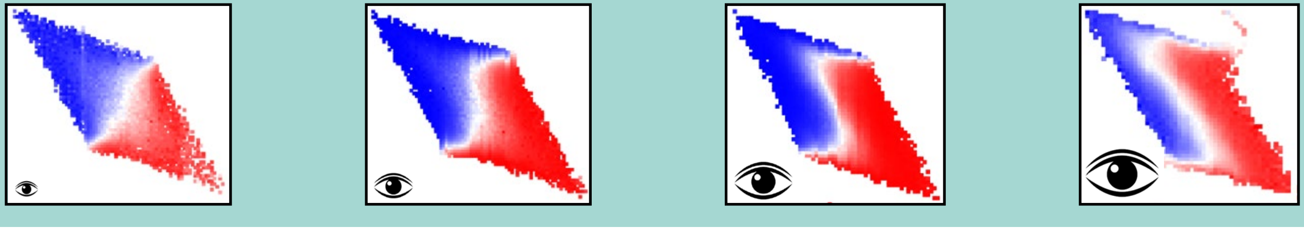
University of Basel

Department of Physics



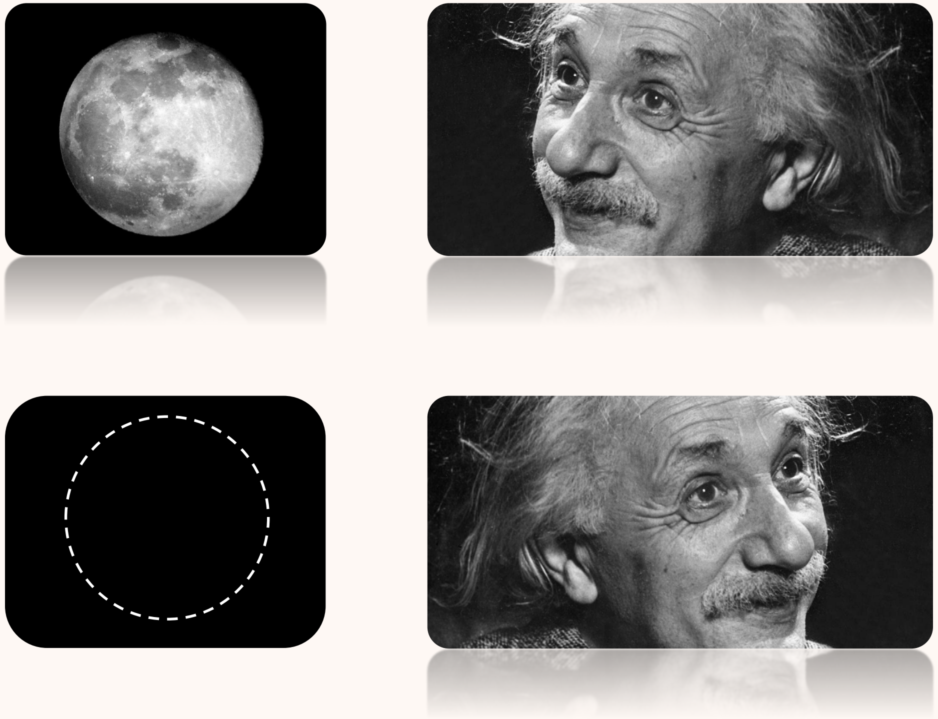
Christian Scheller
FMM 20.11.2020

A quantum measurement induced ground-state transition

M.S. Ferguson et. al, arXiv:2010.04635 (2020)
D.E.F. Biesinger et al, PRL **115**, 106804 (2015)

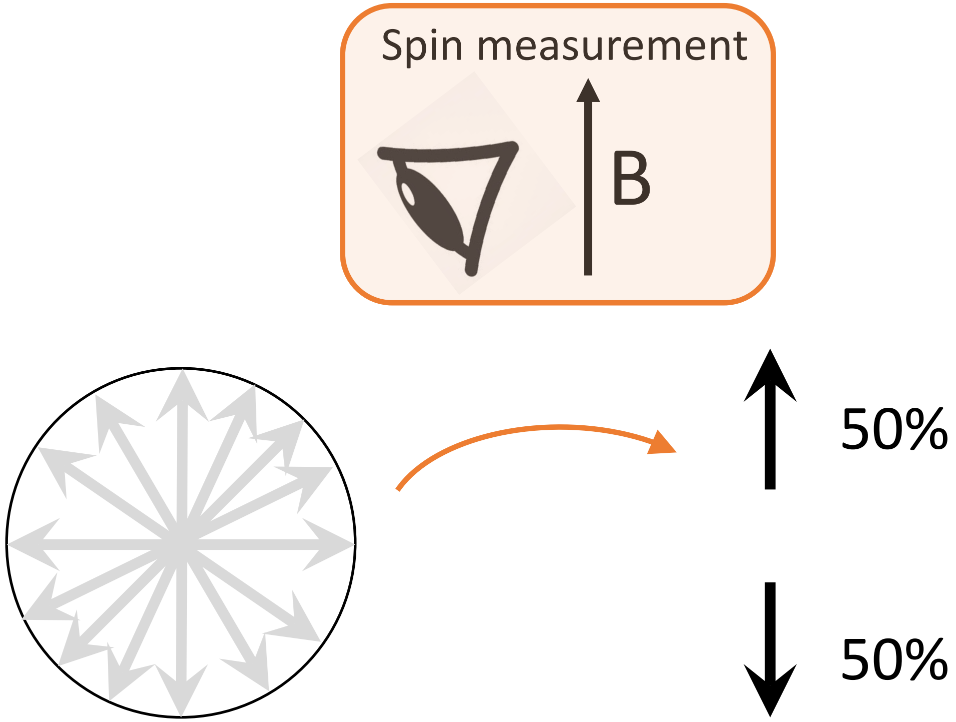
God does not throw dice !

