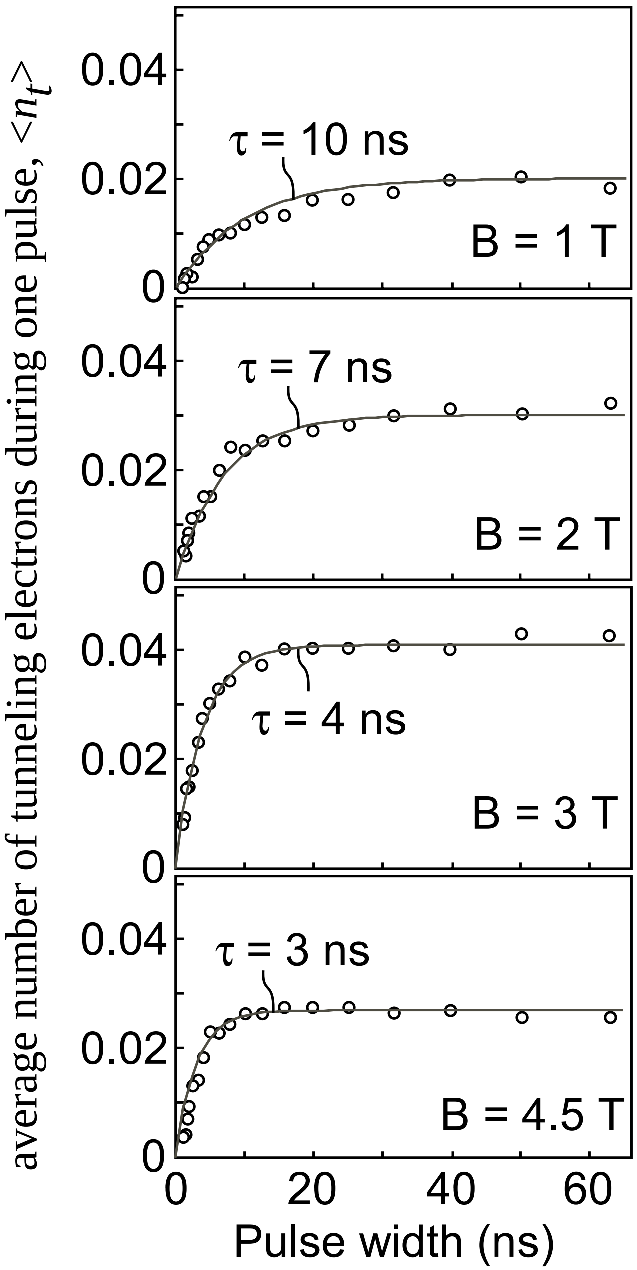
$t_h = 3$ ns

$t_h + t_l = 200$ ns

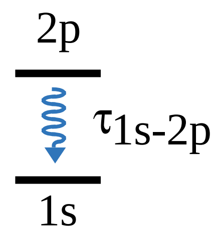
$\langle n_t \rangle = I_p / e f_{rep} = I_p (t_l + t_h)/e$

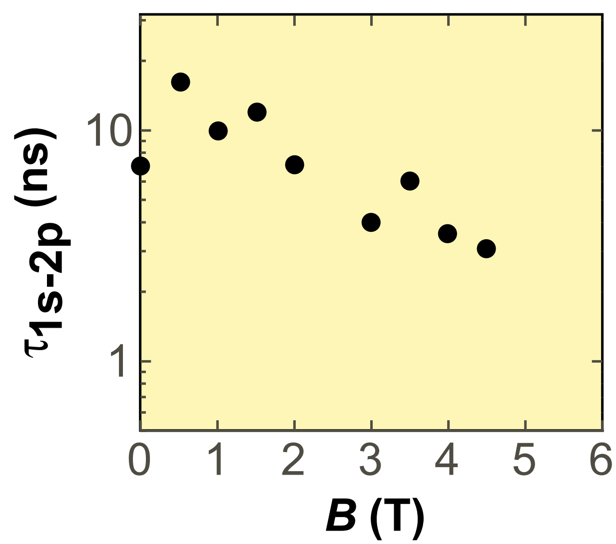


B-dependence of the relaxation time

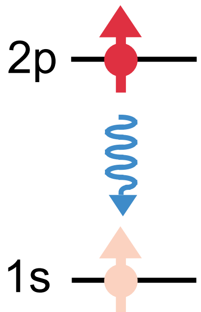


$$\langle n_t \rangle \sim \Gamma_D \tau_{1s\text{-}2p}[1 - \exp(-t_h/\tau_{1s\text{-}2p})]$$





Spontaneous emission of a phonon



At effectively zero-temperature (kT << $\varepsilon_{1s\text{-}2p}$),
spontaneous emission of a phonon dominates the relaxation process.

