Giant Anisotropy of Spin Relaxation and Spin-valley Mixing in a Silicon Quantum Dot

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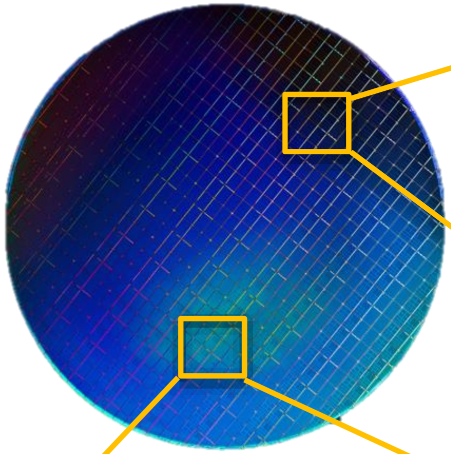
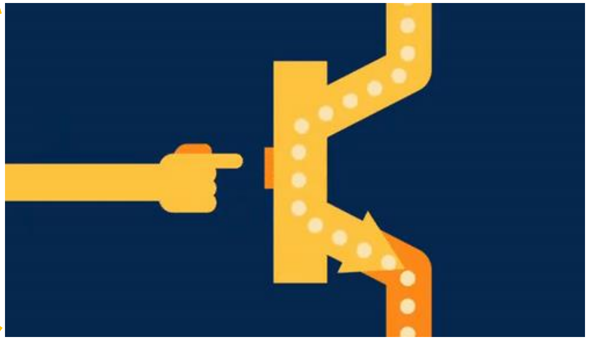
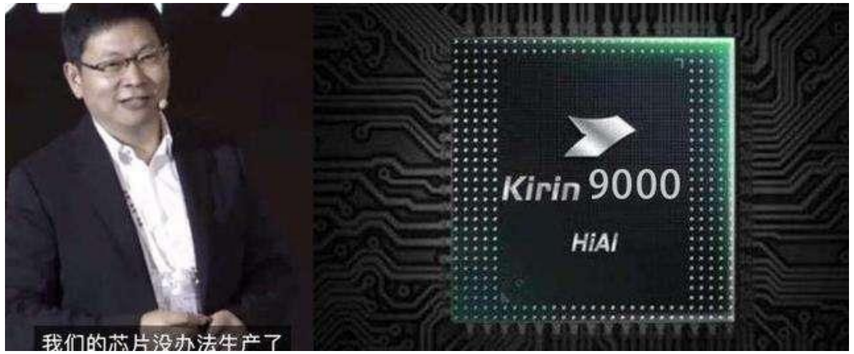
Supervisors: Hai-Ou Li (李海欧)，Guoping Guo (郭国平)

Motivation

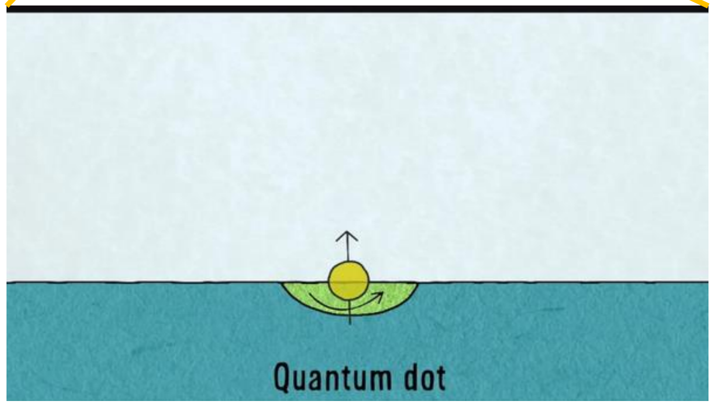


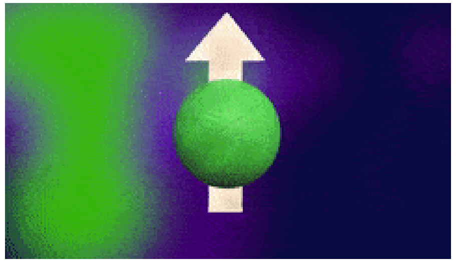


Classical bit

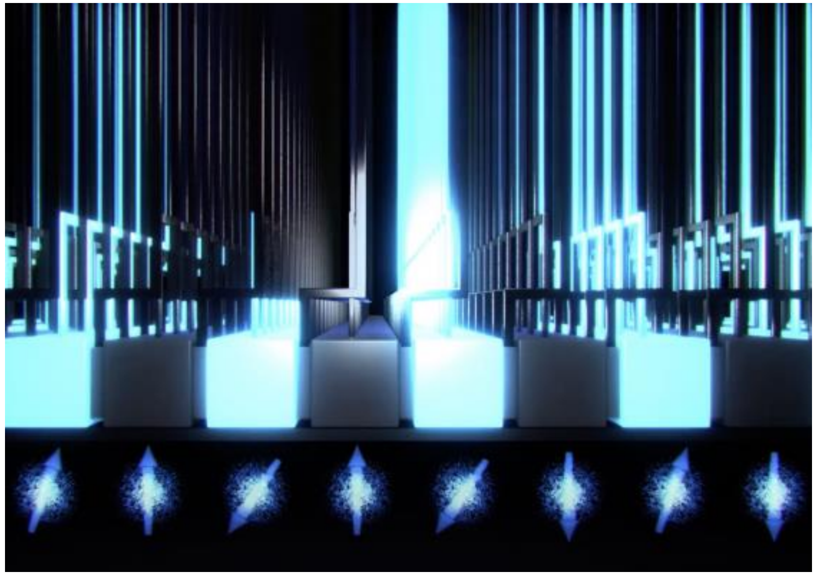


CPU



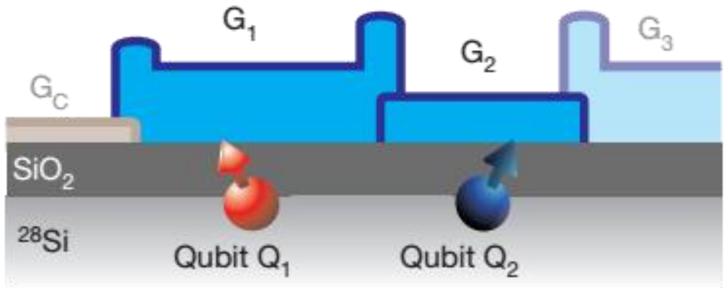


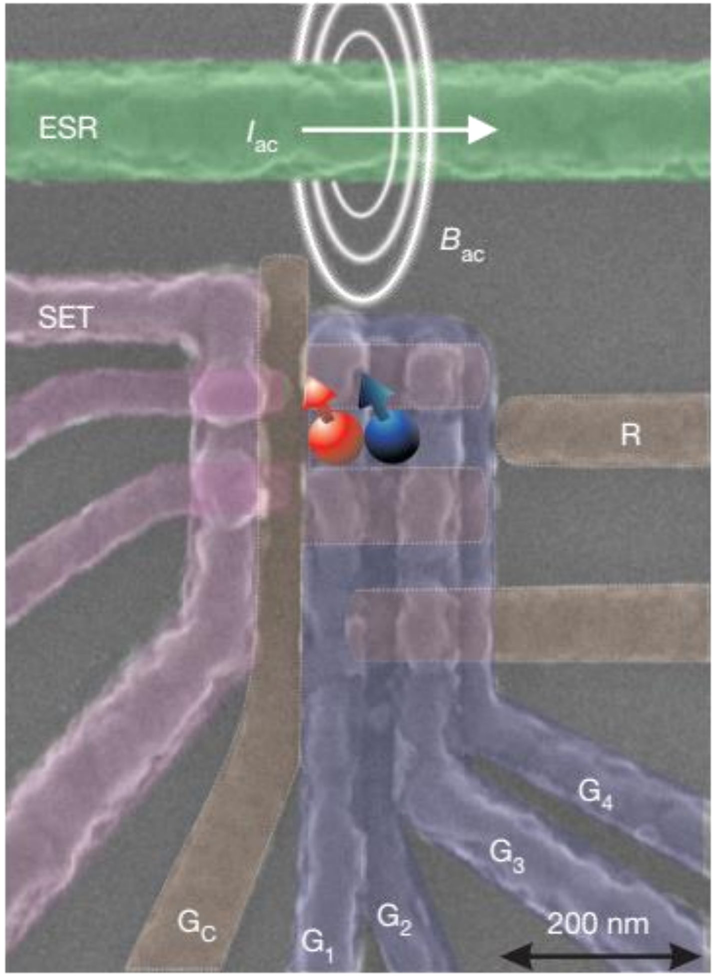
Quantum bit (Qubit)



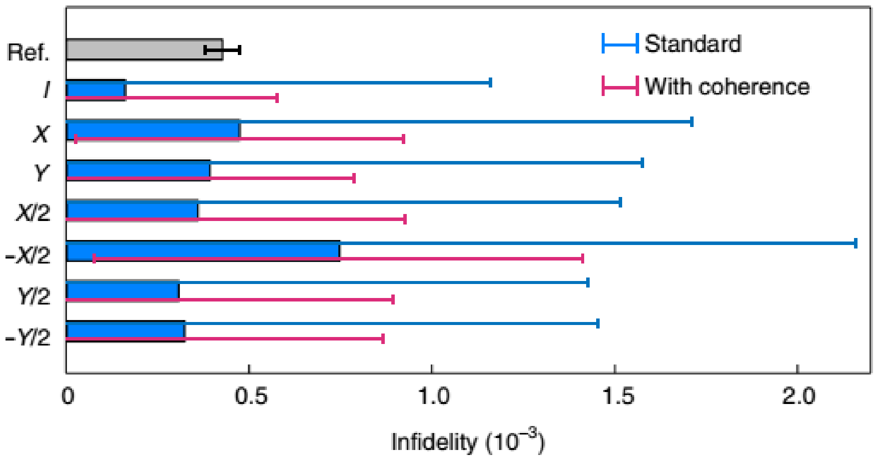
Quantum CPU

Motivation

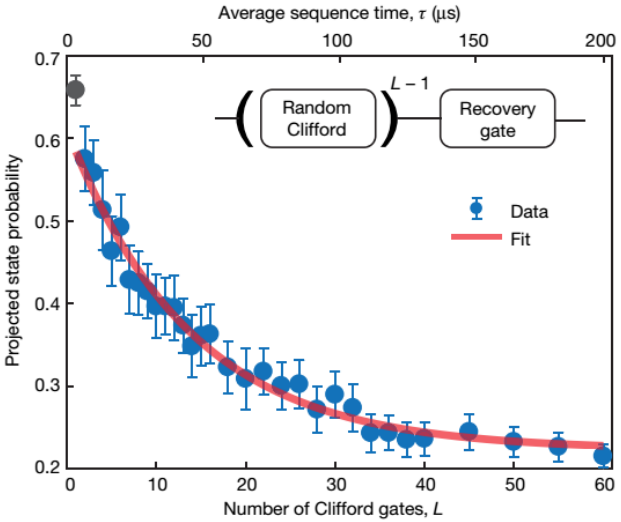


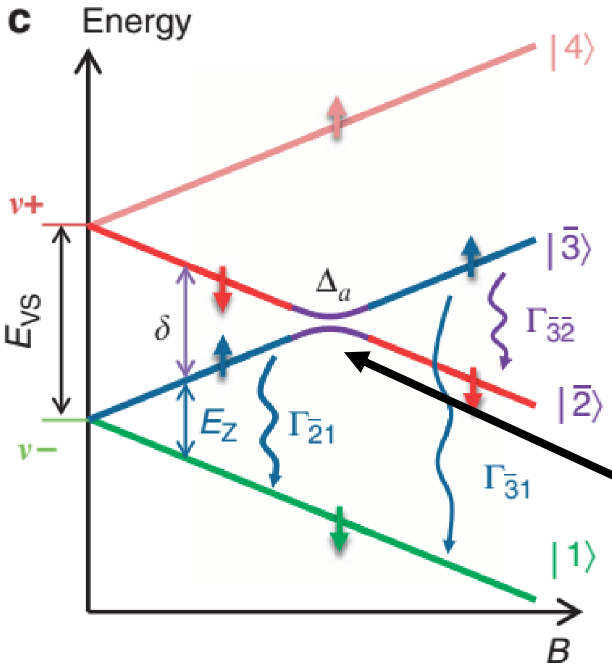


Single-qubit gate fidelity: 99.957% (Clifford)