Is the moon there if nobody is looking ?



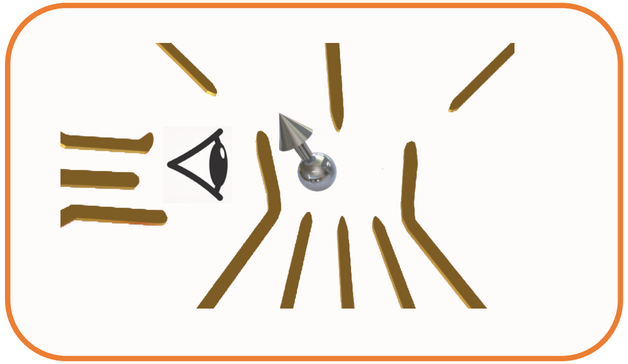
God does not throw dice !

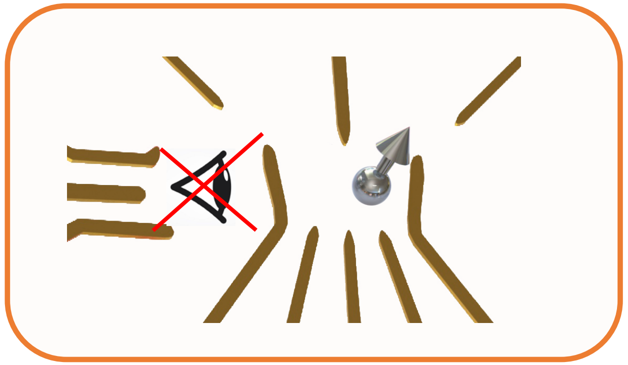
➡ Yes he does !



Is the moon there if nobody is looking ?

➡ That depends !