T. Fujisawa et al., Science 282, 932 (1998).

$$W_{phonon} = \frac{2\pi}{h} |\langle \psi_{1s} | H' | \psi_{2p} \rangle|^2 \rho \, \delta(E_{1s} - E_{2p} + \varepsilon_{phonon})$$

$$H' \propto \varepsilon^{1/2} E_{def} \, e^{i\mathbf{kr}} \text{ (deformation)}$$

$$H' \propto \varepsilon^{1/2} C_{piezo} / k \, e^{i\mathbf{kr}} \text{ (piezoelectric)}$$

GaAs : polar semiconductor

$\varepsilon_{phonon} = \varepsilon_{1s\text{-}2p}$: acoustic phonon energy

$\varepsilon_{phonon} \sim 2$ meV

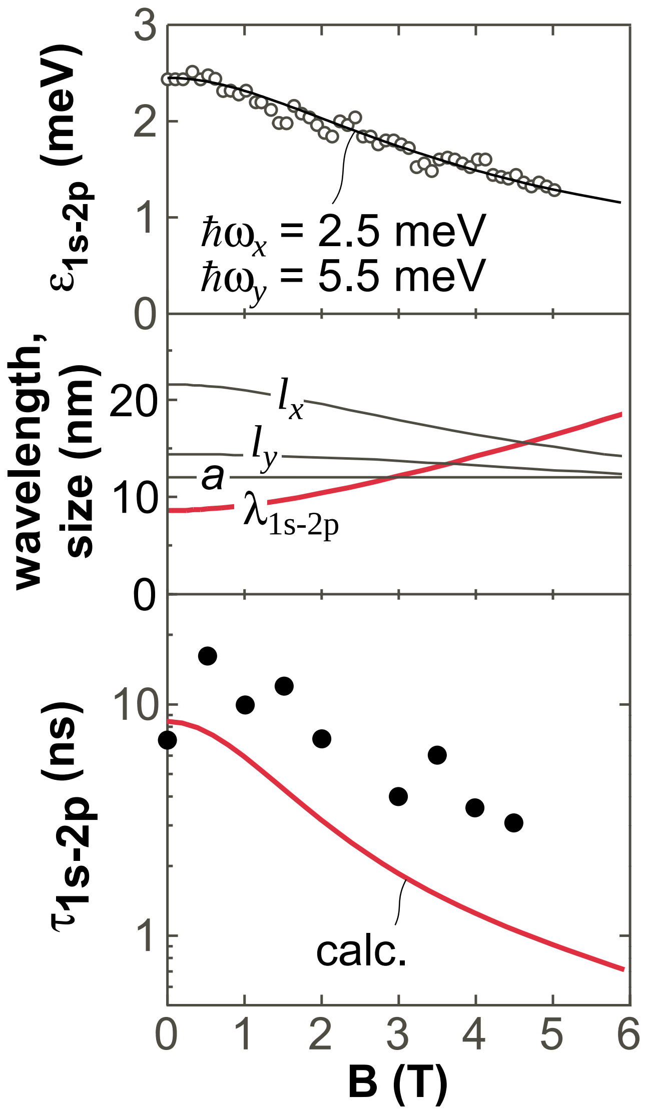
$\lambda_{phonon} = hv/\varepsilon_{1s\text{-}2p}$: phonon wavelength

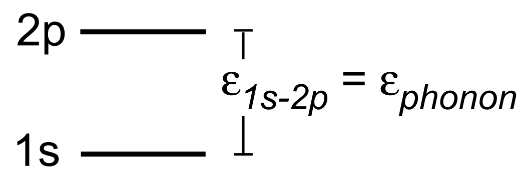
sound velocity: $v = 5100$ m/s
(GaAs LA phonon)

wavelength of the phonon $\lambda \sim 10$ nm	$\lesssim$	size of the quantum dot a = 12 nm, $\ell_{x/y} \sim 20$ nm

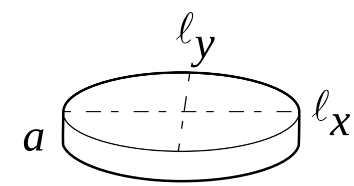
The phonon bottleneck effect is expected.

B- or λ-dependence of phonon emission rate





approx. elliptic dot



wavelength of the phonon

$\lambda_{1s\text{-}2p} = hv/\varepsilon_{1s\text{-}2p}$ (v = 5100 m/s)

size of the dot

z: a = 12 nm

x,y: $l_{x/y} = \sqrt{\hbar/m^*}(\omega_{x/y}^2 + \omega_c^2/4)^{-1/4}$

- ● experiment
- — calculation (Fermi's golden rule)

  approximated to a circular dot

  $$\hbar\omega_{eff} = \hbar\sqrt{\omega_x\omega_y(1+\omega_c^2/(\omega_x+\omega_y)^2)}$$

