Electron Spin Relaxation of Donors in Silicon Nanoelectronic Devices

FINAL EXAMINATION

Yu-Ling Hsueh
Electrical and Computer Engineering
Purdue University

Outline

Introduction to quantum computing and T_1

The spin-relaxation mechanisms : Existing theories

Part I: The tight-binding T_1 method

Part II: T_1 in device with electric fields

Part III: Two-electron T_1 problem

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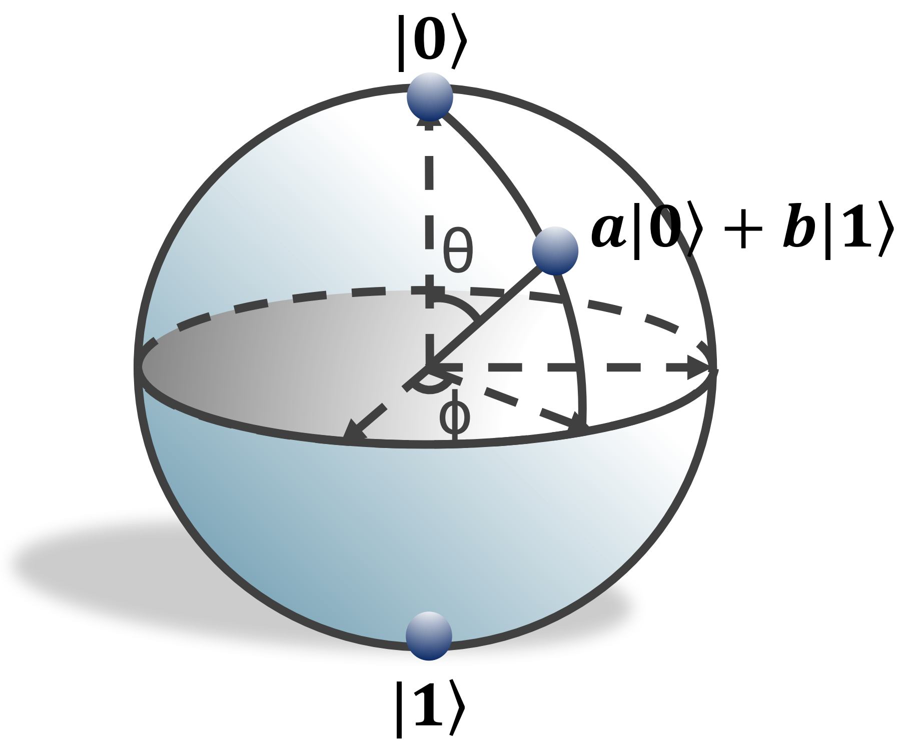
Building Blocks of A Quantum Computer: Quantum Bits (Qubits)

A Single Qubit

Qubits:

- Two basis states $|\mathbf{0}\rangle$ and $|\mathbf{1}\rangle$
- Superposition $\boldsymbol{a}|\mathbf{0}\rangle + \boldsymbol{b}|\mathbf{1}\rangle$

The Bloch Sphere

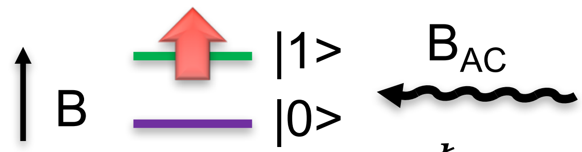


Classical bits: $|\mathbf{0}\rangle, |\mathbf{1}\rangle$

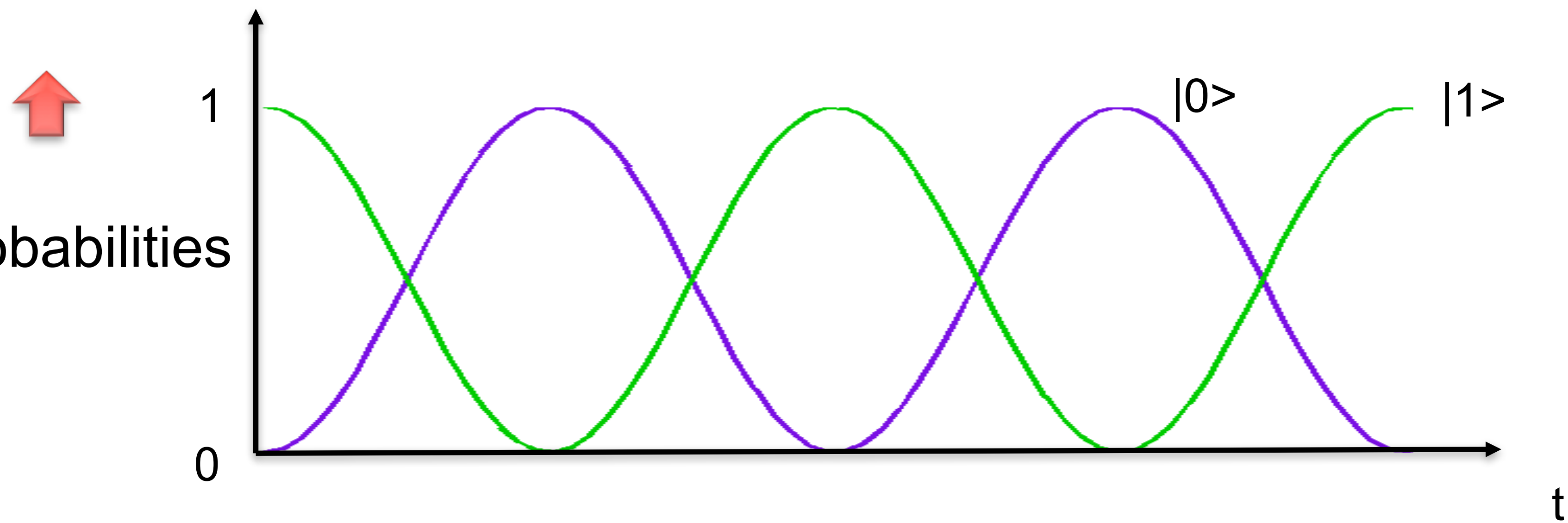
Qubits: $|\mathbf{0}\rangle, |\mathbf{1}\rangle$, $\mathbf{0.71}|\mathbf{0}\rangle + \mathbf{0.71}|\mathbf{1}\rangle$, $\mathbf{0.71}|\mathbf{0}\rangle - \mathbf{0.71}|\mathbf{1}\rangle$, …

Qubit Operation

B field→ split spin states
B_{AC}→ rotate the spin

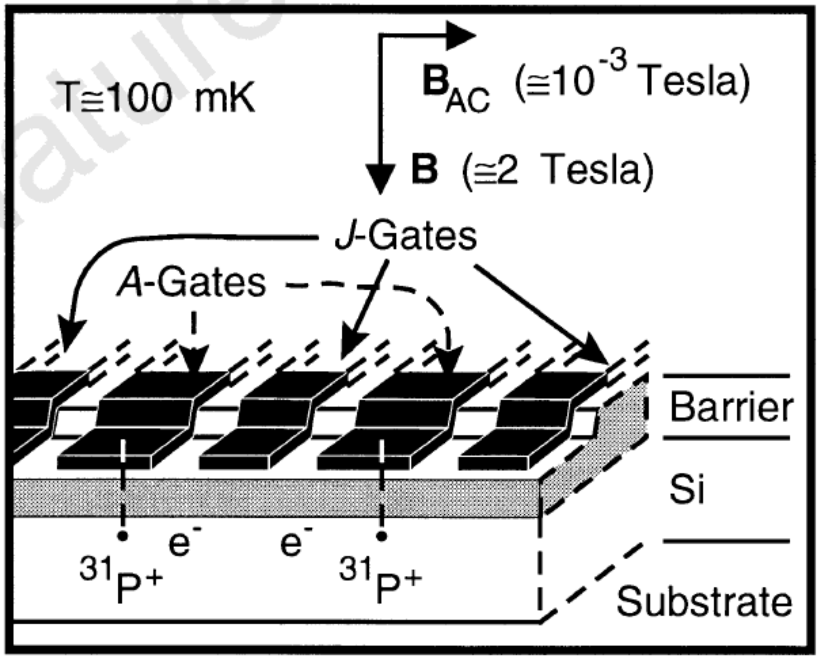


$$\hbar\omega_{ac} = g\mu_B B$$

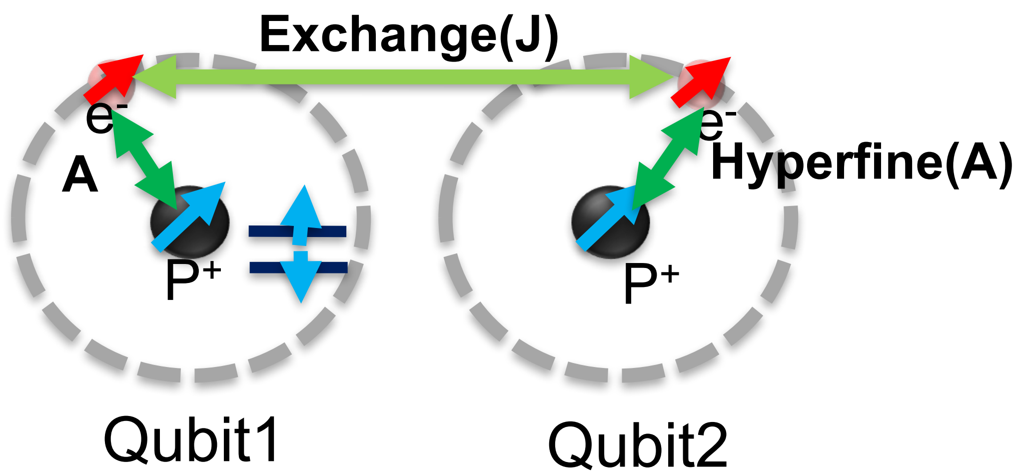


Qubit operation: time evolution of two coherent states.

Kane's Architecture



Kane, Nature 393, 133 (1998)



Kane's Architecture

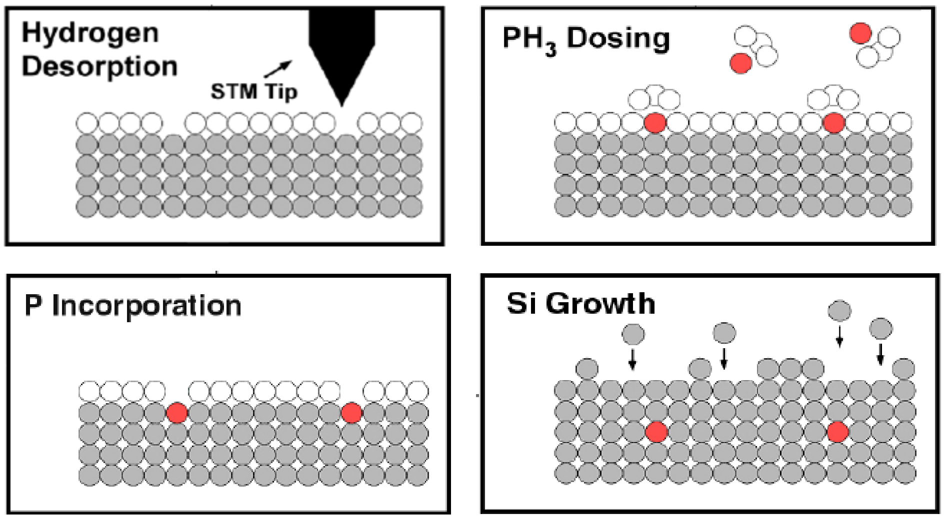
Si donor spin qubit:

- encodes information in the nuclear spin
- 1 donor confines 1 electron
- electron wf can be tuned by gates
  →changes resonance frequencies

Kane proposed using donors in Si nano-devices to build a quantum computer.

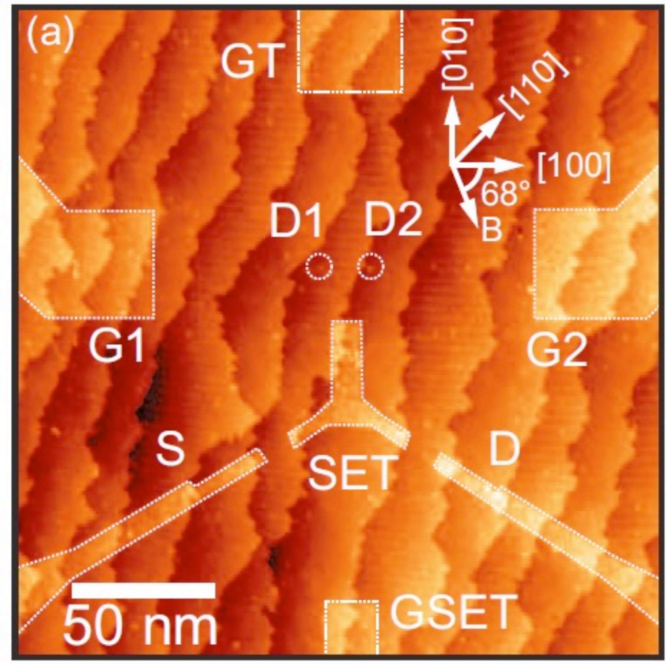
The STM Fabricated Device

Scanning Tunneling Microscope (STM)



“2013_SISC_Tutorial” by Michelle Simmons

- Put a single P atom in a specific location.
- Construct 2D delta-doped P in Si gates.

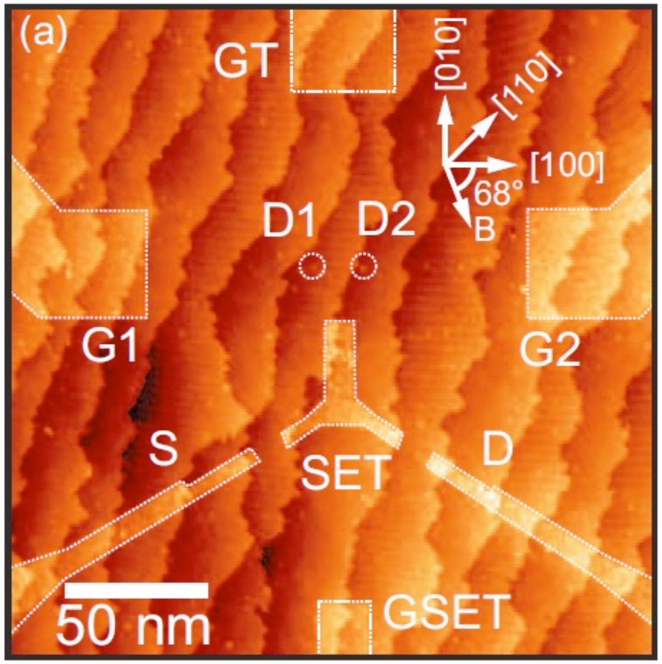


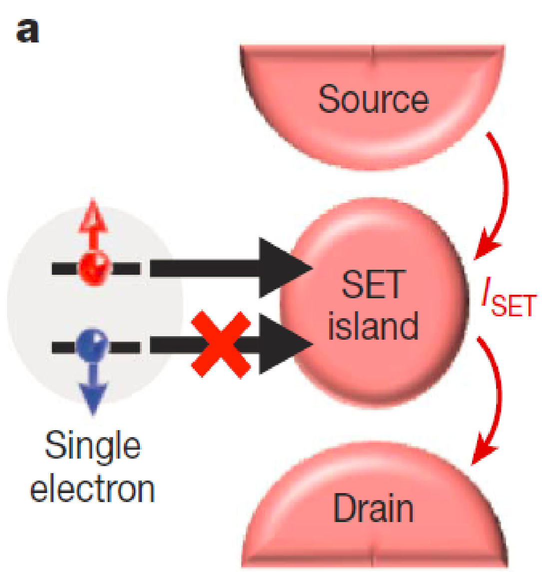
Single-atom STM fabricated device

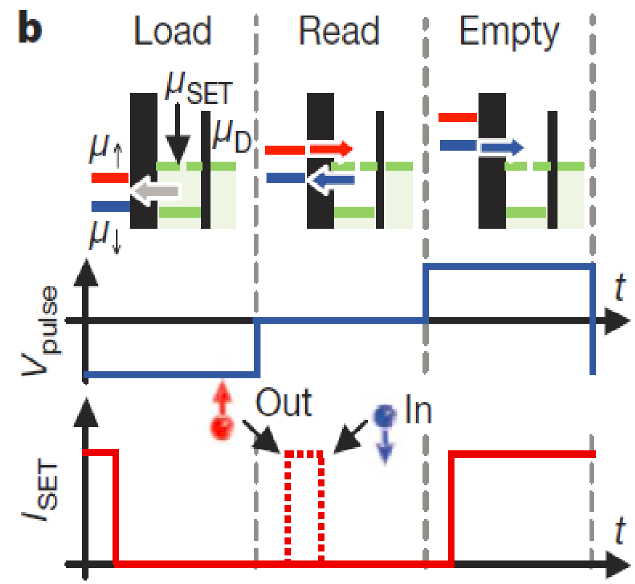
STM technique→ realize Kane’s architecture.

T. F. Watson et al., Science Advance, DOI: 10.1126/sciadv.1602811 (2017)

Load and Read a Single Electron Spin





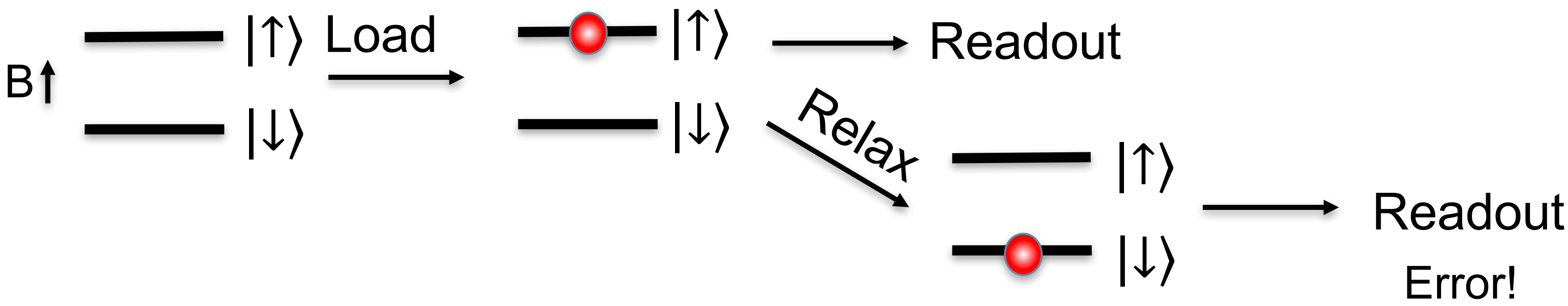


- Change gate voltages such that the donor's electron can tunnel to/from the SET and change the source to drain current.

Tunnel to a nearby SET→ load/read the electron

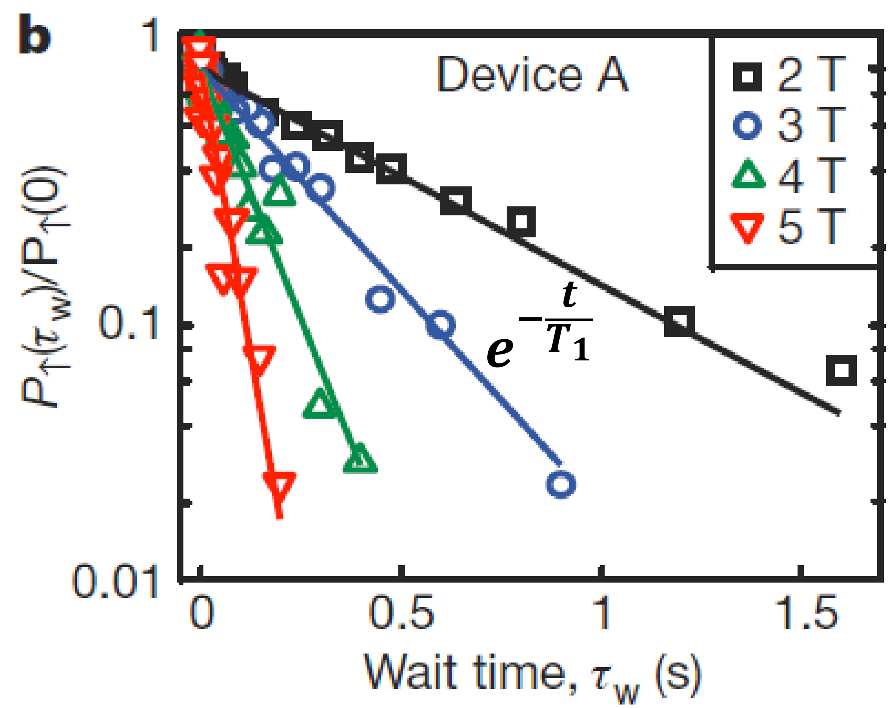
A. Morello et al. Nature 467, 687 (2010)

Spin Relaxation: The T_1 time

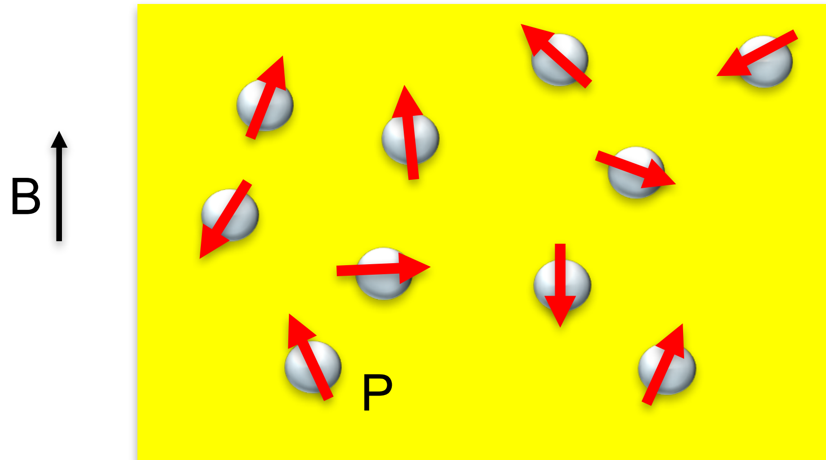


- Long T_1 → High fidelity
- Represents coupling to the environment.
- Serve as an upper bound to T_2.

Long T_1 is desirable.



T. F. Watson et al., Science Advance, DOI: 10.1126/sciadv.1602811 (2017)
A. Morello et al. Nature 467, 687 (2010)

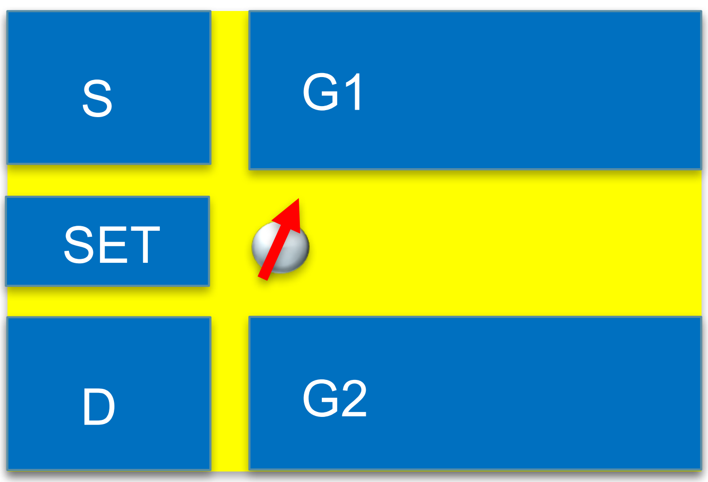


Donors in bulk Si

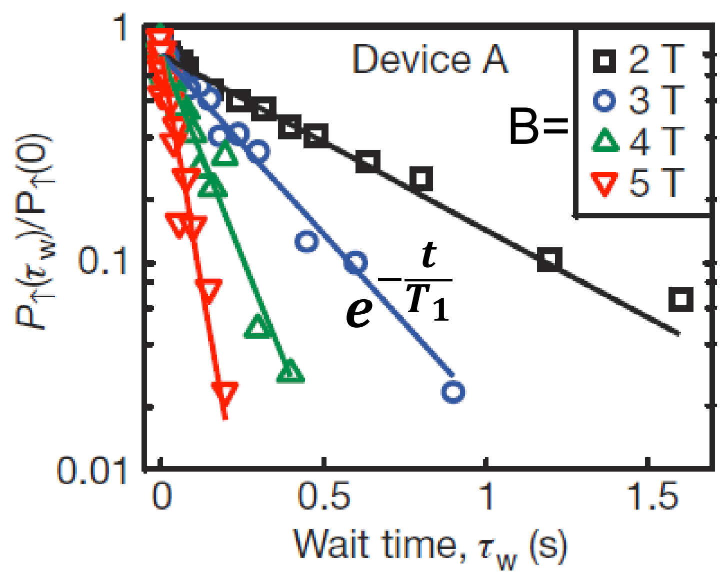
Magnetization M of the whole sample

$$M = M_0(1 - e^{-\frac{t}{T_1}})$$

Local environment doesn't matter.