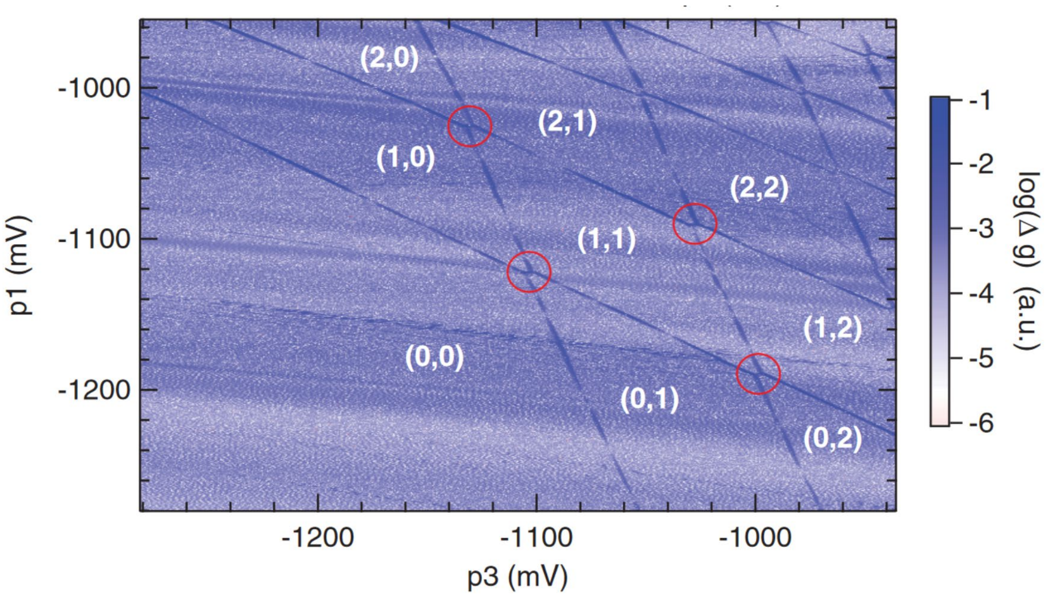


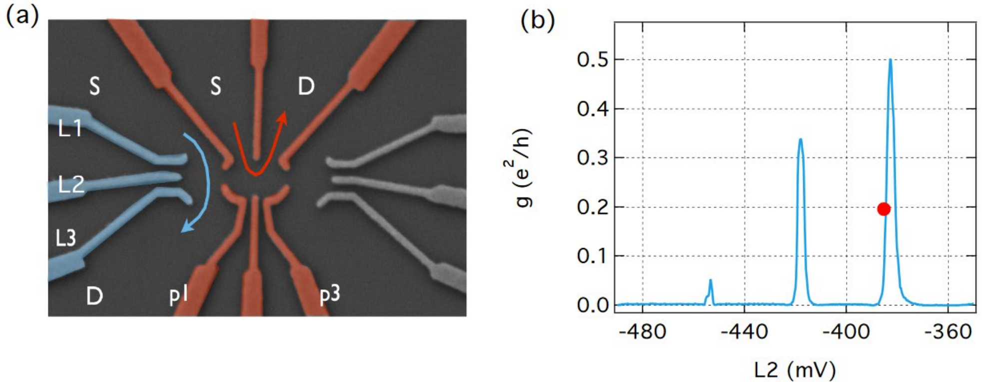


Device & charge sensing

Device:

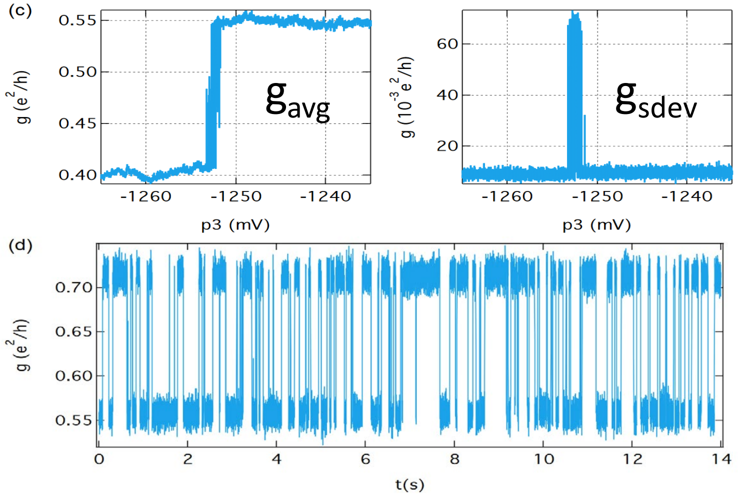
- GaAs double quantum dot
- Left QD charge sensor (same results with right sensor)
- Weak interdot-coupling
- Tuneable charge configuration down to (0,0)
- Standard charge stability diagram





Charge sensing:

- Capacitive coupling → DQD configurations affects g_{sensor}
- Record sensor conductance with fast DAQ → g_{avg}, g_{sdev}
- transitions also visible in g_{sdev} if tunnel rates do not exceed BW



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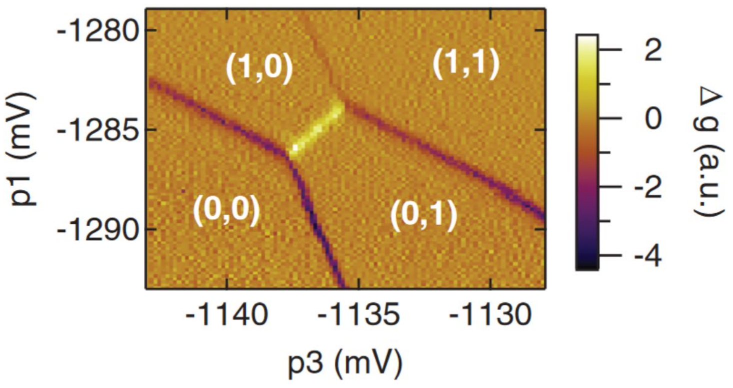
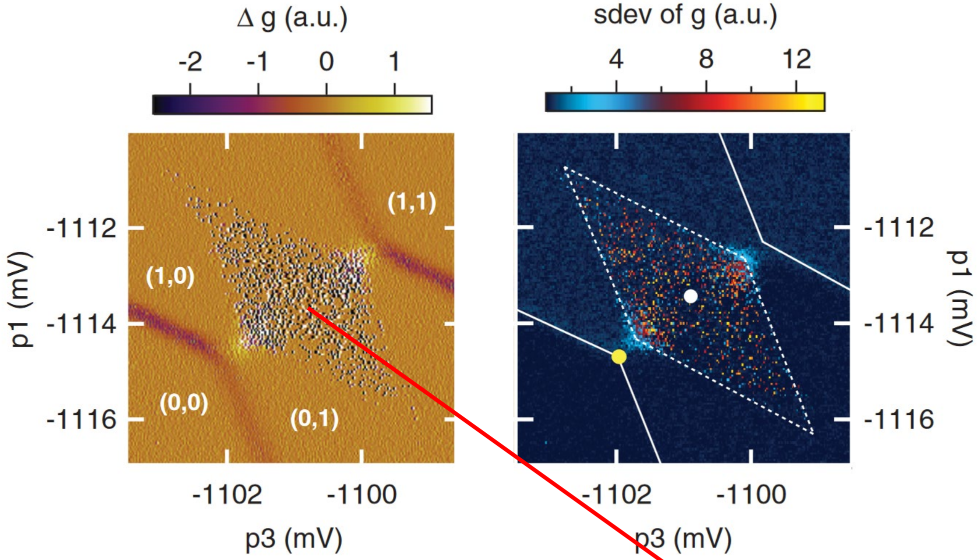
Charge switching diamond