  standard GaAs material parameters

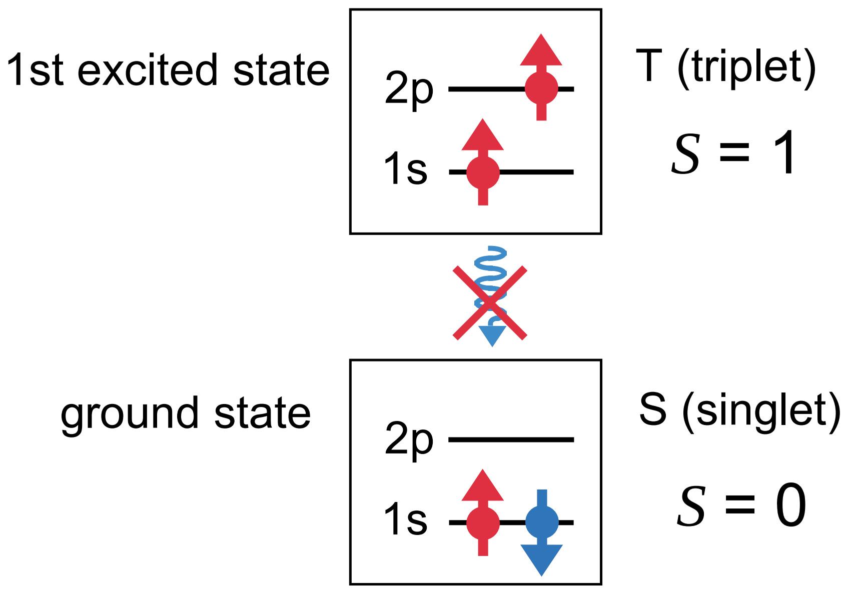
  Deformation potential: 6.8 eV

  Piezoelectric constant: 0.16 C/m^2

U. Bockelmann, Phys. Rev. B 50, 17271 (1994).

a shorter wavelength gives longer lifetime
(bottleneck effect)

Two-electron QD (artificial helium atom)



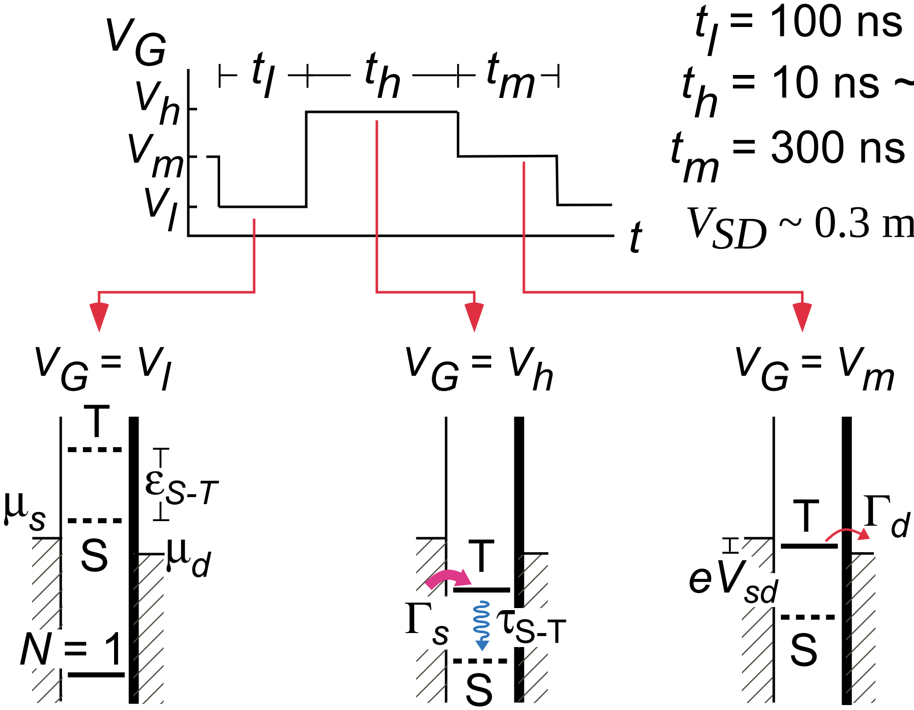
The relaxation should change both orbital and spin parts of the wavefunction.

Forbidden in the Russel-Saunders approx. (if the total spin is a good quantum number)

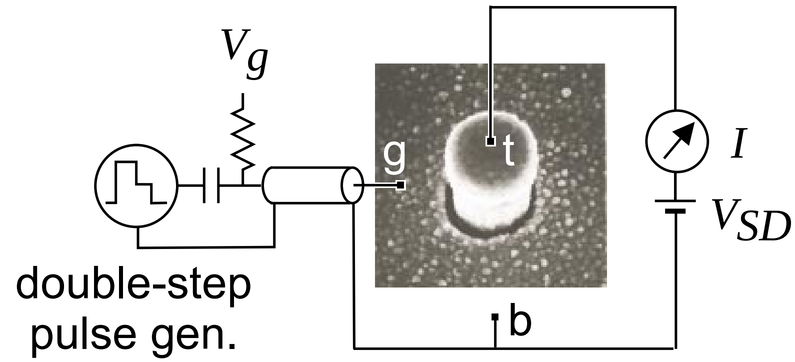
The previous pulse technique used for one-electron QD was unsuccessful.