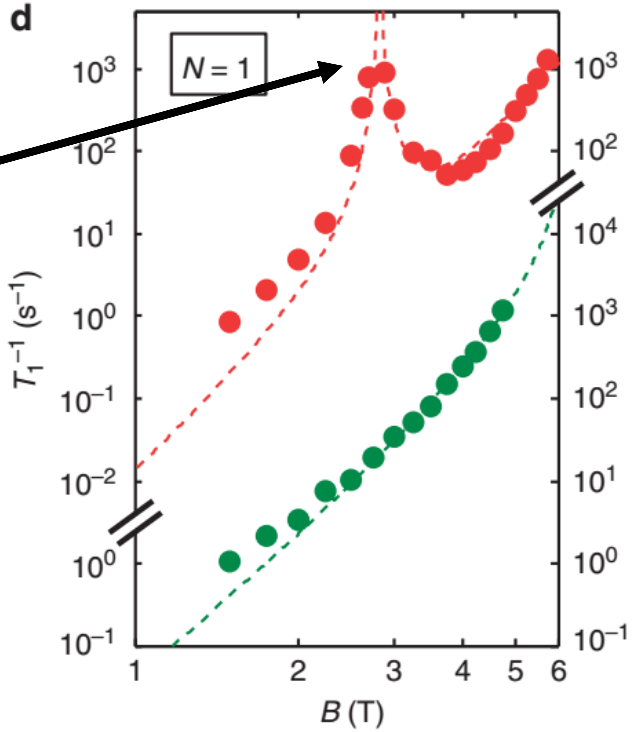
Two-qubit gate fidelity: 98% (CROT)





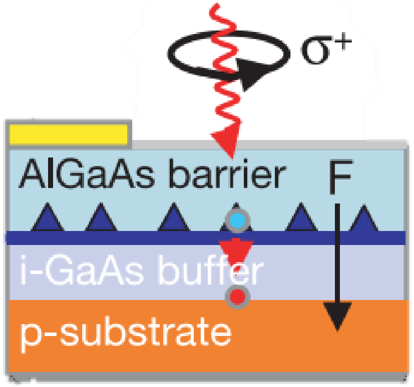
Spin relaxation “hot spot”

Spin-valley mixing



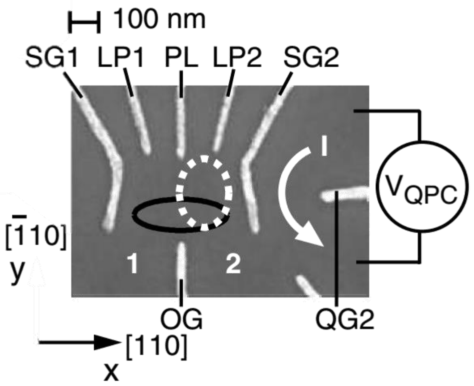
Motivation

B dependence



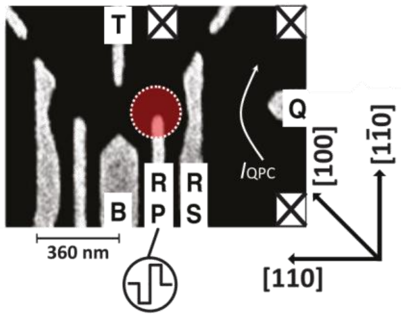
M. Kroutvar et al. Science 2004
L. C. Camenzind et al. Nat. Commun. 2018

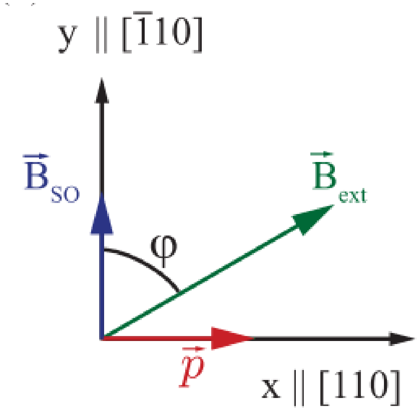
Gate voltage dependence



S. Amasha et al. Phys. Rev. Lett. 2008
V. Srinivasa et al. Phys. Rev. Lett. 2013

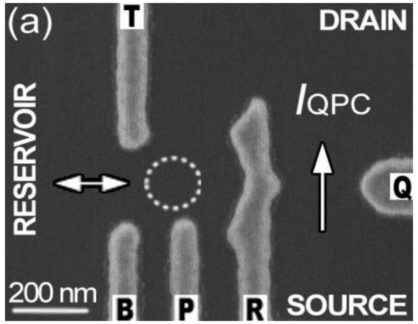
Anisotropy



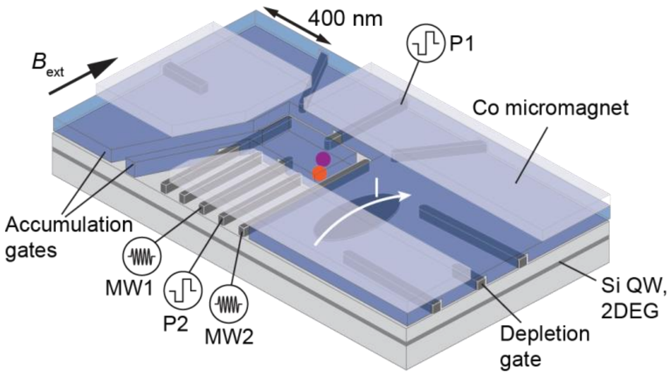


P. Scarlino et al. Phys. Rev. Lett. 2014
A. Hofmann et al. Phys. Rev. Lett. 2017
L. C. Camenzind et al. Nat. Commun. 2018

Variation: $\times$ 10



R. R. Hayes et al. arXiv: 0908.0173
M. Xiao et al. Phys. Rev. Lett. 2010
C. H. Yang et al. Nat. Commun. 2013
L. Petit et al. Phys. Rev. Lett. 2018
F. Borjans et al. Phys. Rev. Appl. 2019
A. Hollmann et al. Phys. Rev. Appl. 2020



T.F. Watson et al. Nature 2018
W. Huang et al. Nature 2019
R. C. C. Leon et al. Nat. Commun. 2020

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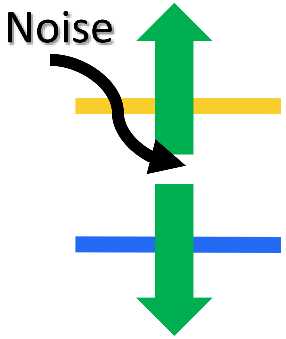
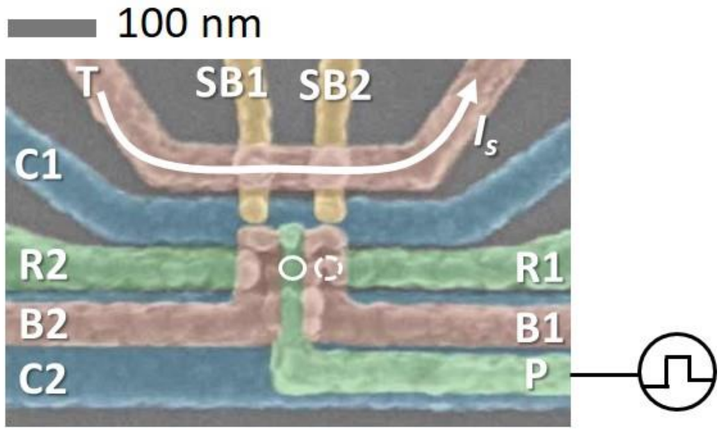
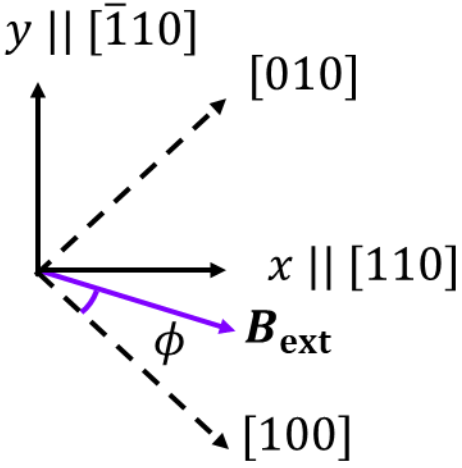
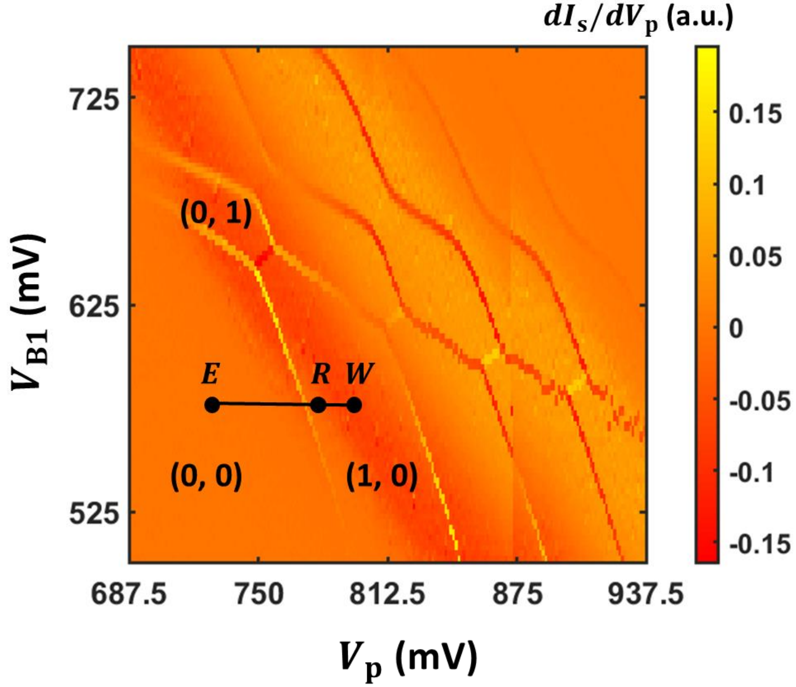