quench interdot tunneling



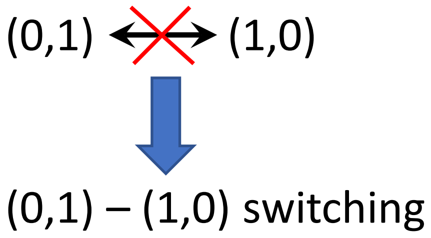
Quenching interdot tunneling

- Reduce interdot tunnel coupling to zero
- Zero detuning line disappears
- Noisy diamond shape appears
- Diamond boarders parallel lead transitions
- Within diamond (0,1) & (1,0) below chemical potential
- Visible in standard deviation as well

⇒ something is switching

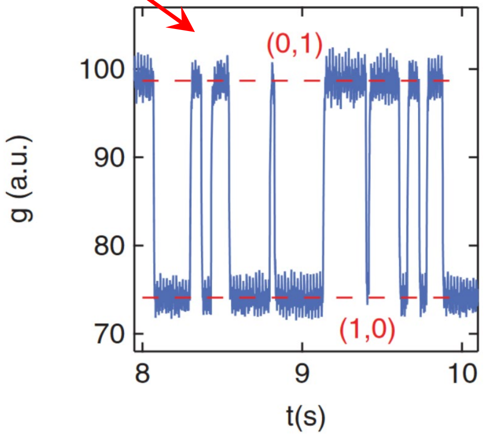
Real time tunneling

- Time trace within noise diamond
- Observe 2-level system
- Charge states are (0,1) and (1,0)



