Single Electron Counting Measurements of Tunneling Rates and Spin Relaxation Rates in Quantum Dots

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Outline

I. **Spin Relaxation Time T_1**

II. **Control of Spin Relaxation**

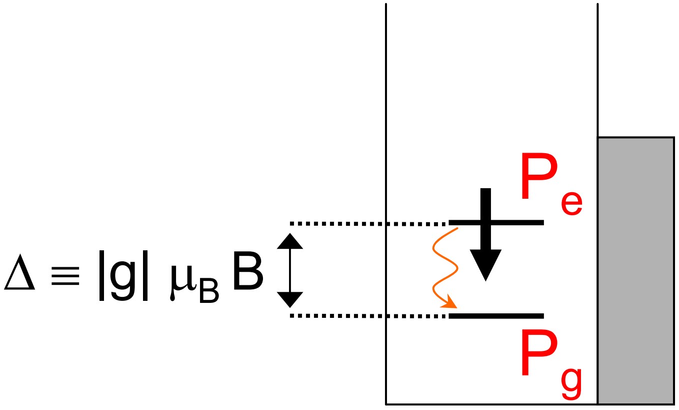
III. **Surprise: Tunneling is spin dependent**

I. Spin Relaxation Time T_1

$W \equiv (T_1)^{-1}$

Amasha et al. cond-mat/0607110

Relaxation Time T_1



- environment → P_e and P_g to thermal equilibrium

$$P_e/P_g = \exp(-\Delta/k_B T)$$

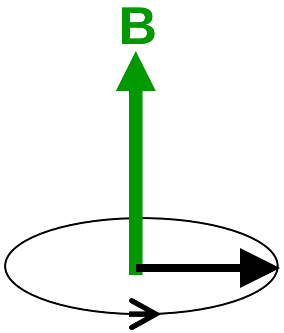
- for $\Delta \gg k_B T$, $|\downarrow\rangle \longrightarrow |\uparrow\rangle$

- timescale T_1

  $W \equiv (T_1)^{-1}$

- $W(B) \sim B^p$, mechanism determines p

Timescales



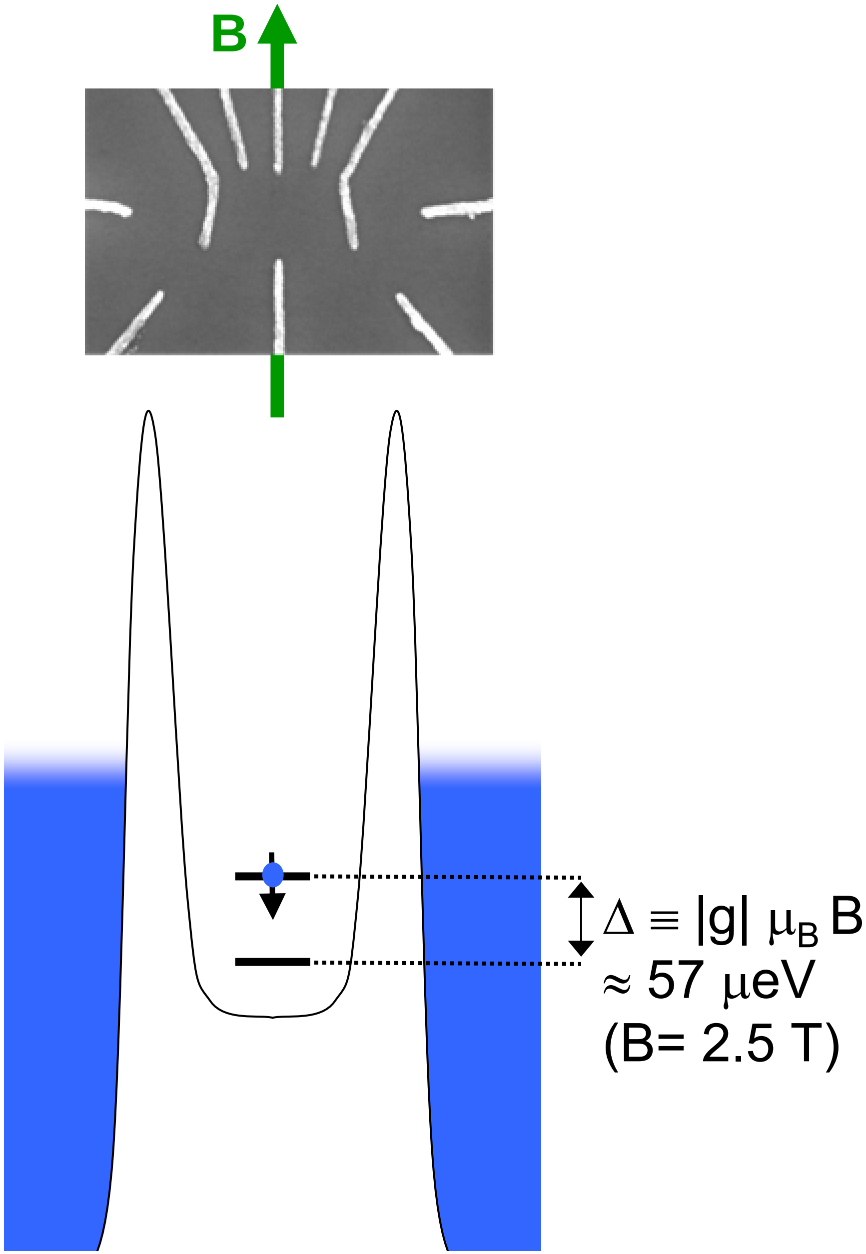
- $\left|\Psi\right\rangle = a(t)\left|\uparrow\right\rangle + b(t)\, e^{i\varphi(t)}\left|\downarrow\right\rangle$

$P_{\downarrow}(t) = [b(t)]^2$
$P_{\uparrow}(t) = [a(t)]^2$

1. environment can disrupt relative phase $\varphi(t)$
   - Ga and As nuclear fields perturb B $\Rightarrow$ alter $\varphi(t)$
   - nuclear fields change slowly: T_2 > 1 μs [Petta, *et al.* 2005]

2. environment can affect a and b
   - corresponds to relaxation: for $\Delta >> k_B T$, $\left|\downarrow\right\rangle \longrightarrow \left|\uparrow\right\rangle$
   - spin-orbit interaction affects a and b [Golovach, *et al.* 2004]
   - **$T_2 < 2T_1$**

Lateral Dots as Spin Qubits



- Spins in dots as basis for qubit
  [D. Loss and D. P. DiVincenzo, PRA 1998]
- Isolate a single spin in a dot
  [Ciorga *et al.*, PRB 2000]
- Coherent manipulation of 1 spin
  [Koppens *et al.*, Nature 2006]
- Entanglement of two spins
  [Petta *et al.*, Science 2005]
- Read-out of spin state
  [Elzerman *et al.*, Nature 2004
  & Hanson *et al.*, PRL 2005]

Spin Relaxation in Dots

Theory for S=1/2:

•**Spin-Orbit mediated coupling to**

- **phonons**: Khaetskii *et al.*, PRB 2001 & Golovach *et al.*, PRL 2004.
- **gates and ohmics**: Marquardt *et al.*, PRB 2005 & San-Jose *et al.*, PRL 2006.
- **QPC**: Borhani *et al.*, PRB 2006.

• **Hyperfine field mediated coupling to**

- **phonons**: Erlingsson *et al.*, PRB 2002.
- **gates**: Marquardt *et al.*, PRB 2005.

Experimental measurements:

• Pulsed gate techniques

- Fujisawa *et al.*, Physica B 2001: T_1 > 1 μs for spin-flip transitions
- Hanson *et al.*, PRL 2003: T_1 > 50 μs for S= 1/2 at B= 7.5 T

• Real-time read-out:

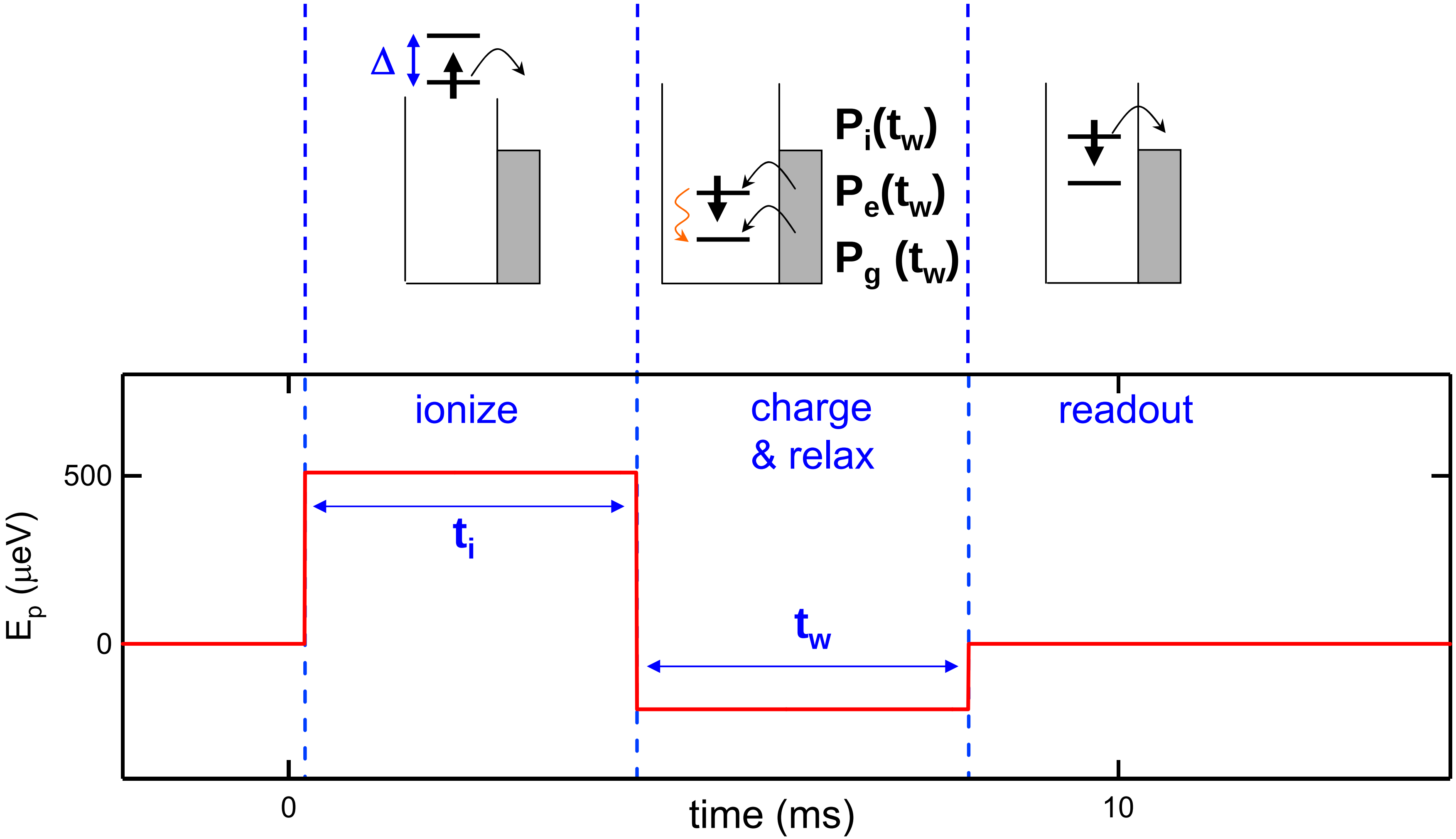
- Elzerman *et al.*, Nature 2004: T_1 = 0.85 ms for S= 1/2 at B= 8 T
- Hanson *et al.*, PRL 2005: T_1 = 2.5 ms for S-T at B= 0.02 T

• Optical methods on arrays of self-assembled Ga(In)As dots

- Kroutvar *et al.*, Nature 2004: spin relaxation mechanism is S.O. + phonons.