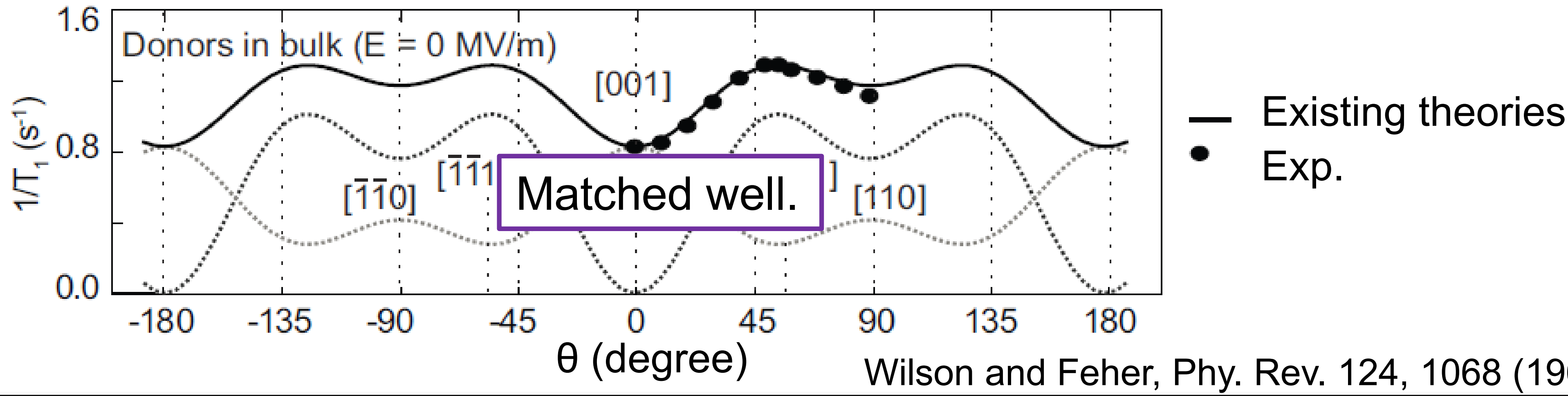


Donor in nano-devices



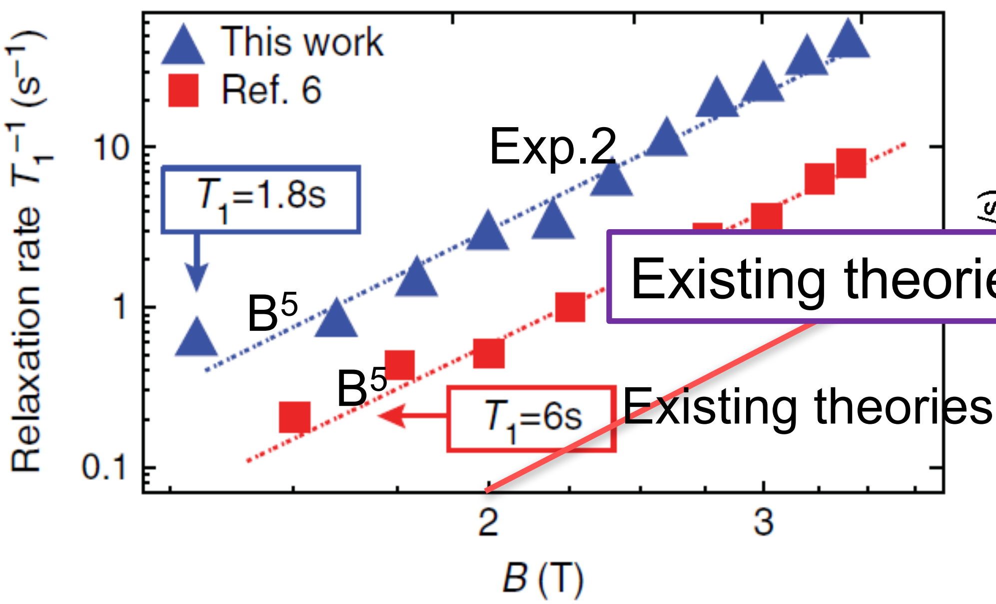
Local environment becomes very important.

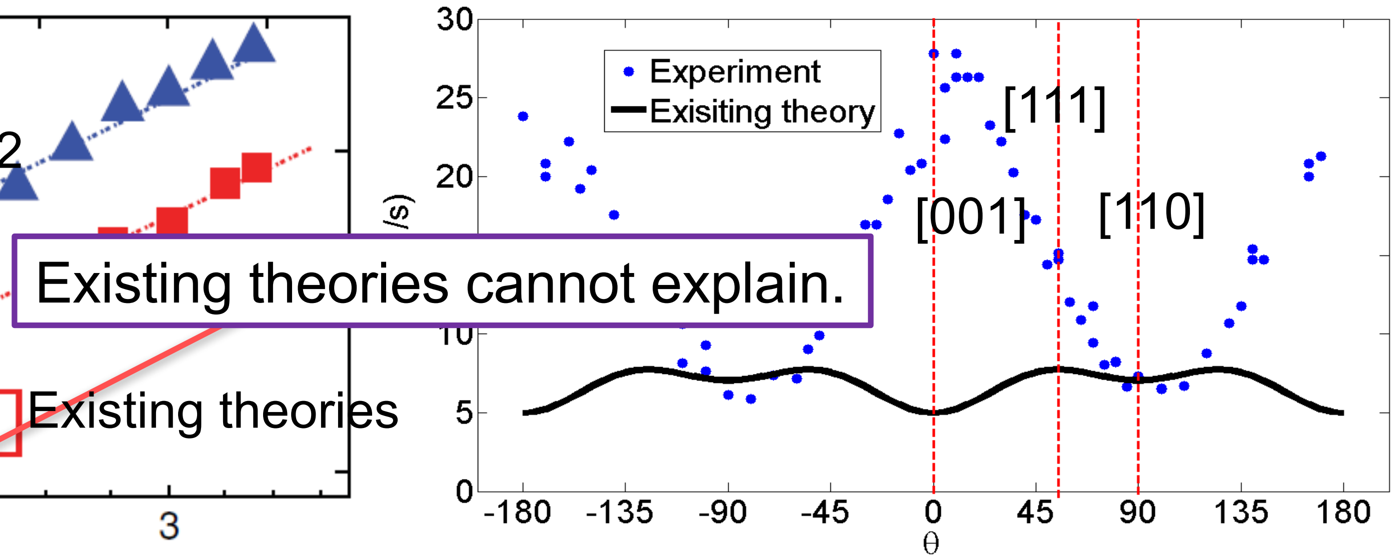
T_1 in Bulk Systems v.s. Nanoelectronic Devices



Wilson and Feher, Phy. Rev. 124, 1068 (1961)

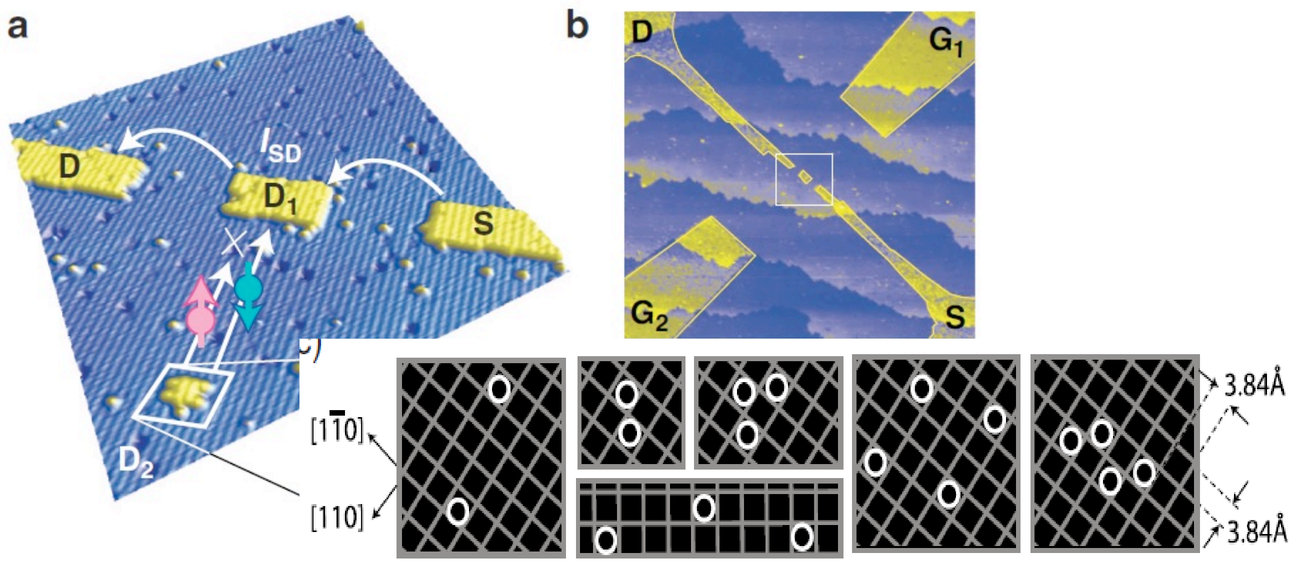
Donor in nano-devices

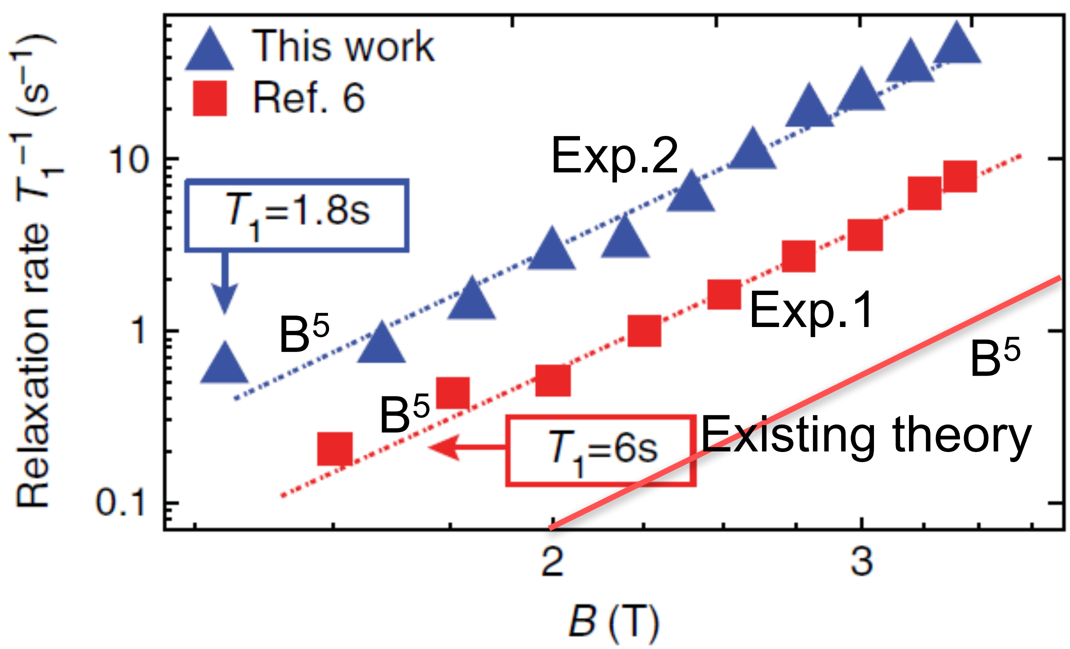




B. Weber et. al., "A Single-Atom Probe of the Silicon Qubit Environment" (submitted) H. Büch et al. Nature Communications 4, 2017 (2013)

Part I: T_1 in Donors and Donor Clusters



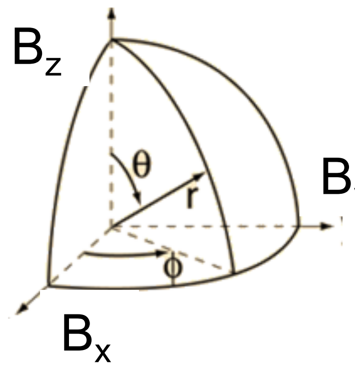


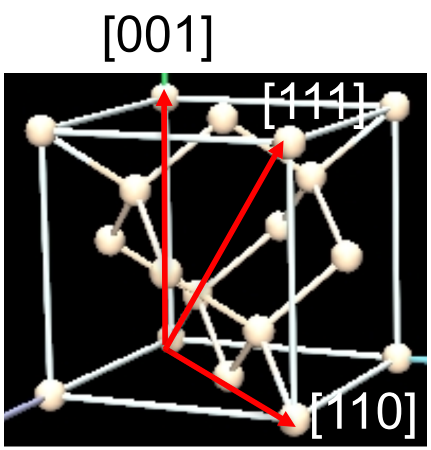
Problem: Existing theories only consider single donors.

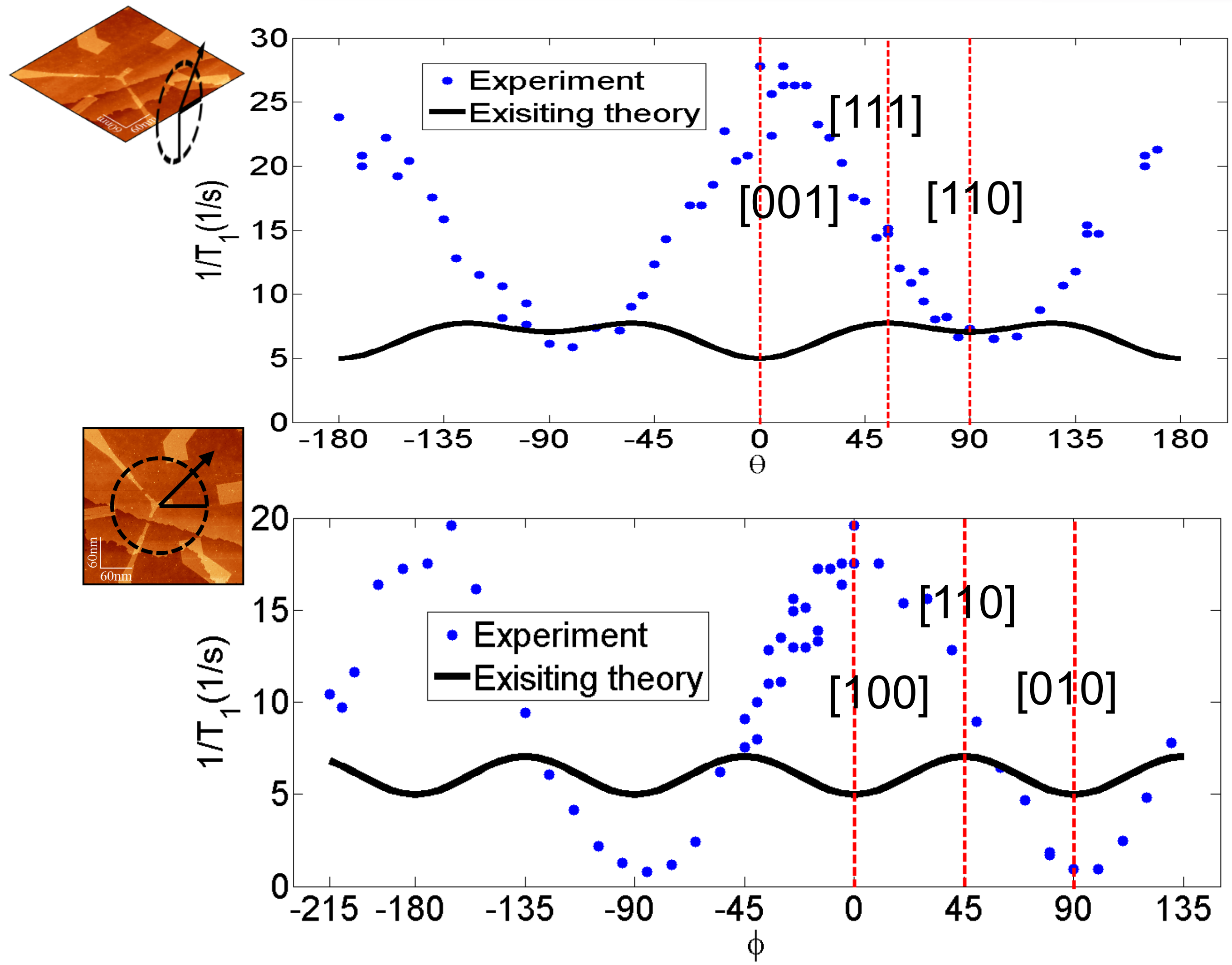
→ Need a comprehensive approach to calculate T_1 in donors and donor clusters.

H. Büch et al. Nature Communications 4, 2017 (2013)

Part II: T_1 in Device with Electric Fields





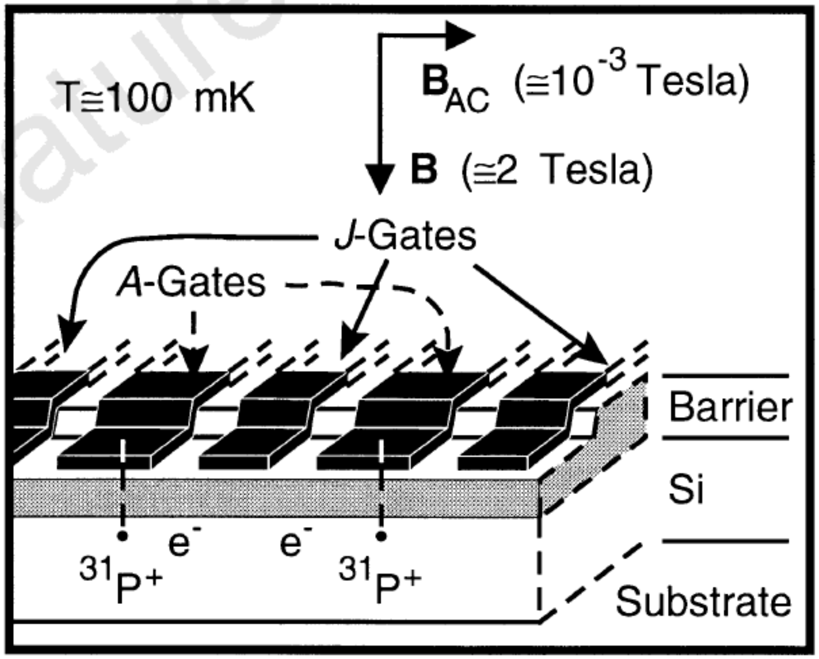


Problem: Existing theory consider bulk systems.

→Need to include the effect of E-fields.

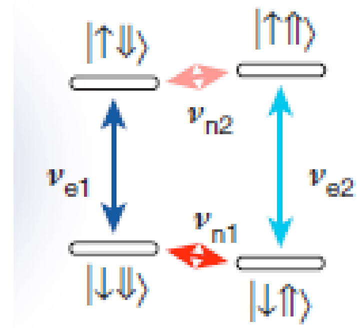
Progress of Kane's Quantum Computer

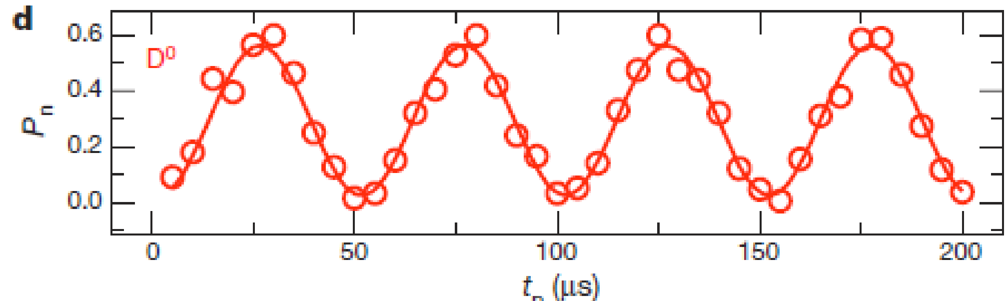
1998: Proposal



Kane, Nature 393, 133 (1998)

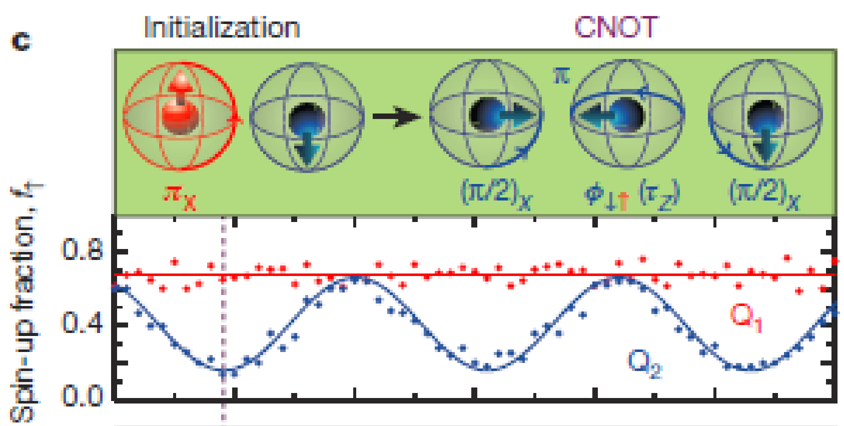
2013: Demonstration of a single qubit operation





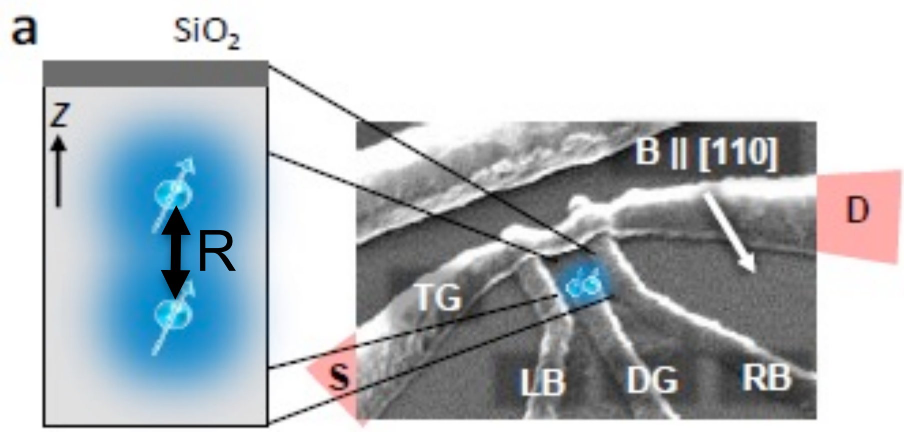
Pla, Nature 496, 334 (2013)

Next step: two-qubit logic gate

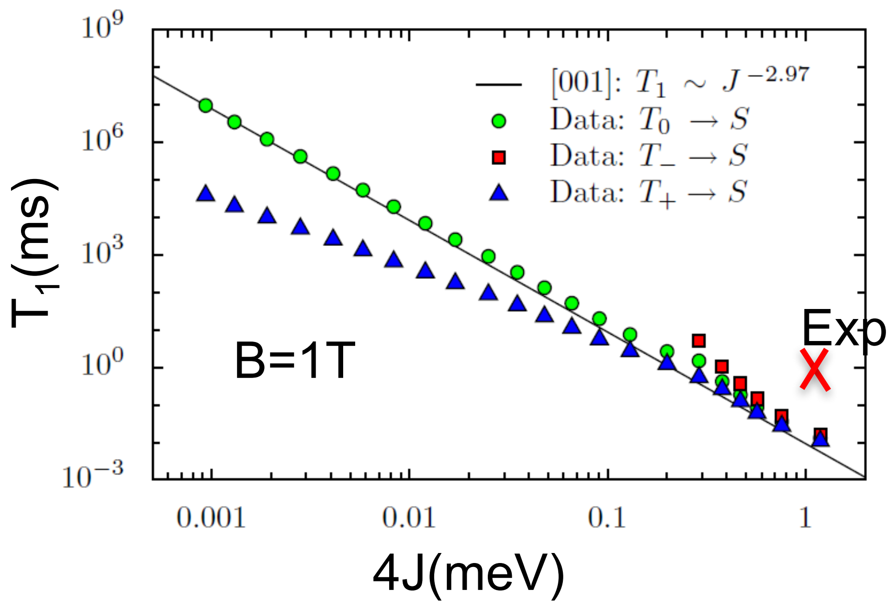


Veldhorst, Nature 526, 410 (2015)

Part III: Two-electron T_1 in Donor-pairs



Measurement:
→T_1~4ms at B=0T, R~6nm.
→Weak B dependence.



Existing work:
→T_1~0.01ms at B=0T, R~6nm.

Problem: Existing work cannot explain measurements.
→Need an accurate way to treat the two-electron T_1 problem.

J. P. Dehollain, et al., Phys. Rev. Lett. **112**, 236801 (2014).
M. Borhani and X. Hu, Phys. Rev. B **82**, 241302 (2010).

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The Spin-Relaxation Channel

How does the electron relax to its lower energy state?

Transition between two energy states needs

1. a non-vanishing matrix element which connects them.

$B\hat{z}$ $|\uparrow\rangle$ $|\downarrow\rangle$

$B^{eff} \perp B$ causes mixing

Spin-orbit (SO) $(\nabla V \times p) \cdot \sigma$ $\boxed{B^{eff}}$

2. a time-dependent interaction.