$(0,1) \cancel{\leftrightarrow} (1,0)$

(0,1) – (1,0) switching

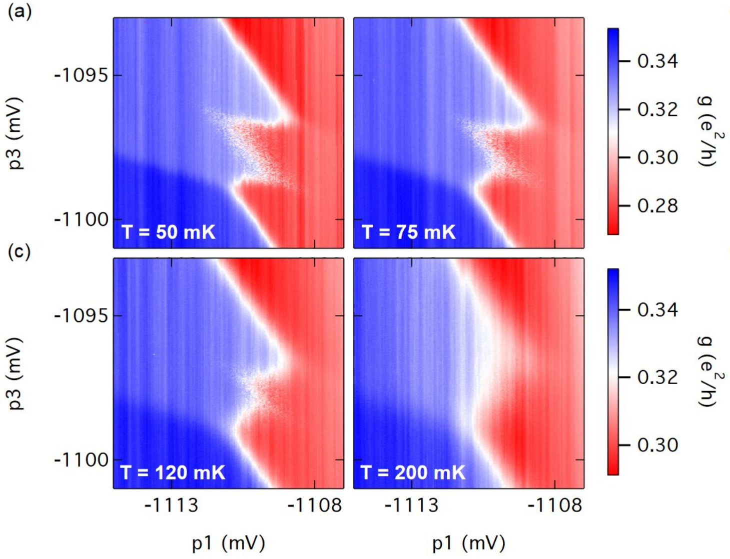


Temperature dependence

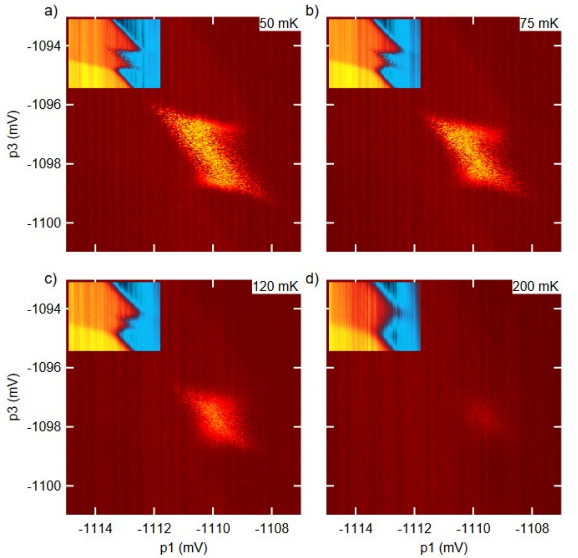
Noise diamond vs T

- Increase Tmc and record sensor signal
- Noise diamond disappears T = 200mK
- Same observation in sdev
- Does T suppress the switching?
  → look at switching rates

Sensor (average) conductance

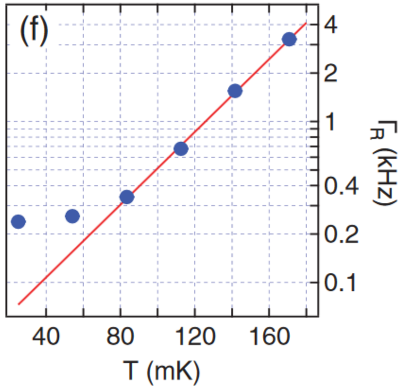


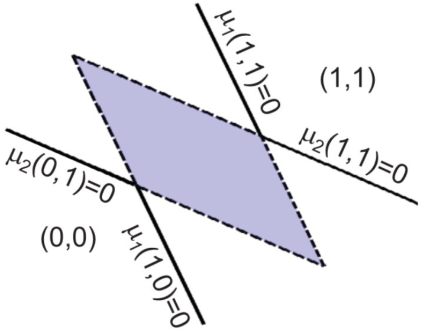
Sensor standard deviation



Switching rate vs T

- Switching rate grows exponentially above 60mK
- Rate saturates below 60mK (electron temperature in the device)
- Switching is thermally activated
- DQD does not have temperature → leads involved?
- Consistent with diamond boarders parallel lead transition lines

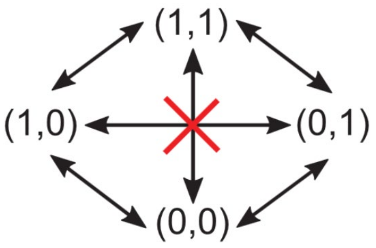


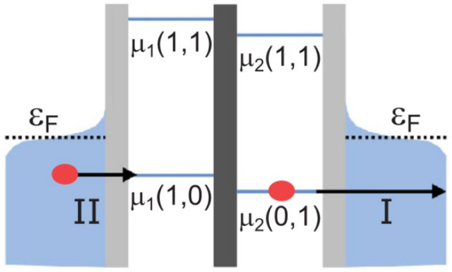


Electron exchange via leads

Proposed model

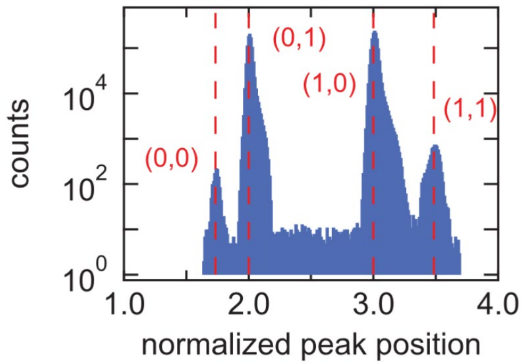
- No interdot tunneling
- (0,1)-(1,0) exchange via leads via (0,0) or (1,1)
- (0,1)-(1,0) metastable, takes long to tunnel out (tail of FD distribution)
- (0,0) & (1,1) high energy states → decay quickly (beyond band width)

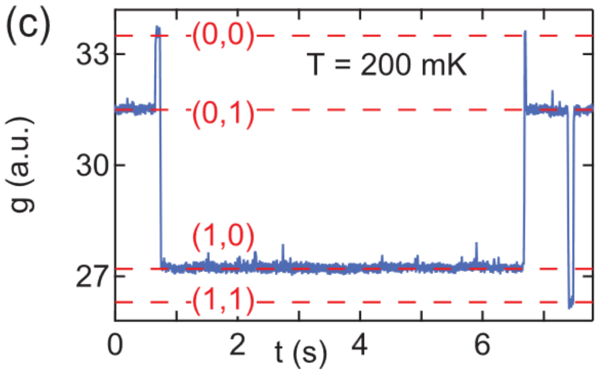




Making all states visible

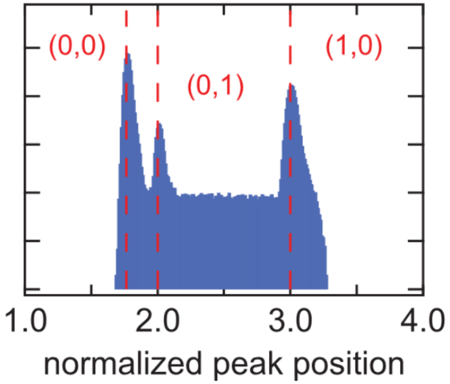
- Reduce tunnel coupling to leads below BW
  ⇒ system does not switch anymore (freq. to low)
- Increase T to boost switching again (broader FD tails)
- All 4 states are visible now
- Switching only occurs via (0,0) and (1,1), never direct