Pulse Sequence

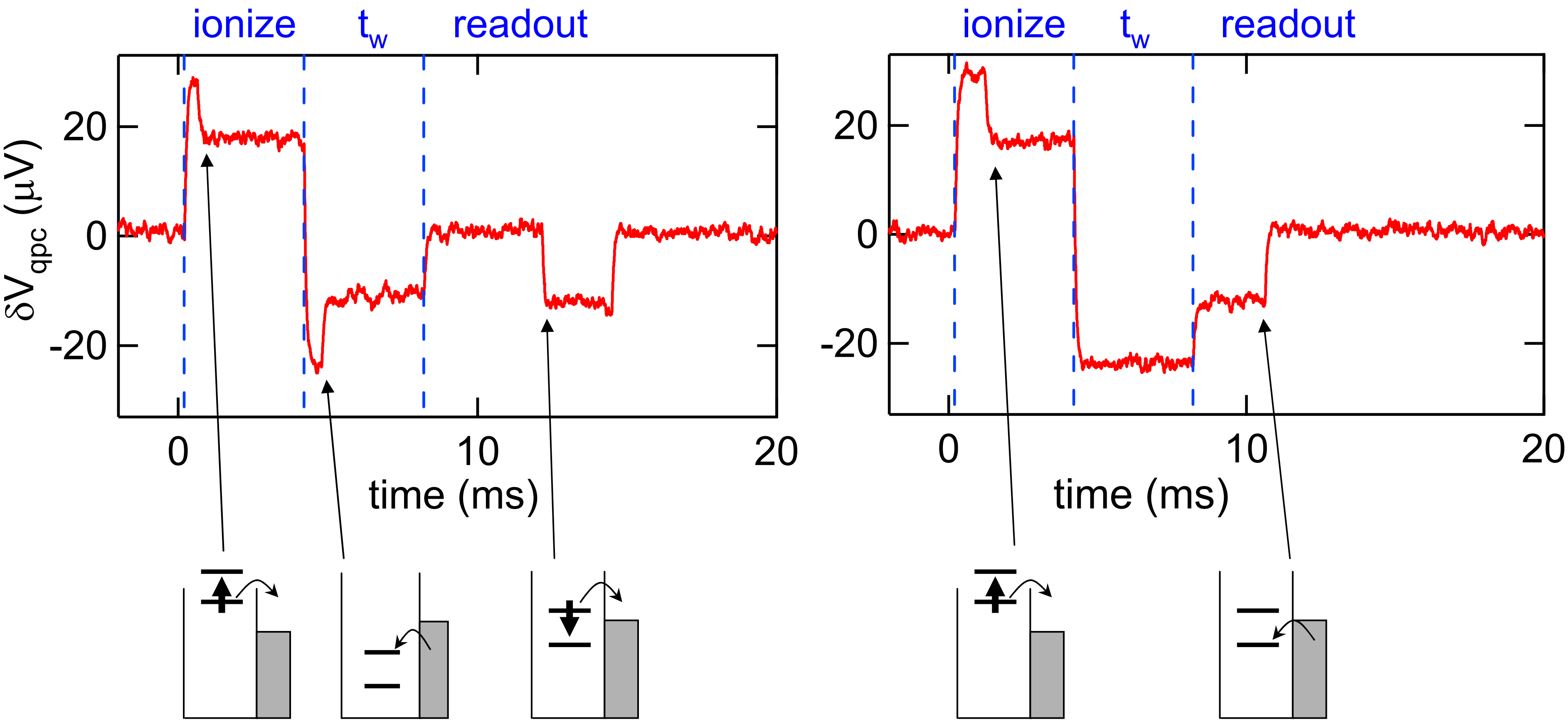
[Fujisawa *et al.*, Physica B 2001, Hanson *et al.*, PRL 2003 & Elzerman *et al.*, Nature 2004]



Note: For subsequent measurements, only one barrier is transmitting.

Pulse Sequence Data

B= 2.5 T, t_w= 4 ms

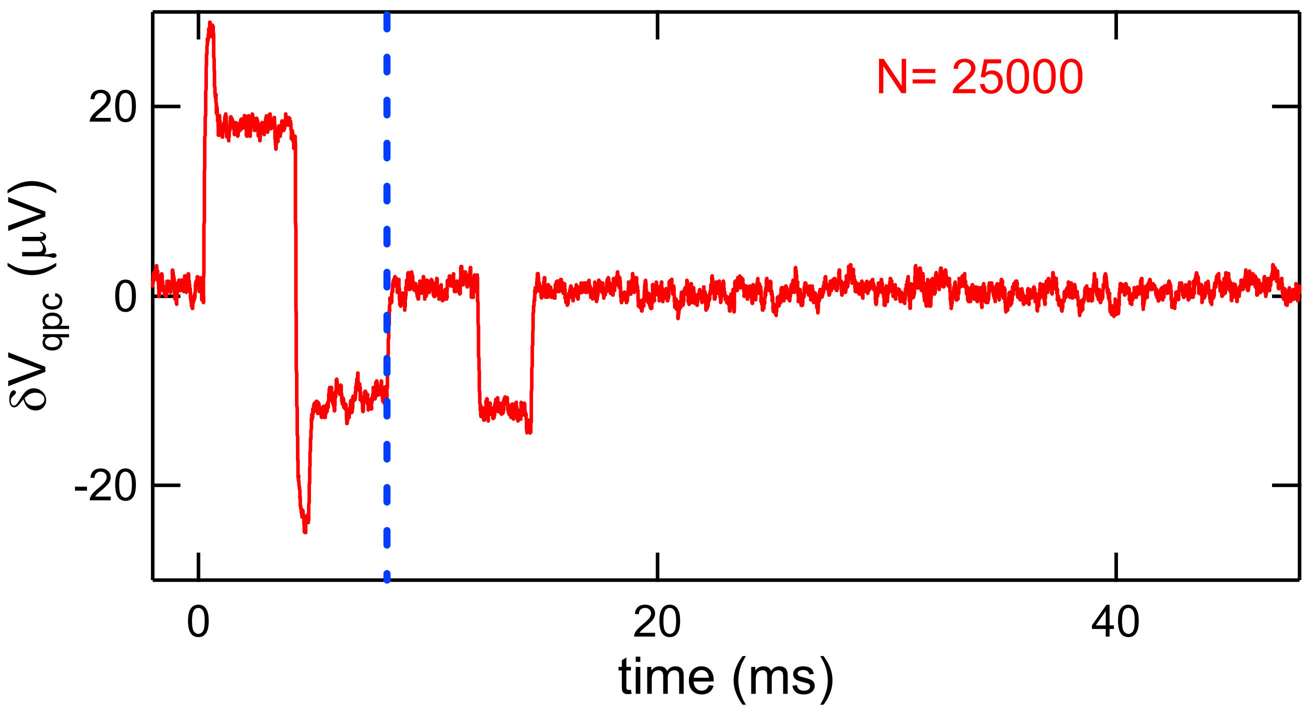


Electron tunnels from excited state

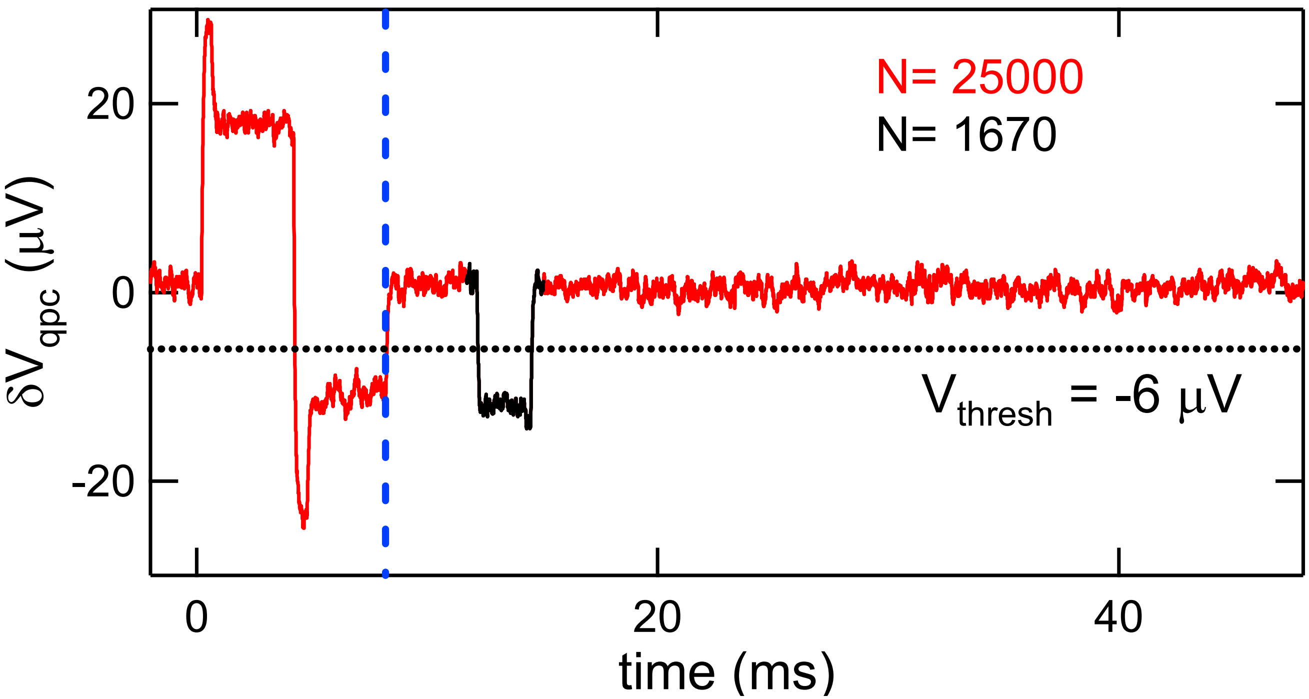
Electron tunnels into empty dot

At B= 2.5 T, we take 300,000 pulses (42 GB of data)!

Data Acquisition

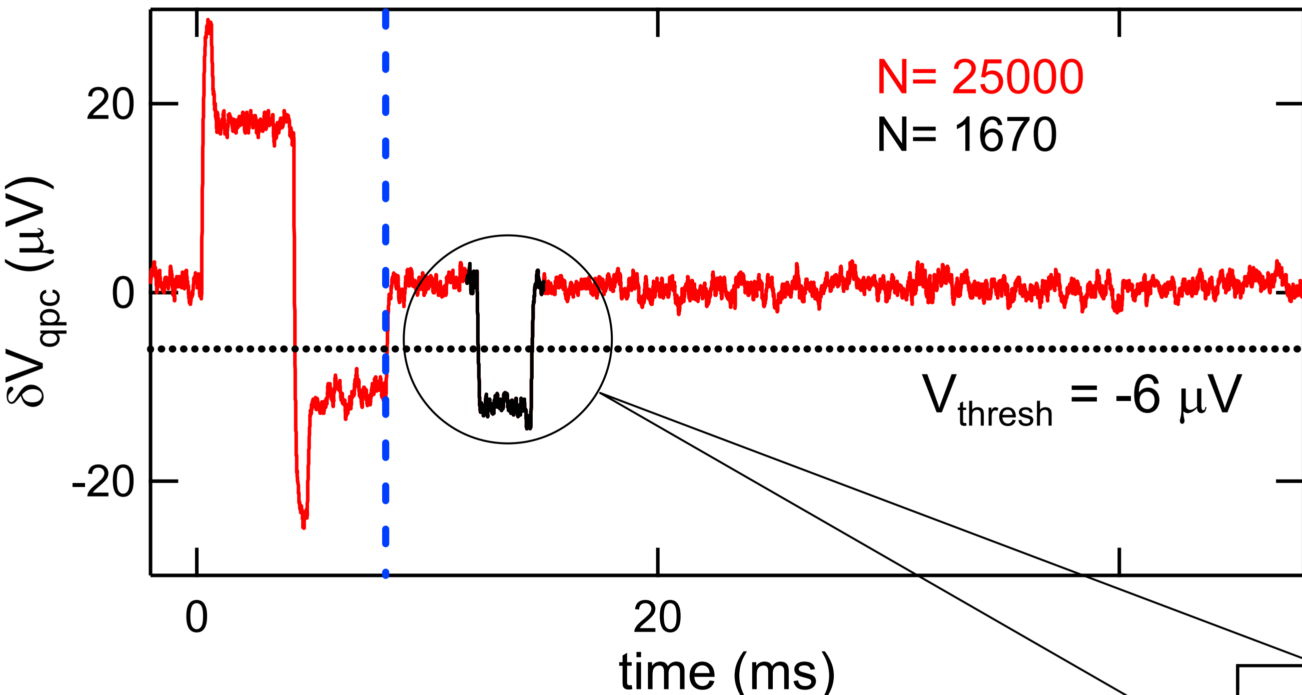


Data Acquisition



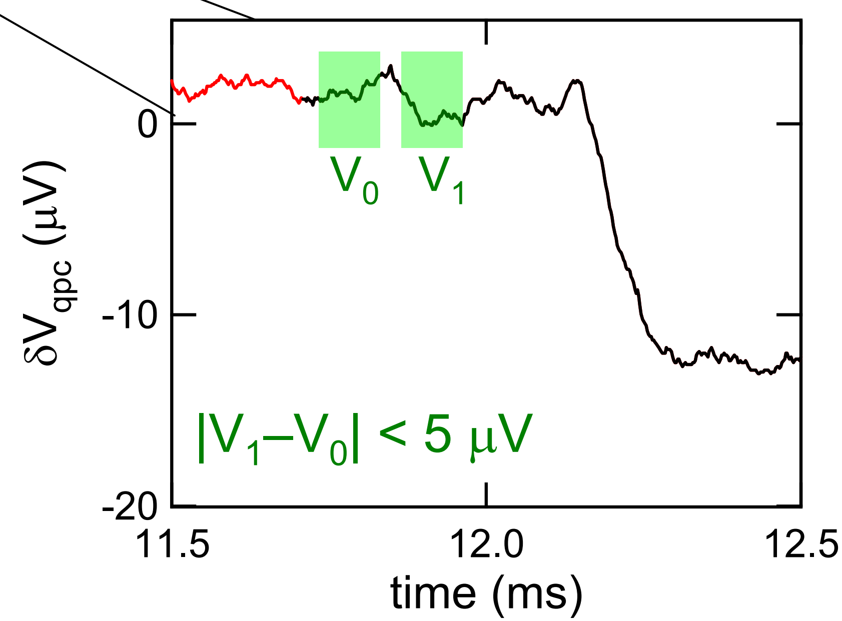
1. Threshold Trigger: save 500 μs around points below V_{thresh}