Γ_D^{-1} (~100 ns) < $\tau_{S\text{-}T}$

Electrical pump-and-probe experiment



t_l = 100 ns
t_h = 10 ns ~ 100 μs
t_m = 300 ns
V_{SD} ~ 0.3 mV

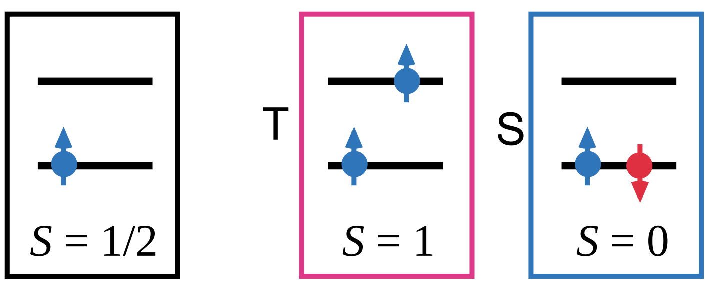


rise time at sample: ~ 0.7 ns
$(< \Gamma_d^{-1}, \Gamma_s^{-1}, \tau_{S-T})$

empty states (become $N = 1$)

pump into T state, wait for relaxation

probe unrelaxed electron



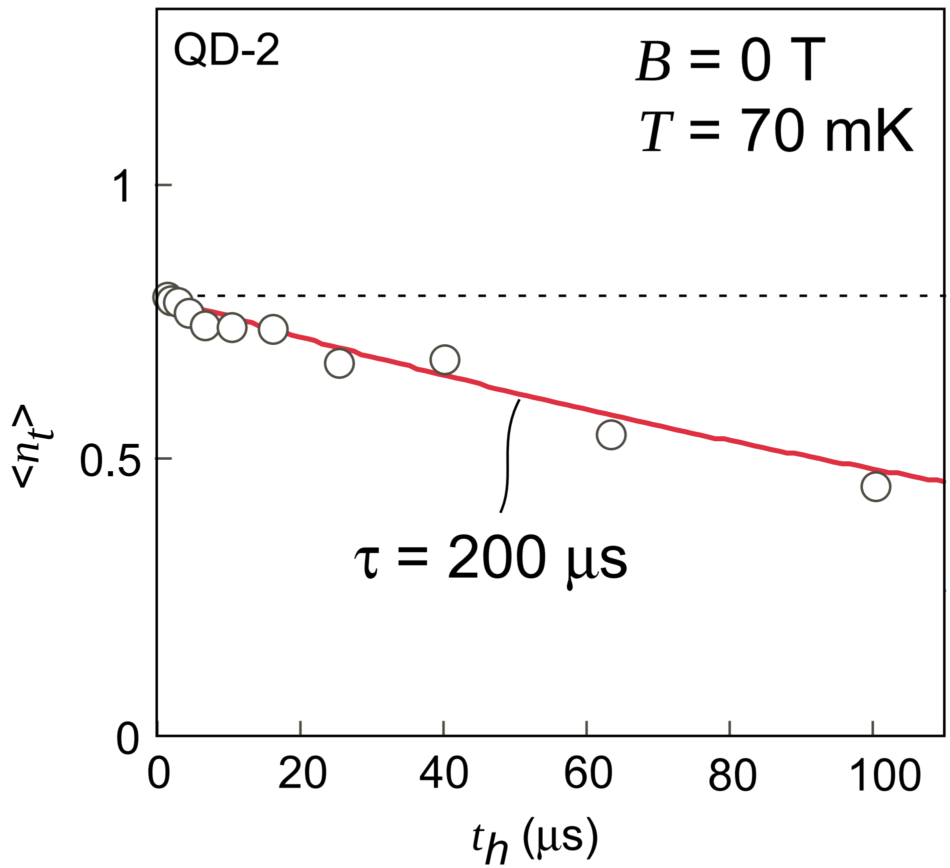
average number of tunneling electrons during one pulse