→Electron-phonon interaction (H_{ep})

$|\uparrow\rangle + \alpha|\downarrow\rangle$

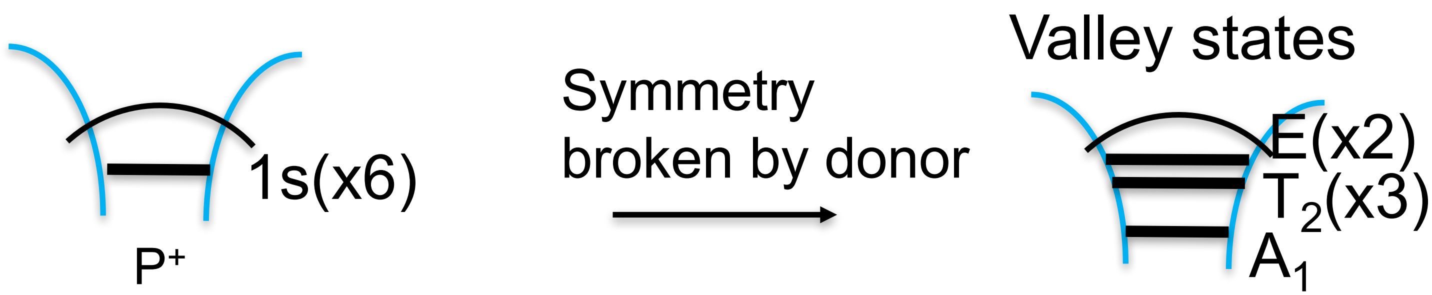
Spin-Orbit

$|\downarrow\rangle + \alpha|\uparrow\rangle$

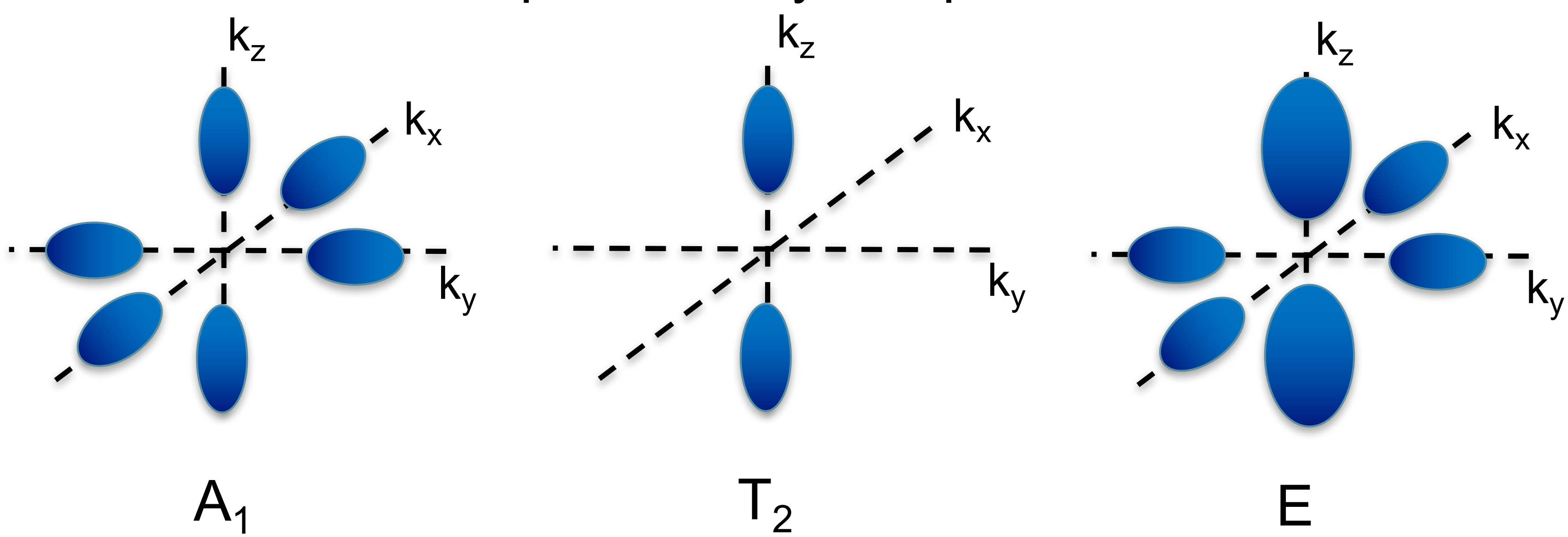
phonon

Si crystal provides spin-orbit and phonons which form a spin-relaxation channel

Electronic states of P in Si: The Valley States



Example of valley compositions



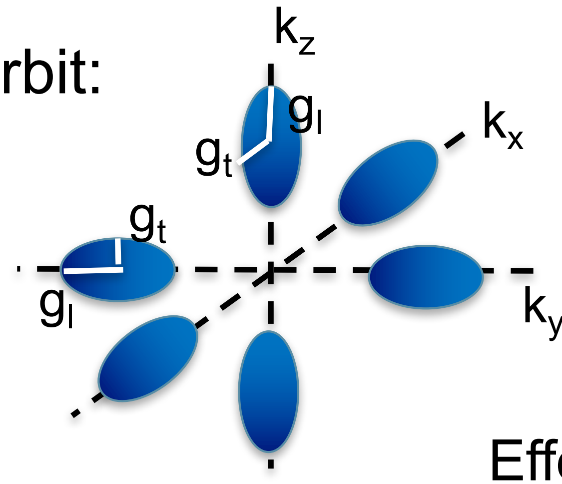
The donor states have different valley configurations.

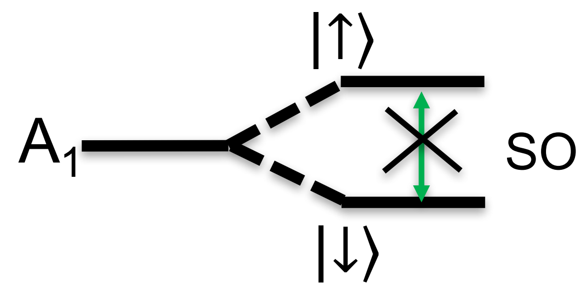
The Spin Relaxation Channel of Si:P

The effect of spin-orbit:

$$H_Z = g\mu_B B \cdot \sigma$$

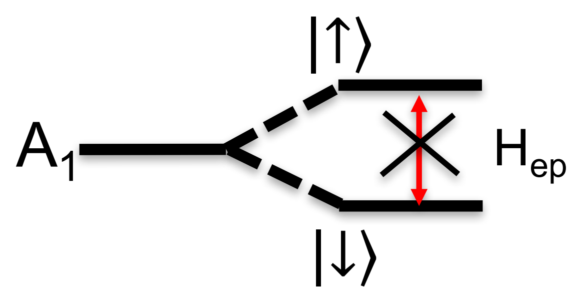
g_l g_t





Effect of SO averaged out.

Phonon cannot change electron spins directly.



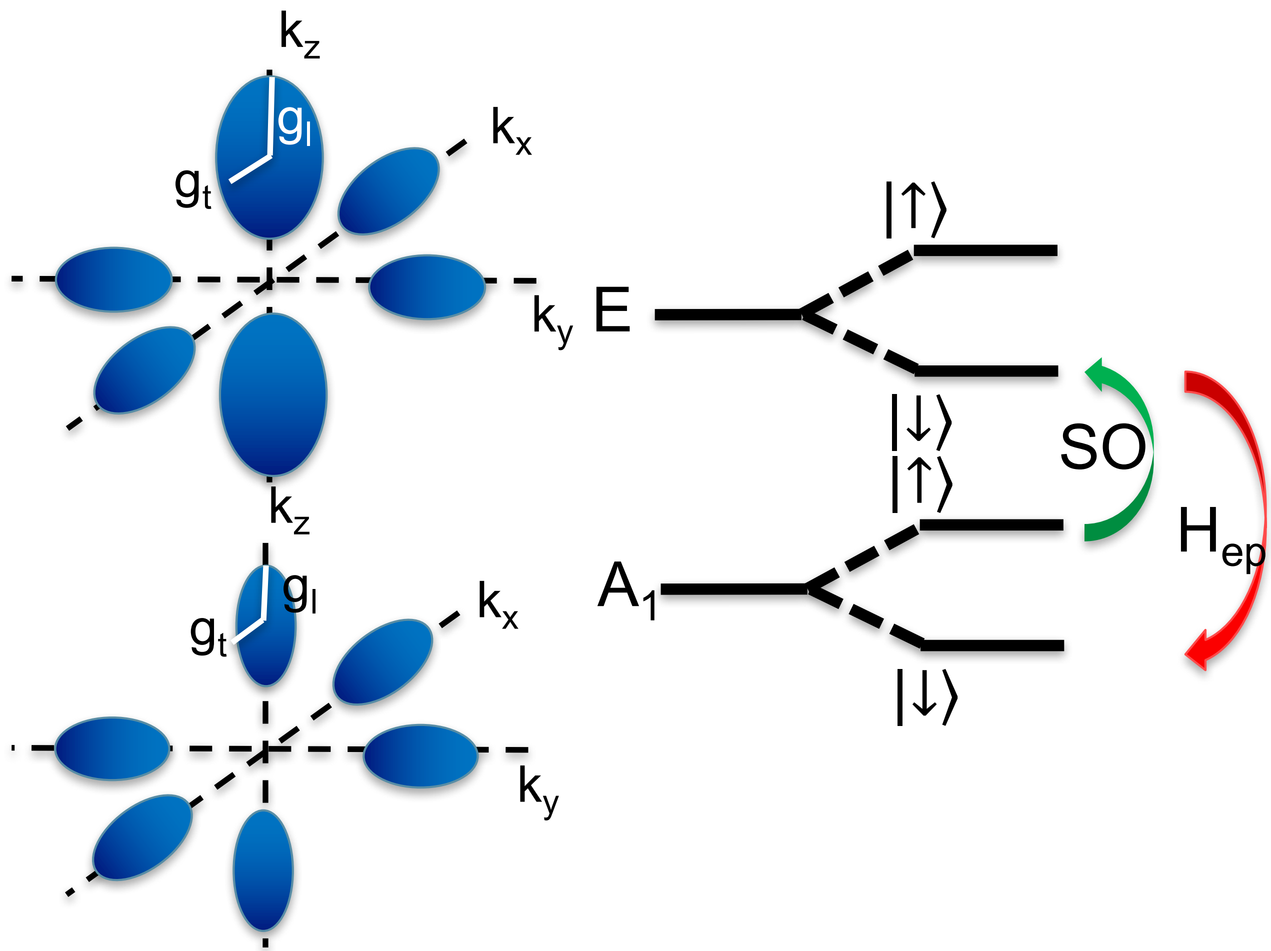
No direct way for the electron to relax.

Existing theory-1: Valley Repopulation Mechanism

The effect of spin-orbit:

$$H_Z = g\mu_B B \cdot \sigma$$

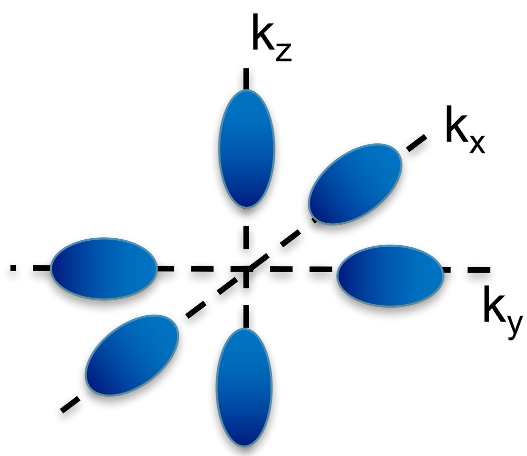
g_l g_t

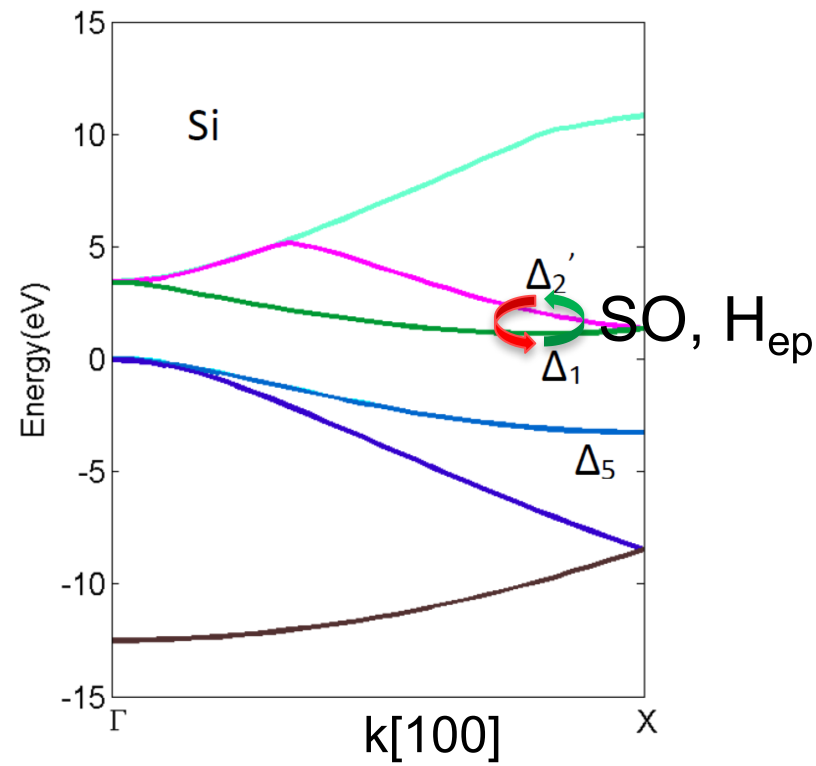


Spin-orbit couples different valley states, a spin-relaxation channel is formed.

Existing theory-2: Single Valley Effect

For a single valley…

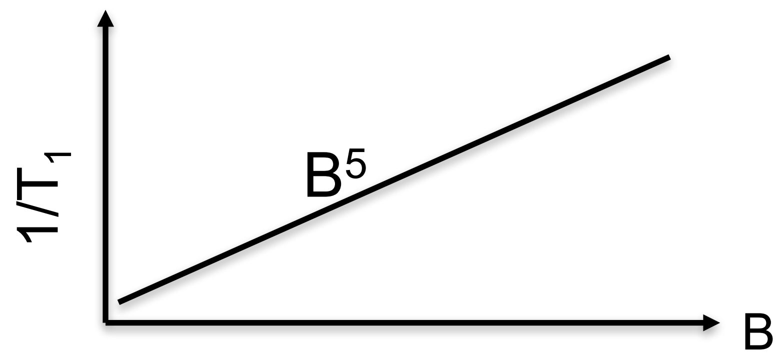




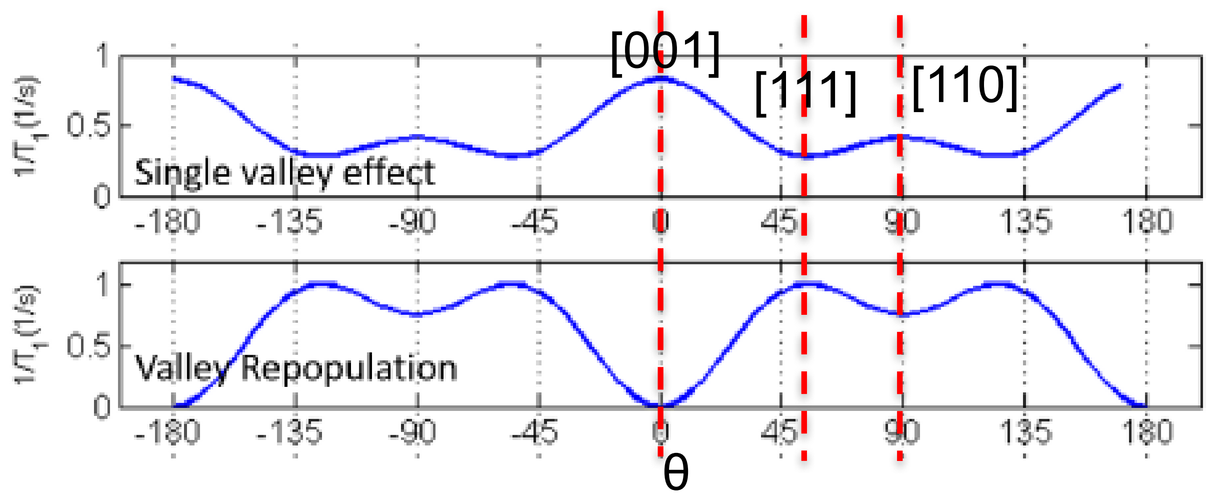
Electron relaxes through mixing with higher-lying conduction bands around each valley.

The Signature of Valley Repopulation and Single Valley Effect

- Magnitude
  $1/T_1 \sim 1s$ for B=3.5T, T=100mK,
- B dependence



- Anisotropy



Existing theories consider T_1 of single donors in bulk Si, have $1/T_1 \sim B^5$ and peaks at B//[111].

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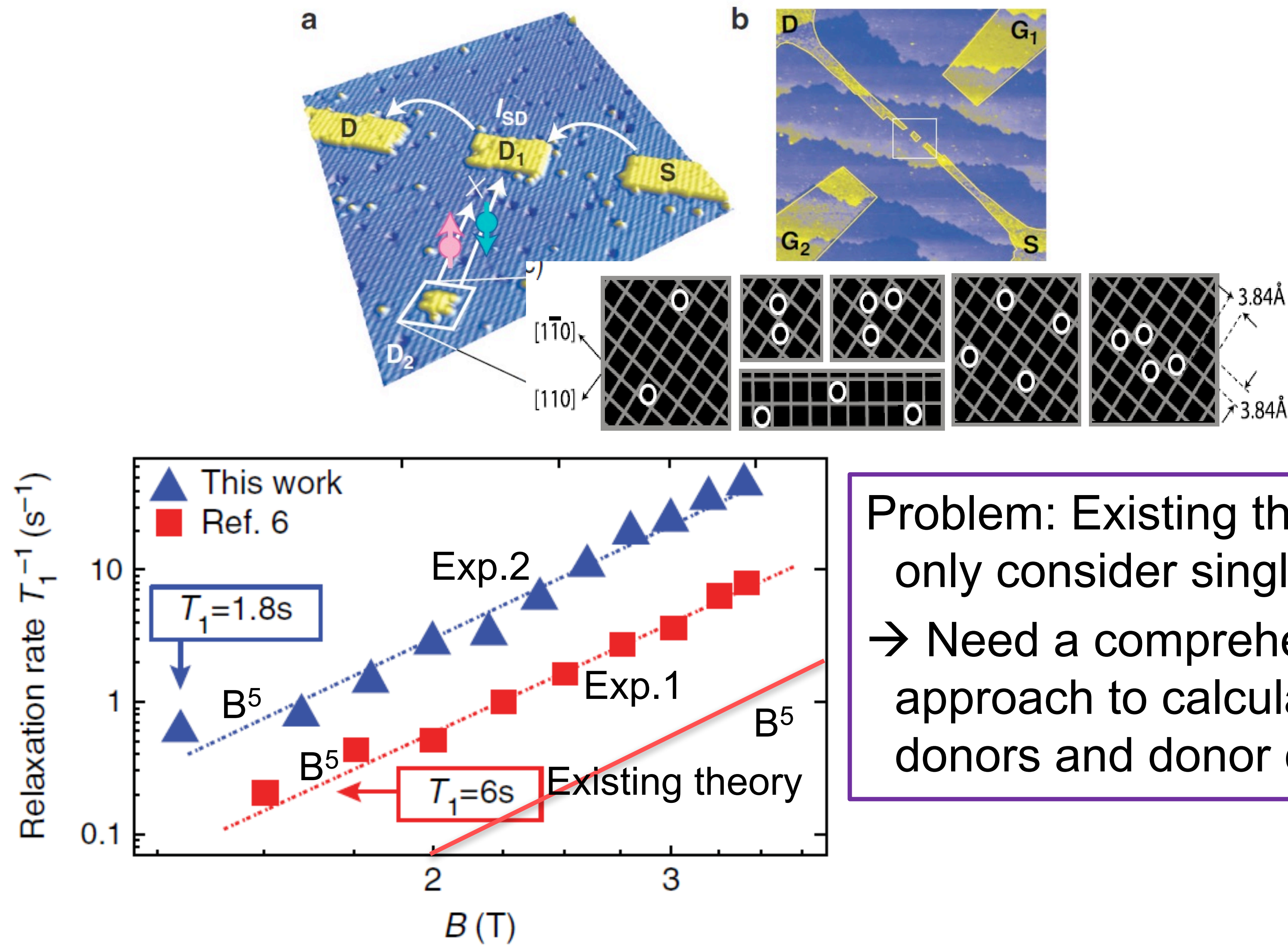
Part I: T_1 in Donors and Donor Clusters



Problem: Existing theories only consider single donors.

→ Need a comprehensive approach to calculate T_1 in donors and donor clusters.

H. Büch et al. Nature Communications 4, 2017 (2013)

The Problem of Calculating T_1: Existing theories v.s. New theory

The phonon modes involved

Acoustic phonon →deformation potential theory

Existing theories:

Valley repopulation:

- effective mass wf. with valleys
- H_{ep}:
  diagonal strain (u_{xx},u_{yy},u_{zz})
  exp. input: deformation potential constants

Single valley:

- H_{ep}:
  off-diagonal strain (u_{xy},u_{xz},u_{yz})
  exp. input: matrix element

A comprehensive approach for T_1

- TB wf.
- H_{ep}:
  strained TB Hamiltonian

$$\hat{H}_{ep} = \sum_{i,j=x,y,z} \hat{\Xi}_{ij} u_{ij} \,,$$

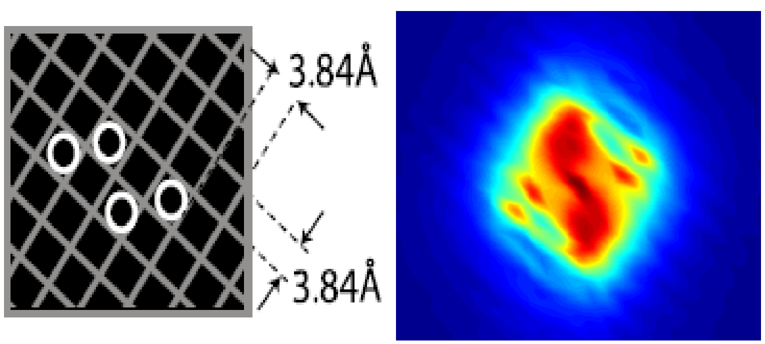
$$\hat{\Xi}_{ij} = \frac{\partial \hat{H}_e}{\partial u_{ij}} = \frac{\hat{H}_e(u_{ij}) - \hat{H}_e(0)}{u_{ij}}$$

→captures both valley repopulation and single valley effects.
→valley information not needed
→no exp. input

New Approach for T_1 Analysis: Atomistic TB Method

The atomistic TB Hamiltonian

- spin-orbit interaction
- magnetic field
- self consistent TB

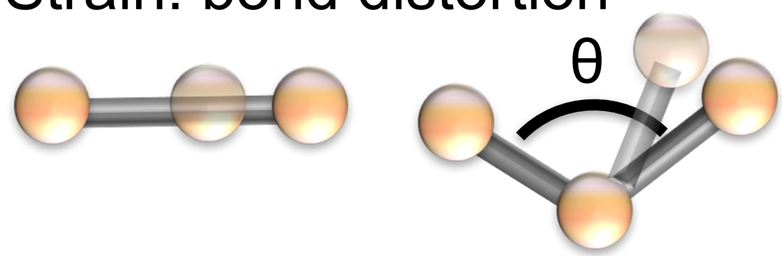


Computed outermost electron wf. of 4P5e

The T_1 time

- Deformation potentials for all strain components from strain-dependent TB Hamiltonian

- Strain: bond distortion

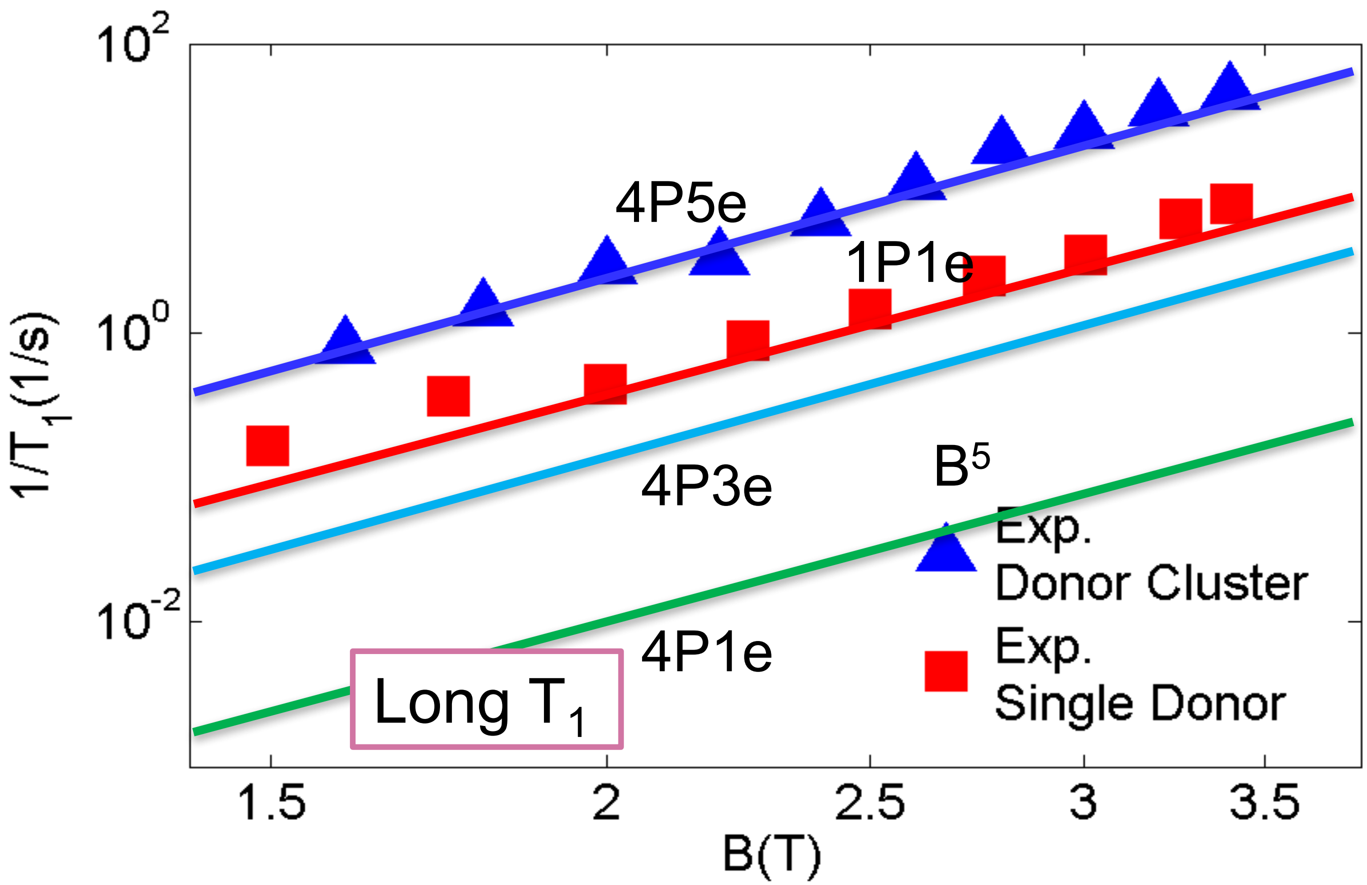


- Fermi's Golden rule for $1/T_1$

Atomic basis captures critical physics of spin-orbit interactions and bond distortions.