Data Acquisition

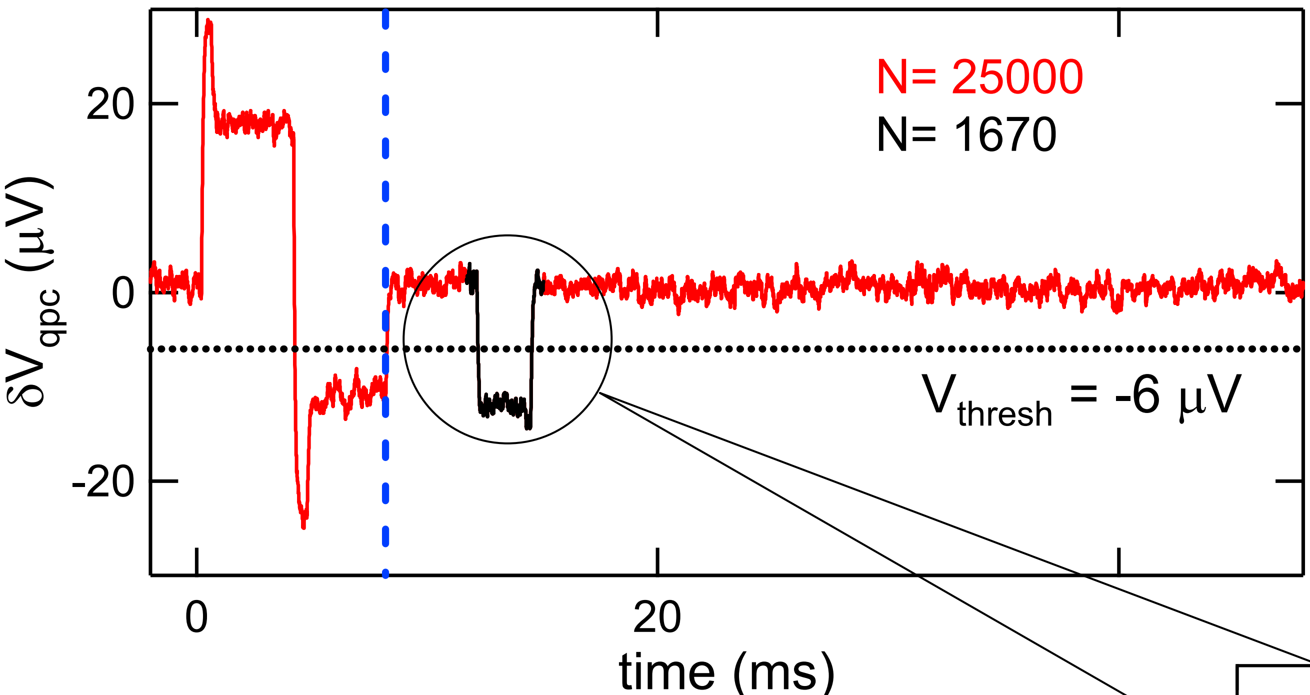


1. **Threshold Trigger**: Save 500 μs around points below V_{thresh}

2. **Edge Trigger:** Average two data segments 36 μs apart. Trigger as soon as $|V_1 – V_0| > V_{edge}$.



Data Acquisition



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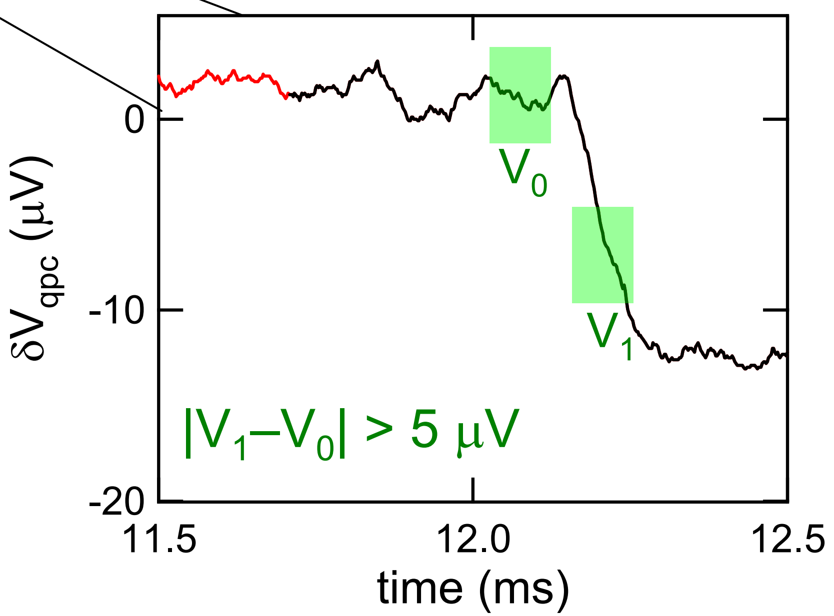
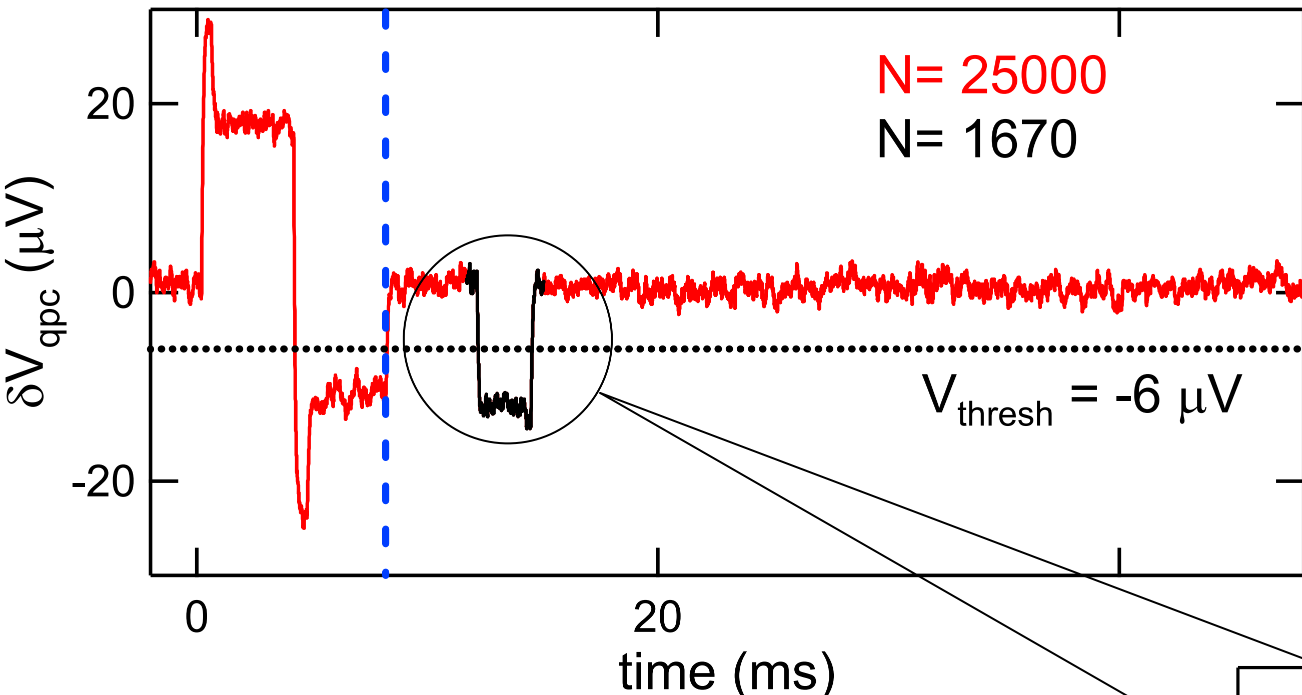
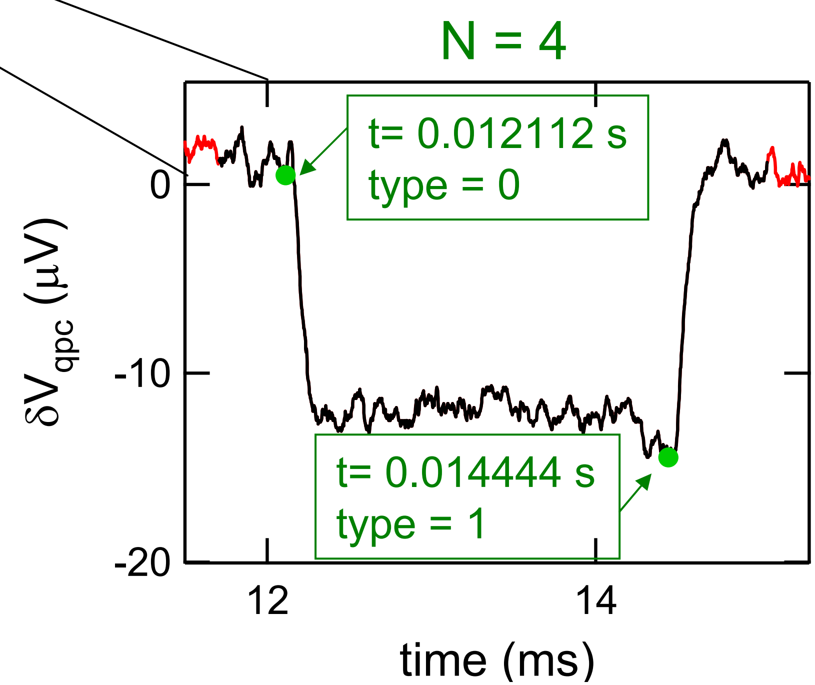


Data Acquisition



1. **Threshold Trigger**:
Save 500 μs around points below V_{thresh}

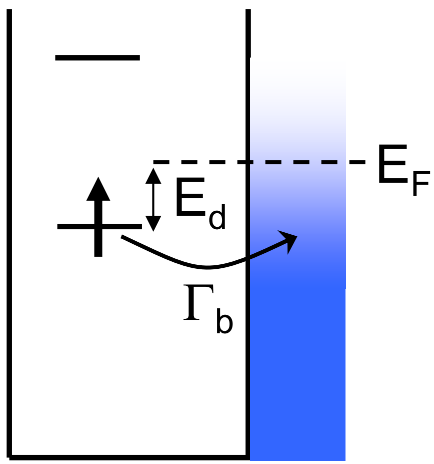
2. **Edge Trigger:**
Average two data segments 36 μs apart.
Trigger as soon as $|V_1 - V_0| > V_{edge}$.
Identifies transition type and time.