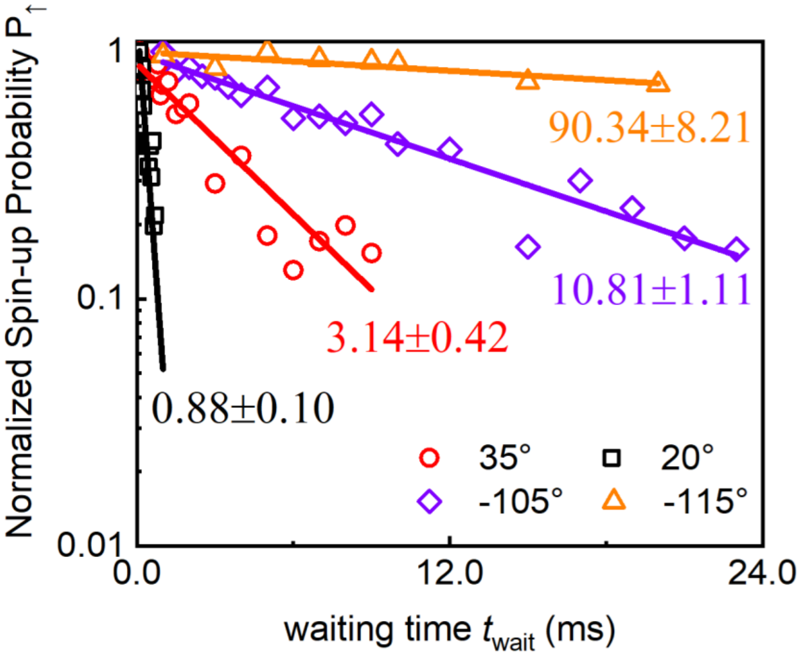
Device and measurement method

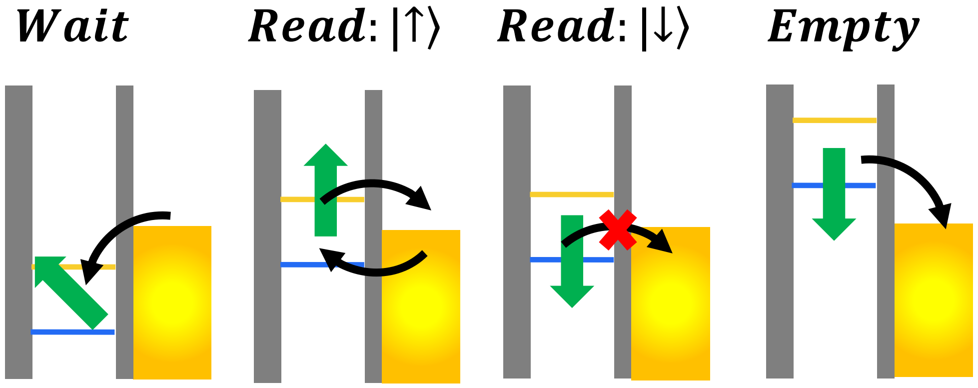






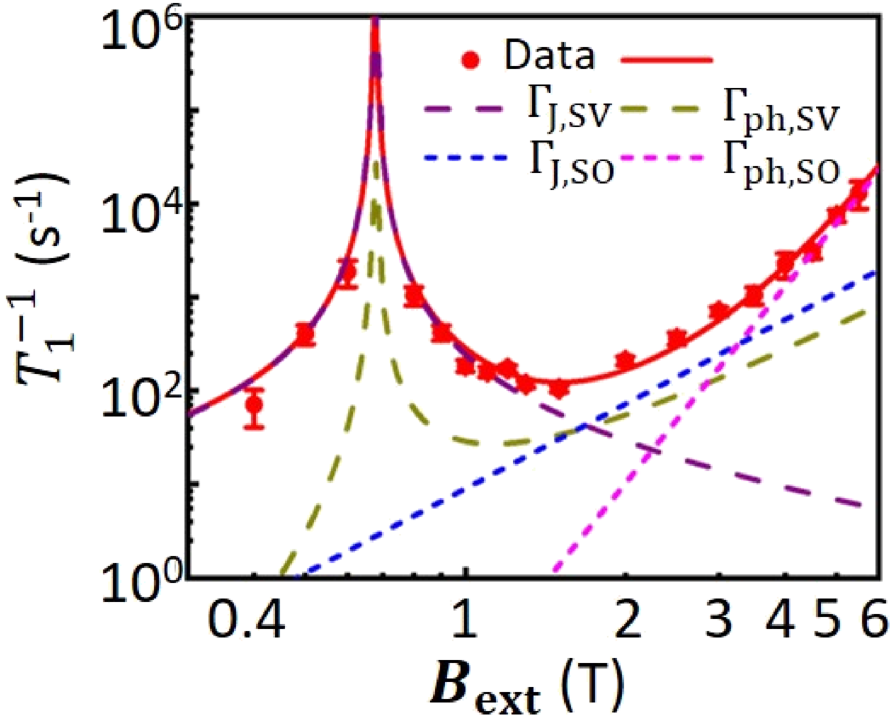
$$P_\uparrow = \rho \exp(-t_{\mathrm{wait}}/T_1) + \alpha$$



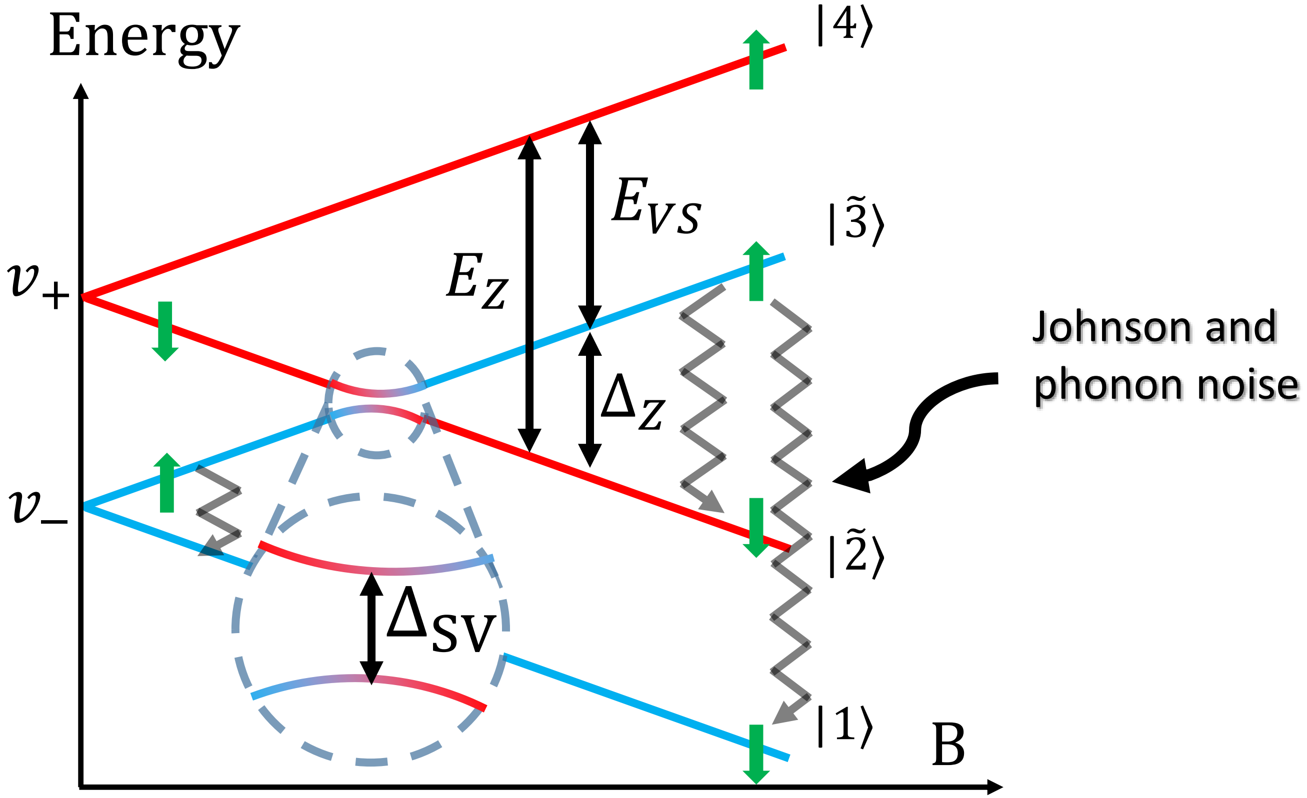


J. M. Elzerman et al. Nature 2004

B dependence: spin-valley relaxation "hot spot"



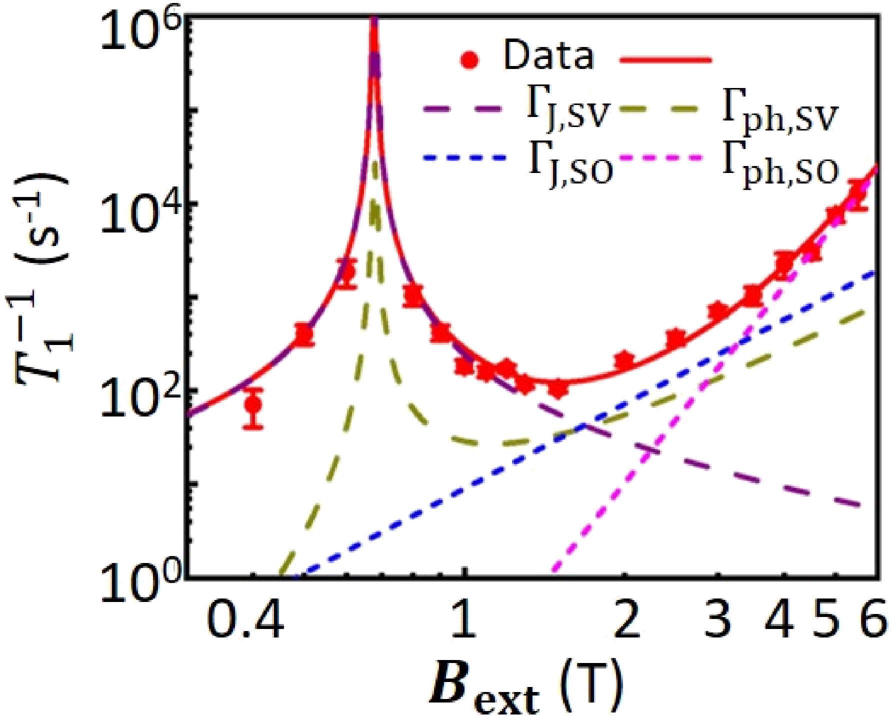
C. H. Yang et al. Nat. Commun. 2013
P. Huang et al. Phys. Rev. B. 2014
C. Tahan and R. Joynt. Phys. Rev. B. 2014
L. Petit et al. Phys. Rev. Lett. 2018
F. Borjans et al. Phys. Rev. Appl. 2019
A. Hollmann et al. arXiv:1907.04146v1



$$T_1^{-1} = \left(c_J E_Z + c_{ph} E_Z^5\right) F_{SV}(E_Z)$$

$$F_{SV}(E_Z) = 1 - 1/\sqrt{1 + (\Delta_{SV}/\Delta_Z)^2}$$

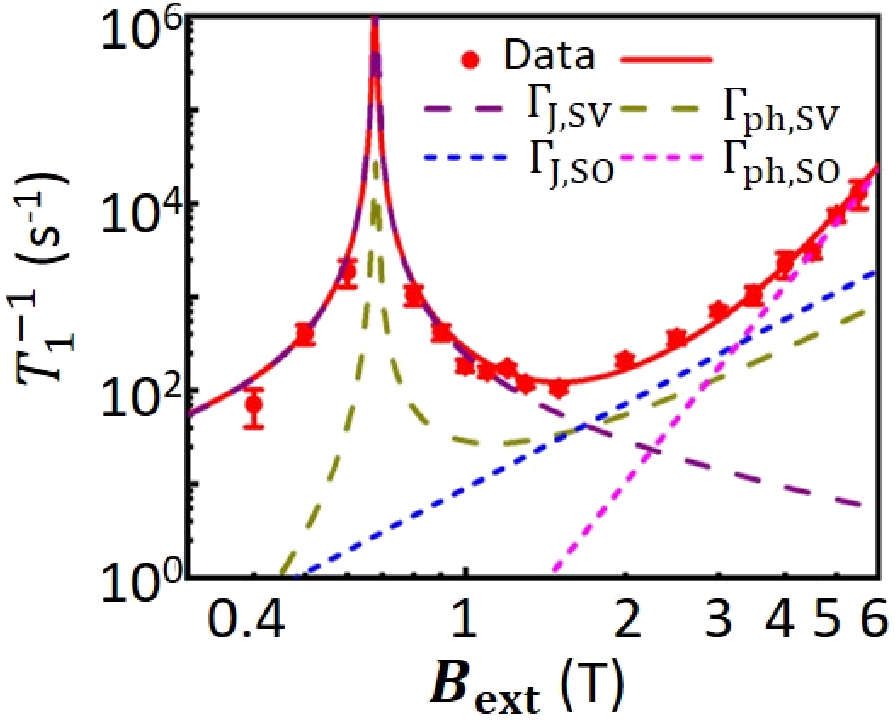
B dependence: different relaxation channels