Atomistic Approach Explains Experiment

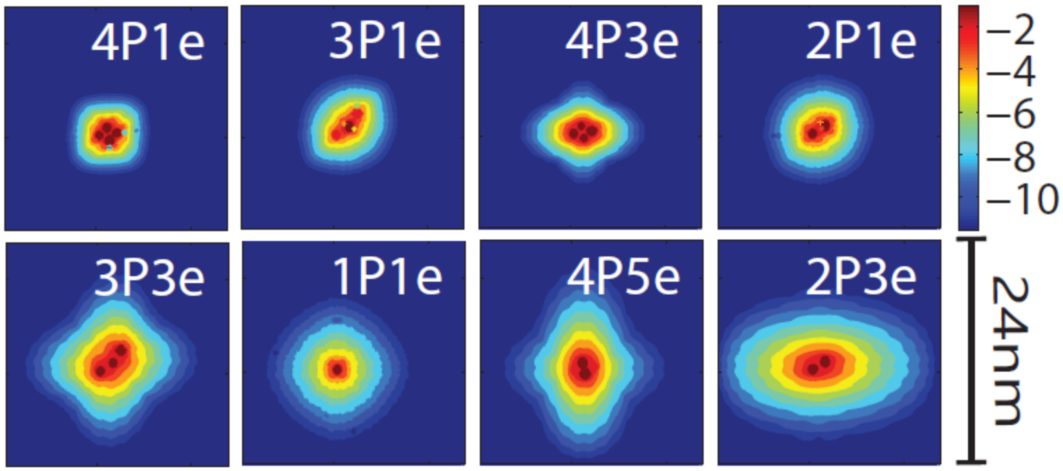
4P5e: Donor cluster with 4 donors 5 electrons.



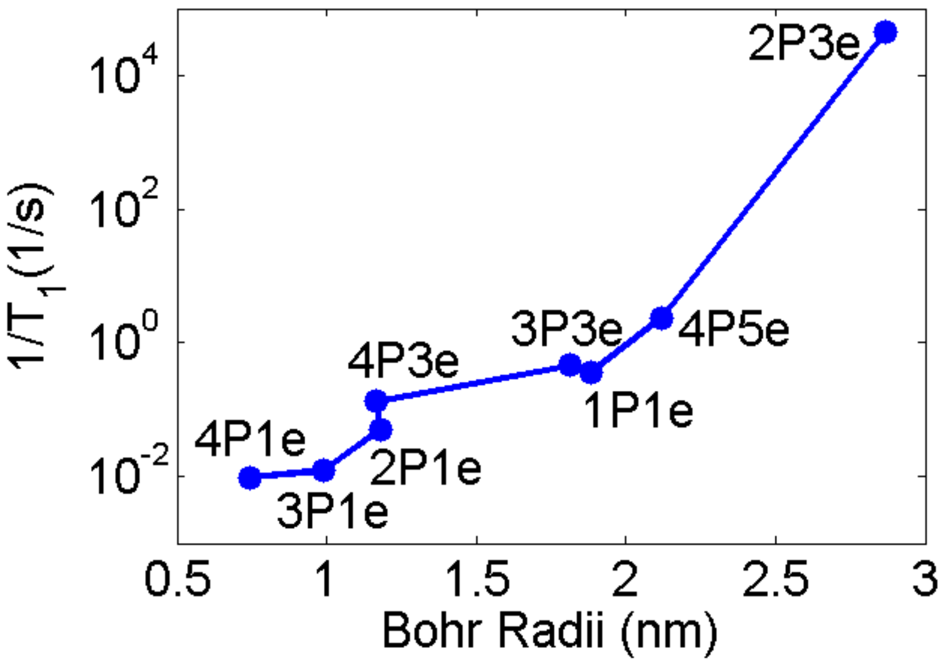
Electron number variation results in orders of magnitude change in T_1

H. Büch et al. Nature Communications 4, 2017 (2013)
Y. L. Hsueh et al., Phys. Rev. Lett. 113, 246406 (2014)

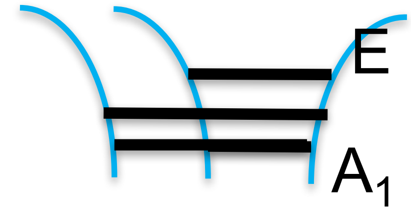
What Determines the T_1 Values?



The computed wf (in log scale).



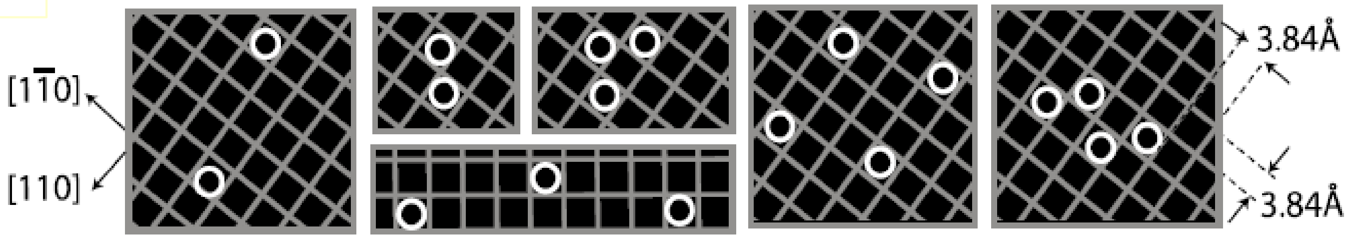
Valley states

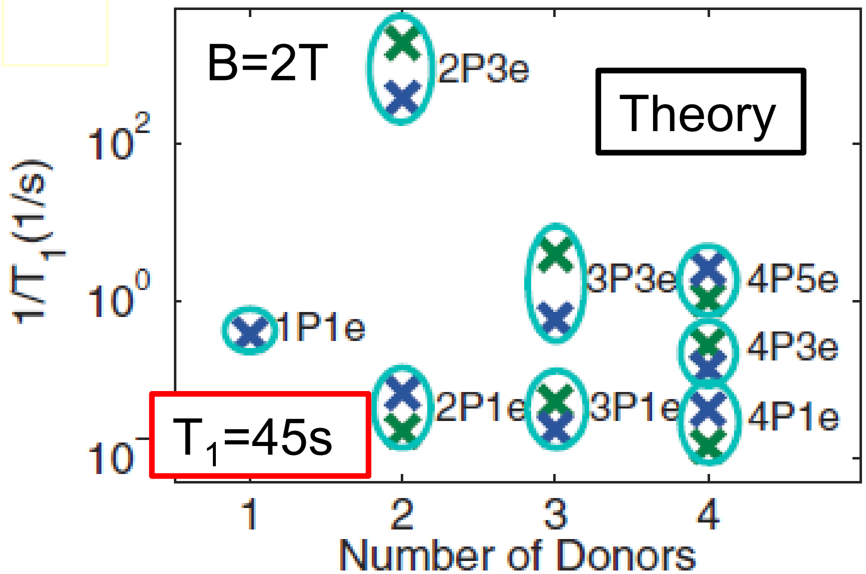


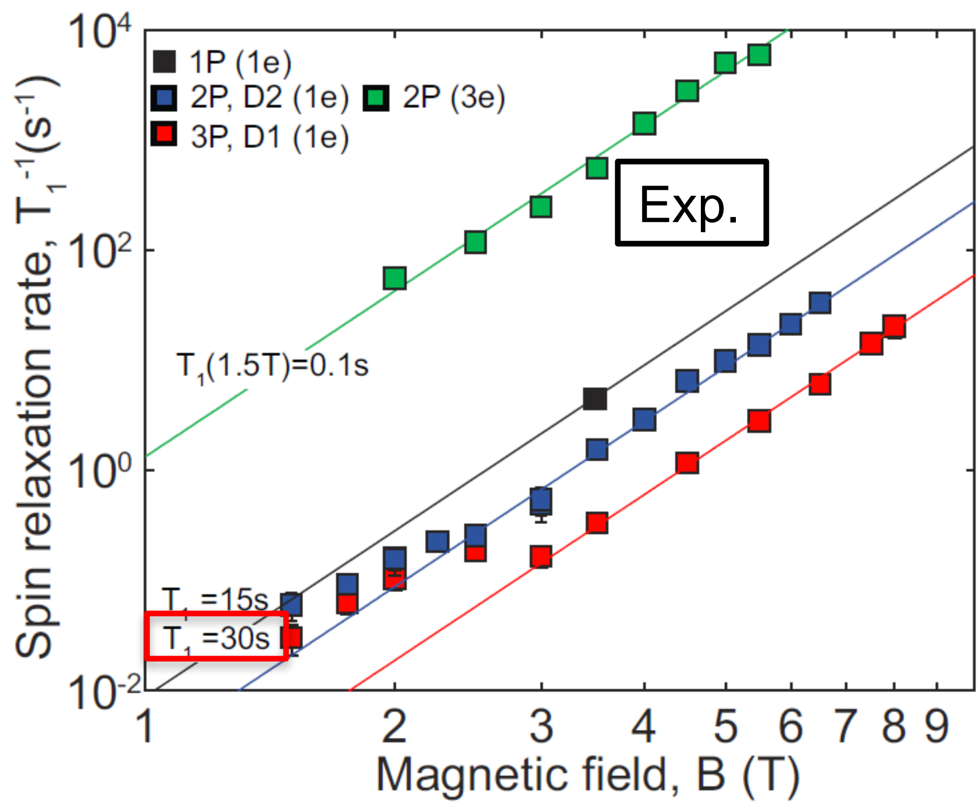
Large electron wf
→valley states are closer
→large $1/T_1$

Small electron Bohr radius results in long T_1 time.

T_1 in Donor Clusters

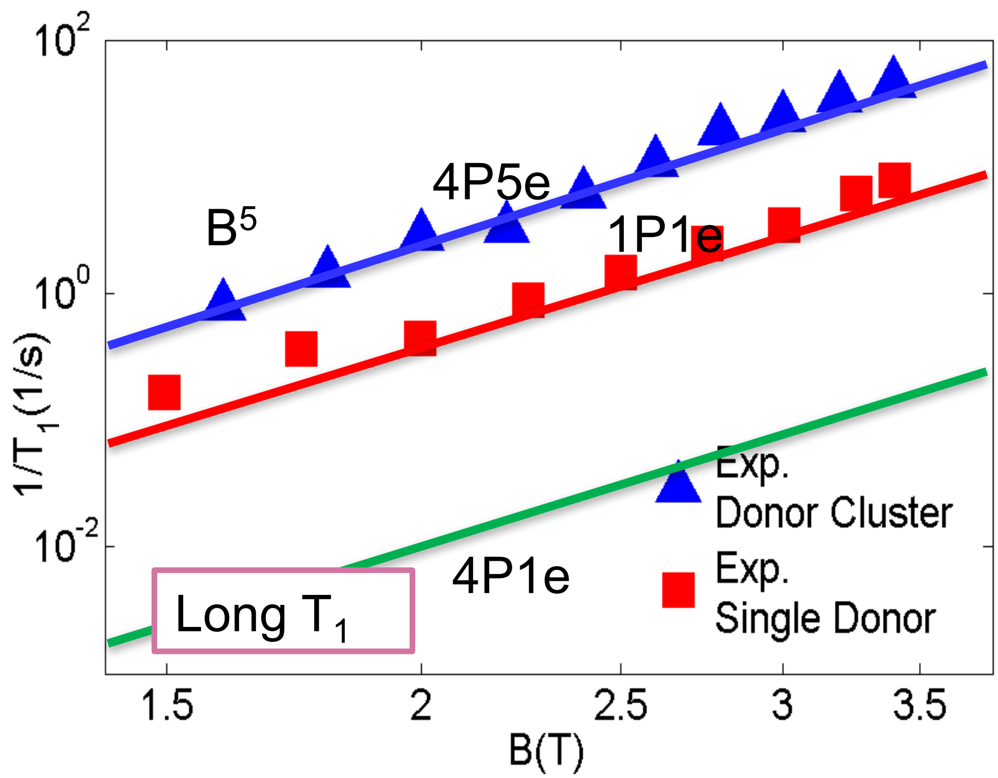






Experimental results confirmed our theoretical prediction.

- A TB method is benchmarked with recent exp. observation.
- Long T_1 times in donor clusters are predicted and confirmed.



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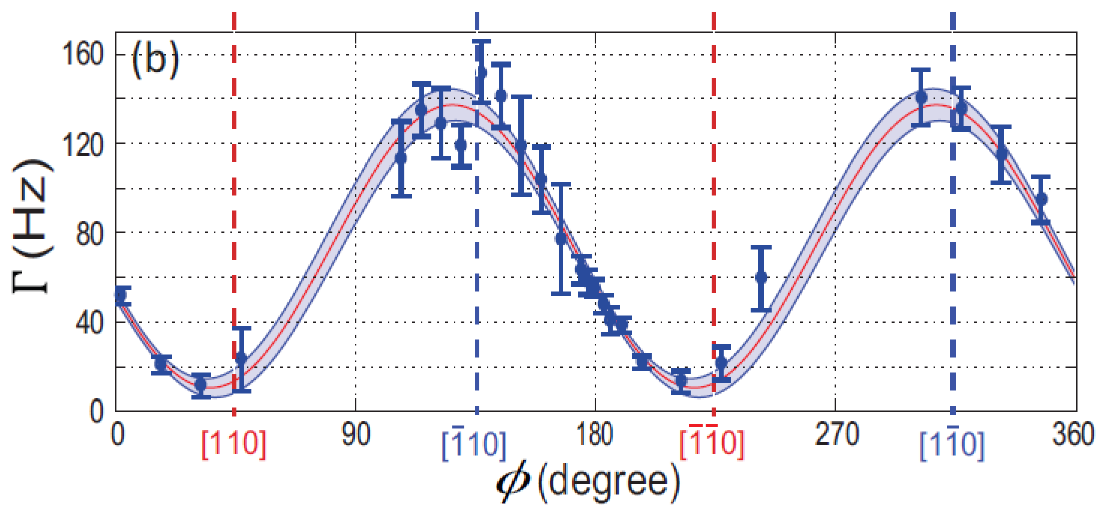
T_1 Anisotropy in GaAs Quantum Dots

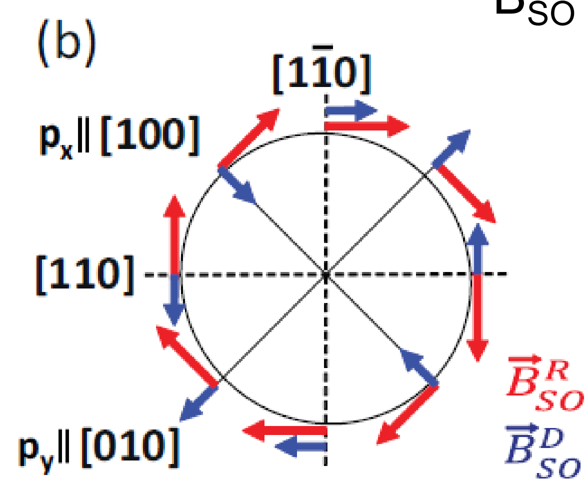
GaAs → bulk inversion asymmetry → **Dresselhaus SO**

QDs → structural inversion asymmetry (E field) → **Rashba SO**

Question: the sign of Rashba and Dresselhaus?
→ Extract from T_1 anisotropy

$$Hso = \sigma \cdot \underbrace{\boxed{\beta(k \times \hat{E})}}_{B_{SO}}$$

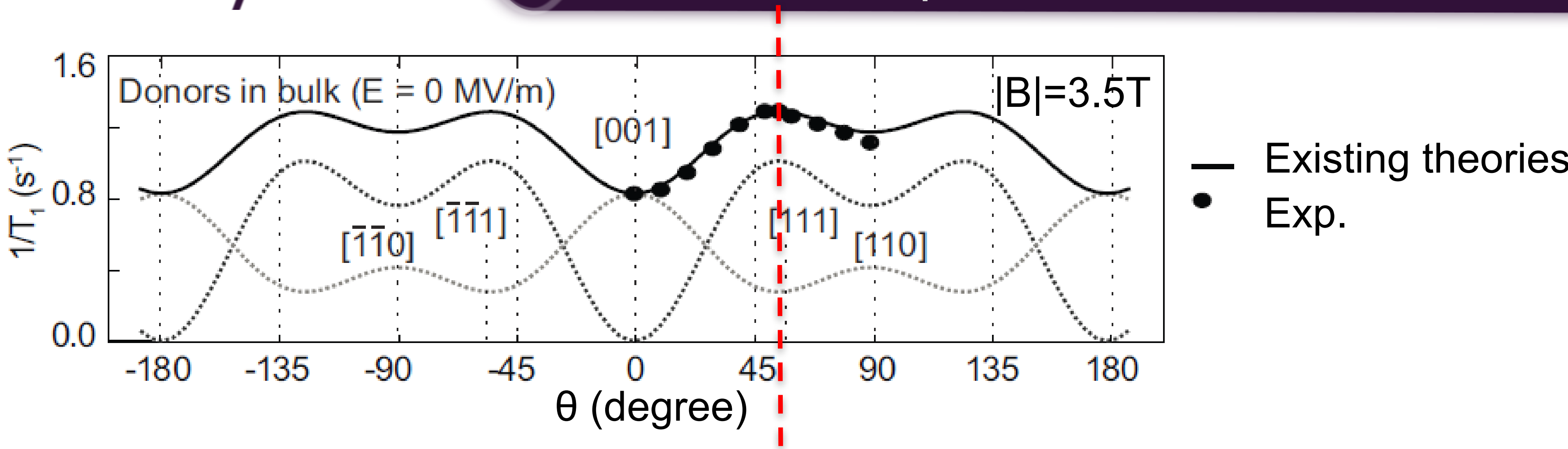




We can extract information about the spin-orbit interaction from measuring T_1 anisotropy.

P. Scarlino et al., Phys. Rev. Lett. 113, 256802

T_1 Anisotropy of P in Bulk Si



Bulk Si→ no Dresselhaus SO

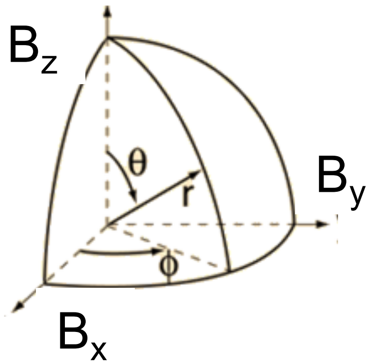
No E field→ no Rashba SO

Only spin-orbit from the crystal $Hso = \sigma \cdot (\nabla V \times p)$

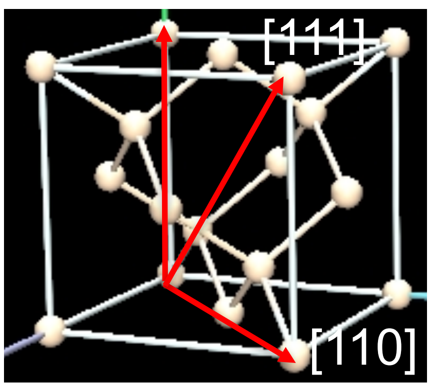
Bulk P in Si: T_1 anisotropy follows crystal symmetry, and is explained by existing theories.

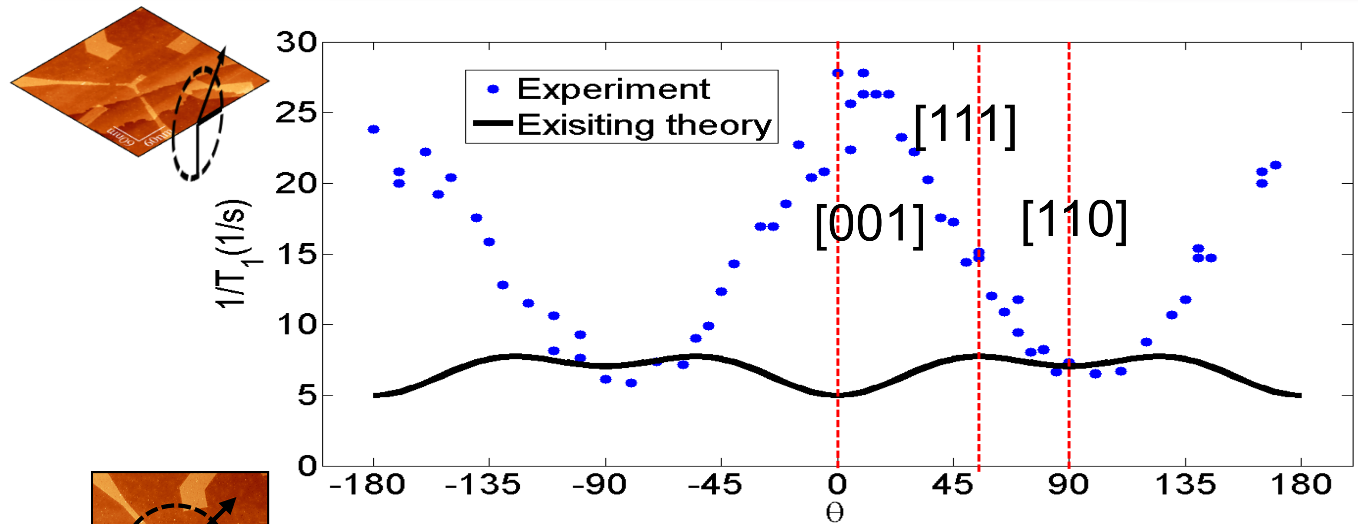
D. K. Wilson and G. Feher, Phys. Rev., 124, 1068 (1961)

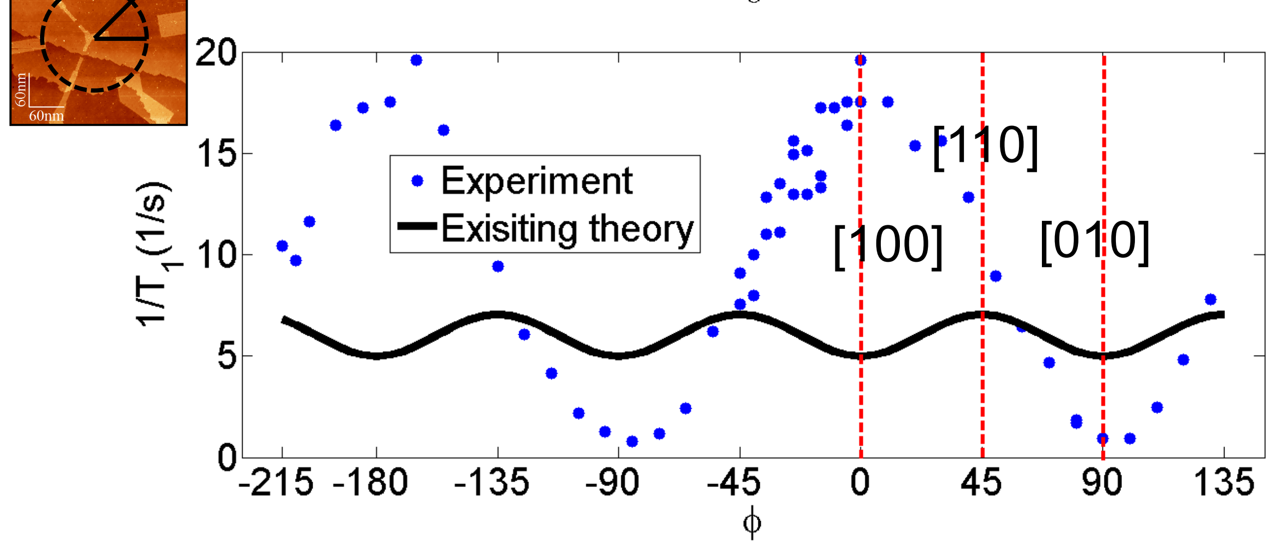
Part II: T_1 in System with Electric Fields



[001]



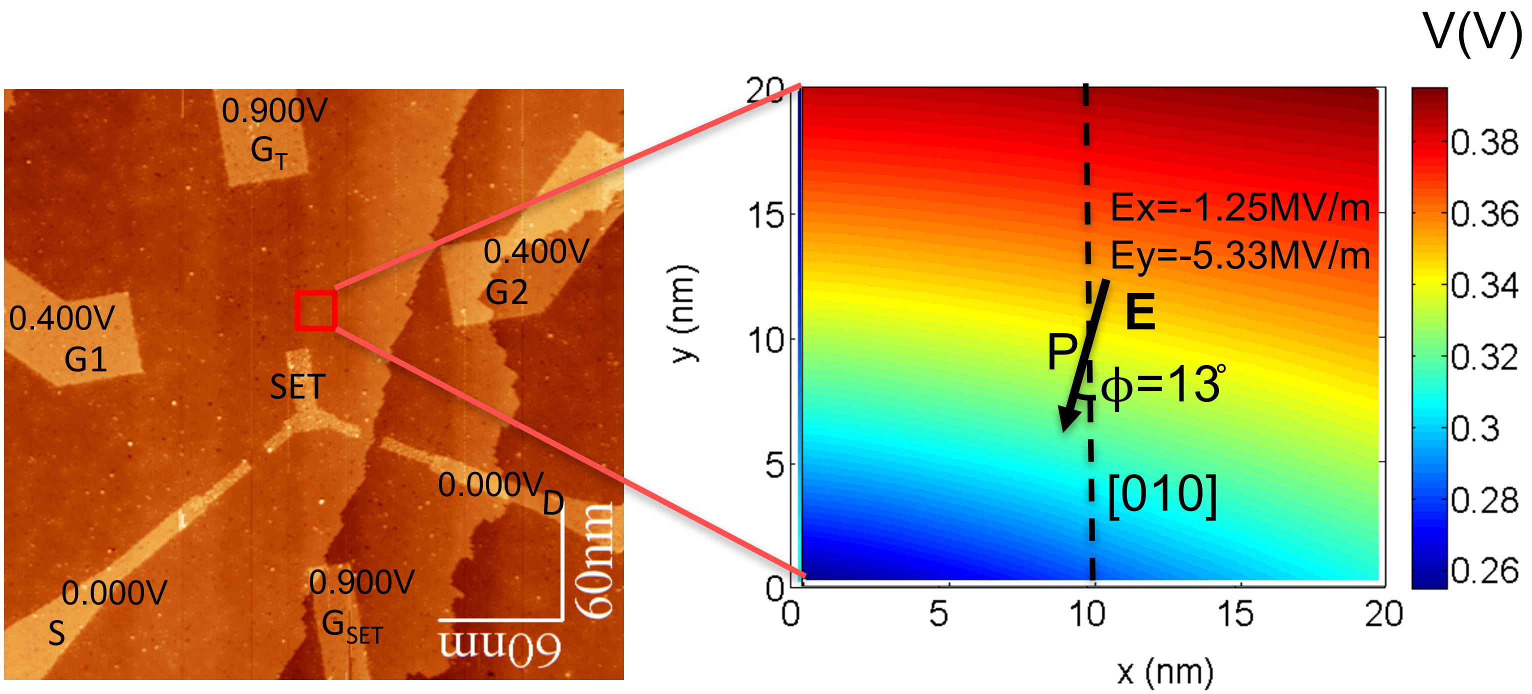




Problem: Existing theory considers bulk systems.