type = 0 ⇒ electron hops off
type = 1 ⇒ electron hops on

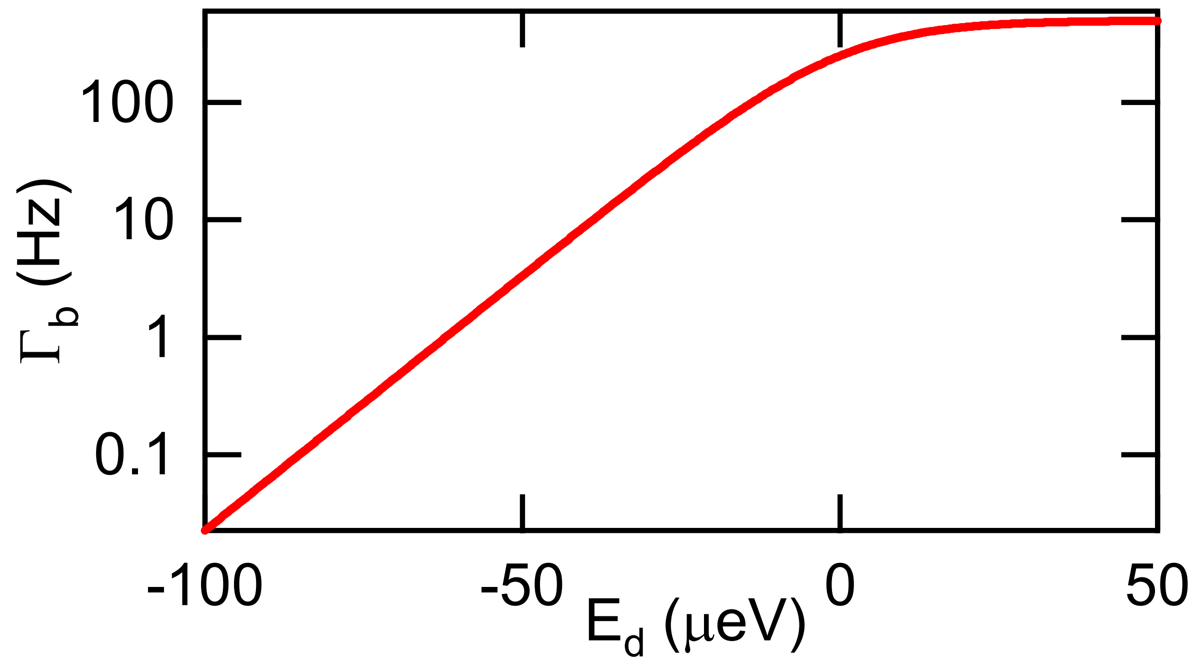
We record 5 MB of 42 GB

Automated Feedback Control

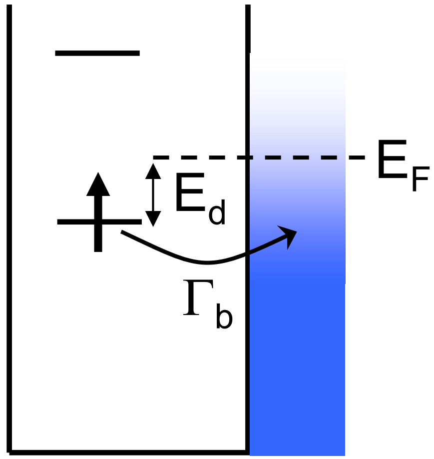


$\Gamma_b = \Gamma\,[1 - f(E_d)]$

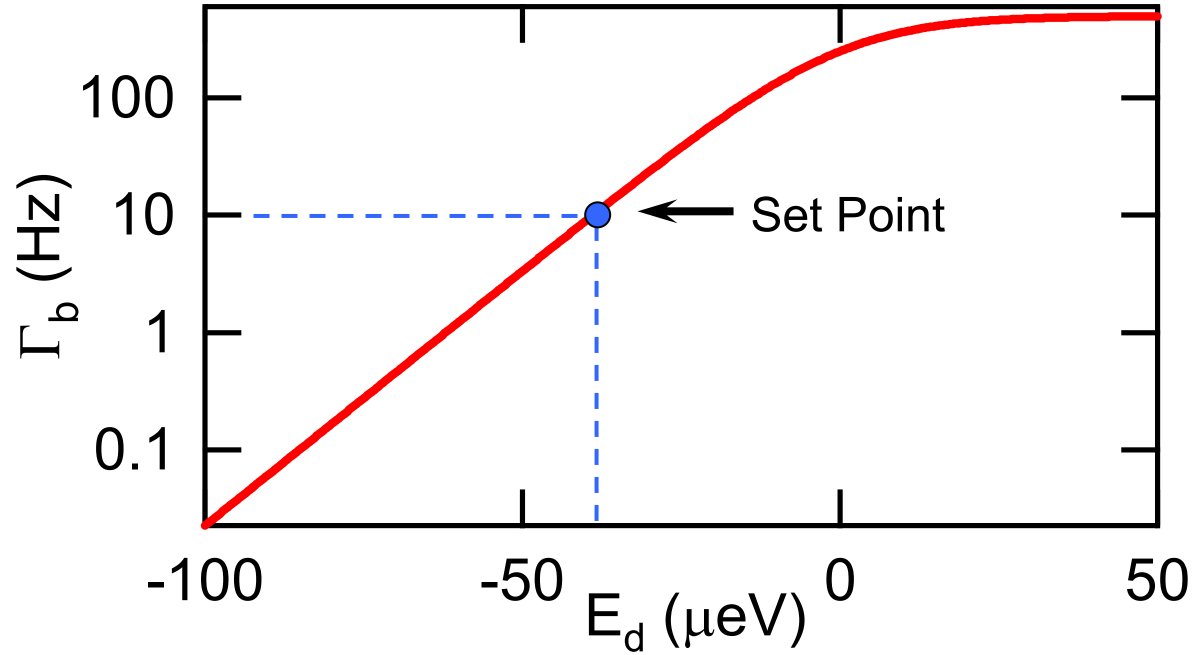
[Schleser *et al.*, APL 2004]

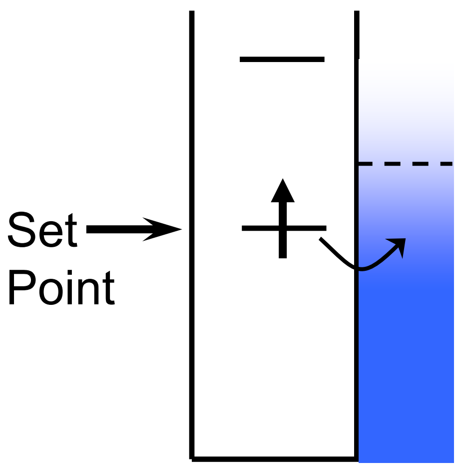


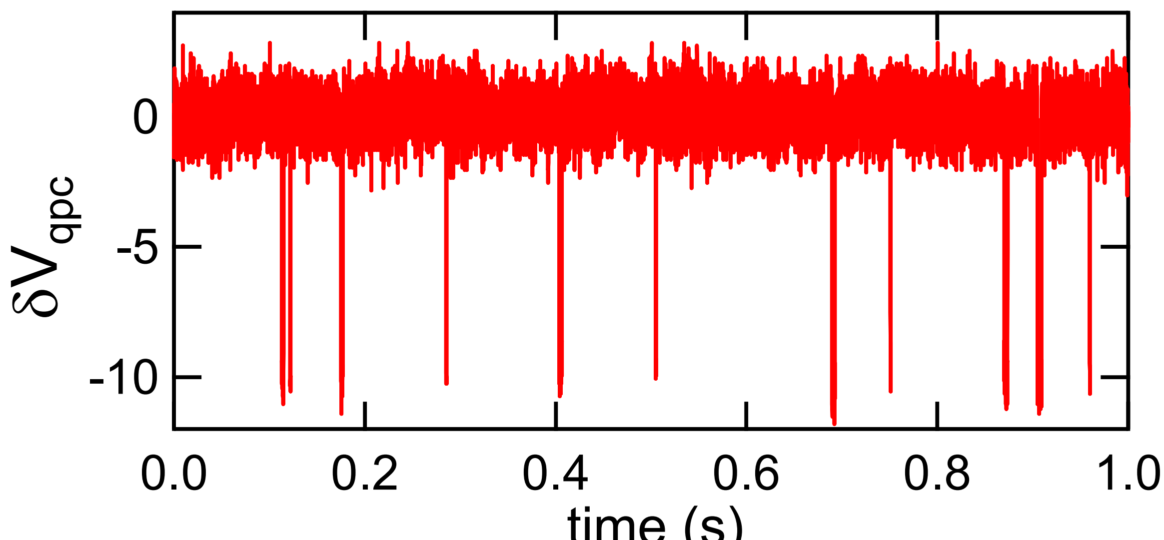
Automated Feedback Control



$\Gamma_b = \Gamma [1 - f(E_d)]$







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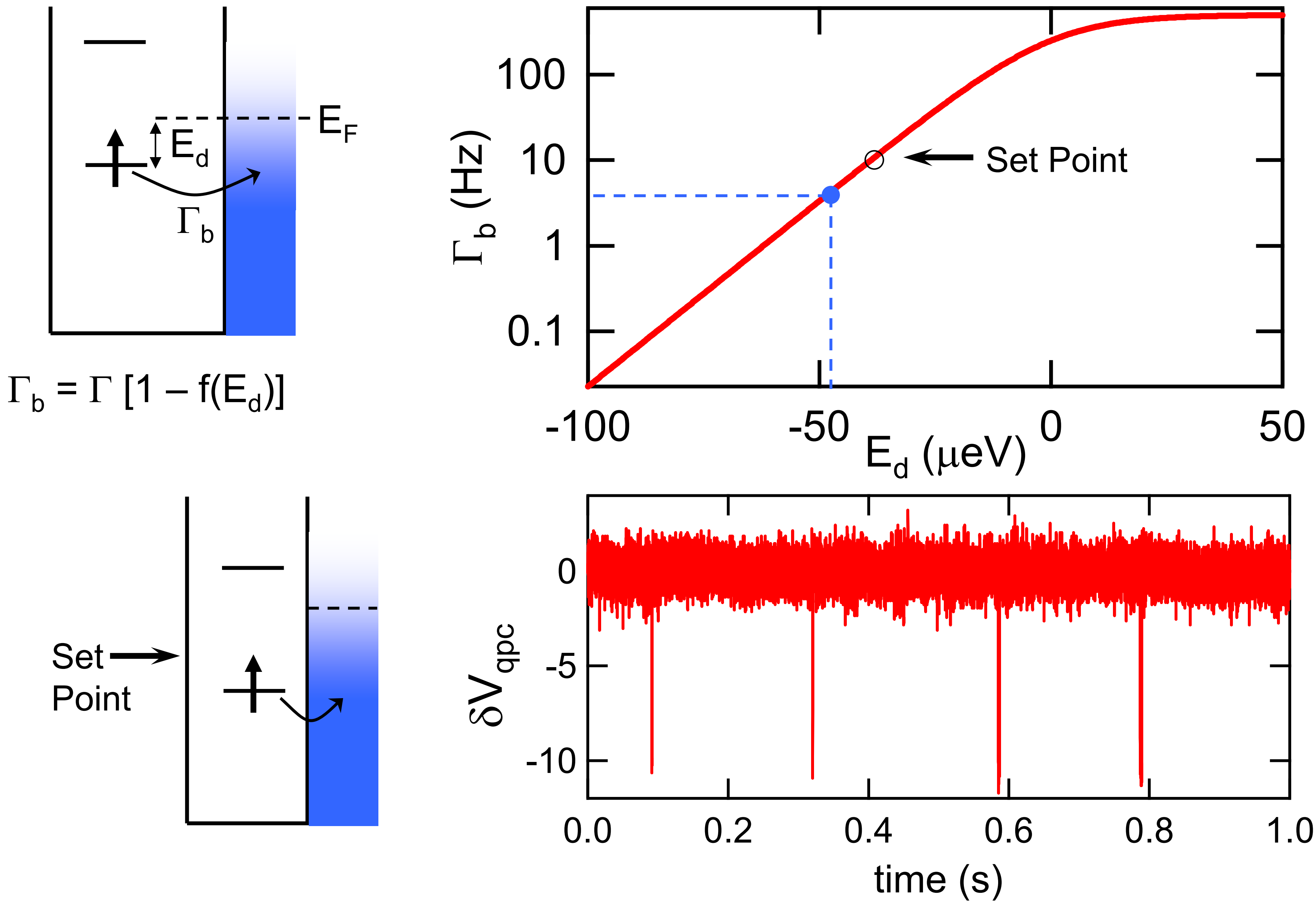
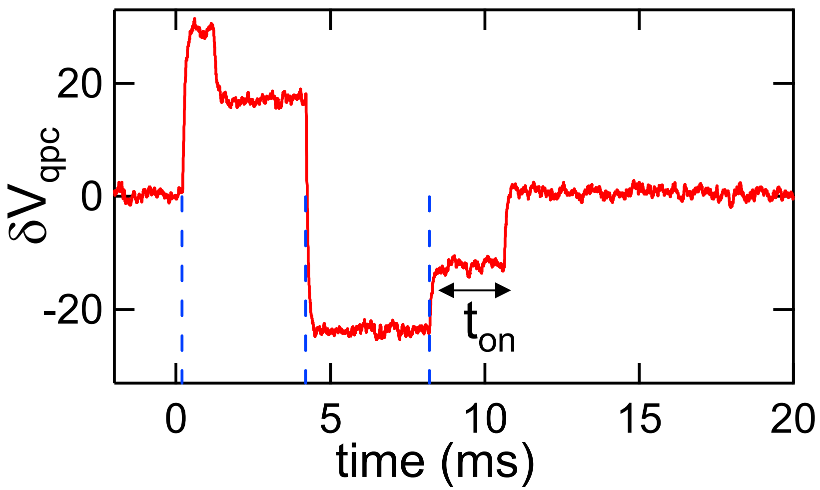
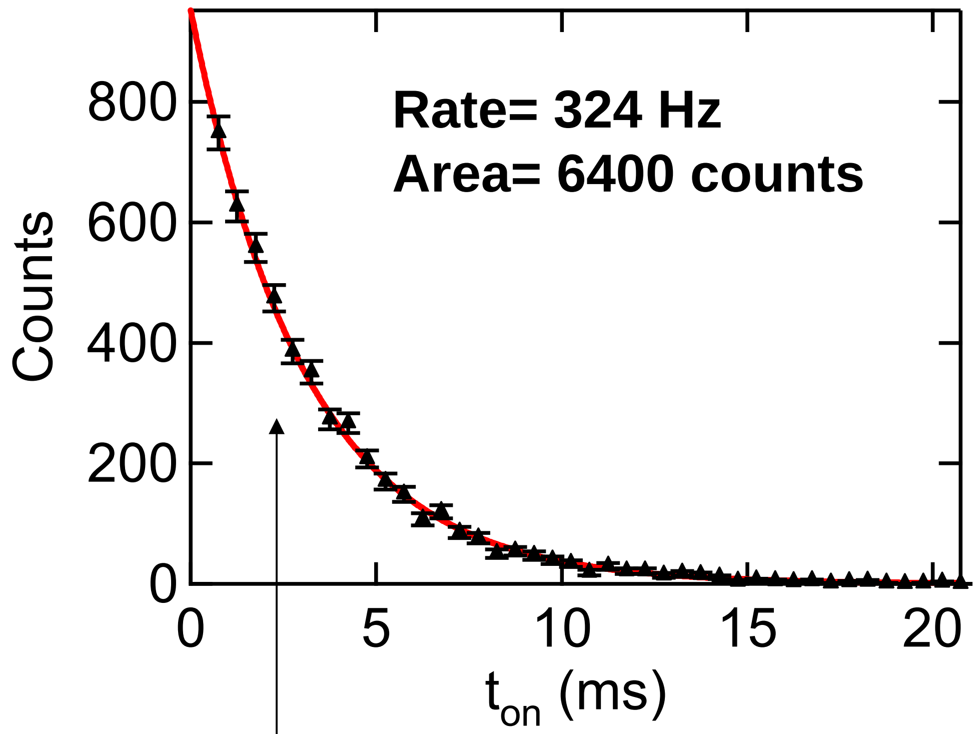