$$\langle n_t \rangle = A\exp(-t_h/\tau_{S-T})$$

A~1: related to the injection efficiency

τ_{S-T}: spin-flip energy relaxation time

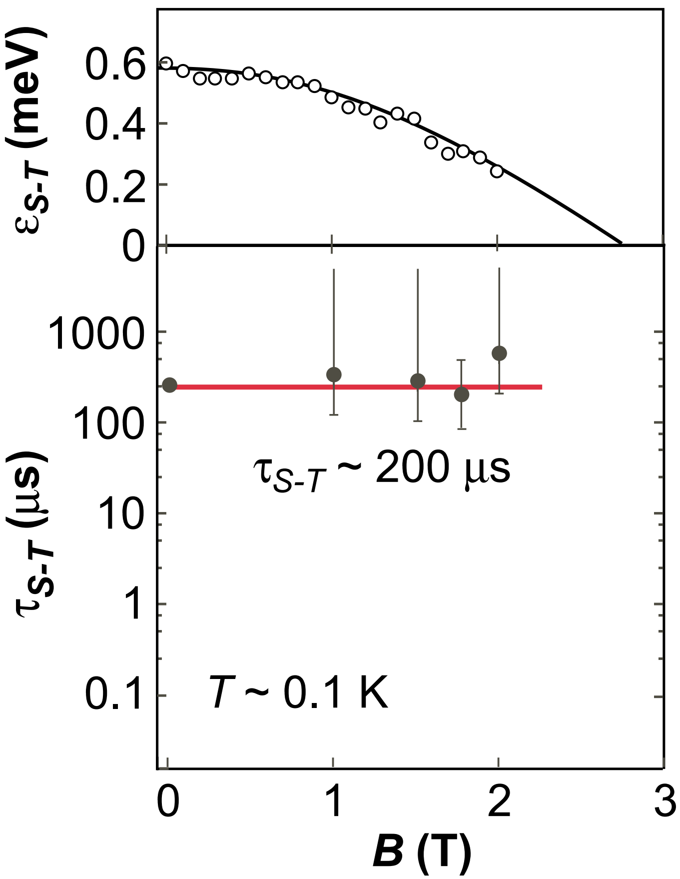
Relaxation time from the triplet to the singlet



$$\langle n_t \rangle = A\exp(-t_h/\tau)$$

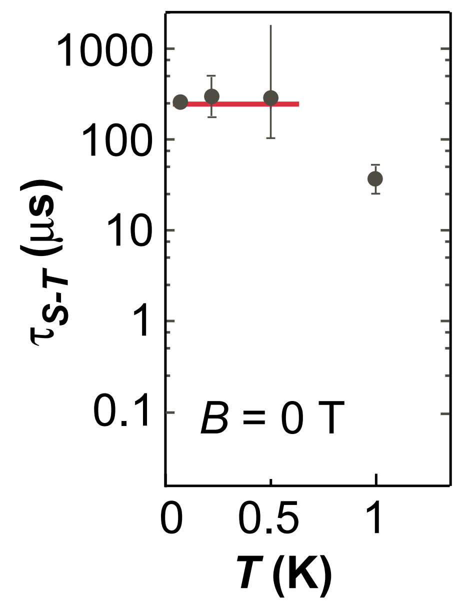
τ: energy relaxation time

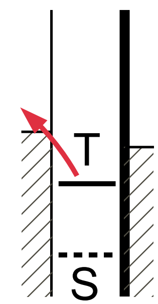
B- and T- dependence of $\tau_{S\text{-}T}$



no measurable B-dependence

thermal excitation from the QD
to the electrode (T > 1 K)

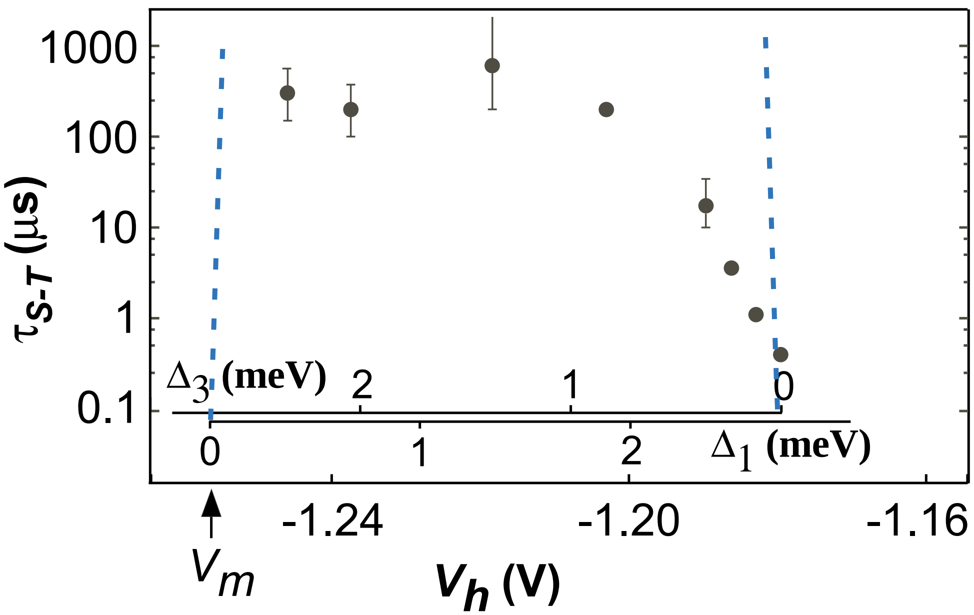




no T-dependence for T < 0.5 K

V_h- dependence of $\tau_{S\text{-}T}$

$\varepsilon_{S\text{-}T}$ = 0.6 meV
B = 0 T



V_h-dependence indicates the interaction with the electrodes.