→Need to include the effect of E-fields.

Evidence of Electric Fields in the Device



Electrostatics solved from COMSOL

Electric field (Ey~5MV/m) at the donor site.

The Effect of Electric Fields: Rashba Spin-Orbit

Rashba spin-orbit

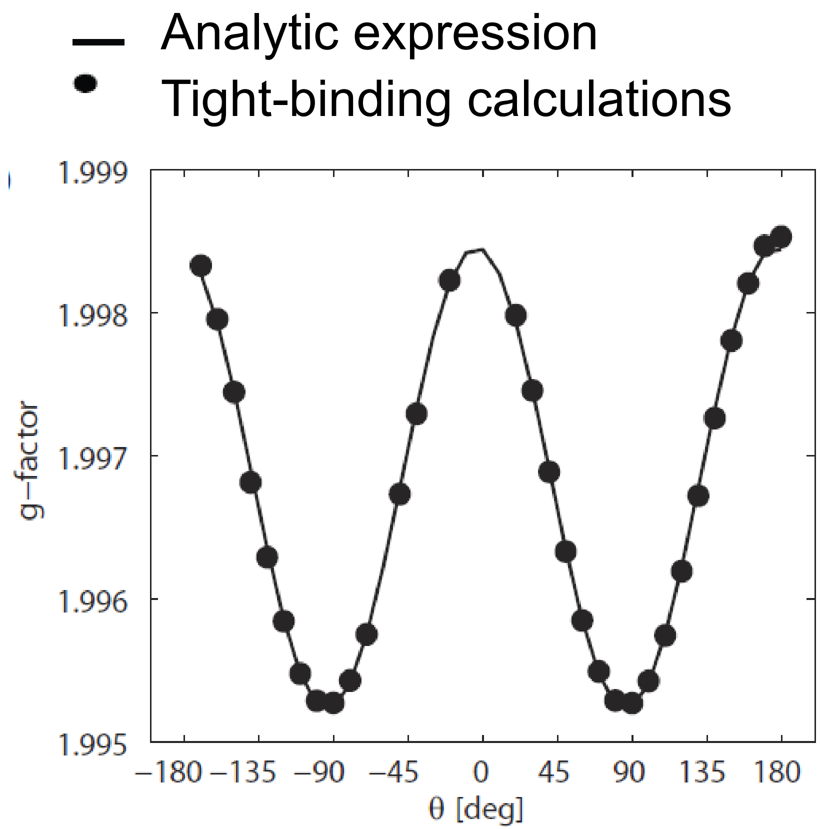
$$H_{SO} = R(\boldsymbol{k}\times\boldsymbol{E})\cdot\sigma$$

Bulk SO　　Rashba SO

$$H_Z = g\mu_B B\cdot\sigma + R(\boldsymbol{k}\times\boldsymbol{E})\cdot\sigma$$

g_l　　g_t

$$\equiv \boldsymbol{g}\mu_B B$$

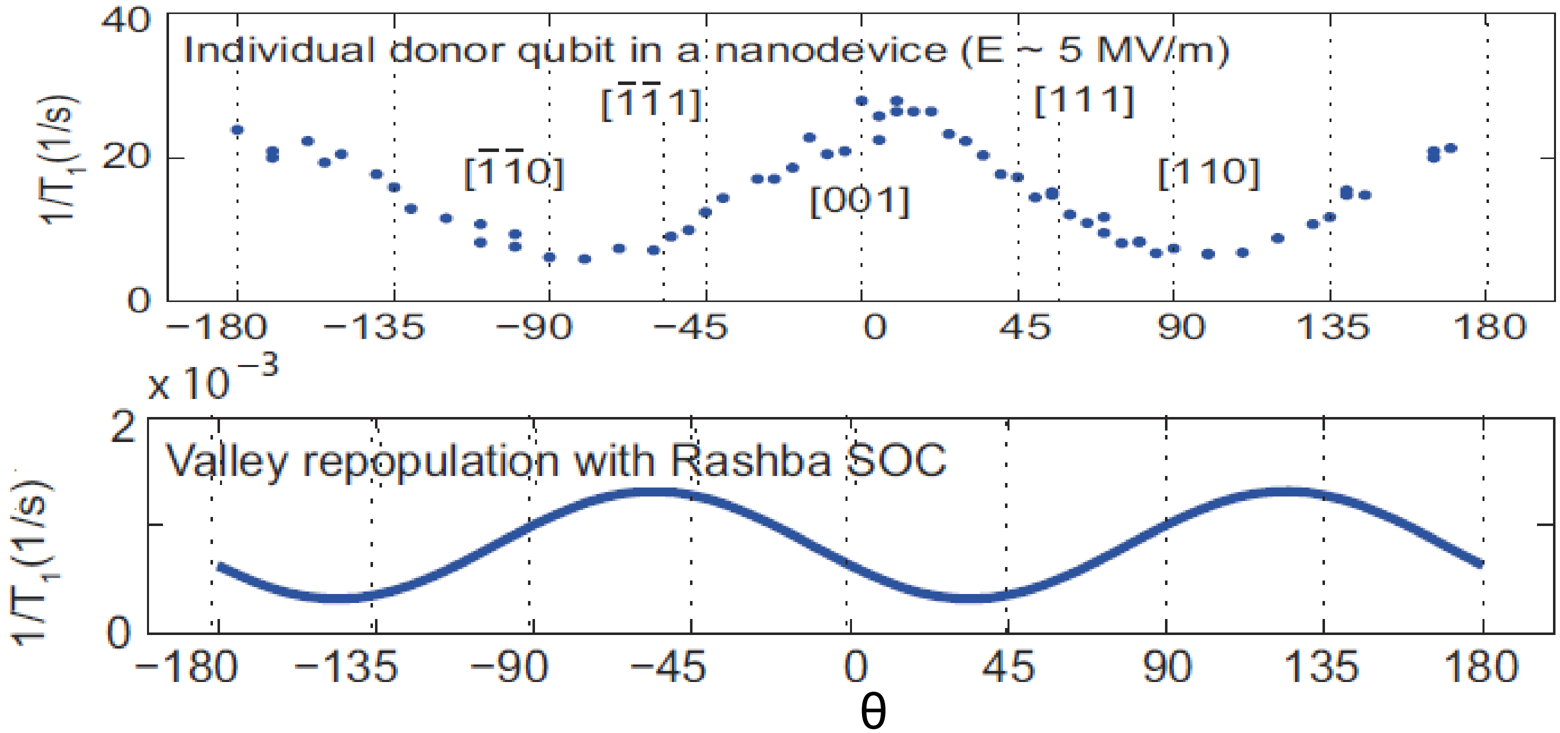


Fit to TB g factor→Rashba B_{eff}~0.1mT

Electron g-factor of donor in Si

From spin-splitting→extract the magnitude of Rashba SO in donors.

The Effect of Electric Fields: Rashba Spin-Orbit



Under E field along y,
B^{eff}//[101] → maximum mixing at B ⊥ [101]

Valley repopulation with Rashba SO cannot explain the observed anisotropy.

The Effect of Electric Fields: H_{ExB} Spin-Orbit

Beyond the usual spin-orbit, we consider the next higher-order term in k·p theory

$$Hso = C(\boldsymbol{E}\times\boldsymbol{B})^{+}\cdot\sigma$$

- Couples the external electric and magnetic field.
- No orbital dependence.
- E along [010], B//E→Hso=0, B⊥E→ Hso largest

A new SO coupling having $(ExB)^{+}$ form might be present.

Note: $(E\times B)^{+} = (E_yB_z + E_zB_y, E_xB_z + E_zB_x, E_xB_y + E_yB_x)$

R. Winkler et al., Spin-Orbit Coupling in Two-Dimensional Electron and Hole Systems.

The Effect of Electric Fields: H_{ExB} Spin-Orbit

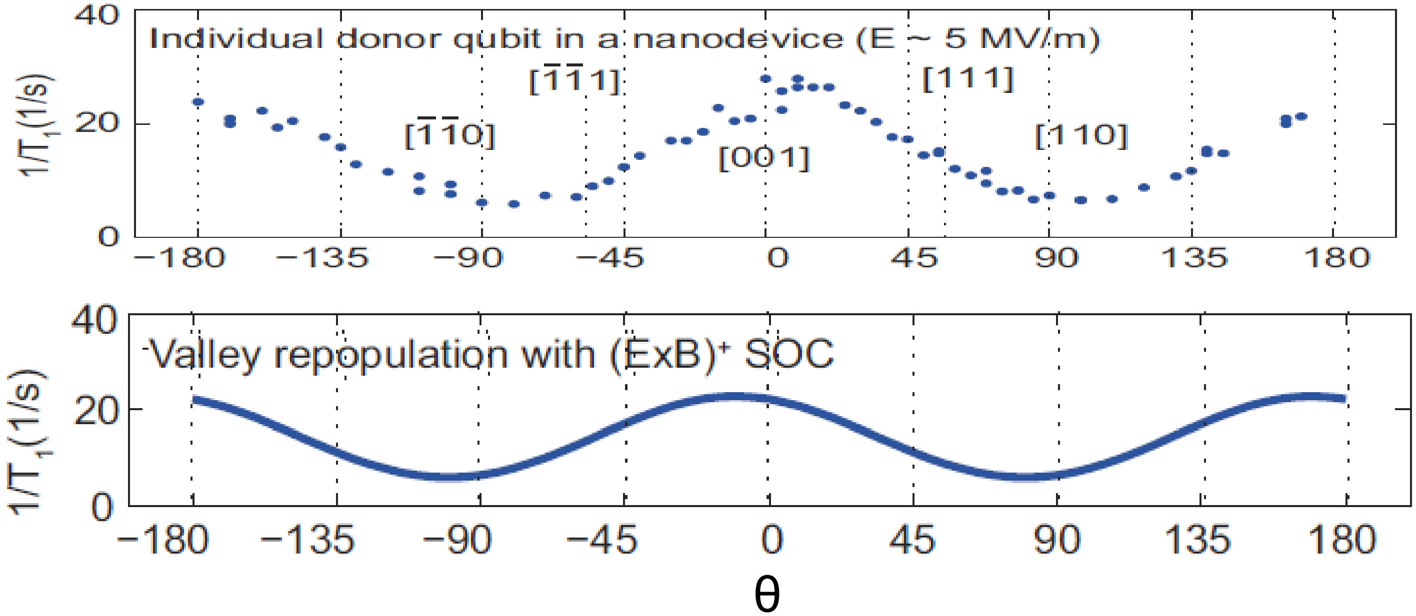
$$\frac{C}{R} = \frac{e}{m_0}\frac{p_{\mu\nu}}{E_{\alpha\mu}}$$

Rashba spin-orbit	$H_{SO} = R(\boldsymbol{k}\times\boldsymbol{E})\cdot\sigma$	**→Rashba B_{eff}=0.1mT**
H_{ExB} spin-orbit	$Hso = C(\boldsymbol{E}\times\boldsymbol{B})^{+}\cdot\sigma$	**→H_{ExB} B_{eff}=18.9mT**

Why Rashba smaller? R>C, but k very small in donors.

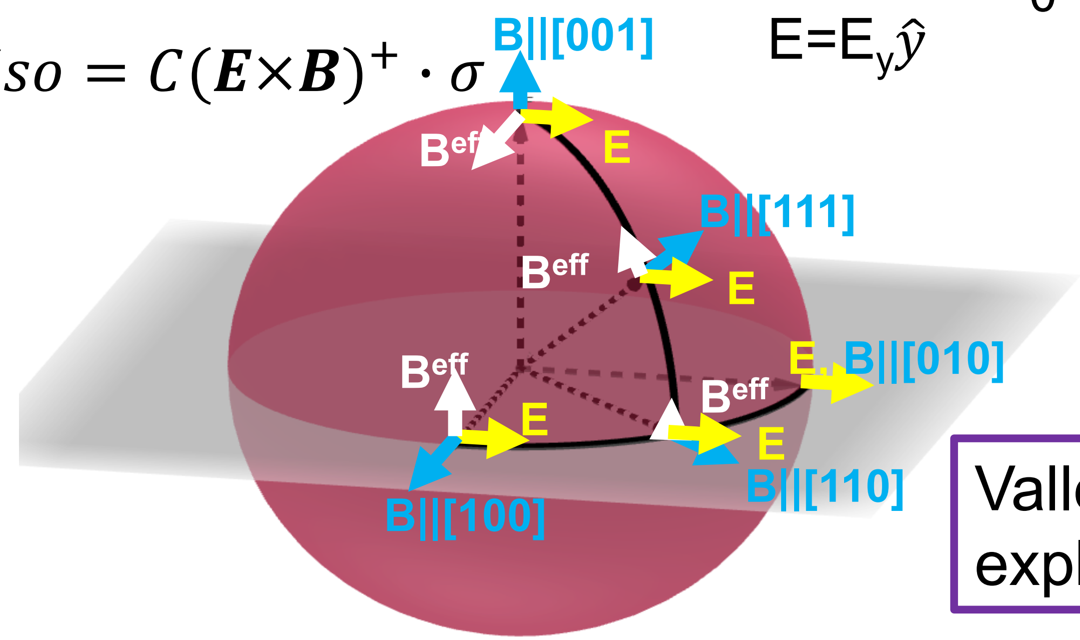
From comparing to Rashba SO
→extract the magnitude of H_{ExB} SO in donors.

The Effect of Electric Fields: H_{ExB} Spin-Orbit



$$Hso = C(\boldsymbol{E}\times\boldsymbol{B})^{+}\cdot\sigma$$

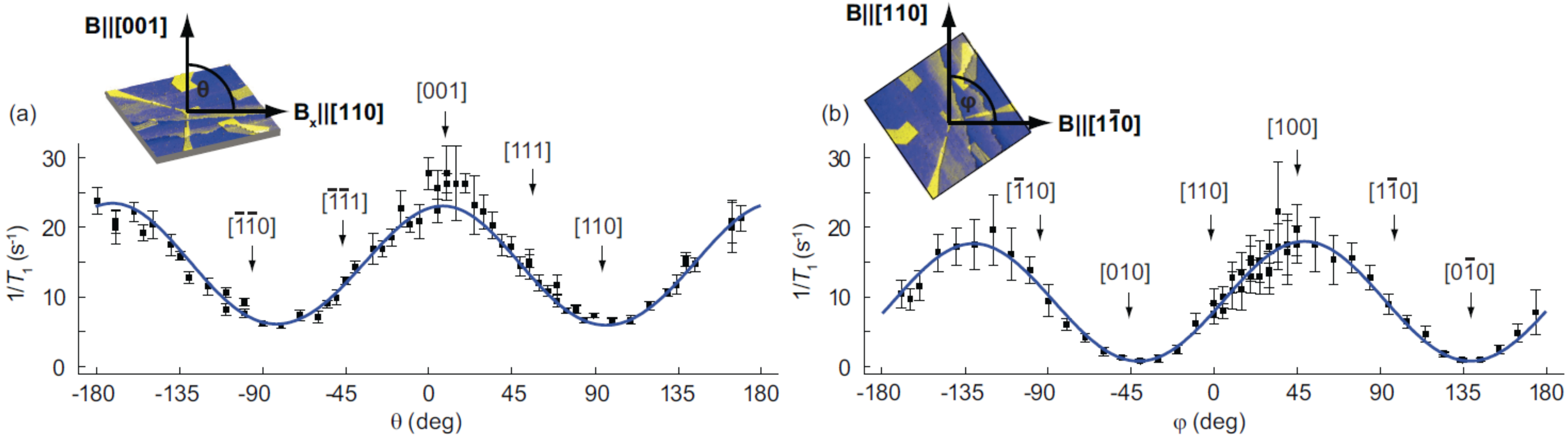
$E=E_y\hat{y}$



Under E field along y,
B^{eff} is largest along [001].

Valley repopulation with $(ExB)^+$ SO explains the observed anisotropy.

T_1 Anisotropy with Electric Fields

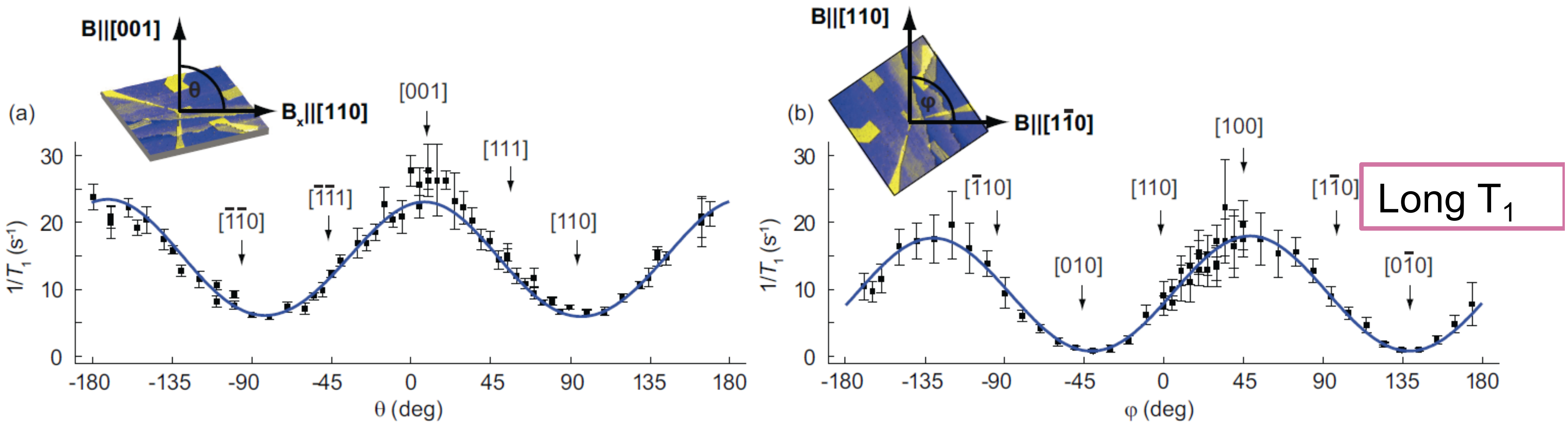


The T_1 anisotropy in a nano device is explained by electric field modified valley repopulation + single valley effect.

B. Weber et. al., “A Single-Atom Probe of the Silicon Qubit Environment” (submitted)

Part II Summary

- A new electric field induced SO: H_{ExB} is found.
- The observed anisotropy is explained by the electric field-modified spin-relaxation mechanisms.



Introduction to quantum computing and T_1

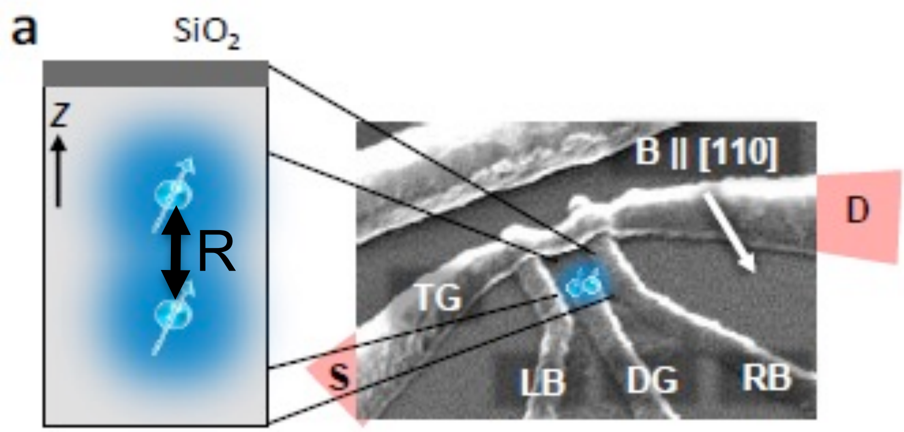
The spin-relaxation mechanisms : Existing theories

Part I: The tight-binding T_1 method

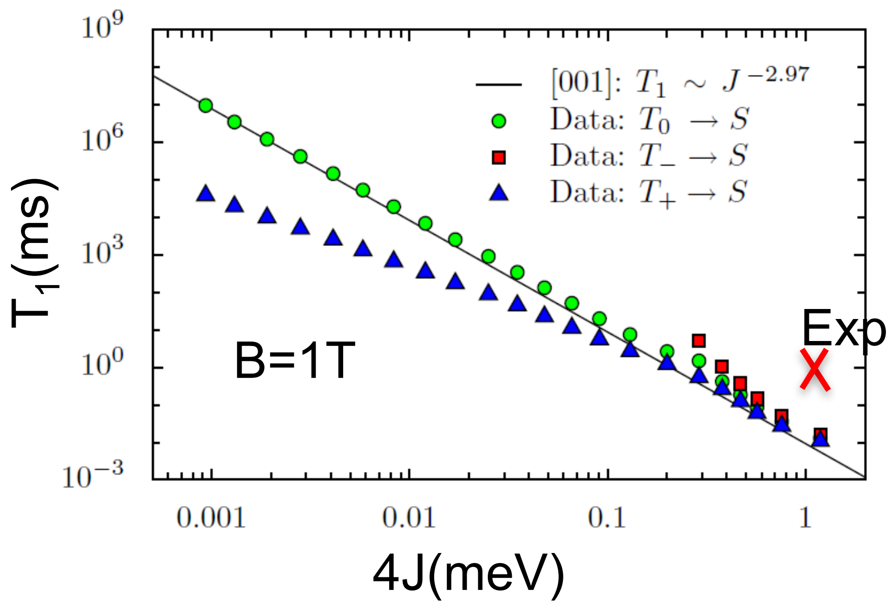
Part II: T_1 in device with electric fields

Part III: Two-electron T_1 problem

Part III: Two-electron T_1 in Donor-pairs



Measurement:
→T_1~4ms at B=0T, R~6nm.
→Weak B dependence.

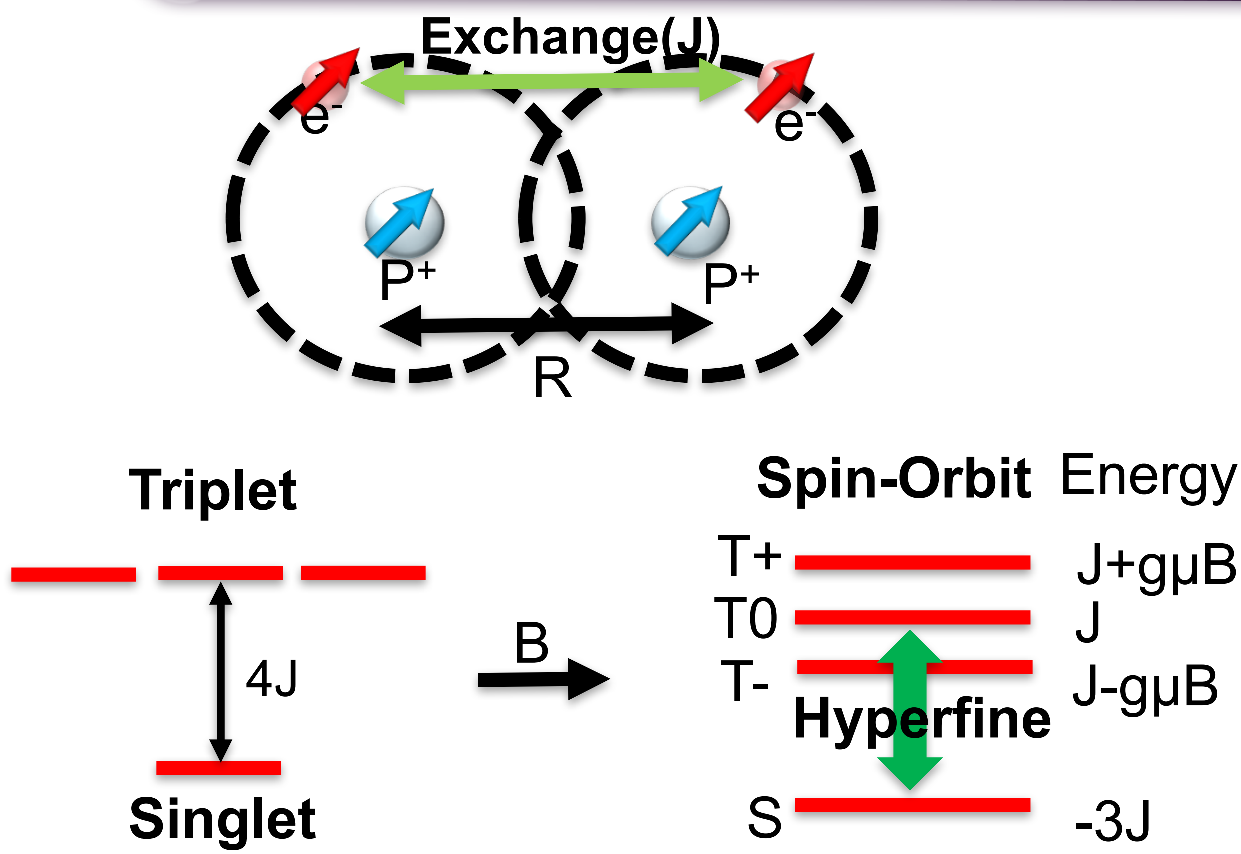


Existing work:
→T_1~0.01ms at B=0T, R~6nm.

Problem: Existing work cannot explain measurements.
→Need an accurate way to treat the two-electron T_1 problem.

J. P. Dehollain, et al., Phys. Rev. Lett. **112**, 236801 (2014).
M. Borhani and X. Hu, Phys. Rev. B **82**, 241302 (2010).