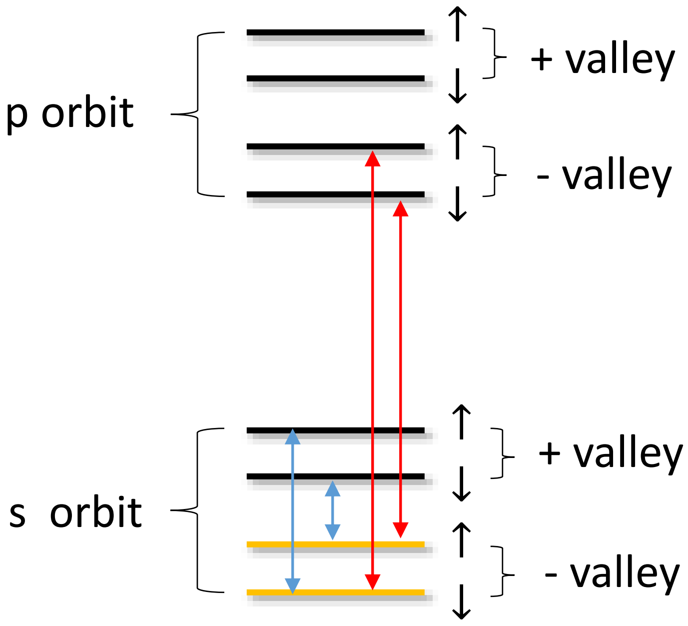


C. H. Yang et al. Nat. Commun. 2013
P. Huang et al. Phys. Rev. B. 2014
C. Tahan and R. Joynt. Phys. Rev. B. 2014
L. Petit et al. Phys. Rev. Lett. 2018
F. Borjans et al. Phys. Rev. Appl. 2019
A. Hollmann et al. arXiv:1907.04146v1

$$T_1^{-1} = \underbrace{\Gamma_{\mathrm{J,SV}} + \Gamma_{\mathrm{ph,SV}}}_{\left(c_{\mathrm{J,SV}}E_Z + c_{\mathrm{ph,SV}}E_Z^5\right)\left(1 - 1/\sqrt{1+(\Delta_{\mathrm{SV}}/\Delta_Z)^2}\right)} + \Gamma_{\mathrm{J,SO}} + \Gamma_{\mathrm{ph,SO}} + \Gamma_{\mathrm{const}}$$

B dependence: different relaxation channels

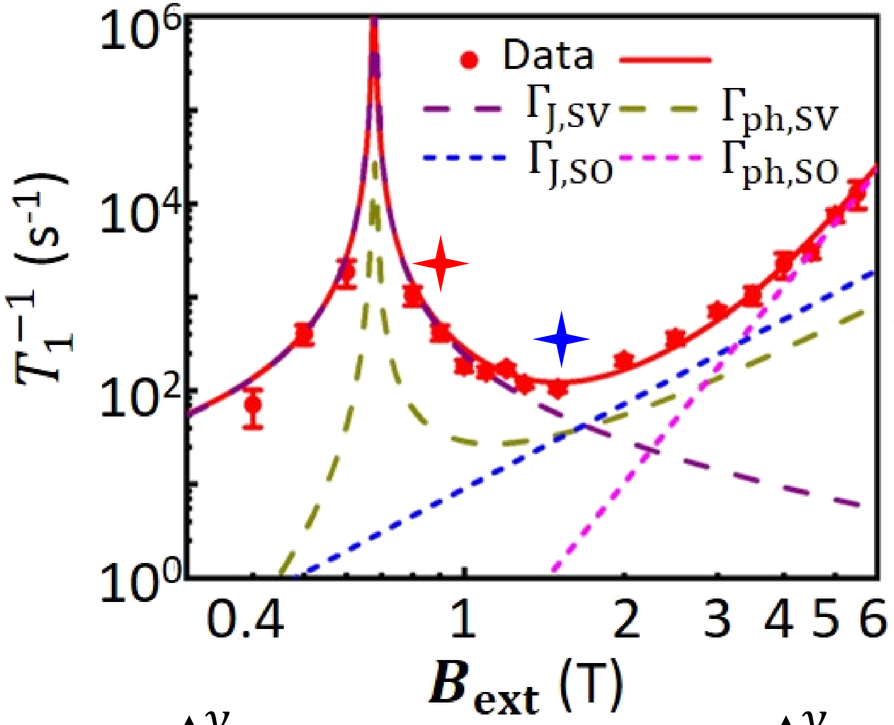


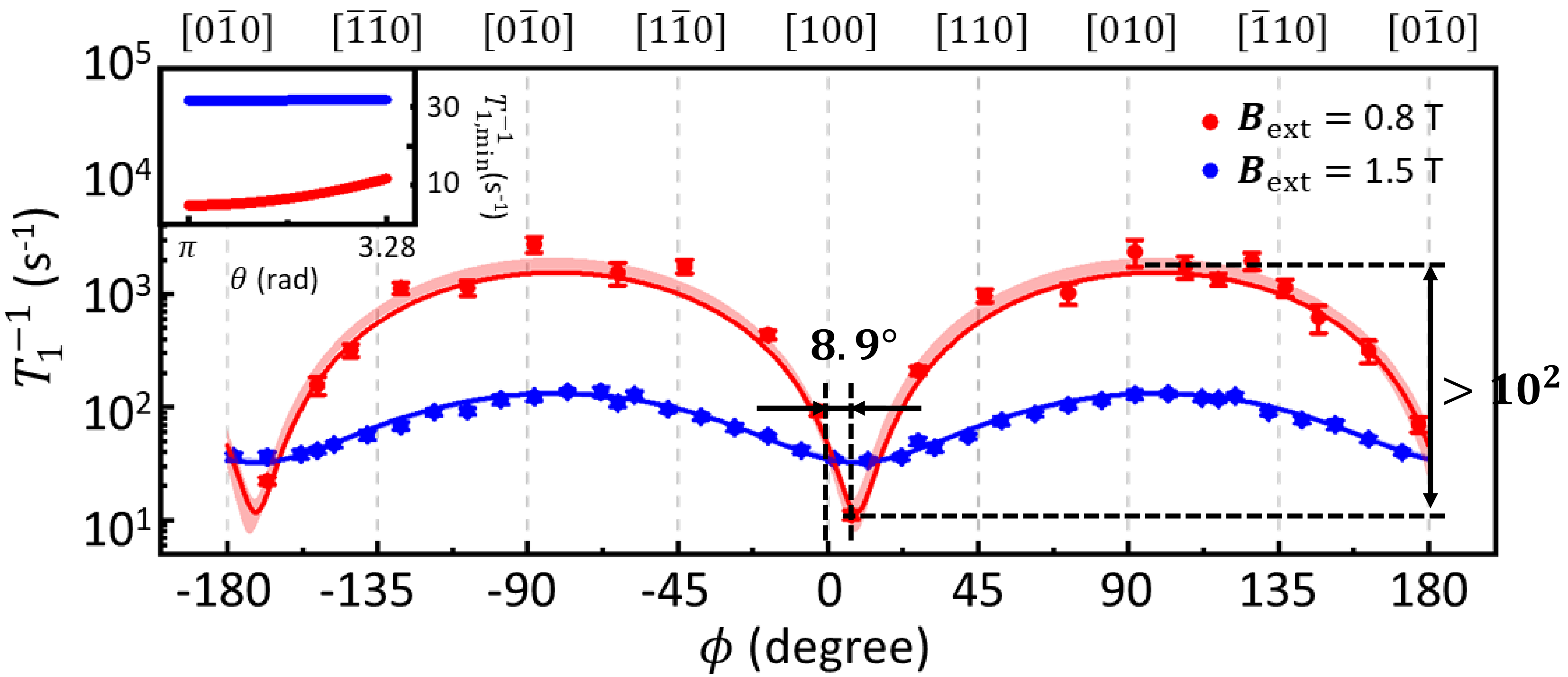


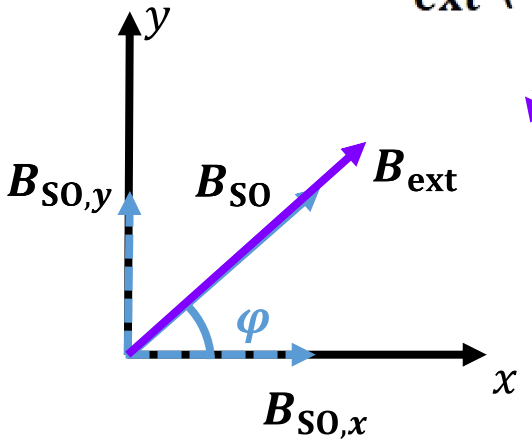
C. H. Yang et al. Nat. Commun. 2013
P. Huang et al. Phys. Rev. B. 2014
C. Tahan and R. Joynt. Phys. Rev. B. 2014
L. Petit et al. Phys. Rev. Lett. 2018
F. Borjans et al. Phys. Rev. Appl. 2019
A. Hollmann et al. arXiv:1907.04146v1

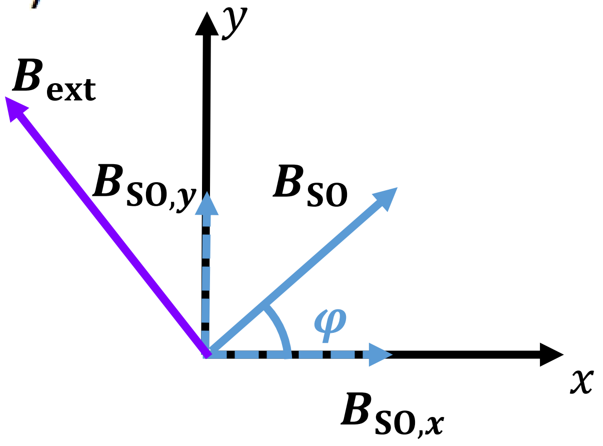
$$T_1^{-1} = \underbrace{\Gamma_{\mathrm{J,SV}} + \Gamma_{\mathrm{ph,SV}}}_{(c_{\mathrm{J,SV}} E_Z + c_{\mathrm{ph,SV}} E_Z^5)\left(1 - 1/\sqrt{1 + (\Delta_{\mathrm{SV}}/\Delta_Z)^2}\right)} + \overbrace{\Gamma_{\mathrm{J,SO}} + \Gamma_{\mathrm{ph,SO}}}^{c_{\mathrm{J,SV}} E_Z^3 + c_{\mathrm{ph,SV}} E_Z^7} + \overset{E_Z^0}{\Gamma_{\mathrm{const}}}$$