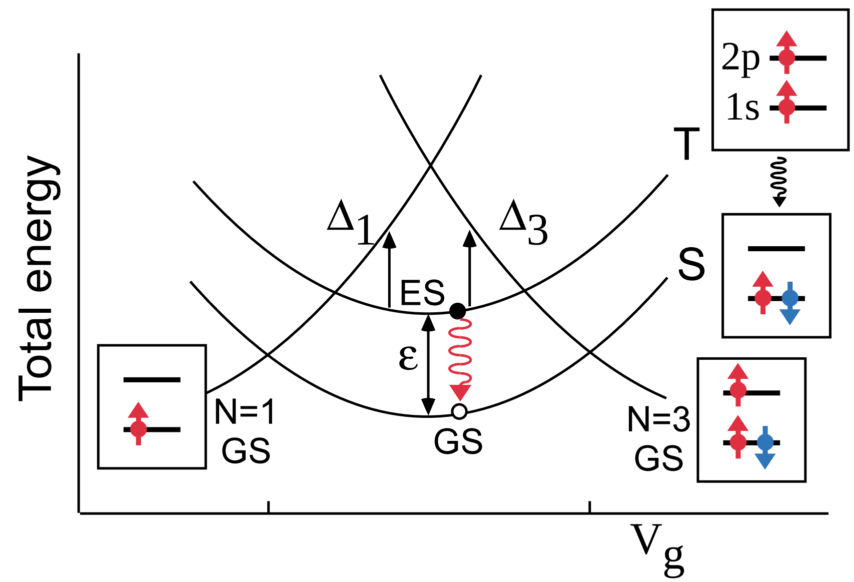
- - - - thermal excitation

Γ_{tot}^{-1} = 3.5 ns T = 70 mK

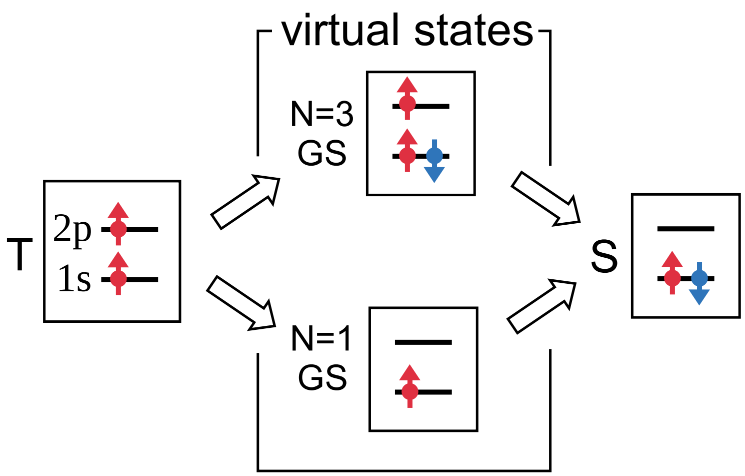
Total energy:

$$U = \frac{(eN - C_g V_g + q_0)^2}{2C_\Sigma} + E_{chem}(N, S)$$

(electrostatic energy + chemical energy)



Inelastic cotunneling process



assuming zero-bias voltage (V_{SD} = 0) and zero-temperature

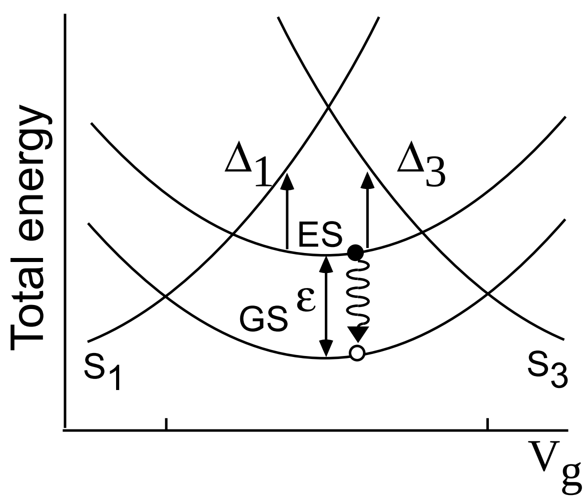
$$\tau_{cot}^{-1} = \frac{1}{h}\left(\frac{1}{\Delta_1} + \frac{1}{\Delta_3}\right)^2 (\hbar\Gamma_{tot})^2\, \varepsilon_{S\text{-}T}$$