Two Electron System



Goal

1. Calculate triplet to singlet T_1 due to SO and hyperfine mixing.
2. T_1 dependencies on J.

The Problem of 2e T_1 Existing Work v.s. A New Method

Fermi's Golden rule $\frac{1}{T_1} = \frac{2\pi}{\hbar} \left|\langle f|\hat{H}_{ep}|i\rangle\right|^2 \delta(E_i - E_f - \hbar\omega_q)$

Existing work:

- $i\rangle, |f\rangle$:
effective mass wf. with Heitler-London approximation.

- Hep:
deformation potential constants.

- Hyperfine mixing.

An accurate method:

- $i\rangle, |f\rangle$:
Full-configuration interaction with slater determinants from one-electron TB wf.

- Hep:
strained TB Hamiltonian.

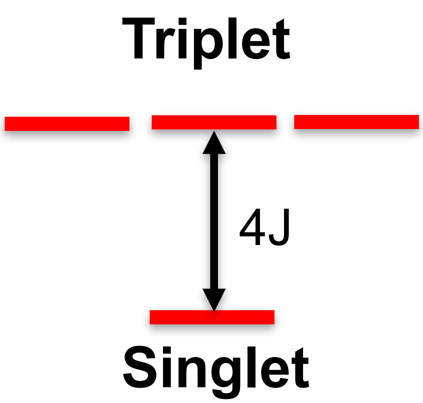
- Spin-orbit + hyperfine mixing.

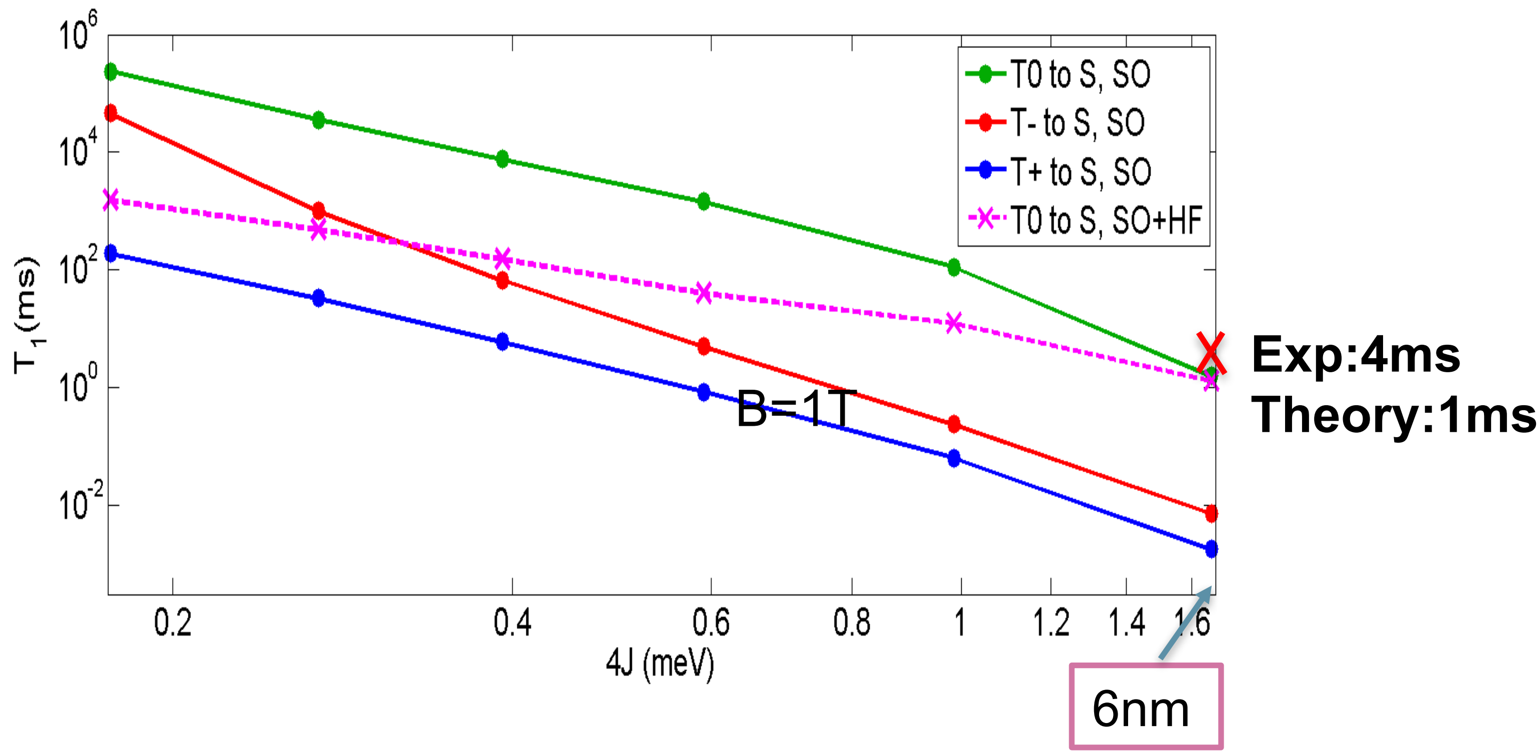
FCI + tight-binding to calculate 2e T_1.

Y. Wang et. al., npj Quantum Information, vol. 2, p. 16008 (2016)

NEMO5

Results: T_1 v.s. J



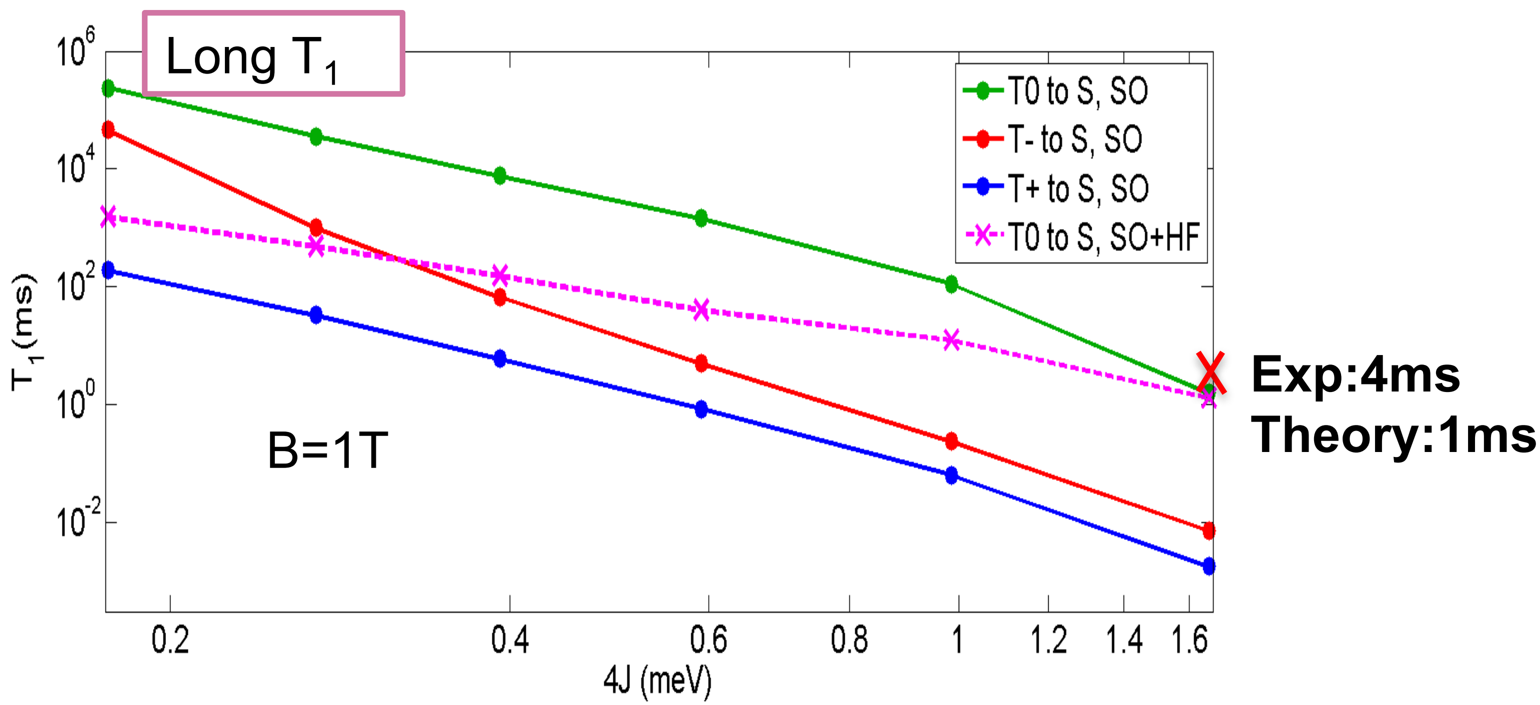


- J increases → energy gap increases → more phonon can couple → shorter T_1
- $H = \begin{pmatrix} -3J & A \\ A & J \end{pmatrix}$ Mixing ~A/J → larger J, smaller mixing, longer T_1

Singlet-triplet T_1 decreases with J, increases with R

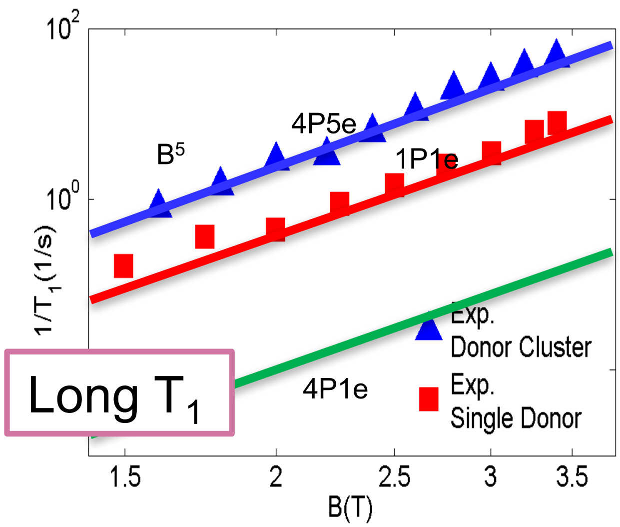
Part III Summary

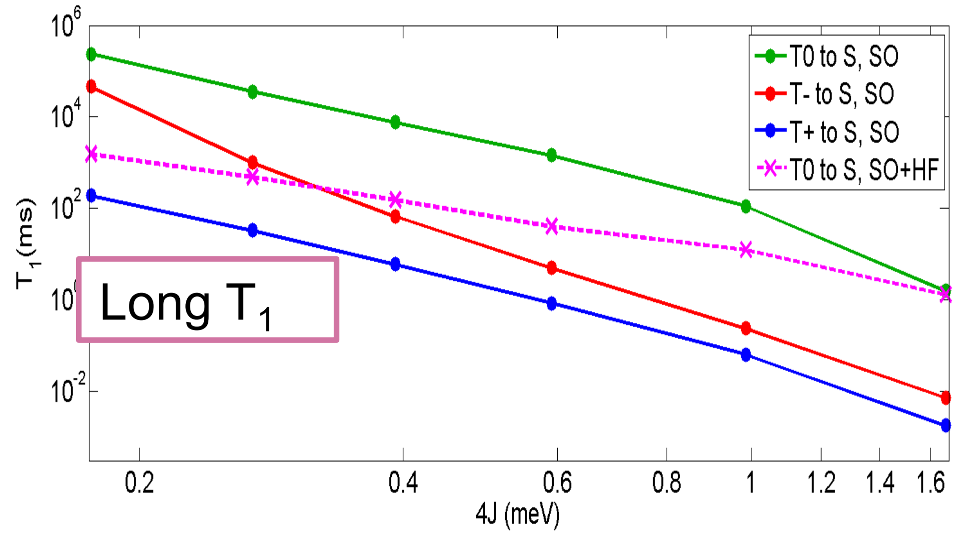
- An accurate method: FCI+TB to treat 2e T_1
- Close match to experiment value.

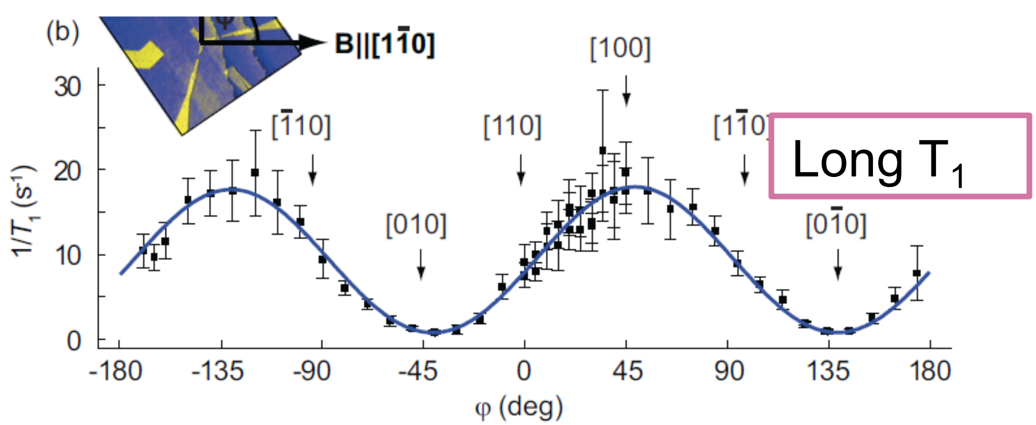


Conclusion

- By developing a method to treat the one-electron to multi-electron spin-relaxation problems and understanding the mechanisms behind, it is easier to design a quantum computer with high-fidelity using donors in Si nanoelectronic devices.







Acknowledgement

- Prof. Rajib Rahman, Prof. Gerhard Klimeck, Prof. Michelle Simmons, Prof. Lloyd Hollenberg, Prof. Supriyo Datta, Prof. Zhihong Chen, Dr. Bent Weber, Dr. Thomas Watson and Dr. Jim Fonseca

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- Thanks to all other friends.

Thank You

Publication Summary

- Part I: The tight-binding T_1 → Y. L. Hsueh et al., Phys. Rev. Lett. 113, 246406 (2014)
- Part II: T_1 in devices with electric fields → B. Weber et. al., “A Single-Atom Probe of the Silicon Qubit Environment” (submitted)
- Part III: Two electron T_1 problem → Drafted

$$\hat{U}_{\mathrm{ij}} = \frac{1}{2}\sum_q \left(\frac{\hbar}{2V\rho\omega_q}\right)^{(1/2)} i(e_{\mathrm{qi}}q_j + e_{\mathrm{qj}}q_i)\{\hat{a}_q^{+}\exp[i(\mathbf{q}\cdot\mathbf{r})] + \hat{a}_q\exp[-i(\mathbf{q}\cdot\mathbf{r})]\}, \tag{4}$$

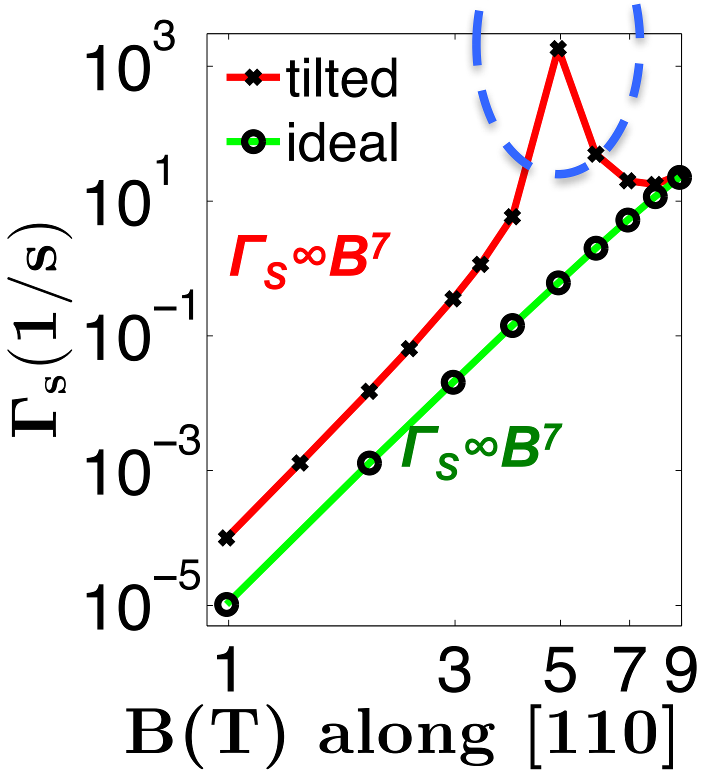
where V is the volume of the crystal, ρ the mass density, and $\mathbf{e_q}$ the phonon polarization unit vector. Using Eqs. 2 and 4, the matrix element of $\hat{H}_{ep}$ can be expressed as,

$$\begin{aligned}\langle n', n_q + 1|\hat{H}_{ep}|n, n_q\rangle &= \frac{1}{2}\sum_q \left(\frac{\hbar}{2V\rho\omega_q}\right)^{(1/2)} \sqrt{n_q + 1} \\ &\times \sum_{i,j} i(e_{\mathrm{qi}}q_j + e_{\mathrm{qj}}q_i)\langle n'|\exp[i(\mathbf{q}\cdot\mathbf{r})]\hat{\Xi}_{\mathrm{ij}}|n\rangle. \end{aligned} \tag{5}$$

Apply to other systems

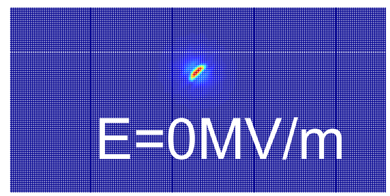
Quantum Dots

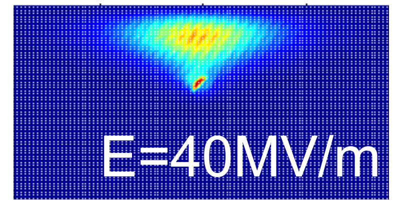
Relaxation hot-spot at $E_{ZS}=E_{VS}$

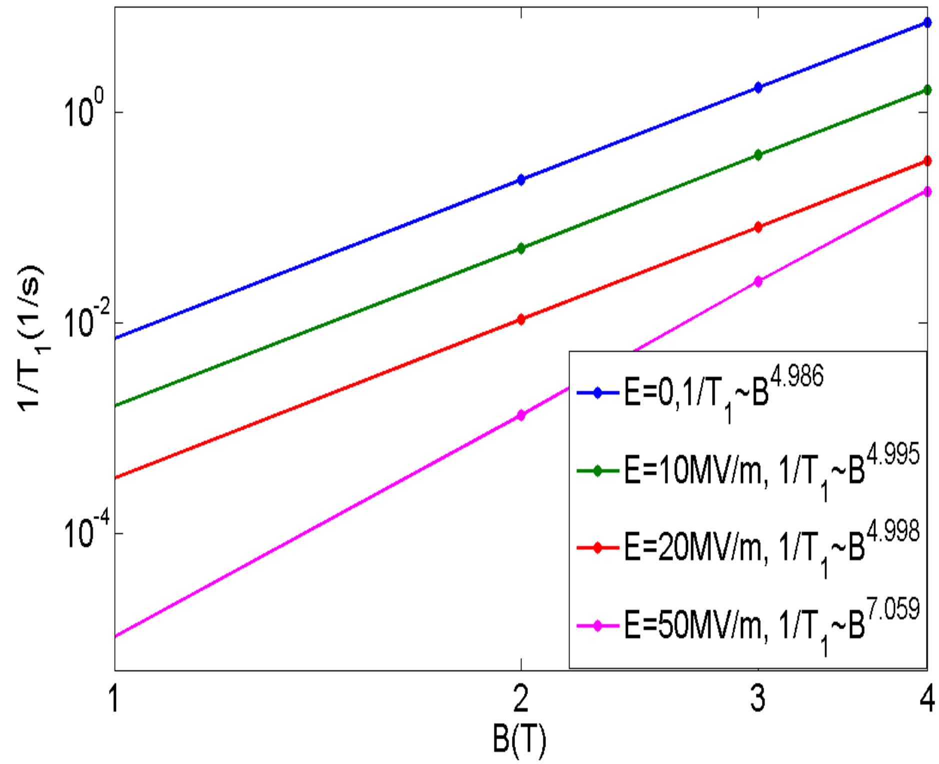


Rifat Ferdous

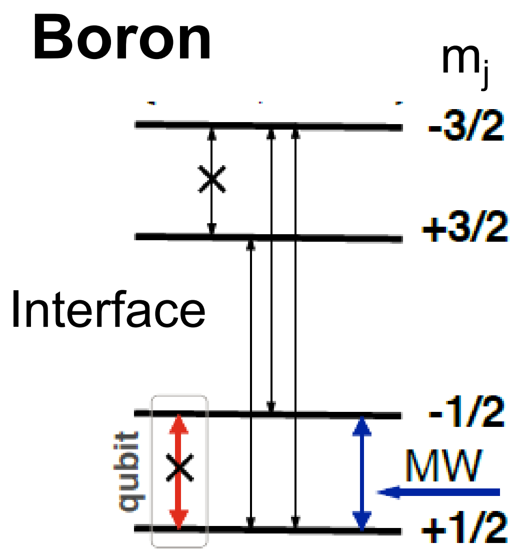
Interface donor

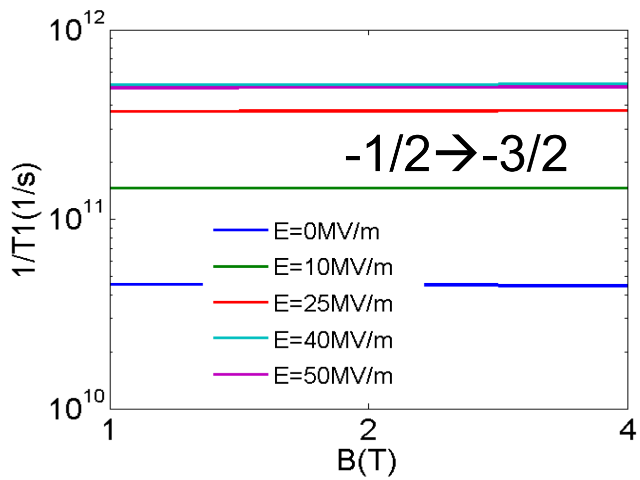


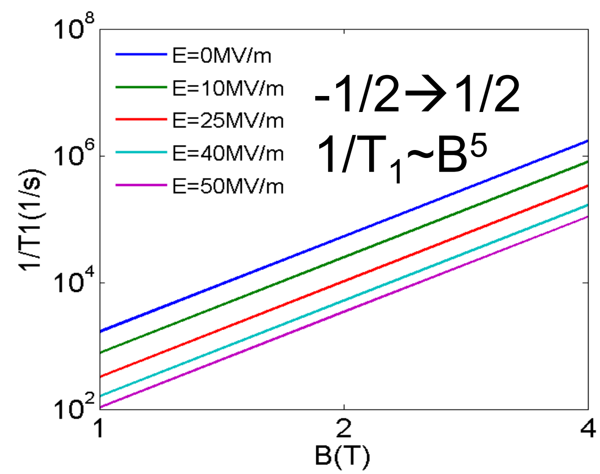




Apply to other systems



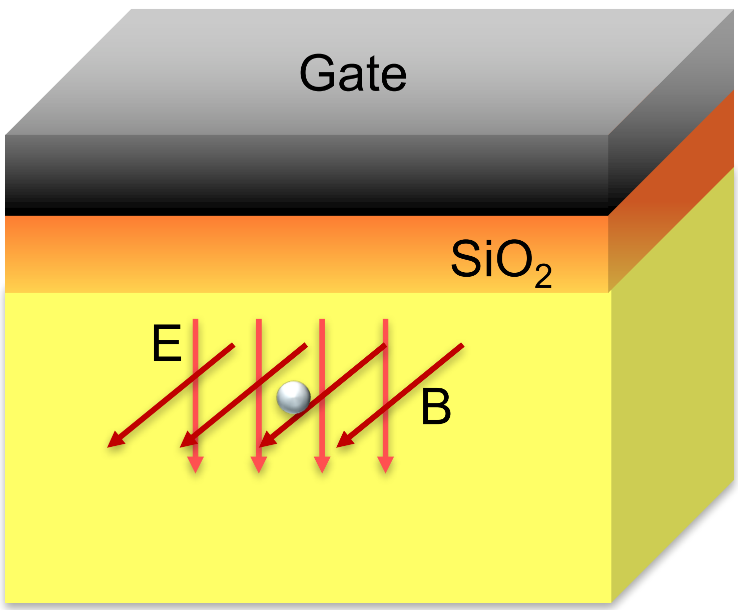


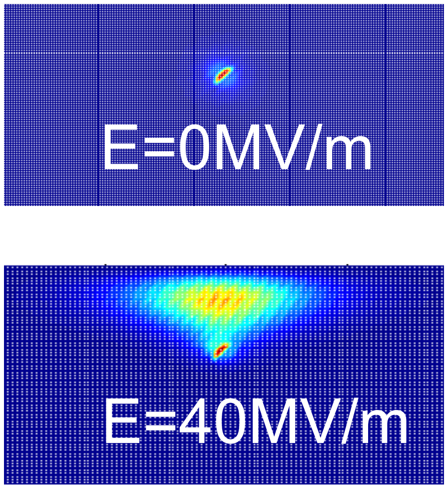


Other work: Interface donor T_1

Motivation

- Hybridized donor states has been investigated both experimentally and theoretically.
- Lack of comprehensive study of T_1 times in these hybridized system.