Ionized Probability P_i

B= 2.5 T, t_w= 4 ms

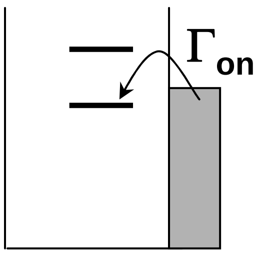




Rate = Γ_{on}

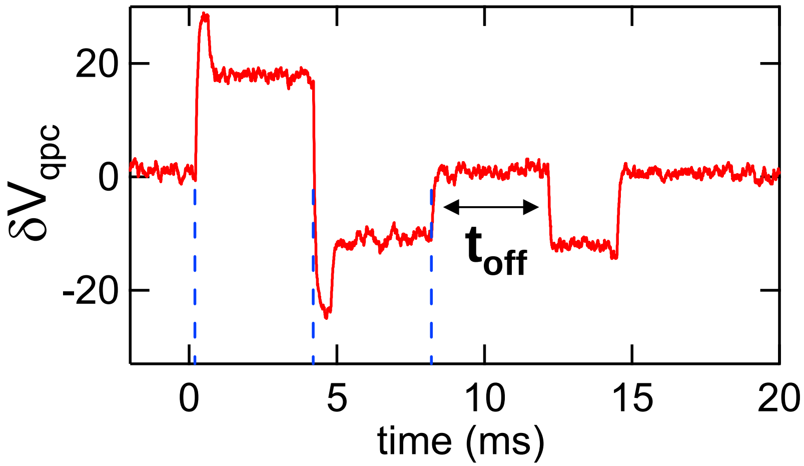
Area = $N_i(t_w)$

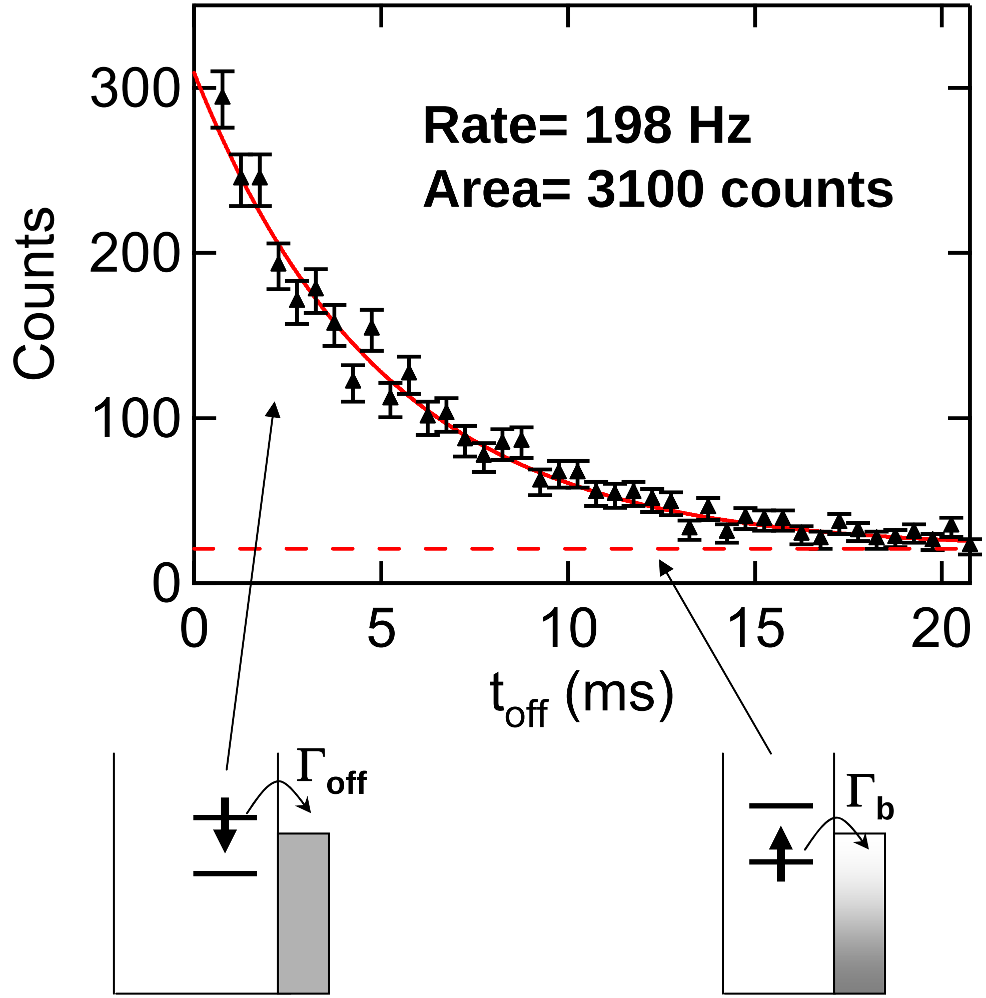
$P_i(t_w) = N_i(t_w) / N_{pulses}$



Excited State Probability P_e

B= 2.5 T, t_w= 4 ms





tunneling from excited state

tunneling from ground state

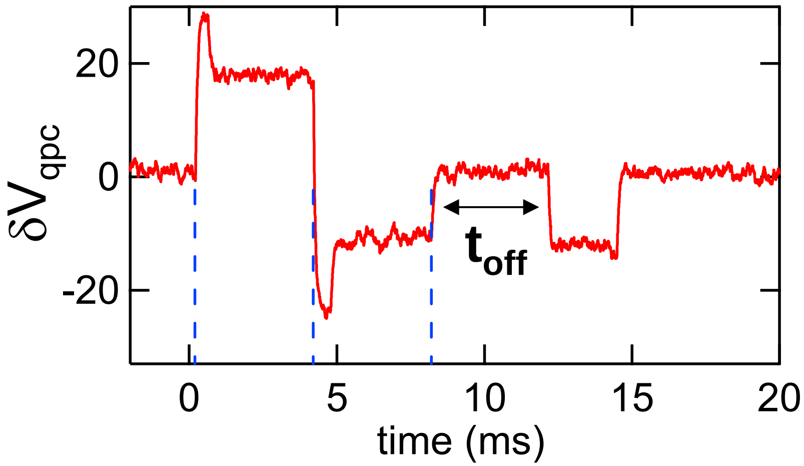
For Γ_{off} >> W:

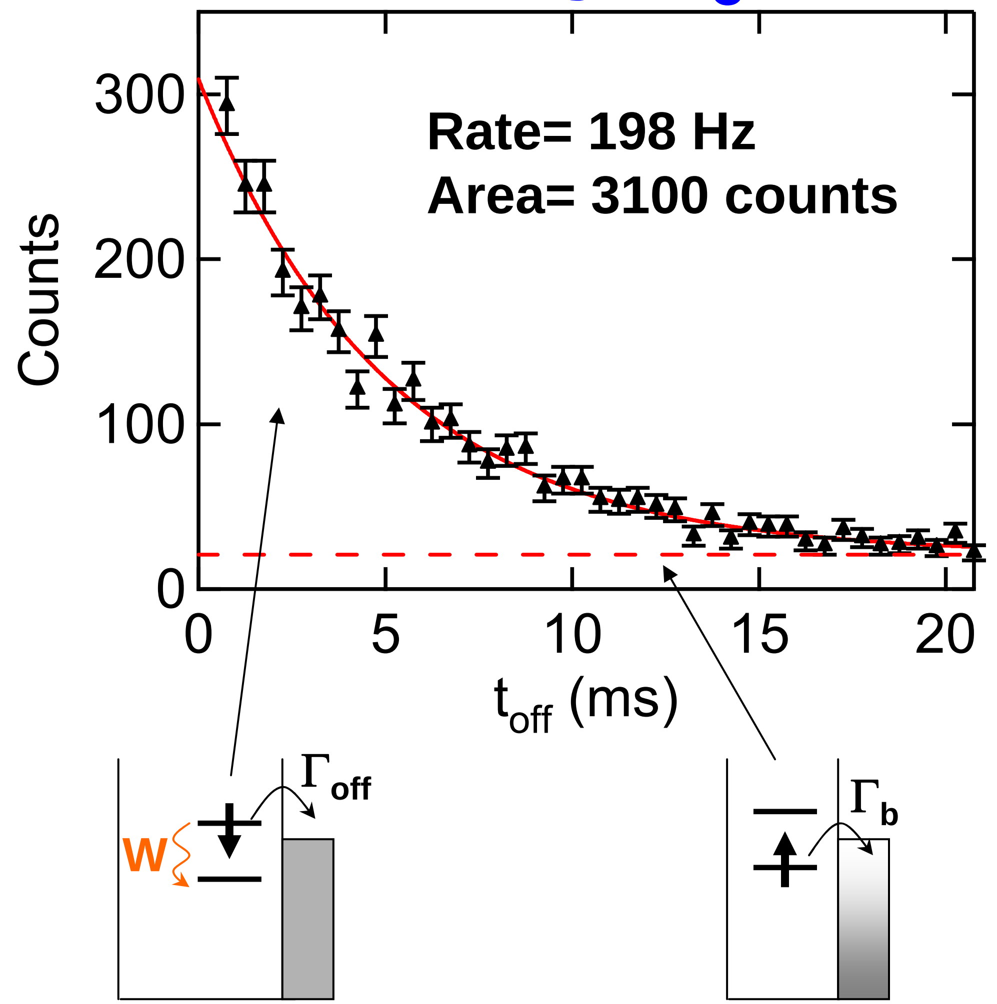
Rate = Γ_{off}
Area = $N_e(t_w)$

$P_e(t_w) = N_e(t_w) / N_{pulses}$

Excited State Probability P_e

B= 2.5 T, t_w= 4 ms





tunneling from excited state

tunneling from ground state

For Γ_{off} ~ W:

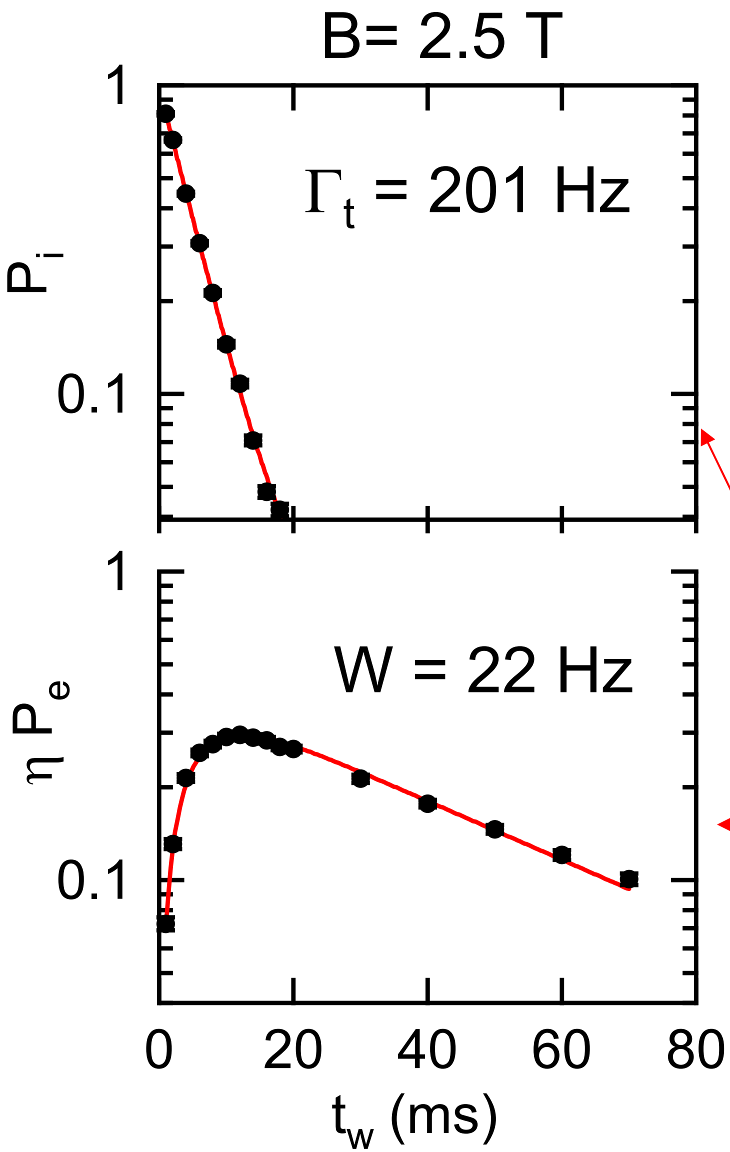
Rate = Γ_{off} + W

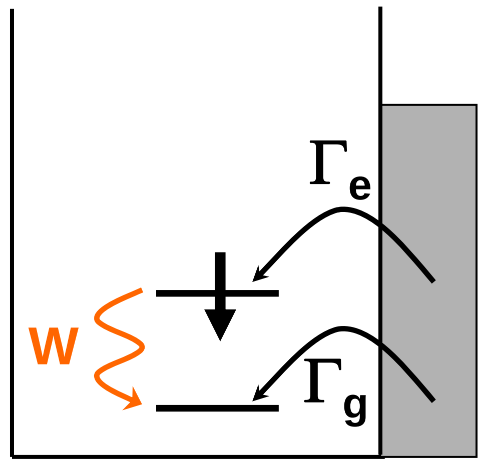
Area = η $N_e(t_w)$

$\eta = \Gamma_{off} / (\Gamma_{off} + W)$

η $P_e(t_w)$ = η $N_e(t_w)$ / N_{pulses}

Data and Rate Model





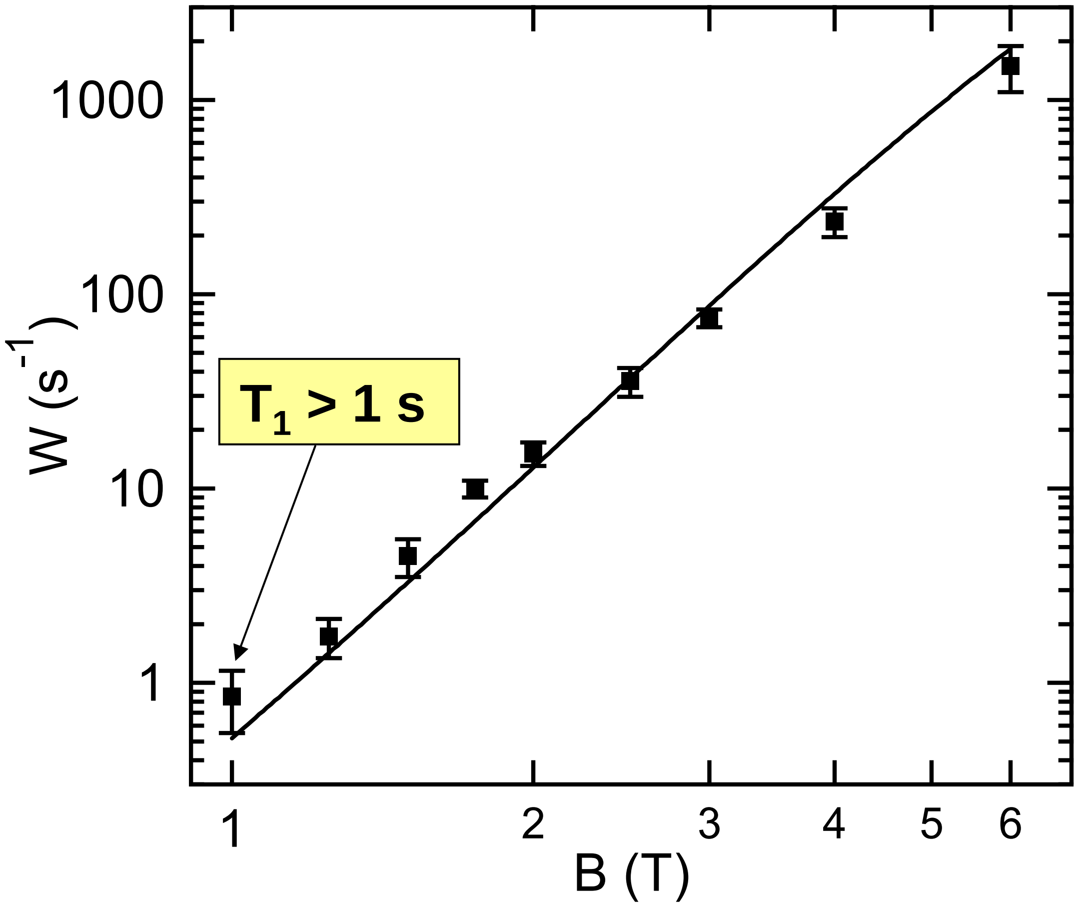
$$W \equiv T_1^{-1}$$

$$\Gamma_t = \Gamma_e + \Gamma_g$$

$$P_i(t_w) = \varepsilon_i\, e^{-\Gamma_t t_w}$$

$$P_e(t_w) = \varepsilon_i \frac{\Gamma_e}{\Gamma_t} \frac{\Gamma_t}{\Gamma_t - W} \left(e^{-W t_w} - e^{-\Gamma_t t_w}\right)$$

Relaxation Rate vs Magnetic Field



- **mechanism: spin-orbit + piezoelectric phonons**

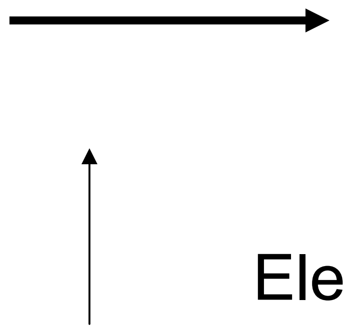
  [Khaetskii *et al*., PRB 2001 & Golovach *et al*., PRL 2004]

- W ~ B^5

- same mechanism observed in arrays of self-assembled dots.

  [Kroutvar *et al*., Nature 2004]

Mechanism



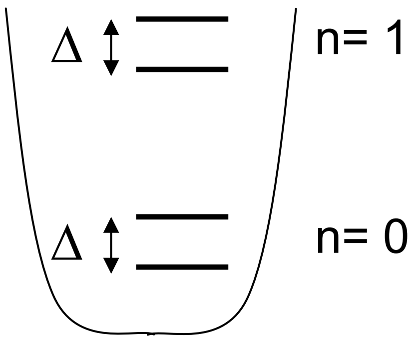
Electric Field
(intrinsic to heterostructure)

Electron with velocity v
(caused by piezoelectric phonon)

Effective magnetic field $B_{SO} \sim p$ is seen in rest frame of electron. Hamiltonian $H_{SO} \sim p\ \sigma$

Admixture Mechanism

- $H_{SO} = \underbrace{\alpha (p_{x'} \sigma_{y'} - p_{y'} \sigma_{x'})}_{\text{Rashba}} + \underbrace{\beta (- p_{x'} \sigma_{x'} + p_{y'} \sigma_{y'})}_{\text{Dresselhaus}}$ $x' = [100]$, $y' = [010]$



- No SO interaction $\Rightarrow$ $|0 \uparrow\rangle$ and $|0 \downarrow\rangle$ are eigenstates.

- Treat SO as perturbation:

$$|0 \uparrow\rangle_{eff} = |0 \uparrow\rangle + |1\downarrow\rangle \frac{\langle 1\downarrow|H_{SO}|0\uparrow\rangle}{E_0 - E_1 - \Delta} + \ldots$$

$$M = {}_{eff}\langle 0 \downarrow| U_{ph} |0\uparrow\rangle_{eff} \approx \frac{\langle 0 \downarrow|U_{ph}|1\downarrow\rangle\langle 1\downarrow|H_{SO}|0\uparrow\rangle}{-E_{orb} - \Delta} + \frac{\langle 0 \downarrow|H_{SO}|1\uparrow\rangle\langle 1\uparrow|U_{ph}|0\uparrow\rangle}{-E_{orb} + \Delta}$$

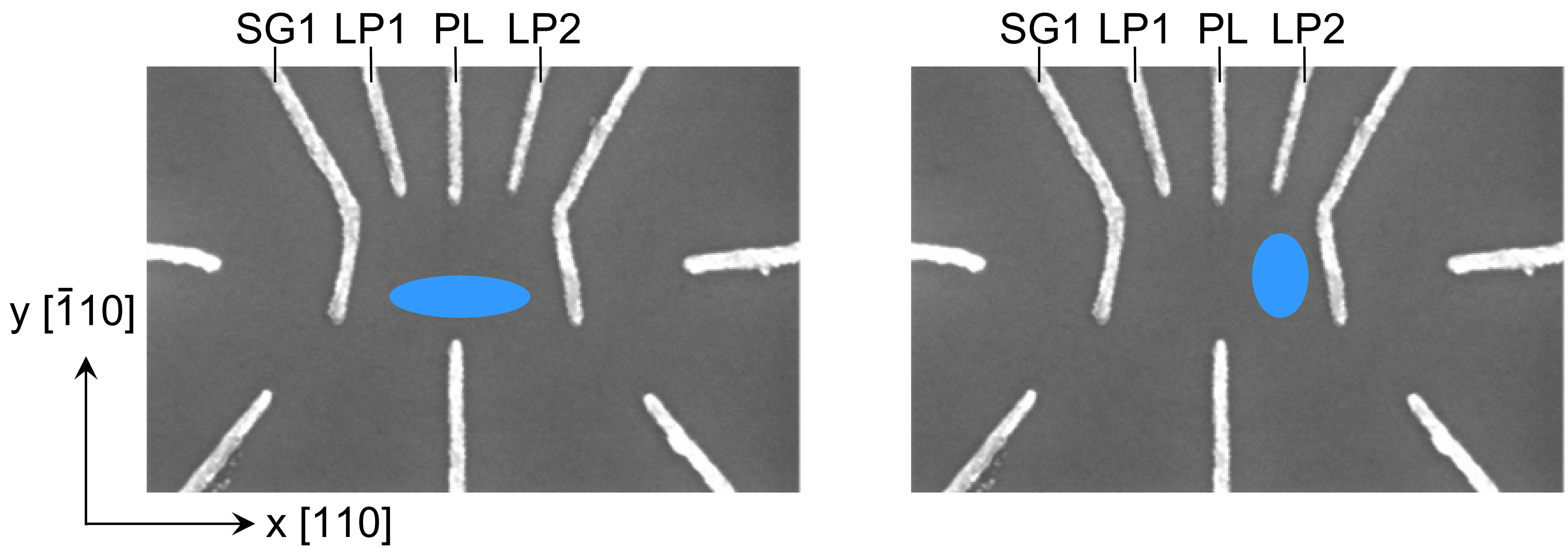
$$M \propto q^{1/2} \frac{H_{SO}}{E} \frac{|g|\mu_B B}{E}$$

$$W \propto \underbrace{|q^{1/2} B E^{-2}|^2}_{M} \underbrace{q^2}_{D_{ph}(q)} \propto B^5 E^{-4} \qquad \text{since } q \propto B$$