3 states for triple point

- Use triple point for sanity check
- Only 3 states are expected
- Lower triple point: (0,1), (1,0), (0,0)



Tunnelling rates Exp vs Theory

Master equation approach for transition rates

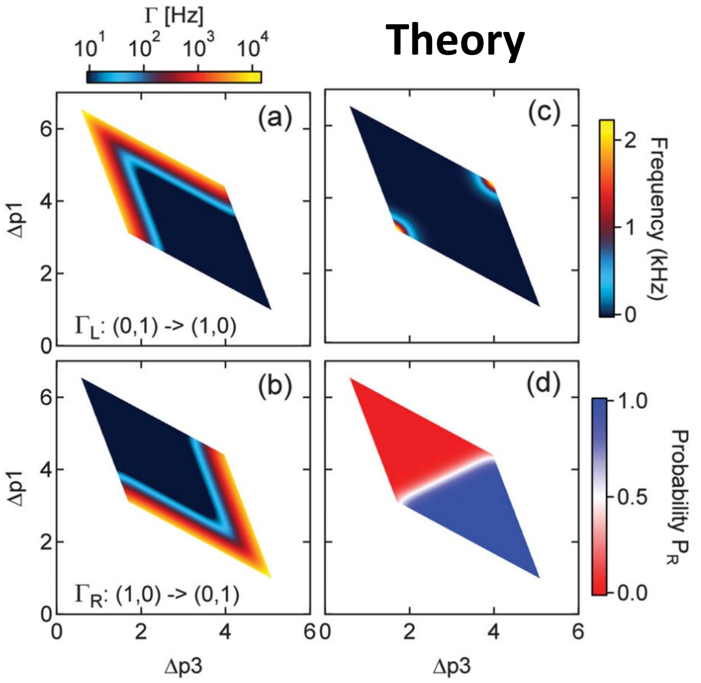
- Tunnelling from (0,0) & (1,1) with bare lead tunnel rate
- Tunnelling from (0,1) & (1,0) given by tail of FD
- Obtain transition rates $T_{L\to R}$ and $T_{L\to R}$
- Switching frequency (large if both $T_{L\to R}$ and $T_{L\to R}$ are large)
- Standard occupation probability recovered
- S-shape, scaling with sensor bias → backaction

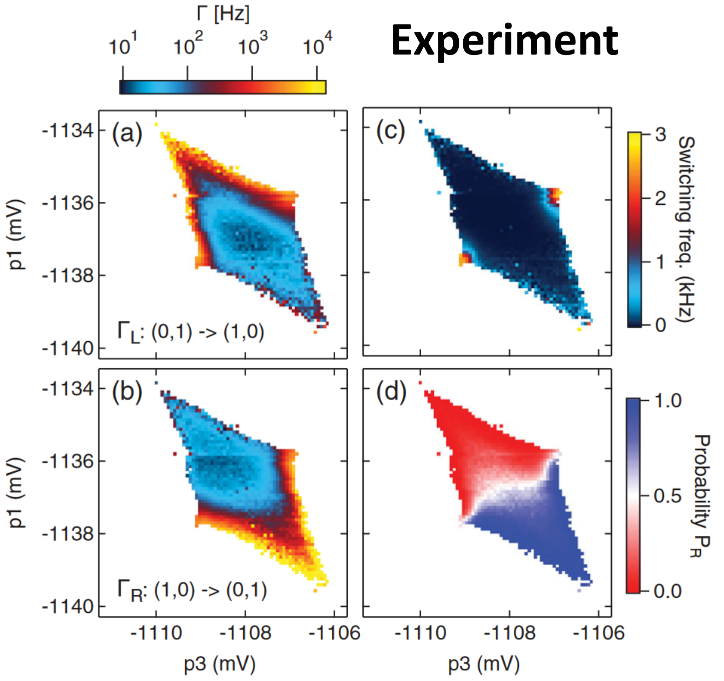
$$\Gamma_{(0,0)\to(0,1)} = \Gamma_2 f(\mu_2(0,1)),$$