Gabriel Lansbergen et al., Nature Physics, Vol. 4, pg. 656 (2008)
Rajib Rahman et al., Phys. Rev. B, Vol. 80, 098936 (2009)

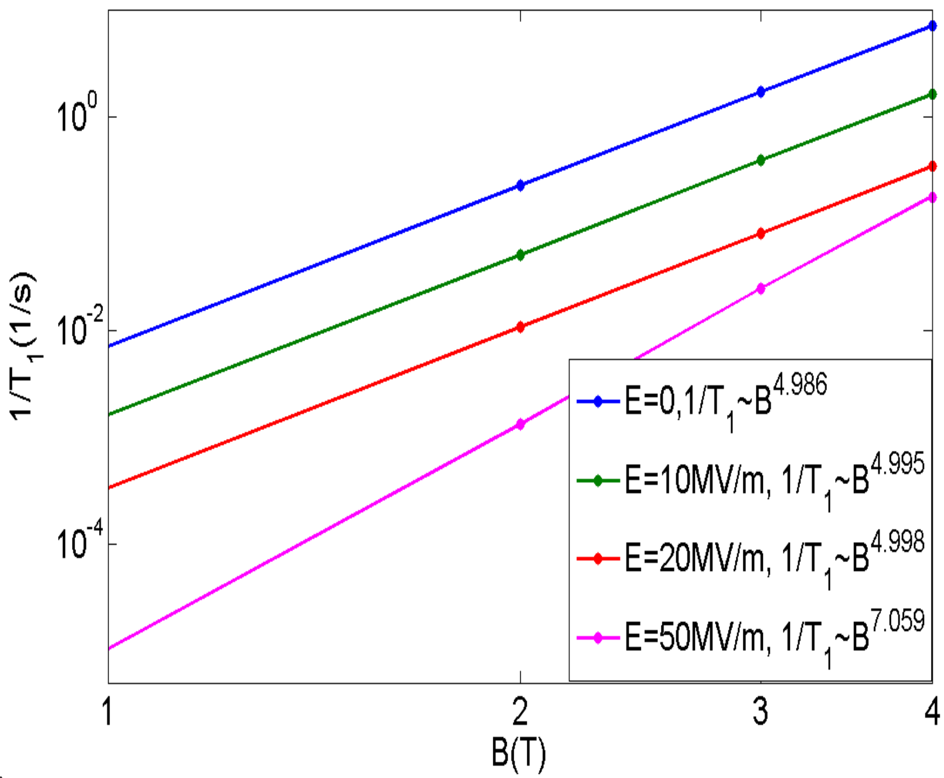
Interface donor T_1

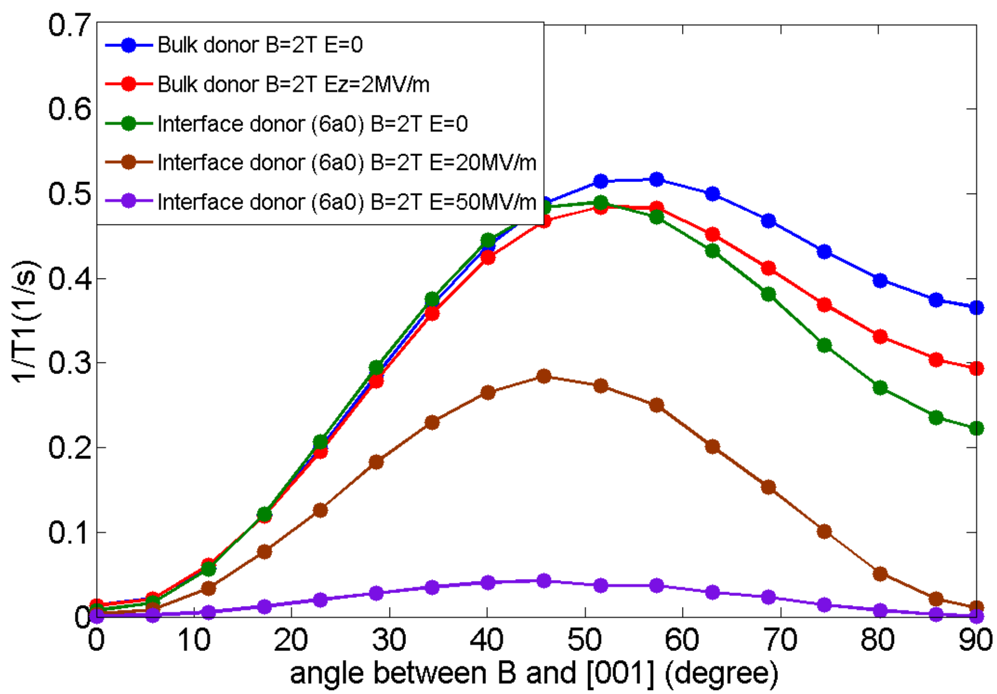
Method

- Interface donor states obtained from full-band tight-binding approach.
- Atomistic T_1 calculation.

Results

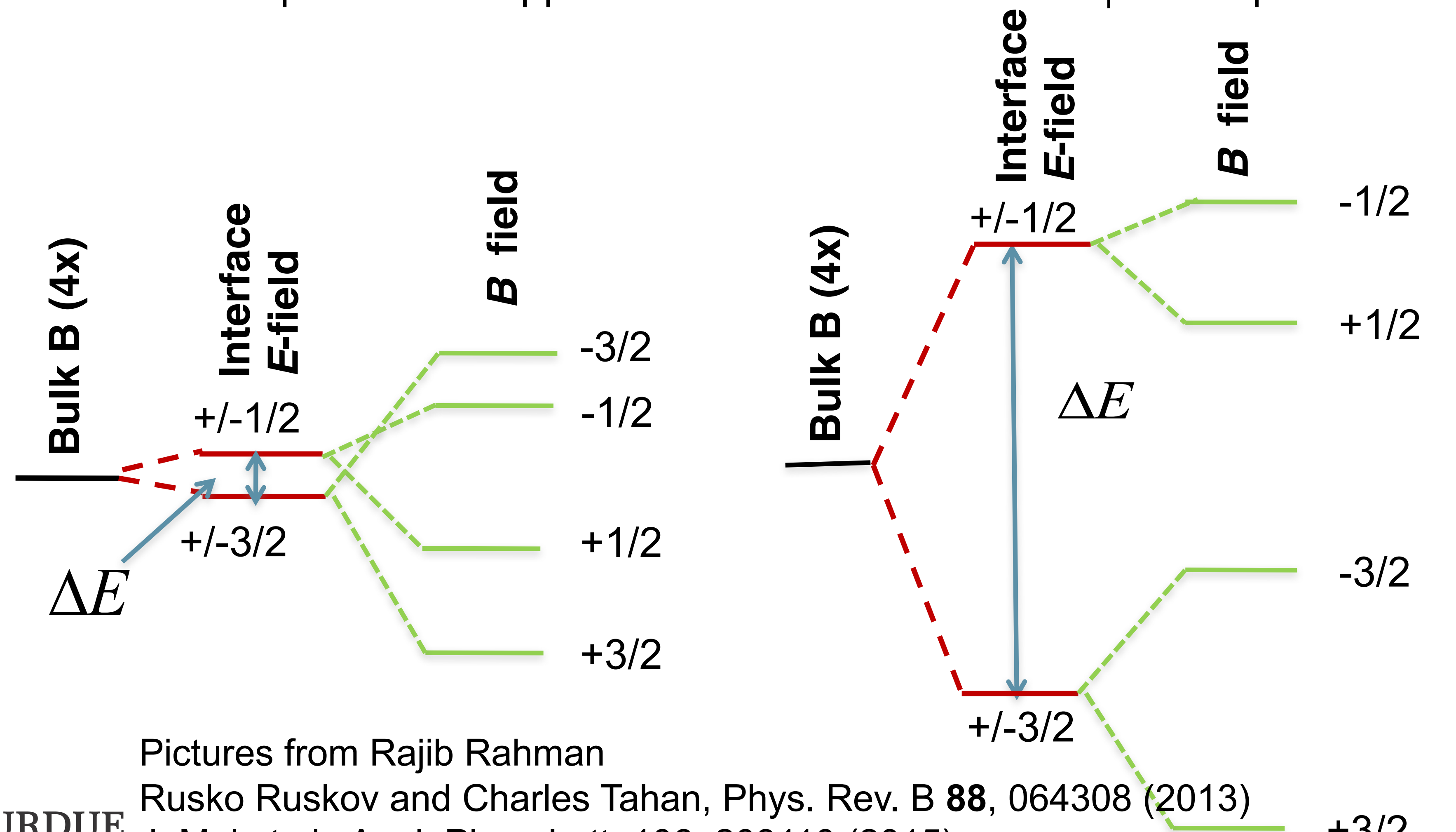
- $1/T_1 \sim B^5$ to B^7 transition as electron states move to the interface.
- T_1 anisotropy change with symmetry/valley information.





Motivation

- Qubit proposal using Boron acceptor has attracted some interest.
- T_1 mechanism in Boron has been studied theoretically.
- Need a comprehensive approach to understand Boron T_1 times quantitatively.

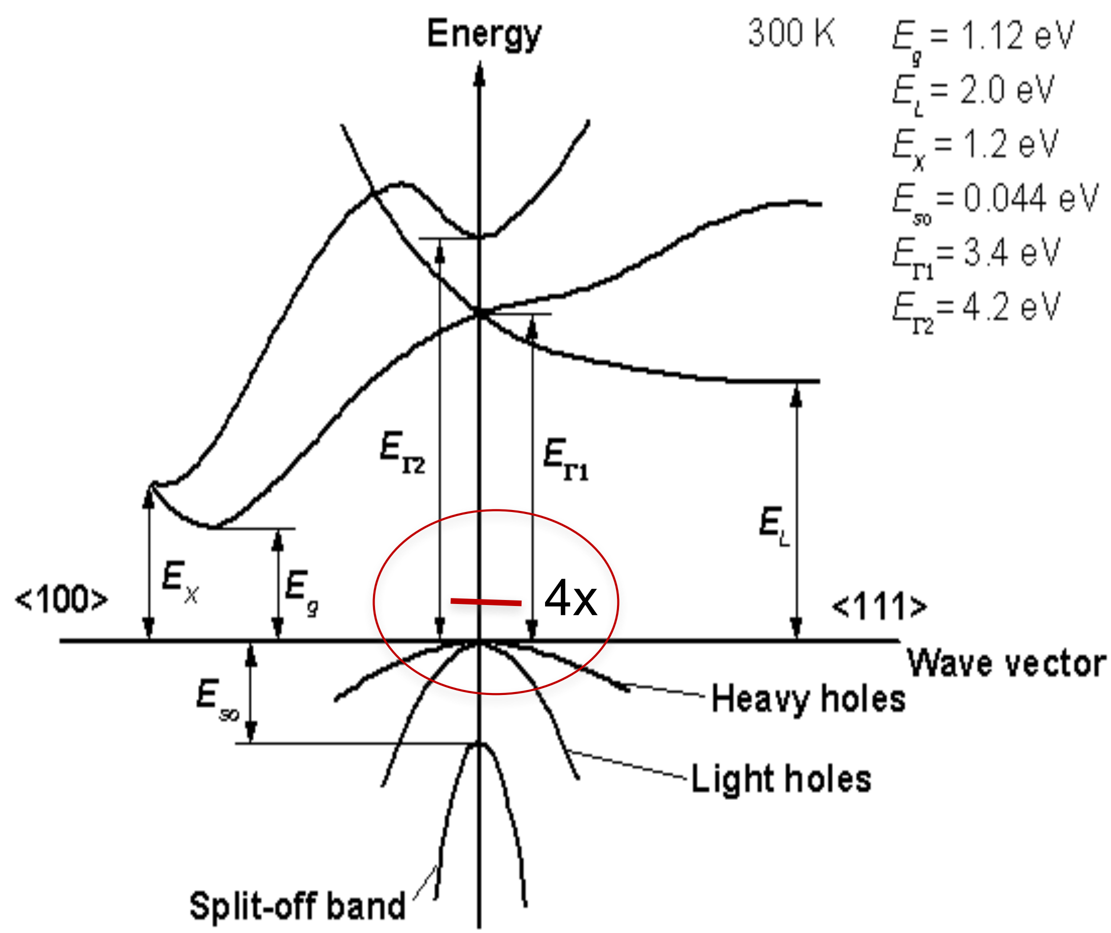


Pictures from Rajib Rahman
Rusko Ruskov and Charles Tahan, Phys. Rev. B **88**, 064308 (2013)
J. Mol et al., Appl. Phys. Lett. 106, 203110 (2015)

Method

- Bulk Boron and interface Boron states obtained from full-band tight-binding approach.
- Atomistic T_1 calculation.

Ground state of Boron at 45 meV above VB

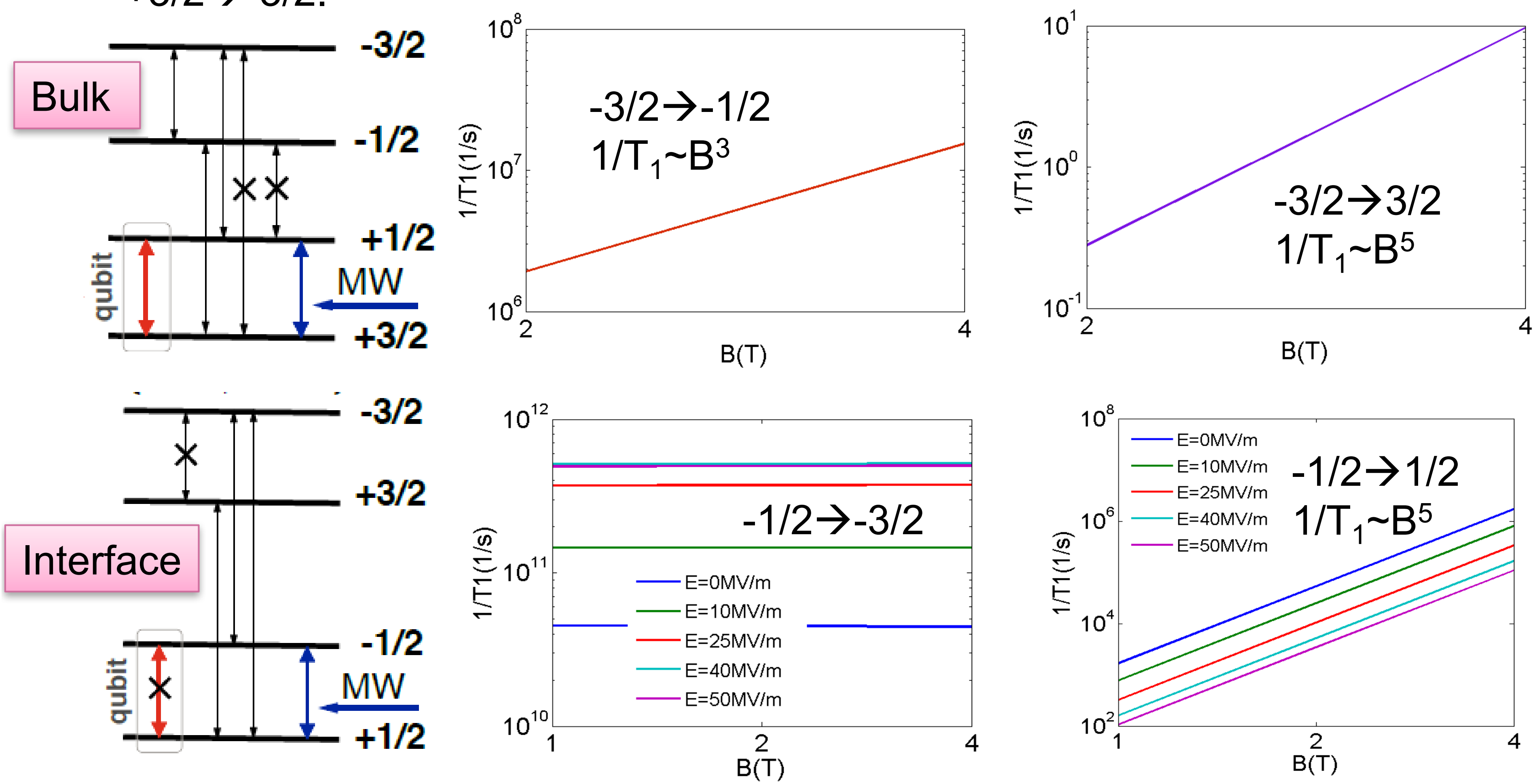


Si Bandstructure

Picture from Rajib Rahman

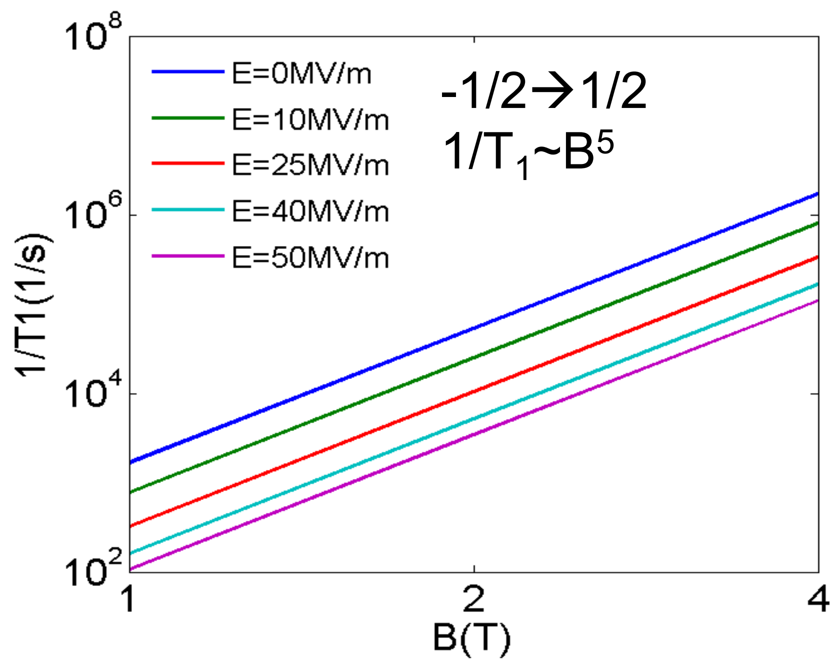
Preliminary Results

- Bulk Boron: $1/T_1 \sim B^3$ for $\pm 1/2 \rightarrow \pm 3/2$, $1/T_1 \sim B^5$ for $+1/2 \rightarrow -1/2$ and $+3/2 \rightarrow -3/2$
- Interface Boron: No B dependency for $\pm 1/2 \rightarrow \pm 3/2$, $1/T_1 \sim B^5$ for $+1/2 \rightarrow -1/2$ and $+3/2 \rightarrow -3/2$.

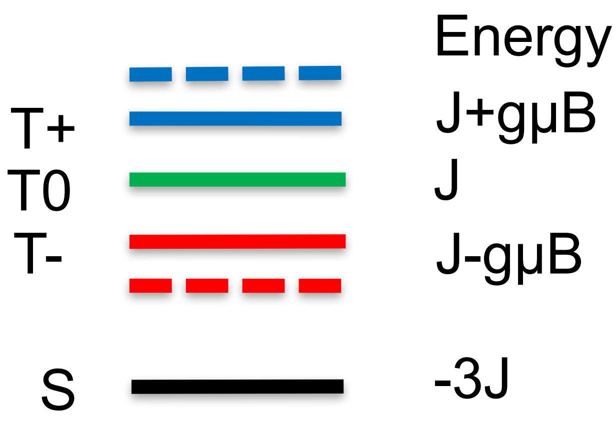


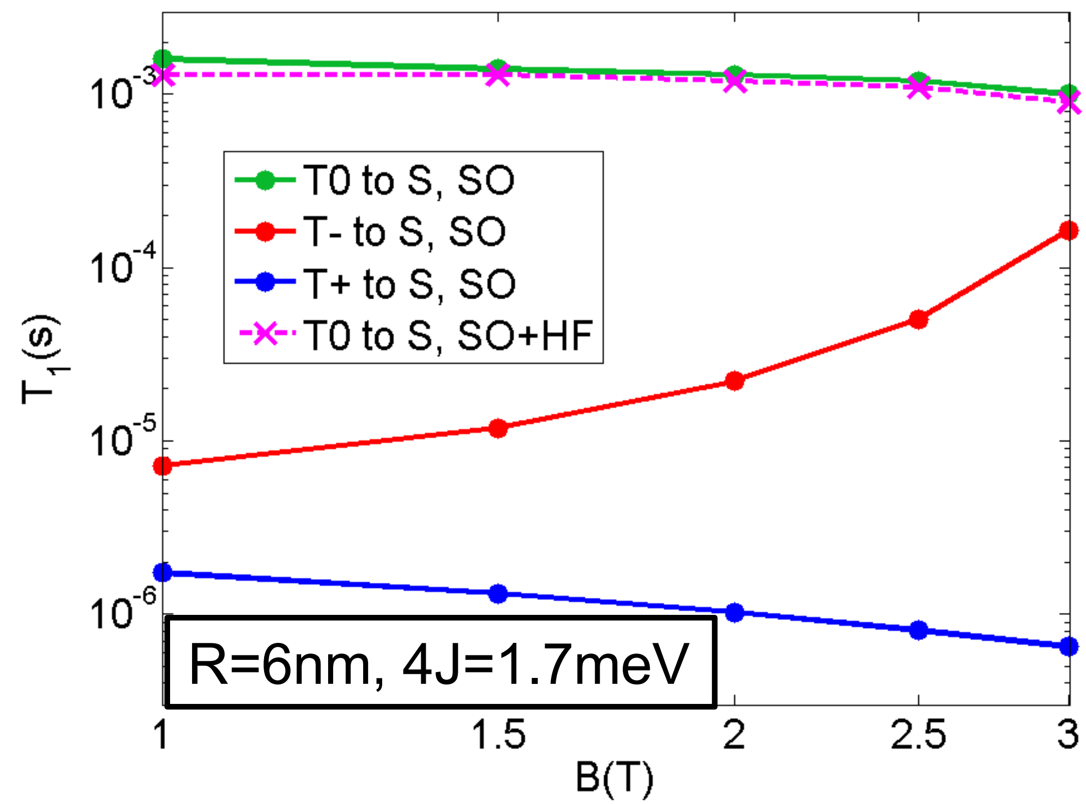
Expected Reuslts

- Explain the $1/T_1$ magnitude and B dependencies in both bulk and interface Boron.
- Explain the T_1 magnitude change with electric field for Boron near interface.



Results: T_1 v.s. B, J>gμB

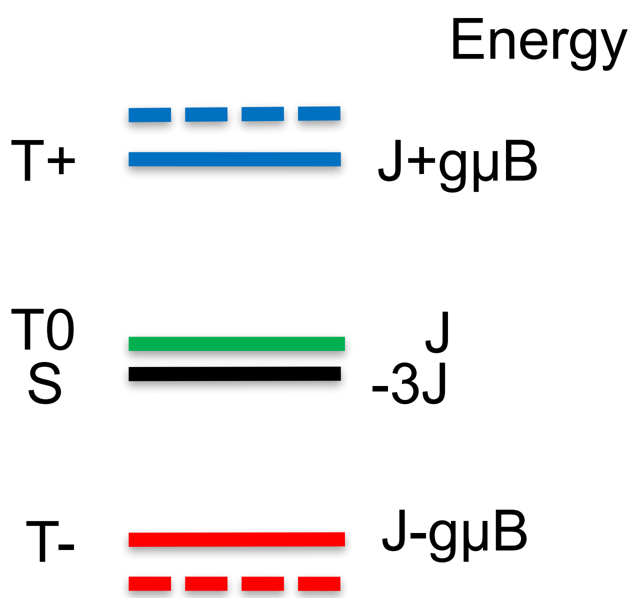


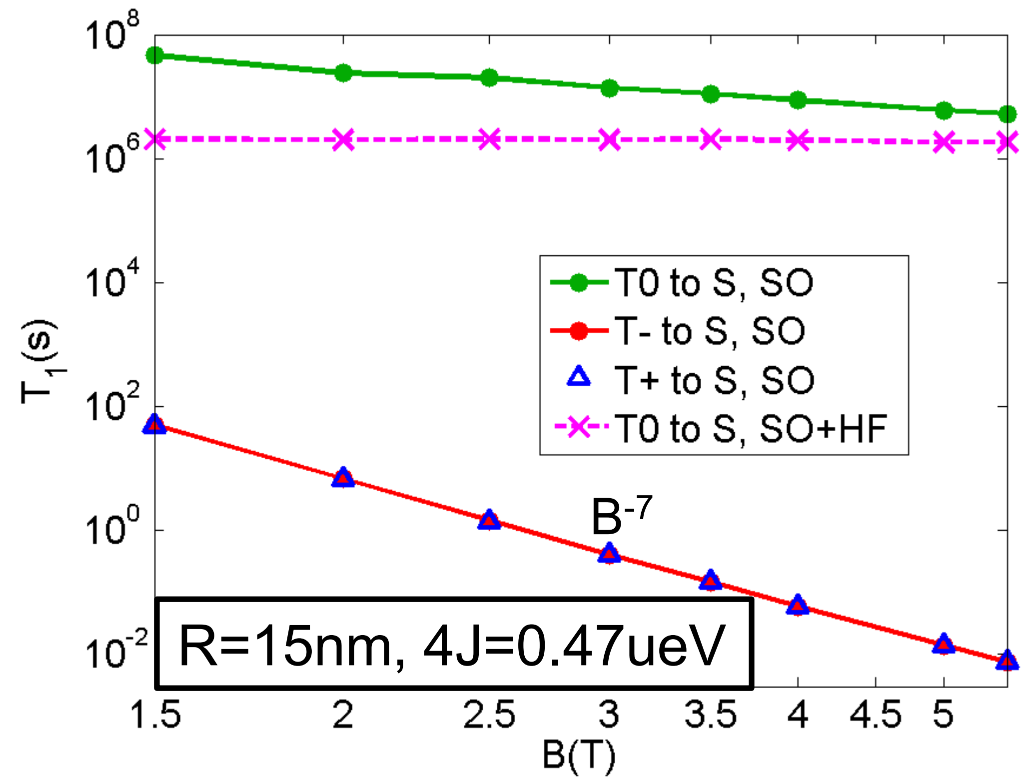


- As energy gap increases→ more phonon can couple → shorter T_1
- Weak B dependence
- SO dominates (A/J~0)

For R=6nm, weak B dependence, SO dominates.