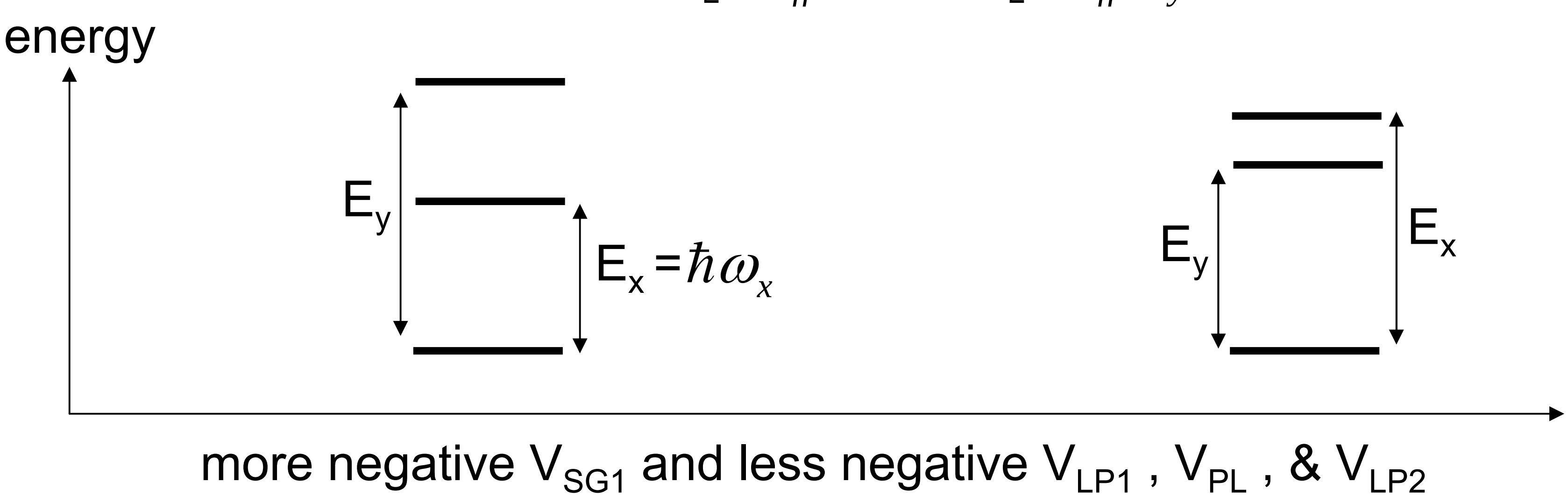
III. Control of Spin Relaxation

Amasha et al. arXiv:0707.1656v1

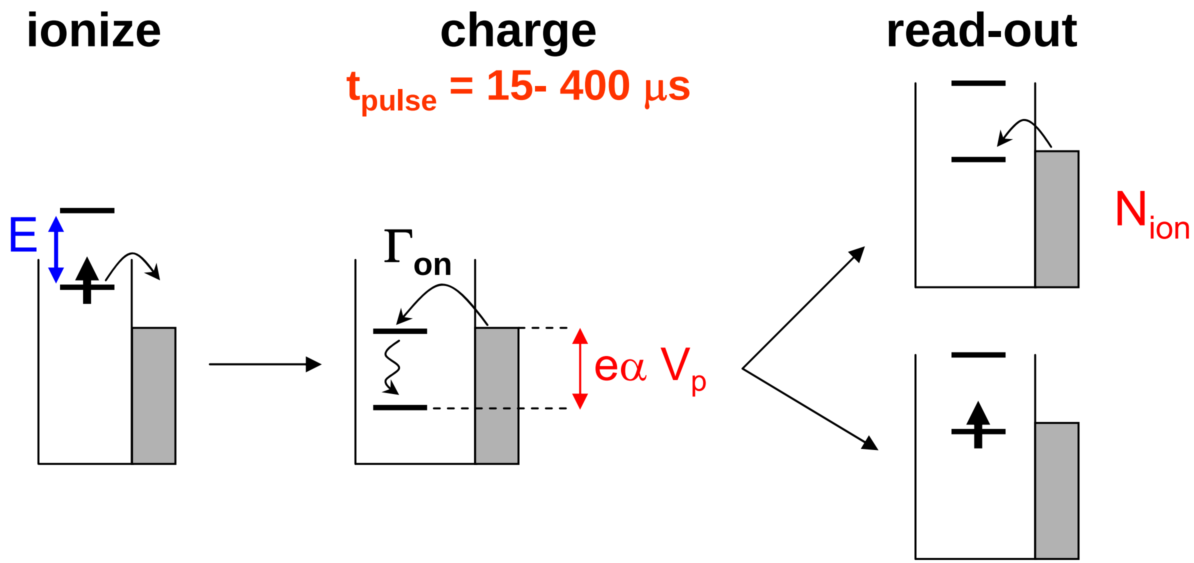
Control of the Orbital States

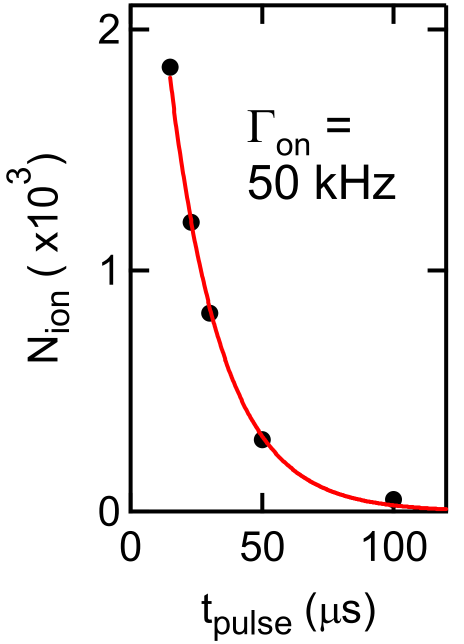


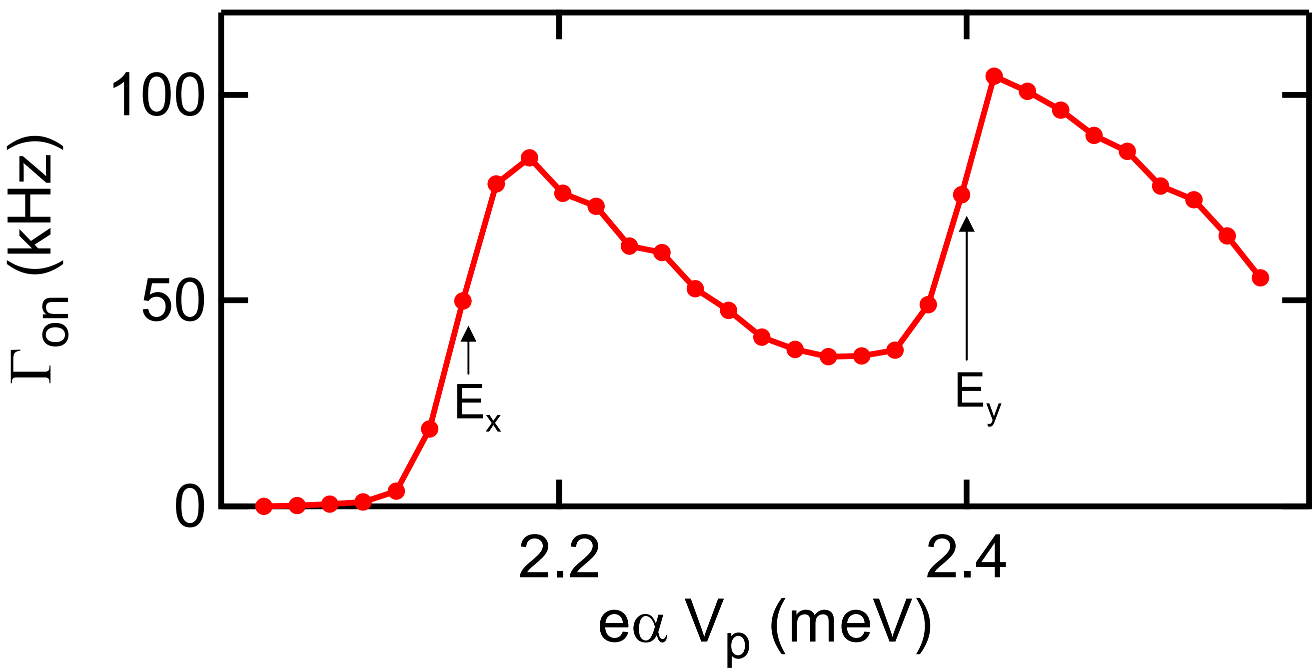
$$U(x,y) = \tfrac{1}{2} m_{eff} \omega_x^2 x^2 + \tfrac{1}{2} m_{eff} \omega_y^2 y^2$$



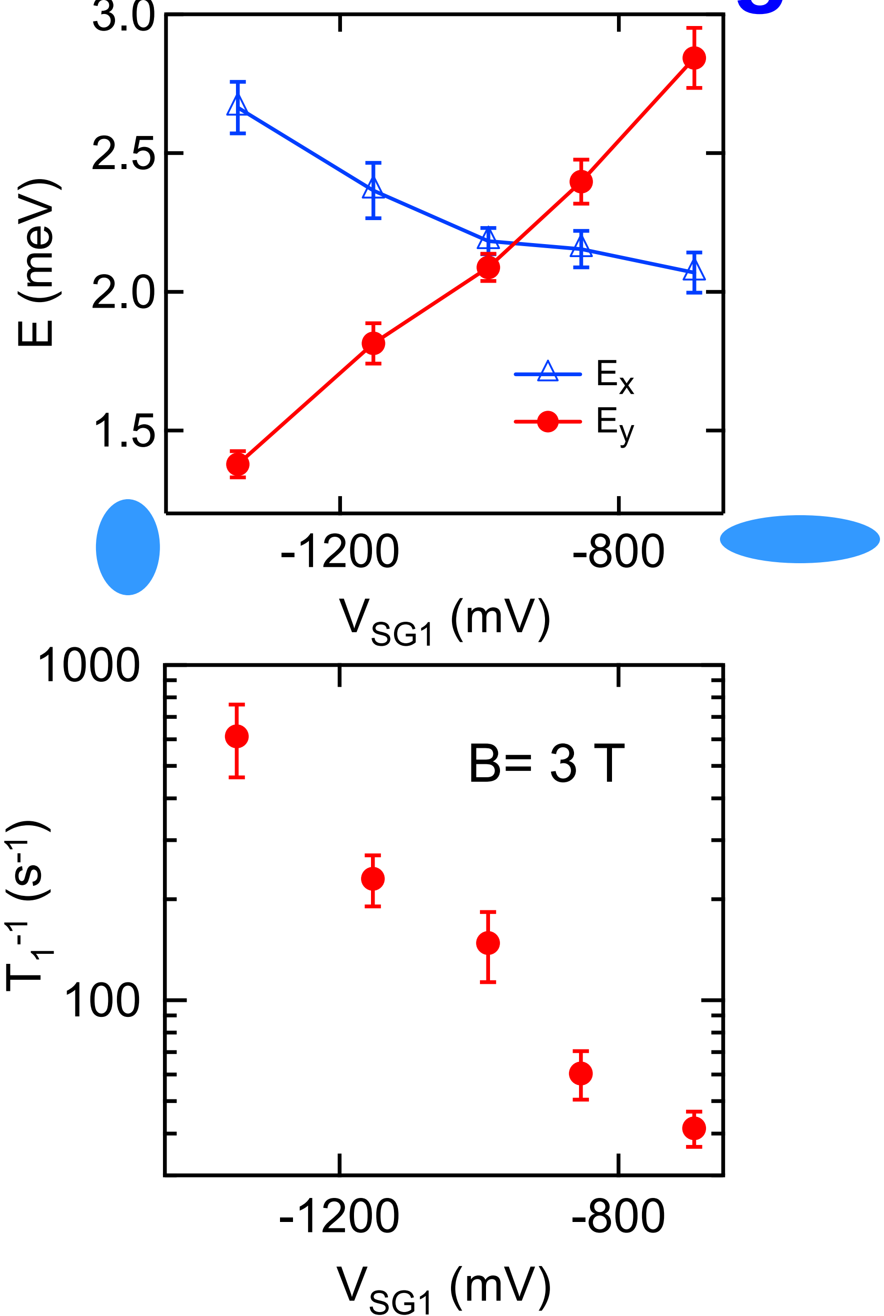
Excited State Energies





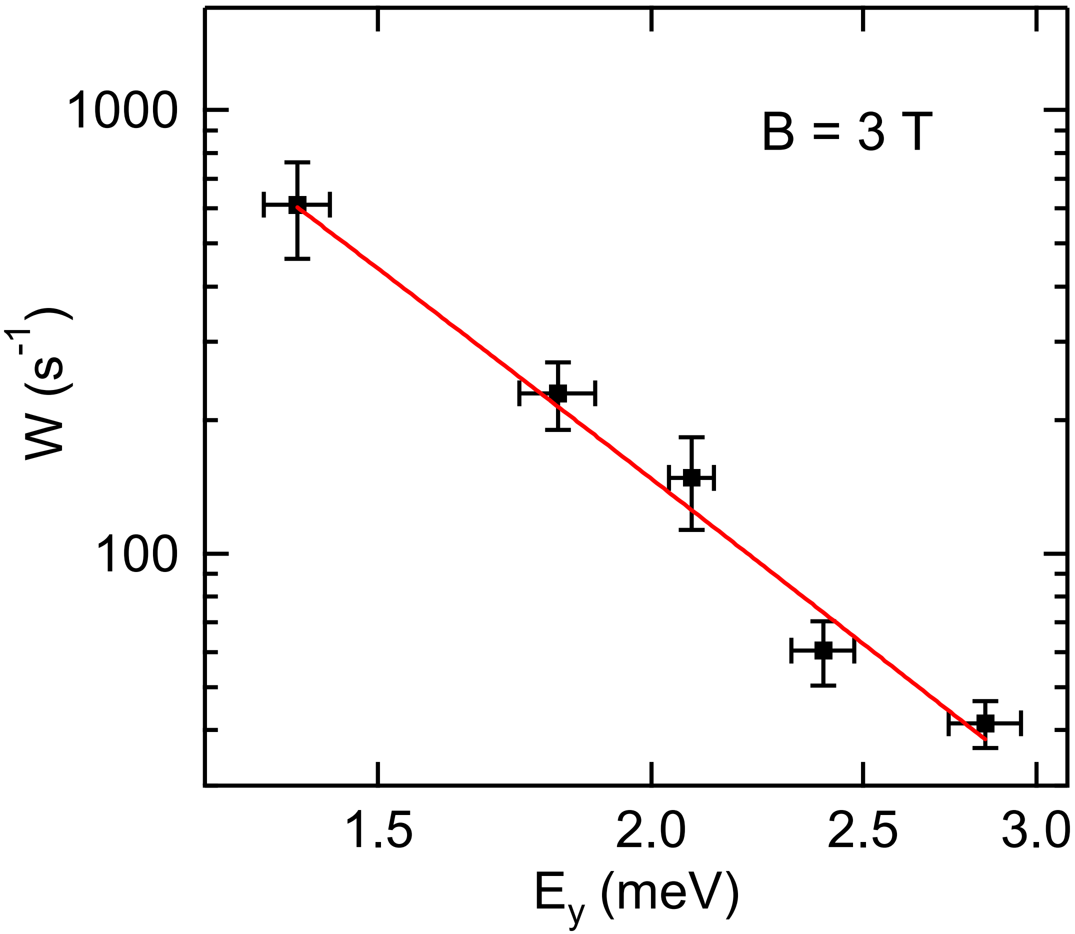


Voltage Tunable T_1



Relaxation Rate vs Orbital Energy

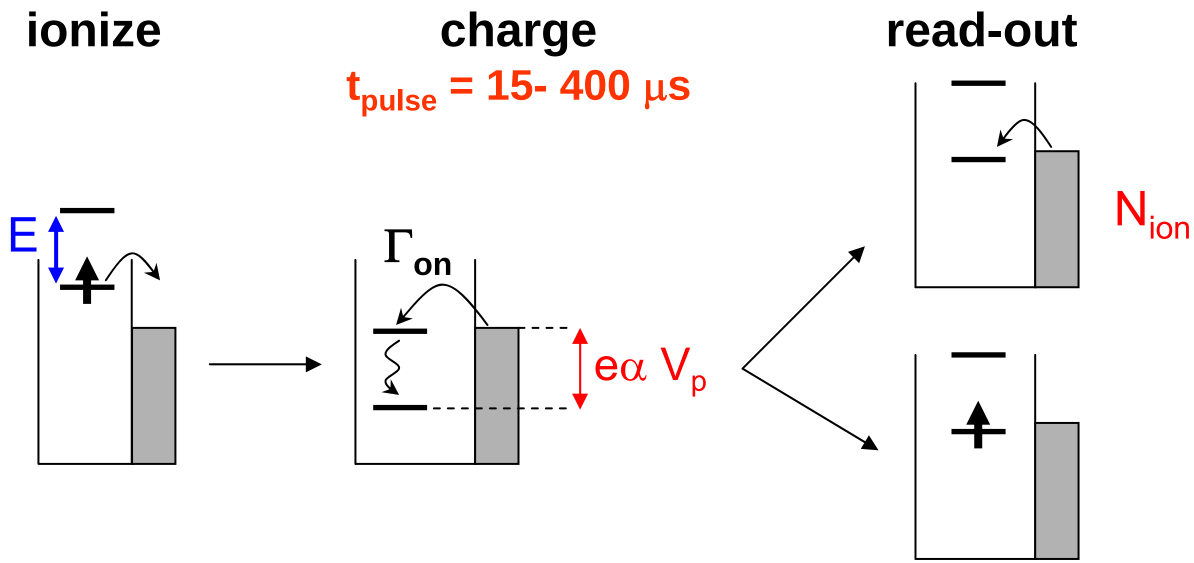
Spin-orbit mediated coupling to piezoelectric phonons.
[Khaetskii, *et al.* 2001 & Golovach, *et al.* 2004]