$$\Gamma_{(0,1)\to(0,0)} = \Gamma_2[1 - f(\mu_2(0,1))],$$

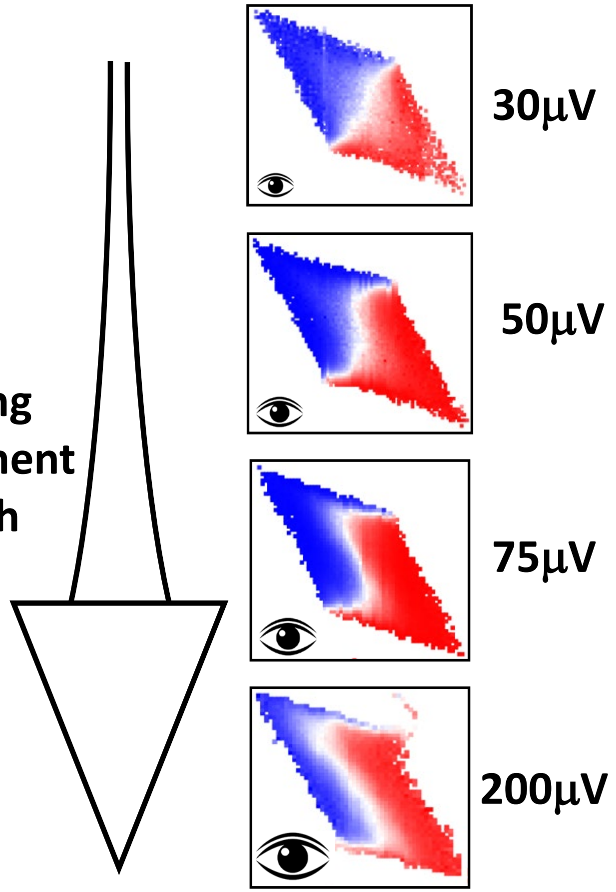
$$\Gamma_{(0,1)\to(1,1)} = \Gamma_1 f(\mu_1(1,1)),$$

$$\Gamma_{(1,1)\to(0,1)} = \Gamma_1[1 - f(\mu_1(1,1))].$$


Theory


Experiment

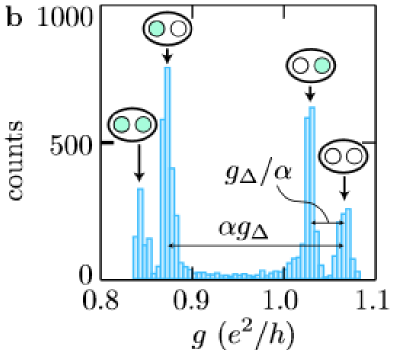
increasing measurement strength

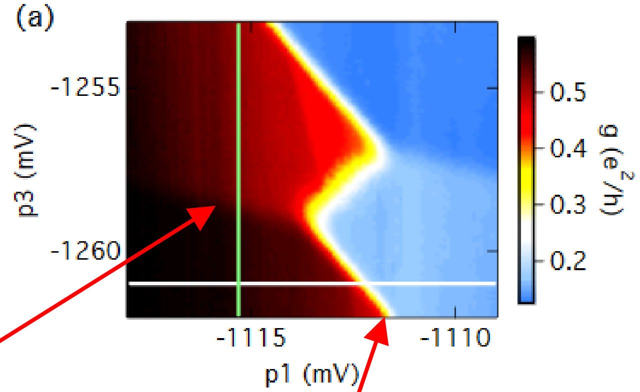


Sensor induced level broadening

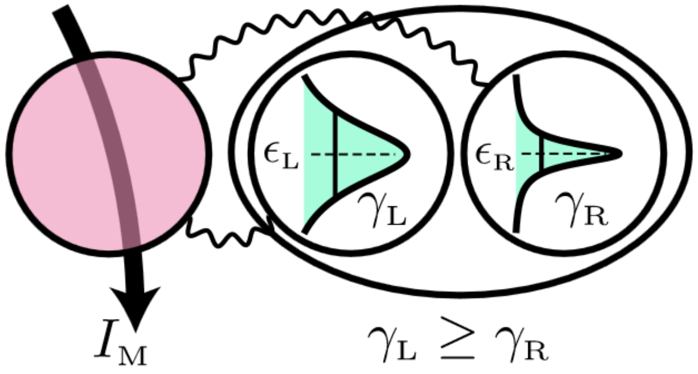
Line broadening

- DQD charge configuration affects sensor conductance
- Electron passing sensor also shifts DQD level
- Sensor current shakes DQD levels ⇒ level broadening
- Broadening scales with capacitance (distance to sensor)
  - ⇒ only significant broadening for adjacent dot
- Comparing sensor response → ratio coulomb interactions $\alpha^2 = U_{LM}/U_{RM}$