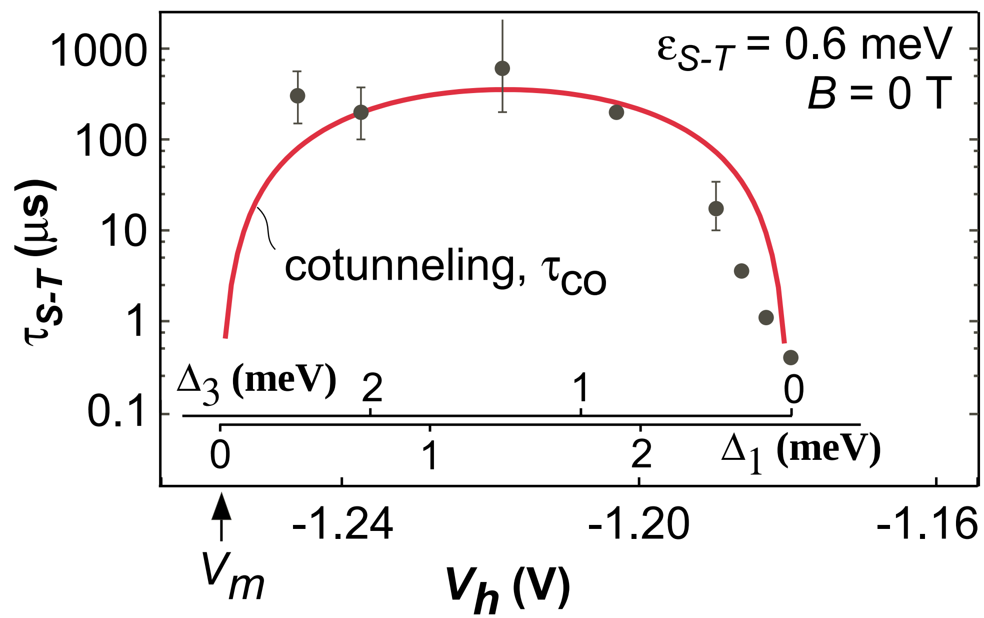
$\varepsilon_{S\text{-}T}$ = 0.6 meV

$\Gamma_{tot} = \Gamma_s + \Gamma_d = (7\ \mathrm{ns})^{-1}$ (N=2 - N=3)

(obtained from an independent meas.)

M. Eto, Jpn. J. Appl. Phys. 40, 1929(2001).
E.V. Sukhorukov, G. Burkard, D. Loss, Phys. Rev. B 63, 125315 (2001).





Spin-orbit effect on the spin relaxation

Spin-orbit interaction: (dominant spin relaxation mechanism in 2D system)

lack of crystal inversion symmetry, local electric field,
impurities, interfaces, etc.

Spin relaxation in quantum dots

reduction of spin relaxation time (large energy spacing)

$$\boxed{\tau_{so,theory} = \tau_{e\text{-}ph} \frac{E_Z^{\,2}}{\delta\varepsilon_{S\text{-}T}} \sim 600\ \mu\text{s}}$$

(lack of crystal inversion symmetry)

$\Gamma_{e\text{-}ph}$: phonon emission rate, ~ (3 ns)$^{-1}$
δ: spin splitting energy, ~ 4 μeV
ε: energy spacing, ~ 1 meV
E_Z: vertical confinement energy, ~ 30 meV

A. V. Khaetskii and Yu. V. Nazarov, Phys. Rev. B 61, 12639 (2000).

Our electrical measurements:

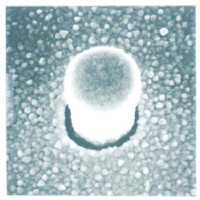
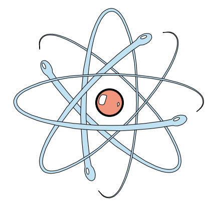
$\tau_{S\text{-}T}$ ~ 200 μs (cotunneling process)

The spin-orbit interaction should have weaker effect.

$$\boxed{\tau_{SO} > \tau_{CO} \sim 200\ \mu\text{s}}$$

Comparison between artificial and real atoms

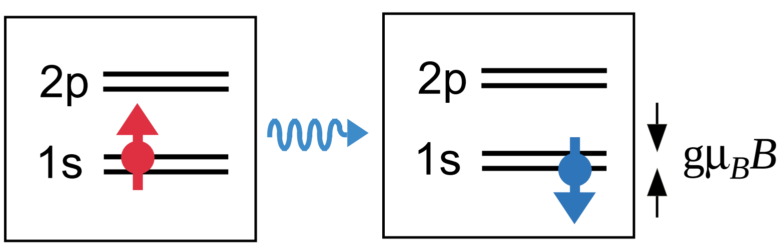
- transition from the 1st excited state to the ground state -