Results: T_1 v.s. B, J<gμB

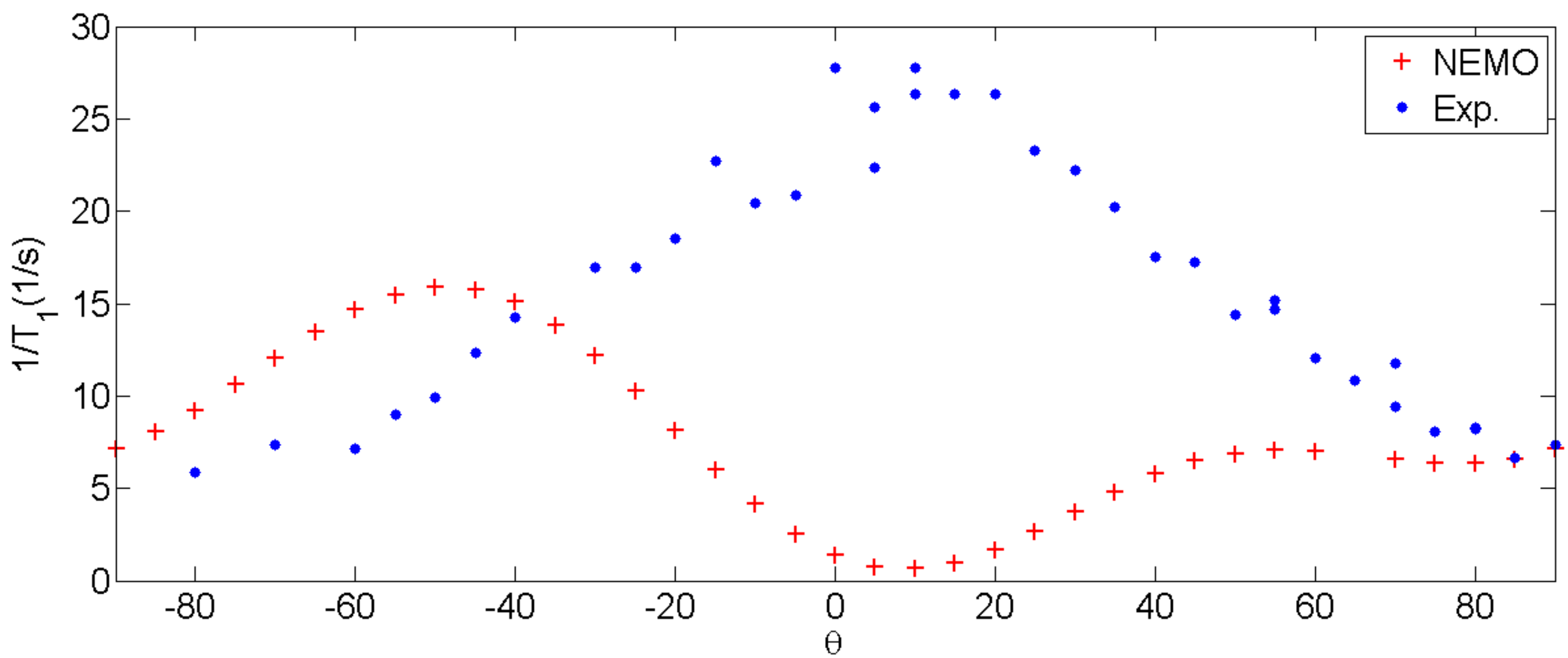




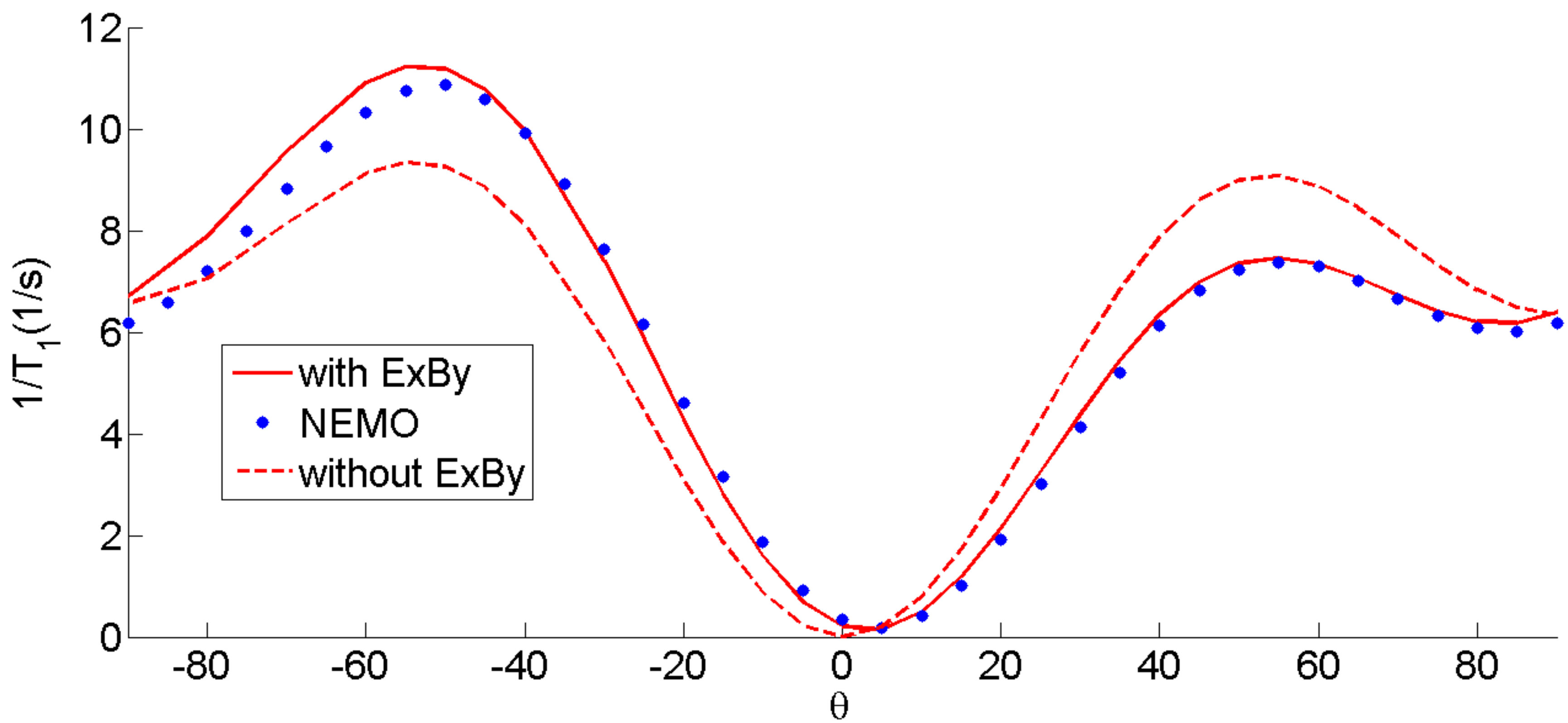
- As energy gap increases→ more phonon can couple → shorter T_1
- Strong B dependence
- Hyperfine dominates (A/J large)

For R=15nm, strong B dependence, hyperfine dominates.

NEMO v.s. Experiment

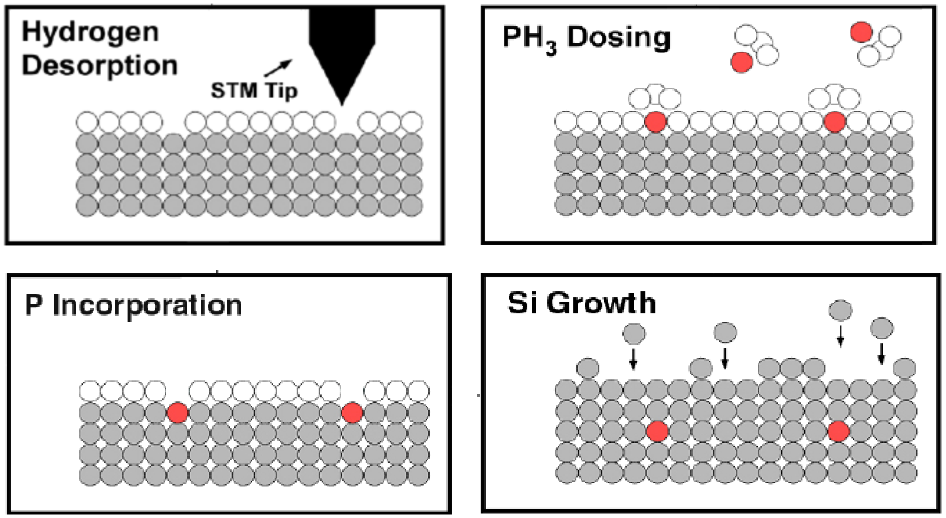


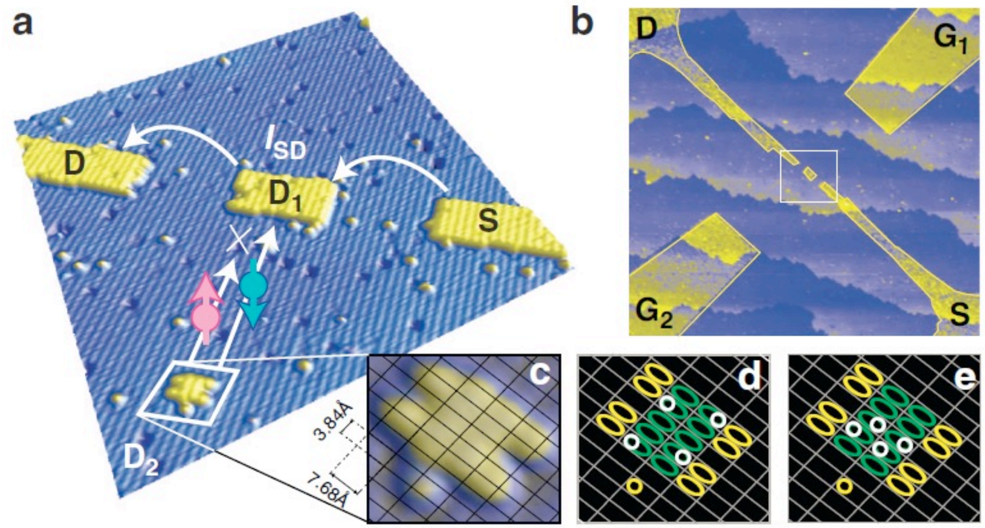
NEMO has ExBy



The Uncertainty in a STM Device

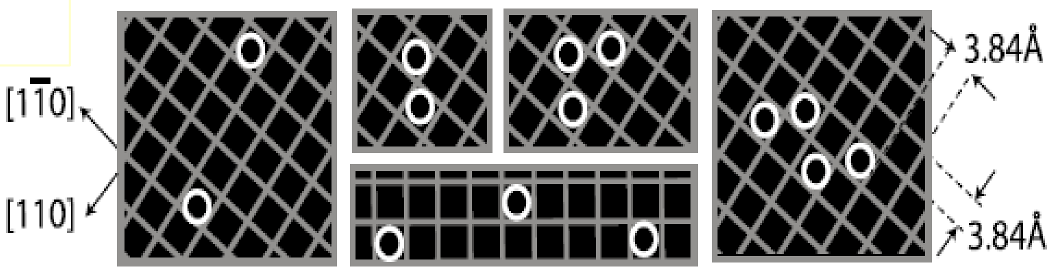
Place donor with atomic precision





H. Büch et al. Nature Communications 4, 2017 (2013)

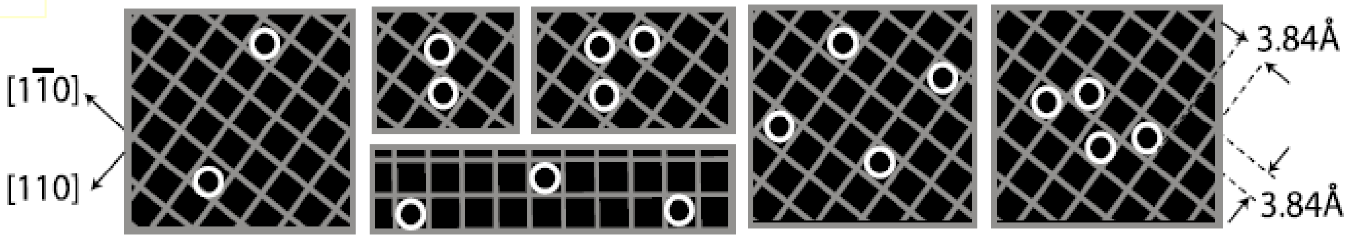
Donor Cluster

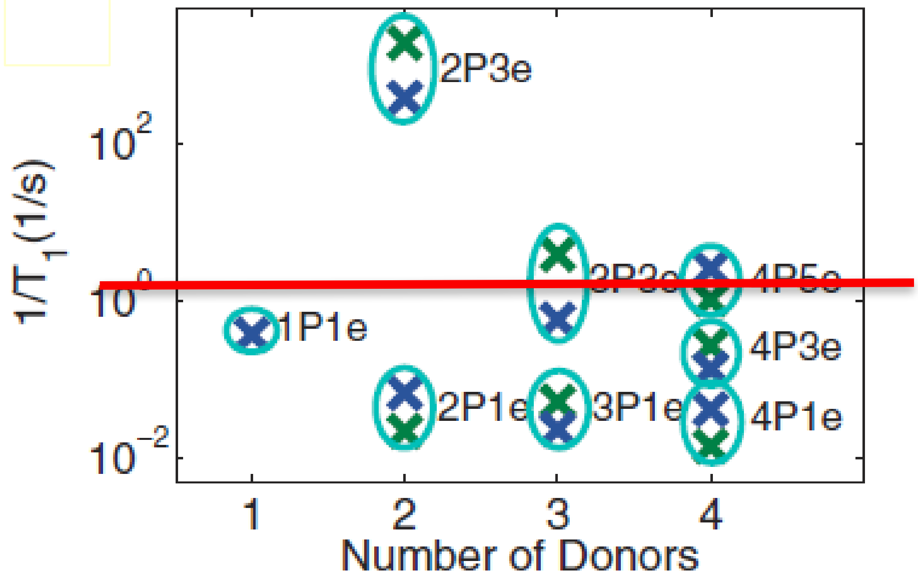


Unknown:
Donor/electron number

The exact donor/electron number in a donor cluster is unknown.

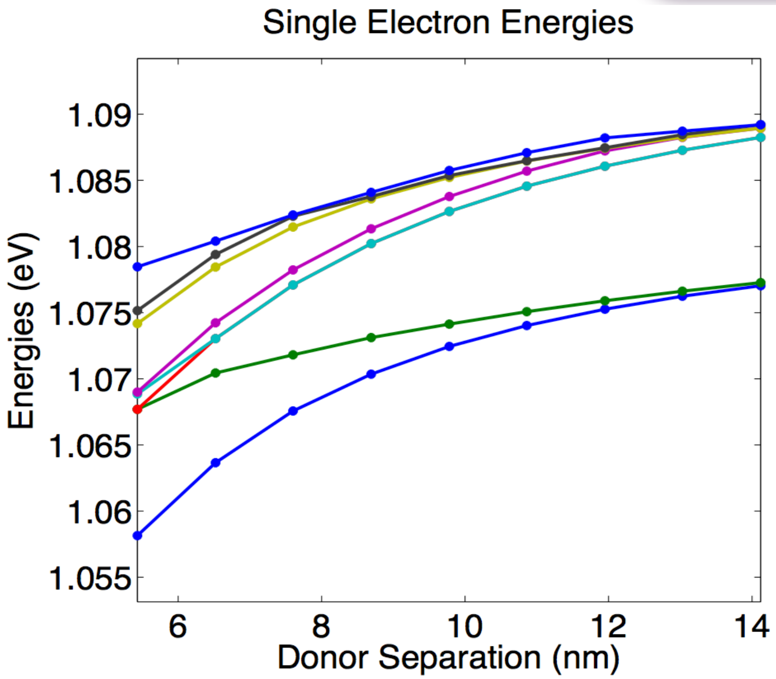
T_1 as a new method for determining donor/electron number

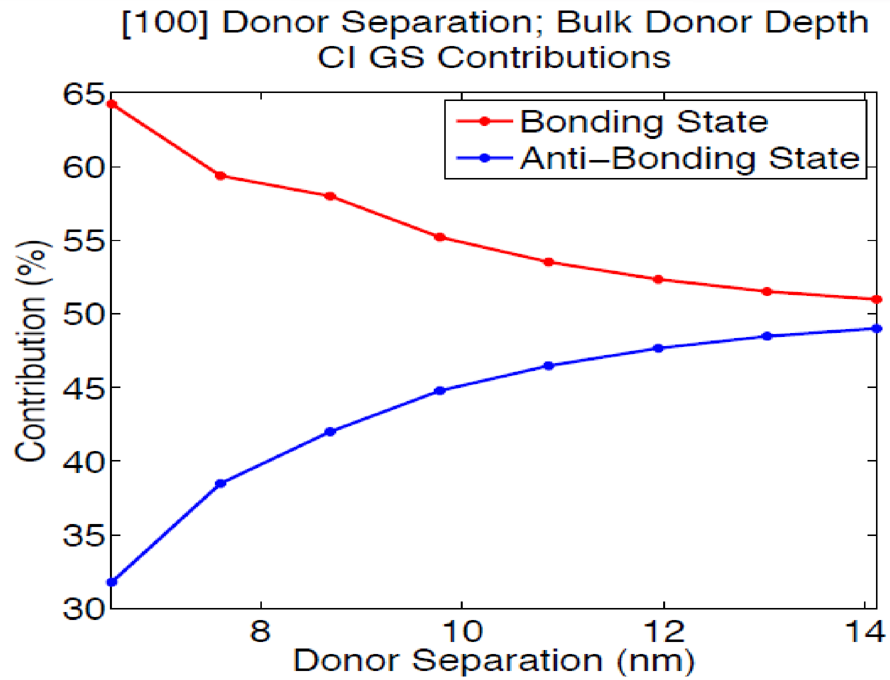




Measuring T_1 can serve as a non-invasive method to help determine the donor/electron number in the donor cluster.

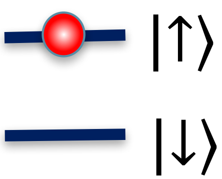
Y. Hsueh et al., Phys. Rev. Lett. 113, 246406 (2014)


Single Electron Energies
Energies (eV)
1.09
1.085
1.08
1.075
1.07
1.065
1.06
1.055
6
8
10
12
14
Donor Separation (nm)


[100] Donor Separation; Bulk Donor Depth
CI GS Contributions
Bonding State
Anti–Bonding State
Contribution (%)
65
60
55
50
45
40
35
30
8
10
12
14
Donor Separation (nm)

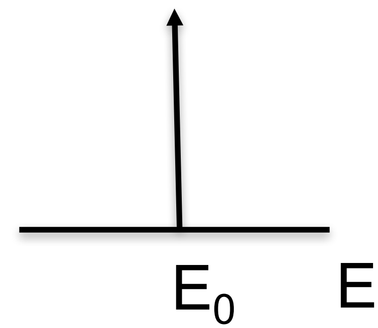
$$Hep(r_1,r_2)=Hep(r_1)+Hep(r_2)$$

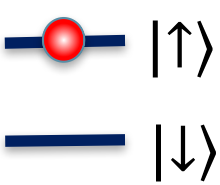
The Finite Lifetime



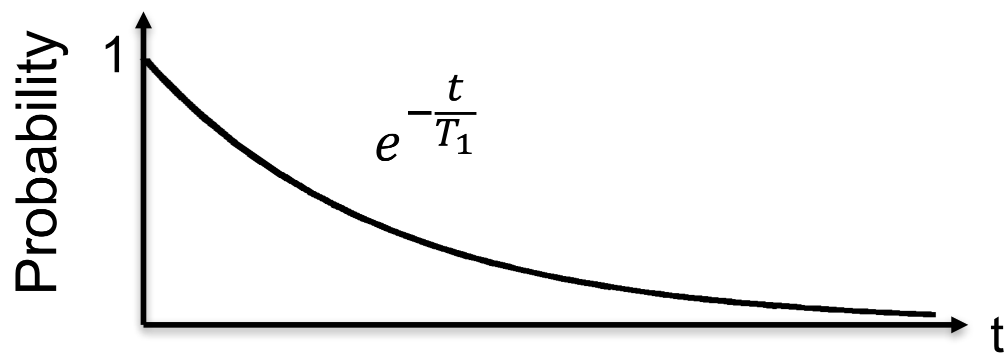
Stationary states

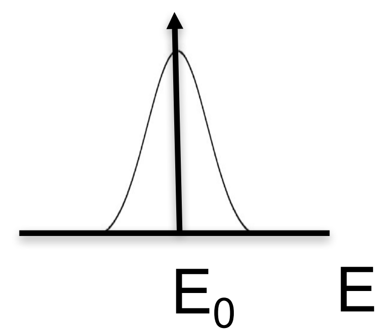
Energy spectrum





States with finite lifetime

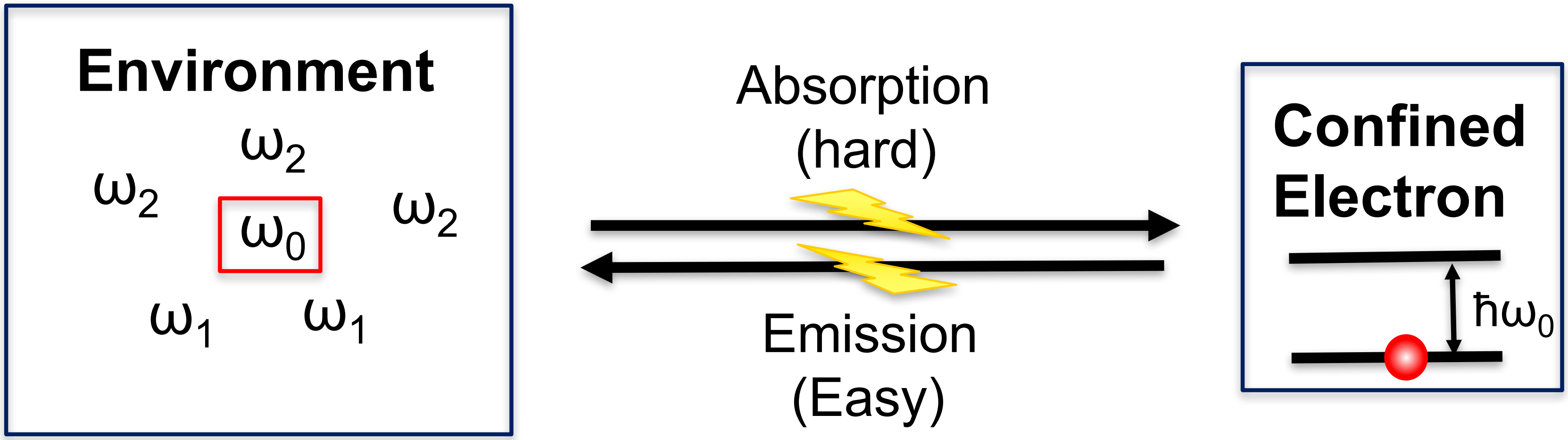


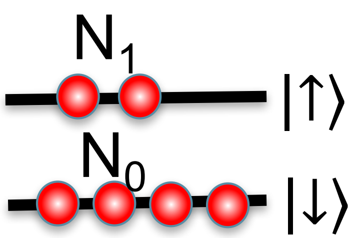


Scattering processes result in finite lifetime of electron states and energy broadening.

System at Thermal Equilibrium

Why does the electron wants to be at its lower energy state?





N_0x(Absorption rate)=N_1x(Emission rate)

large small small large

Emission rate is always greater than absorption rate at thermal equilibrium→$N_0 > N_1$

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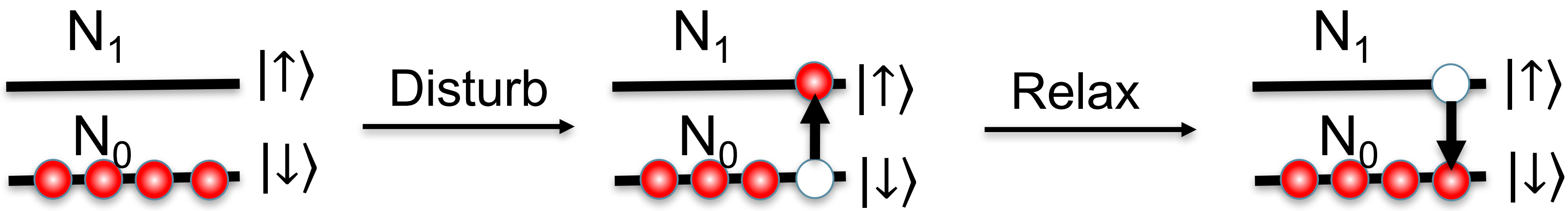
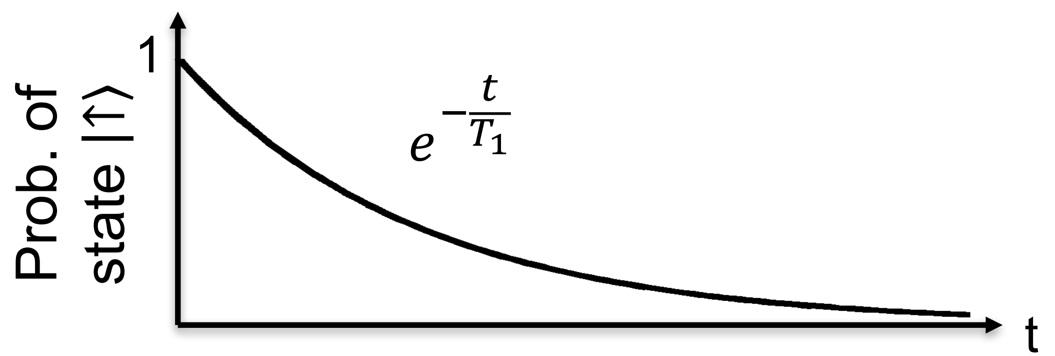
The Relaxation Process

At low temperature (<2K)





The T_1 time is the characteristic time to restore the system to thermal equilibrium

Rashba effective field

$$H_{SO}^{eff} = \underbrace{R(\boldsymbol{k}\times\boldsymbol{E})}_{\mathrm{B^{eff}}} \cdot \begin{pmatrix} \alpha_X & & \\ & \alpha_Y & \\ & & \alpha_Z \end{pmatrix} \cdot \sigma$$