Spin relaxation anisotropy









$$\Delta_{SV} = 2\langle \uparrow | H_{SV} | \downarrow \rangle = \langle \uparrow | \boldsymbol{B}_{SO} \cdot \boldsymbol{\sigma} | \downarrow \rangle$$

$$\boldsymbol{B}_{SO} = \frac{2im^* E_{VS}}{\hbar\gamma} \left(\alpha_- r_y^{-+} \hat{\boldsymbol{x}} + \alpha_+ r_x^{-+} \hat{\boldsymbol{y}} \right)$$

P. Stano and J. Fabian, Phys. Rev. B. 2005

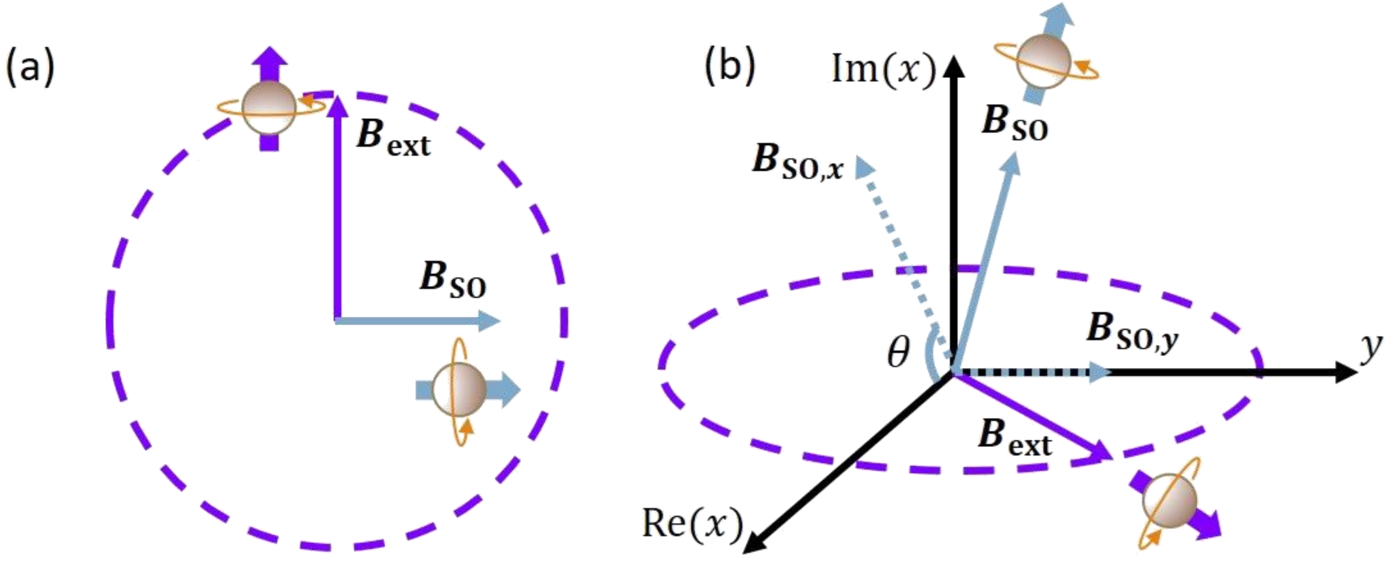
A. Hofmann et al. Phys. Rev. Lett. 2017

The complex nature of intervalley transition element

$$\boldsymbol{B}_{\mathbf{SO}} = \frac{2im^* E_{\mathrm{VS}}}{\hbar\gamma}\left(\alpha_- r_y^{-+}\hat{\boldsymbol{x}} + \alpha_+ r_x^{-+}\hat{\boldsymbol{y}}\right)$$

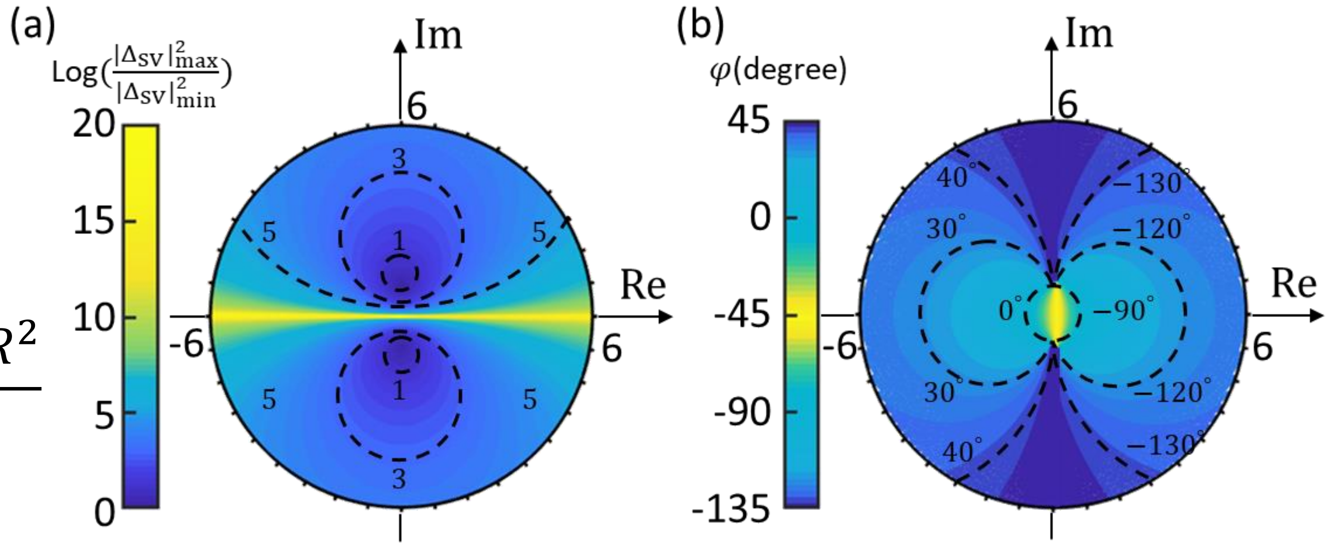
$$\boldsymbol{B}_{\mathbf{SO},x} \sim \alpha_- r_y^{-+}/\gamma \qquad \boldsymbol{B}_{\mathbf{SO},y} \sim \alpha_+ r_x^{-+}/\gamma$$

$$\boldsymbol{B}_{\mathbf{SO},x}/\boldsymbol{B}_{\mathbf{SO},y} = \alpha_- r_y^{-+}/\alpha_+ r_x^{-+} = \boldsymbol{R} = Re^{-i\theta}$$

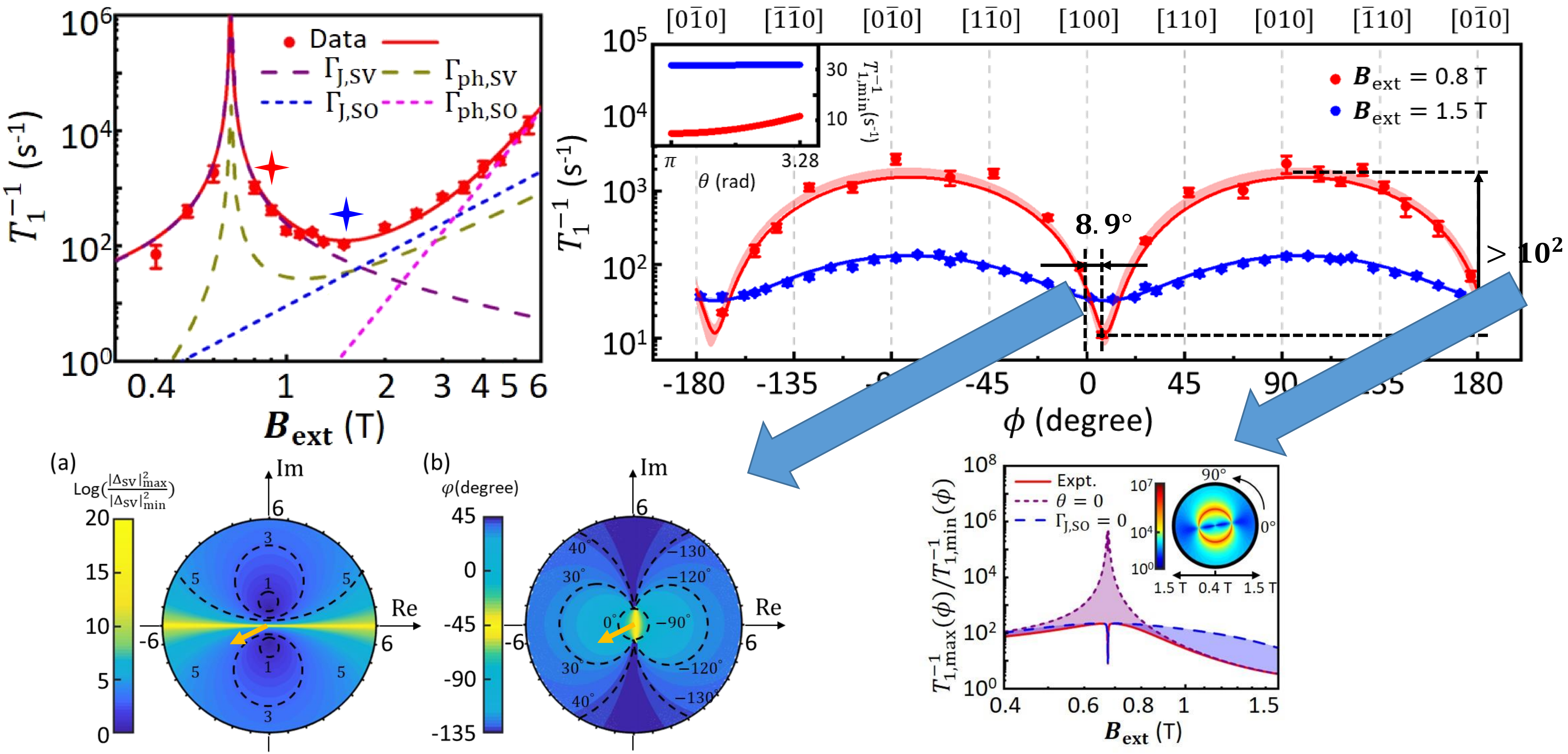


$$\Delta_{\mathrm{SV}} = 2\langle\uparrow|H_{\mathrm{SV}}|\downarrow\rangle = \langle\uparrow|\boldsymbol{B}_{\mathbf{SO}}\cdot\boldsymbol{\sigma}|\downarrow\rangle$$