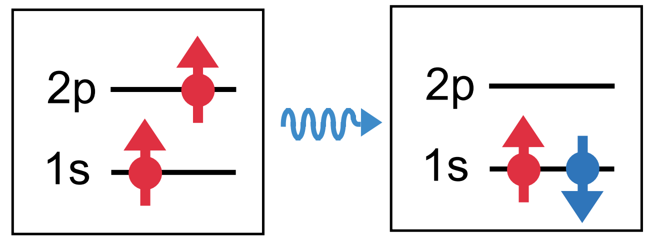
	 artificial atoms (quantum dots)	 real atoms	
one-electron system	2p - 1s allowed for ***phonon*** emission τ = 3 - 10 ns ($h\nu$ ~ 2 meV)	**H** 2p - 1s (Lyman α) allowed for ***photon*** emission τ = 1.6 ns ($h\nu$ = 10.2 eV)	**K** 4p - 4s allowed for ***photon*** emission τ = 2.6 ns ($h\nu$ = 1.61 eV)
two-electron system	(1s)(2p) ^3P - (1s)^2 ^1S forbidden by ***spin*** conservation τ ~ 200 μs ($h\nu$ ~ 0.5 meV)	**He** (1s)(2s) ^3S - (1s)^2 ^1S forbidden by ***spin*** & ***parity*** τ = 7860 s ($h\nu$ = 19.8 eV)	**Ca** (4s)(4p) ^3P - (4s)^2 ^1S forbidden by ***spin*** τ = 385 μs ($h\nu$ = 1.89 eV)
$\dfrac{\tau_{forbidden}}{\tau_{allowed}}$	$\boxed{> 3\text{x}10^4}$	$\boxed{4.5\text{x}10^{12}}$	$\boxed{1.5\text{x}10^5}$

Spin states in artificial atom are almost ideal, comparable to real atoms.

Spin relaxation time between Zeeman sub-levels

Estimate the spin relaxation time by only considering spin-orbit interactions and phonon emission.





$$\tau_{spin,so} = \left(\frac{\varepsilon_{1s\text{-}2p}}{\Delta_{so}}\right)^2 \tau_{phonon}(g\mu_B B)$$

using $\Delta_{so} < 4\ \mu\text{eV}$,

$\tau_{spin,so} > 1$ ms at B = 5 T

($\varepsilon_{1s\text{-}2p} \sim 1.2$ meV, $g\mu_B B \sim 0.1$ meV)

$\tau_{spin,so} > 100\ \mu$s at B = 9 T

($\varepsilon_{1s\text{-}2p} \sim 0.8$ meV, $g\mu_B B \sim 0.18$ meV)

$$\tau_{S\text{-}T,so} = \left(\frac{\varepsilon_{S\text{-}T}}{\Delta_{so}}\right)^2 \tau_{phonon}(\varepsilon_{S\text{-}T})$$

$\tau_{S\text{-}T,so} > 200\ \mu$s

$\tau_{phonon} \sim 3$ ns

$\Delta_{so} < 4\ \mu$eV : spin-orbit coupling energy between 1s and 2p orbitals

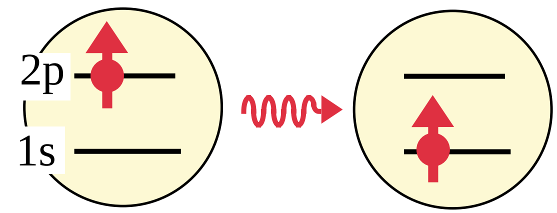
W.P. Halperin, Rev. Mod. Phys. 58, 533 (1986).

cf. $T_1 \sim 100\ \mu$s at B = 9 T (ESR study of donor state in GaAs)

M. Seck, M. Potemski, P. Wyder, Phys. Rev. B 56, 7422 (1997).

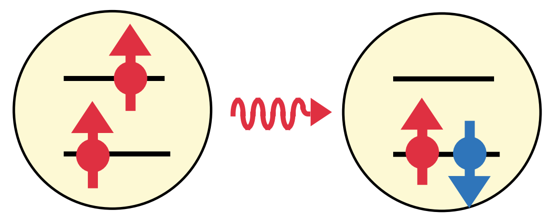
Summary

I. Momentum relaxation
phonon emission



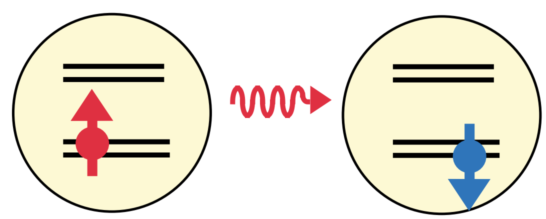
~ 10 ns (experiment)

II. Spin & momentum relaxation
cotunneling effect
spin-orbit interaction



~ 200 μs (experiment)

III. Spin relaxation between Zeeman sub-levels
(spin-orbit interaction)



> 1 ms @ B = 5 T(estimation)