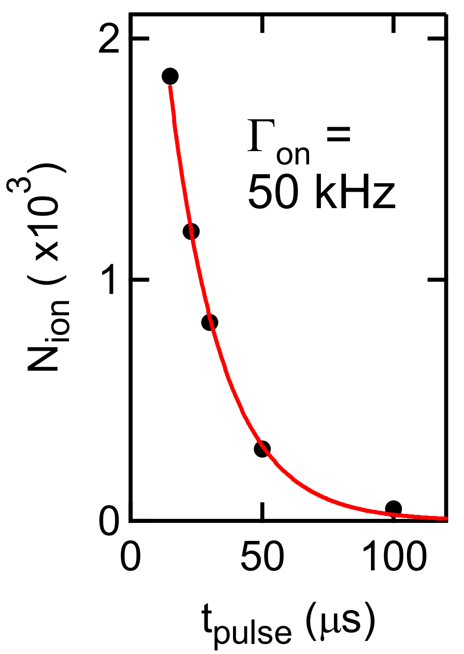


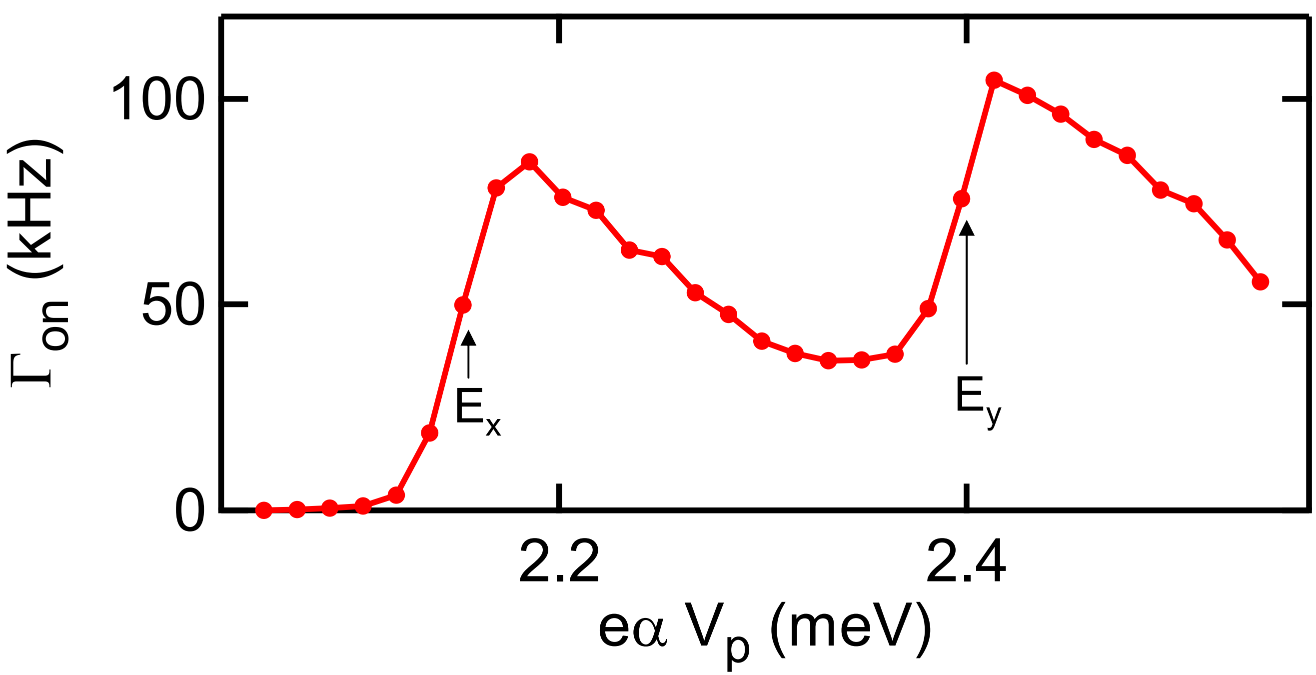
- $W \approx A \dfrac{B^5}{\lambda_{SO}^2 \; E_{orb}^4}$
- $\lambda_{SO} = 1.7 \pm 0.2\ \mu m$
- B constant $\Rightarrow$ Δ constant
  We change state admixture,
  not the phonon wavelength!

Can control the spin relaxation rate in lateral quantum dots

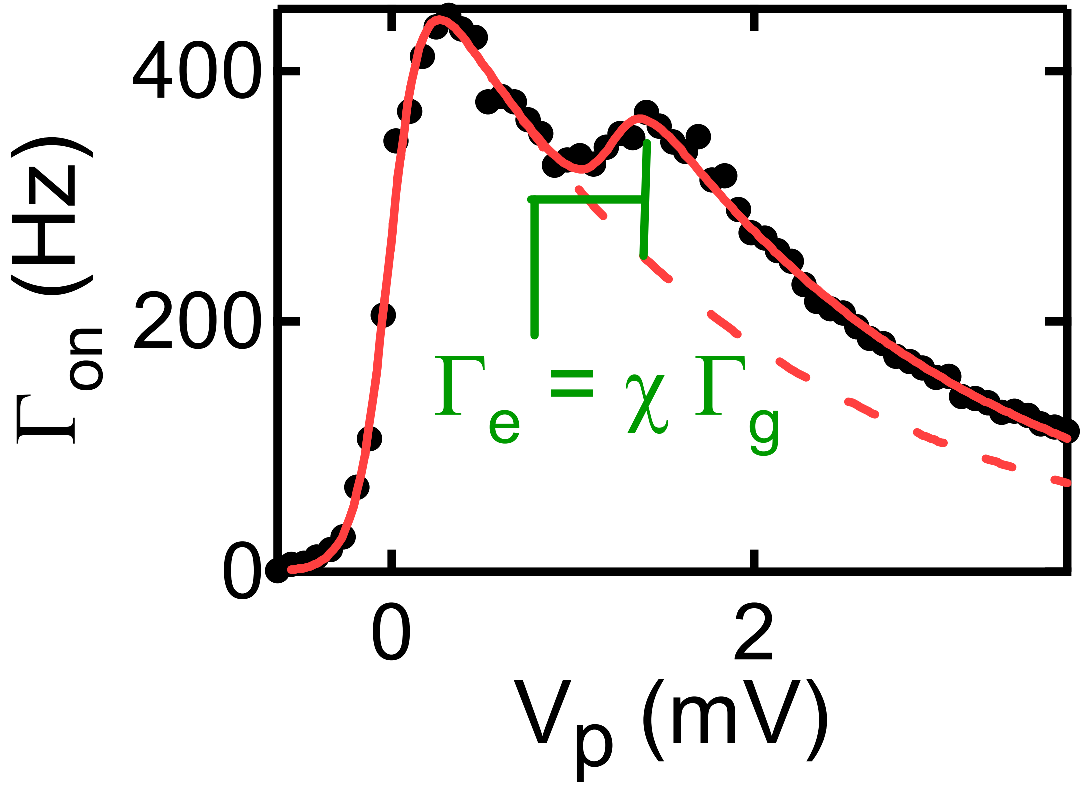
Excited State Energies





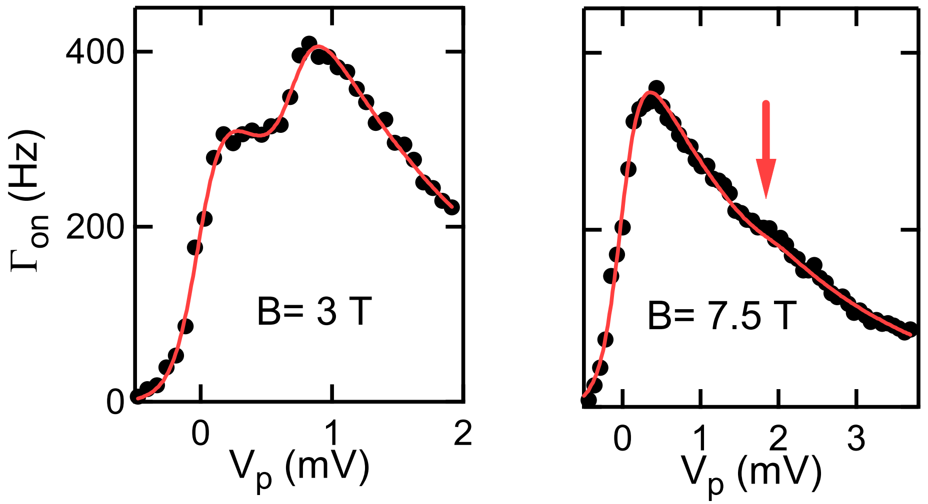


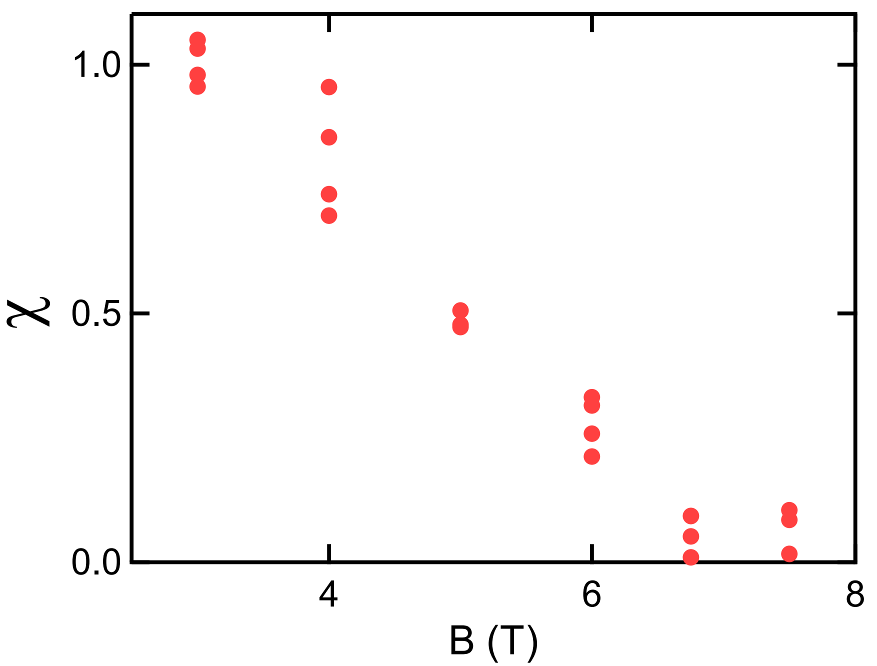
Spin Excited State



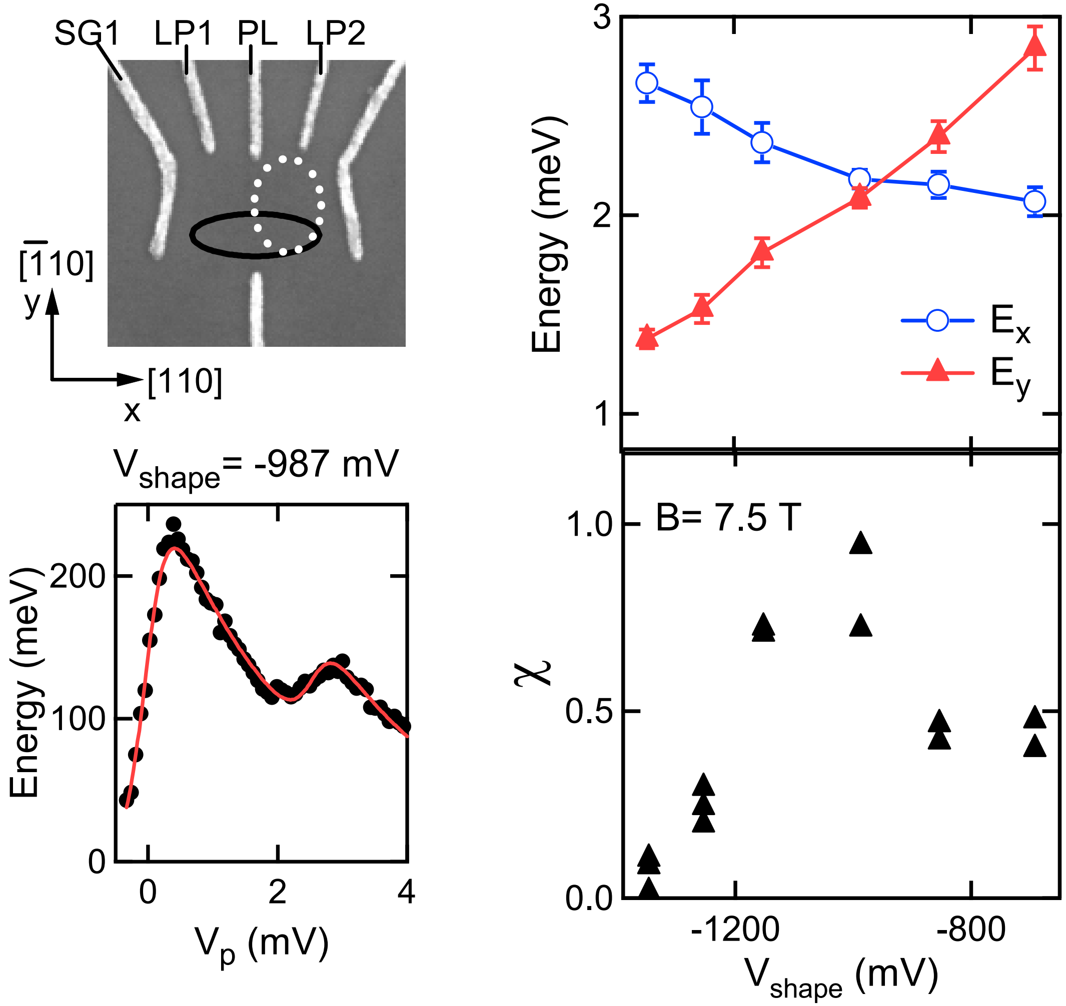
With no spin polarization $\chi = 1$

Tunneling at High Field





Depends on Shape



Summary

I. Single Electron Tunneling Spectroscopy

- Tunneling is elastic
- Depends exponentially on barrier height

II. Spin Relaxation

- Use pulsing, DAQ, and active feedback to measure T_1
- Mechanism: spin-orbit and piezoelectric phonons.
- Measure spin-orbit length

III. Control of Spin Relaxation

- Gate voltages control dot orbital states
- Voltage tunable spin-relaxation rate in quantum dots

IV. Tunneling into ground orbital state is spin dependent

- Depends on field
- Depends on shape

Field and Crystal Orientation