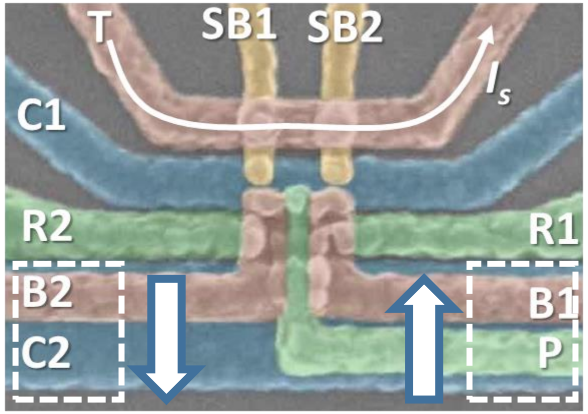
$$|\Delta_{SV}|^2 \sim \frac{1-R^2}{2}\cos\left(2\phi - \frac{\pi}{2}\right) - R\cos\theta\sin\left(2\phi - \frac{\pi}{2}\right) + \frac{1+R^2}{2}$$

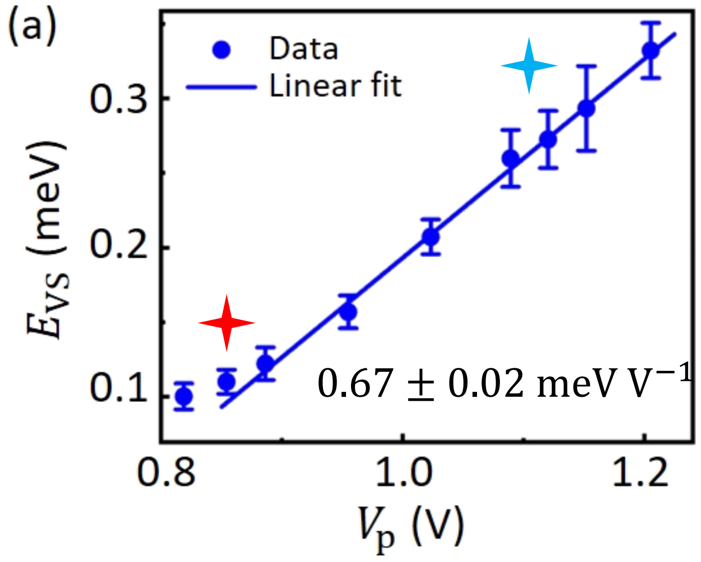


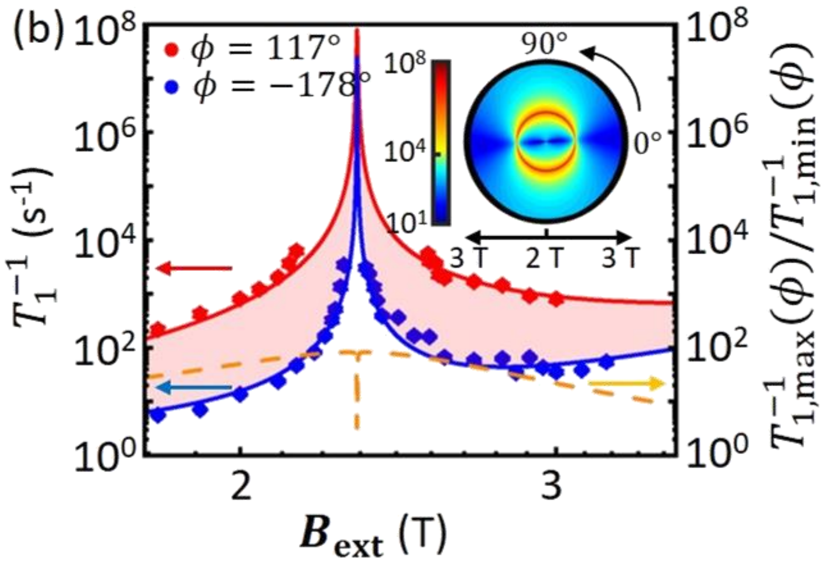
Explanation of Spin relaxation anisotropy

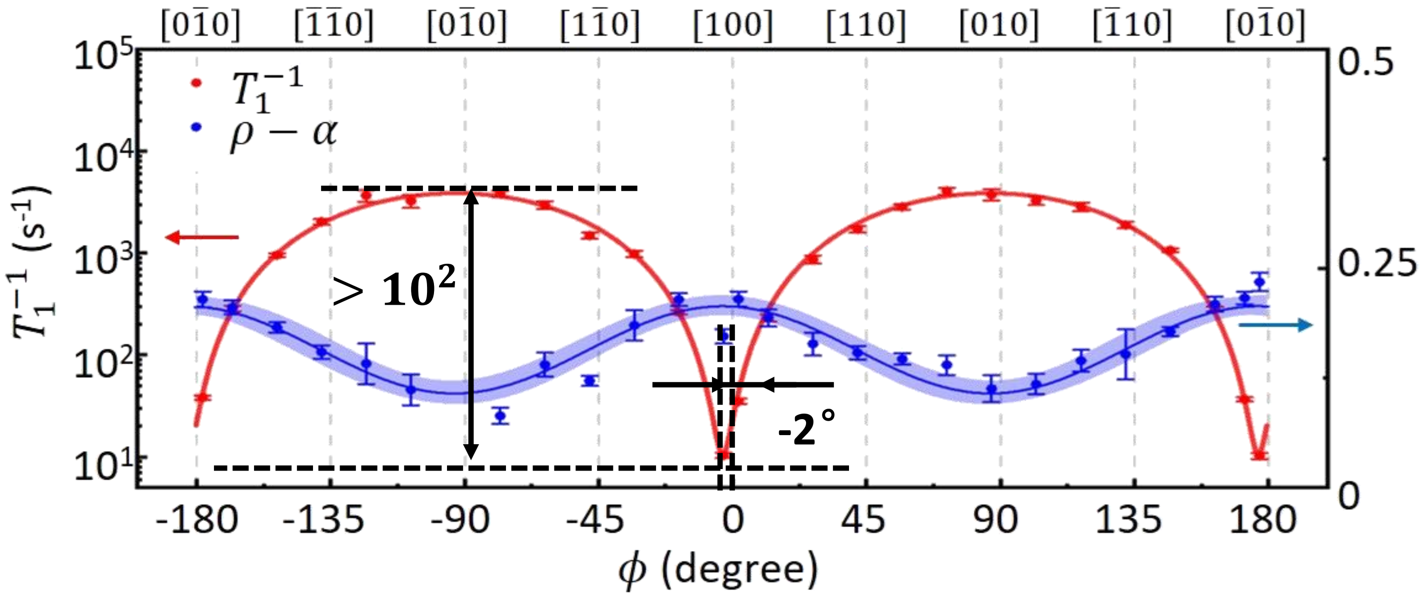


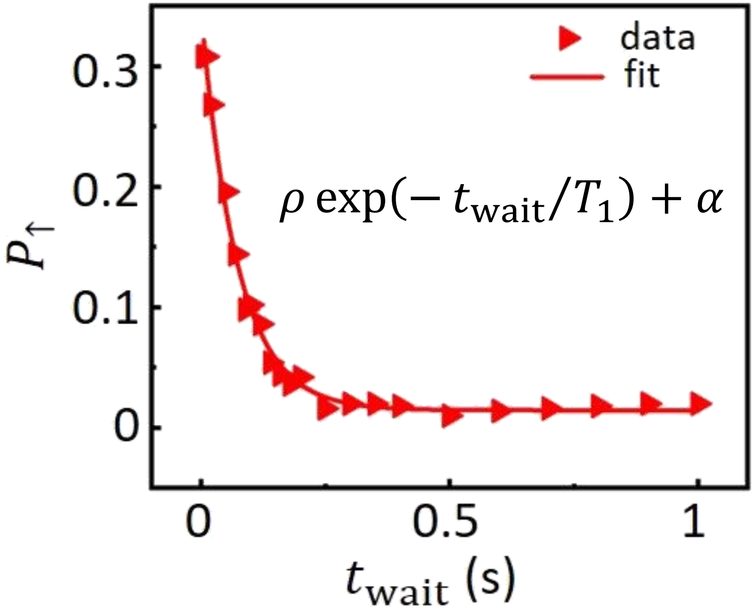
Spin relaxation anisotropy with a large valley splitting





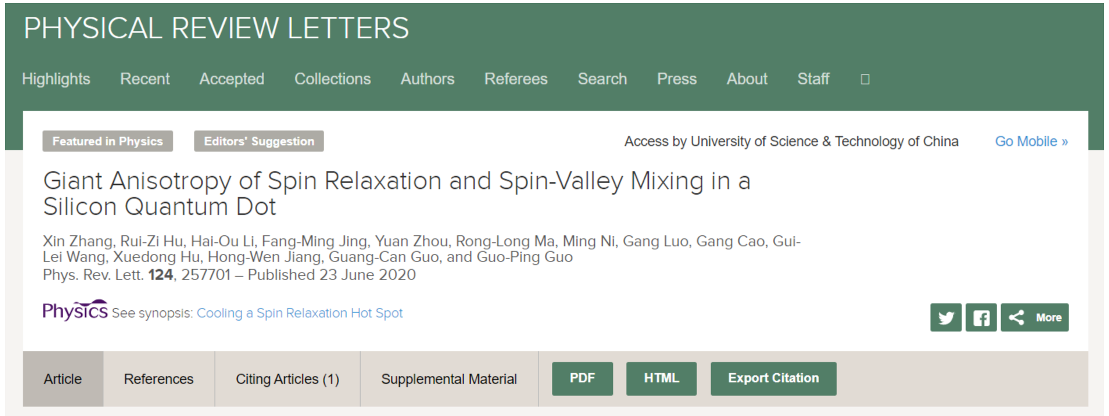


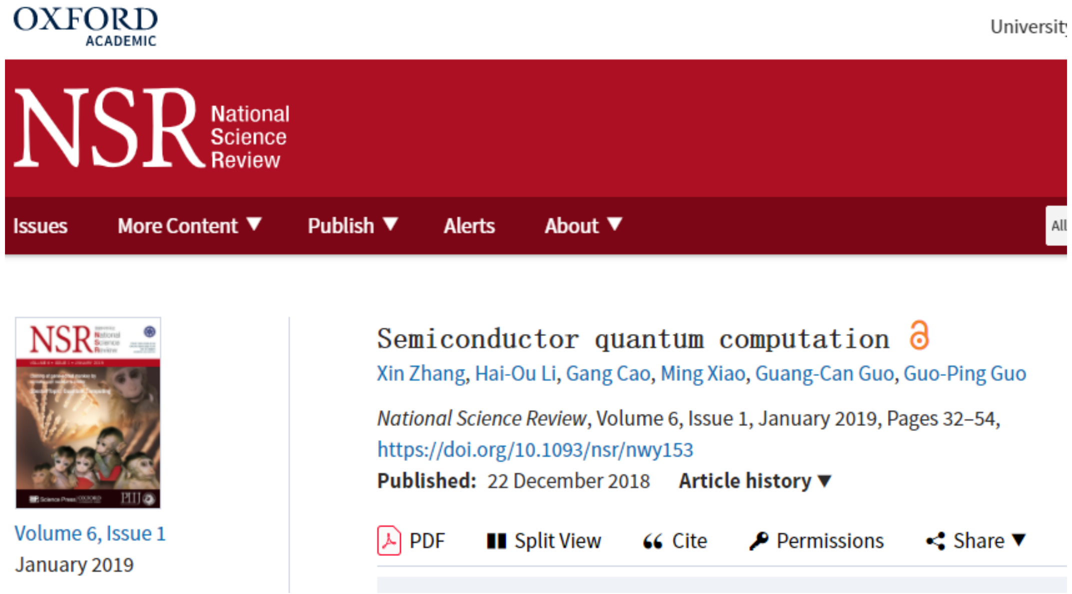




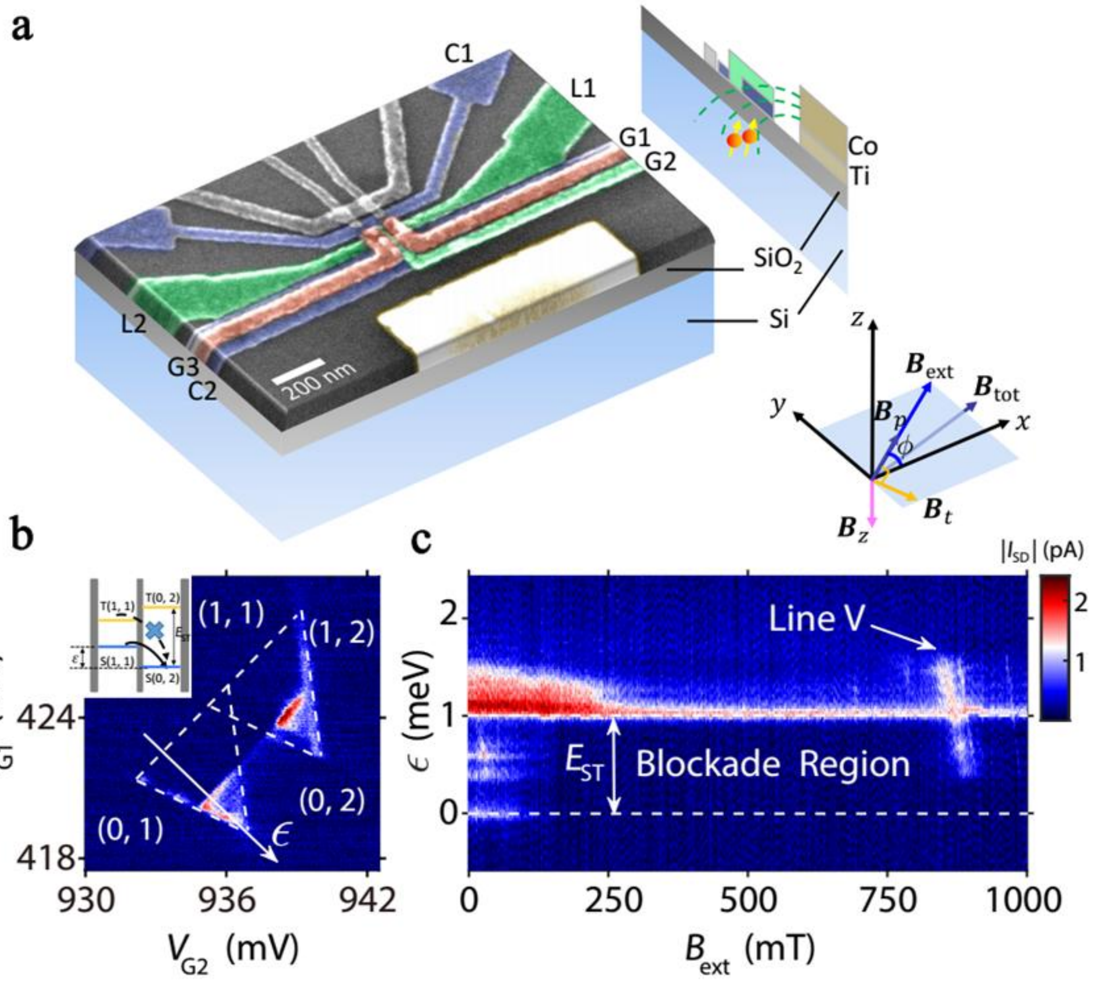
Summary

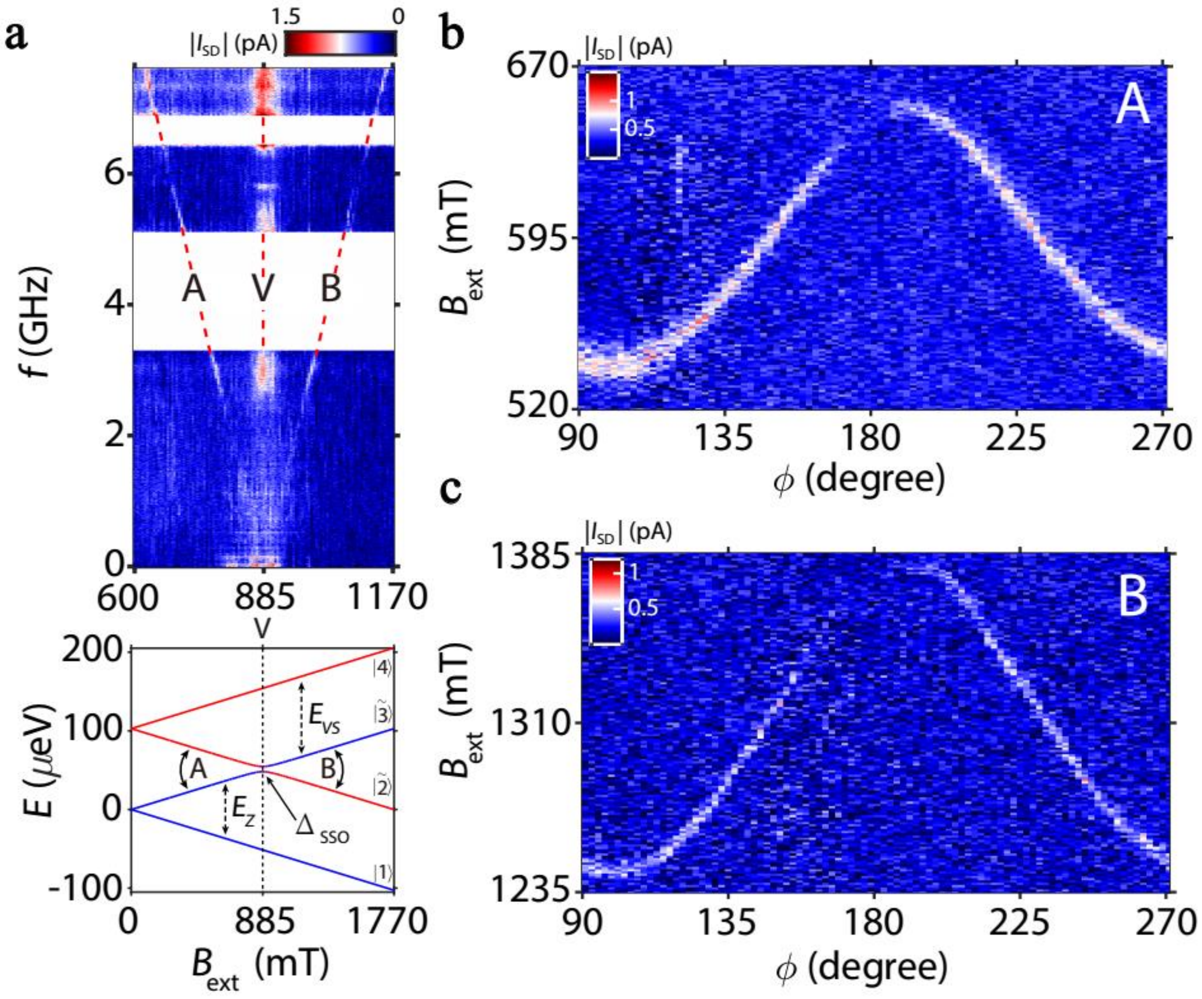
- Giant anisotropy of spin-relaxation rate: > 100, limited by different relaxation channels
- Complex valley transition elements lead to finite anisotropy of spin-valley mixing and also affects the anisotropy angle
- Electric field can affect valley splitting severely, but has much smaller effect on anisotropy magnitude of spin-valley mixing

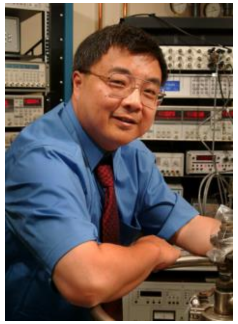




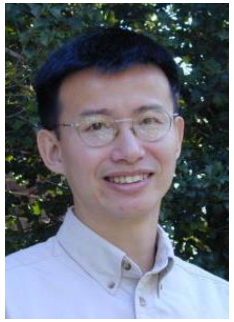
Ongoing work







HongWen Jiang



Xuedong Hu

Peihao Huang

Dimitrie Culcer

Jianjun Zhang

Guilei Wang

Appendix I: the origin of complex valley transition element

$$|v_-\rangle = \frac{1}{\sqrt{2}}(e^{-ik_0z}u_{-z}(r) - e^{ik_0z}u_{+z}(r))\psi_-(\mathrm{r}), \quad (\mathrm{S2})$$

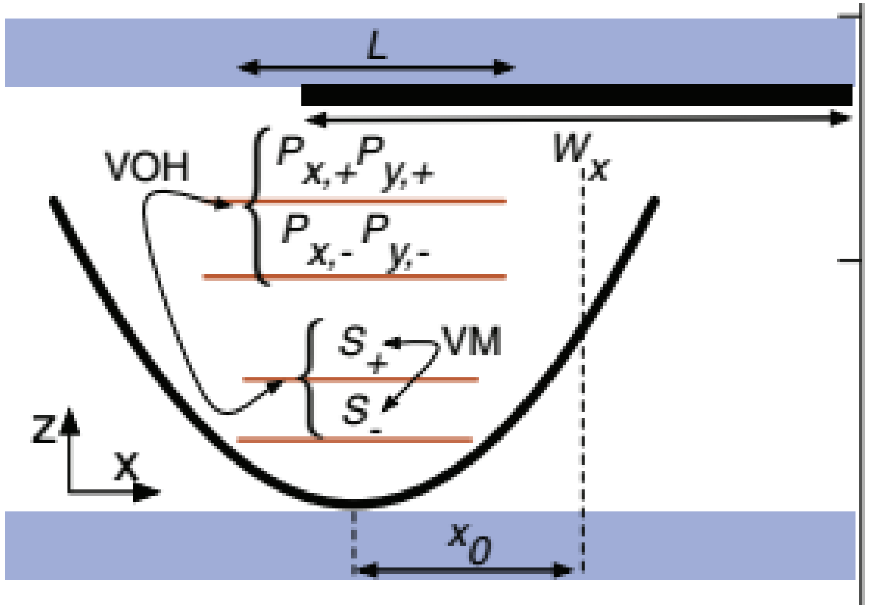
$$|v_+\rangle = \frac{1}{\sqrt{2}}(e^{-ik_0z}u_{-z}(r) + e^{ik_0z}u_{+z}(r))\psi_+(\mathrm{r}), \quad (\mathrm{S3})$$

$$r_{-+} = \langle v_-|r|v_+\rangle$$

$$= \frac{1}{2}\psi_-(\mathrm{r})^+[u_{-z}(r)^+ r u_{-z}(r) - u_{+z}(r)^+ r u_{+z}(r)]\psi_+(\mathrm{r})$$

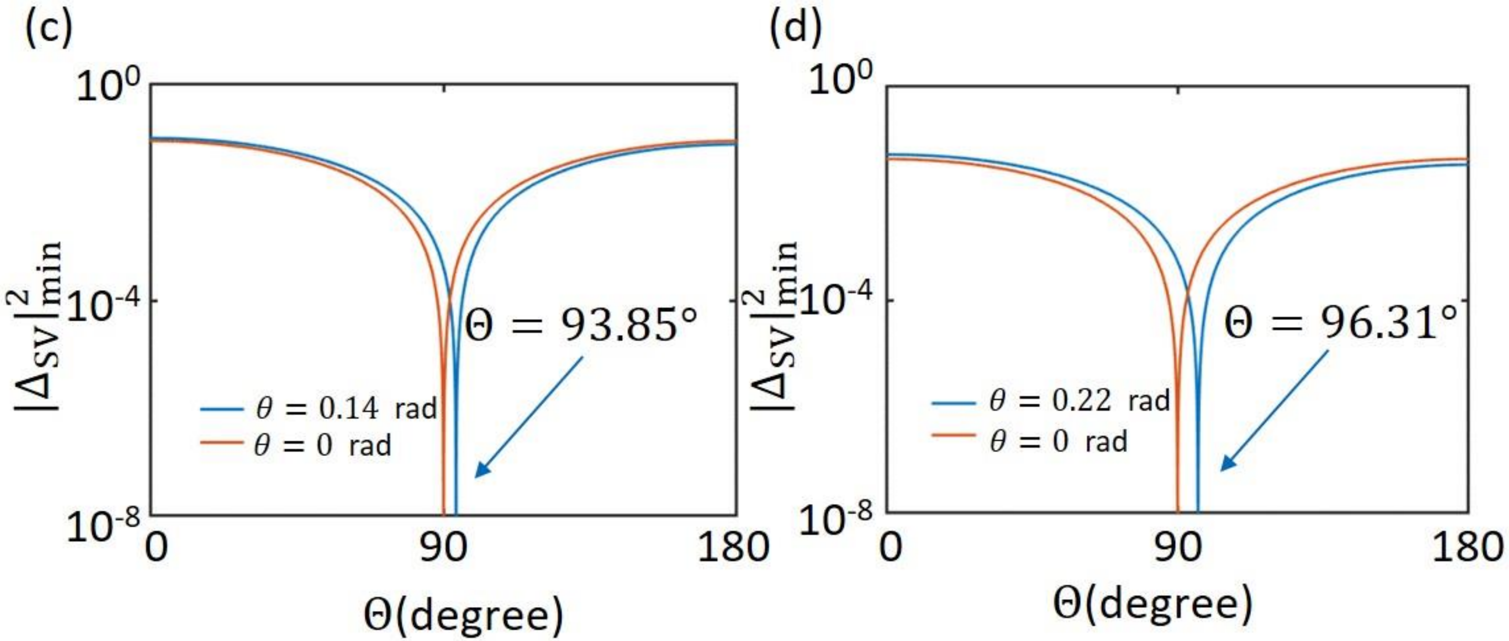
$$+\frac{1}{2}\psi_-(\mathrm{r})^+[e^{i2k_0z}u_{-z}(r)^+ r u_{+z}(r) - e^{-i2k_0z}u_{+z}(r)^+ r u_{-z}(r)]\psi_+(\mathrm{r})$$

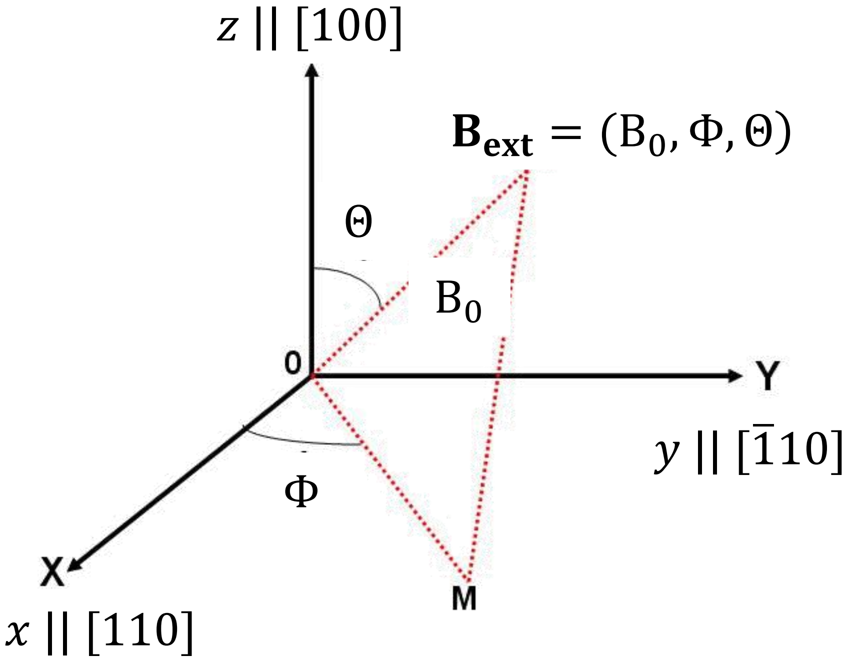
Containing phase



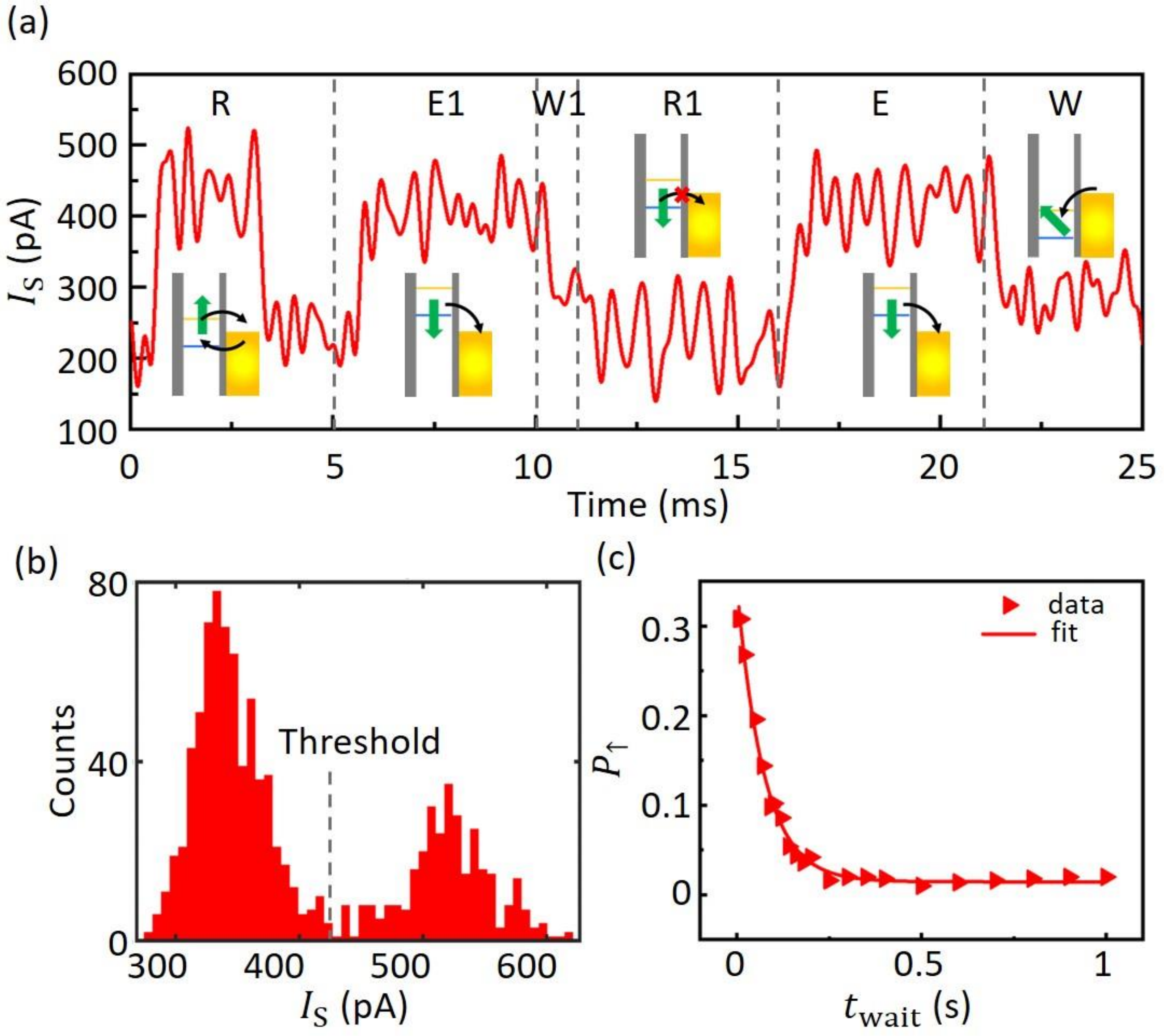
Appendix II: the situation with tilted magnetic field

$$|\Delta_{SV}|^2 = c_{SV}\{[(R\cos\Phi + \sin\Phi)^2 - R(\cos\theta - 1)\sin 2\Phi]\cos^2\Theta - 2R\sin\theta\cos\Theta$$



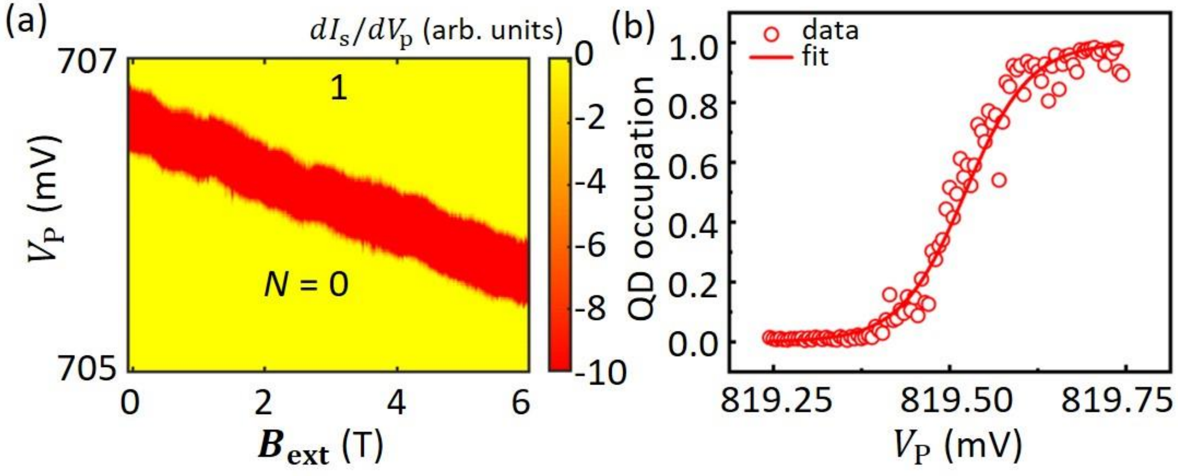


Appendix II: Measurement details



$\alpha_P = 0.34$ eV/V

$T_e = 180.5 \pm 8.1$ mK



$\Gamma_{\uparrow,out} = 2937 \pm 424$ Hz

$\Gamma_{\downarrow,in} = 313.1 \pm 61.0$ Hz