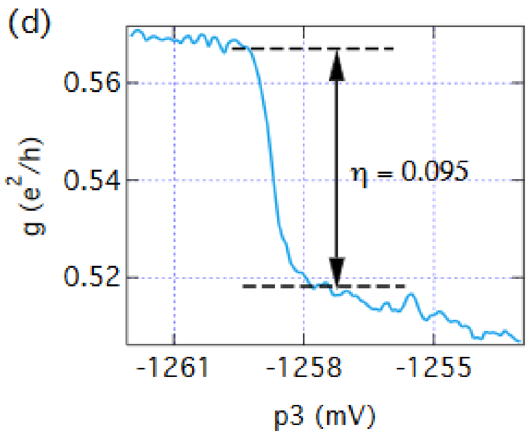


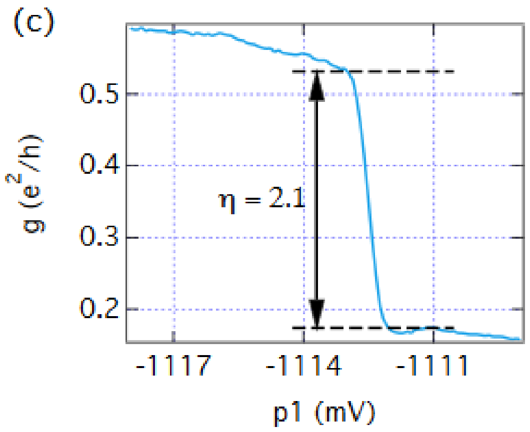
Large level broadening for close dot



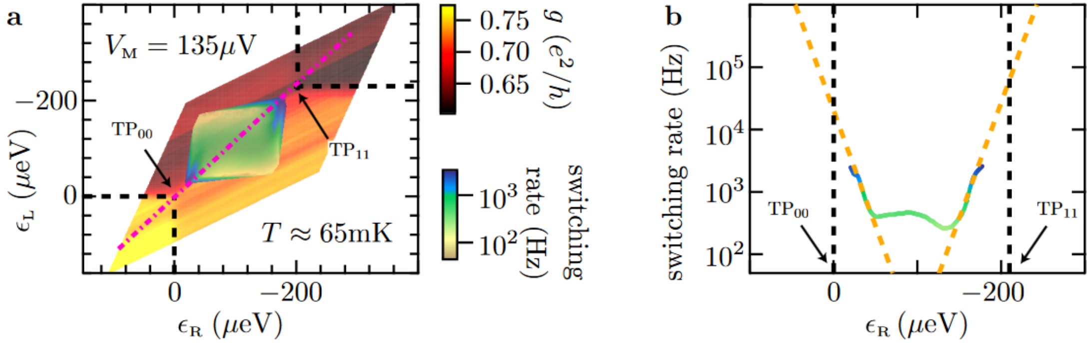
Add electron to right dot

Add electron to left dot





Sensor backaction model



Model input parameters

- Ratio coulomb interaction strength (left vs right dot, previous slide)
- Lever arms: Transition width (thermally broadened) vs T
- Extrapolate dot-lead tunnelling rates (beyond band-width)

Complete Model

$$H = H_{\mathrm{dd}} + H_{\mathrm{leads}} + H_{\mathrm{tun}} + H_{\mathrm{M}} + H_{\mathrm{int}}$$

$$H_{\mathrm{dd}} = \epsilon_{\mathrm{L}} d_{\mathrm{L}}^\dagger d_{\mathrm{L}} + \epsilon_{\mathrm{R}} d_{\mathrm{R}}^\dagger d_{\mathrm{R}} + U d_{\mathrm{L}}^\dagger d_{\mathrm{L}} d_{\mathrm{R}}^\dagger d_{\mathrm{R}}$$

$$H_{\mathrm{leads}} = \sum_{k,i=\mathrm{L,R}} \epsilon_{ik} c_{ik}^\dagger c_{ik}$$

$$H_{\mathrm{tun}} = \sum_{k,i=\mathrm{L,R}} t\,(d_i^\dagger c_{ik} + h.c.)$$

$$H_{\mathrm{M}} = \epsilon_{\mathrm{M}} d_{\mathrm{M}}^\dagger d_{\mathrm{M}} + \sum_{k,i=\mathrm{s,d}} \left[\epsilon_{ik} c_{ik}^\dagger c_{ik} + t_{\mathrm{M}}(d_{\mathrm{M}}^\dagger c_{ik} + h.c.)\right]$$

$$\boxed{H_{int} = (U_{\mathrm{LM}} d_{\mathrm{L}}^\dagger d_{\mathrm{L}} + U_{\mathrm{RM}} d_{\mathrm{R}}^\dagger d_{\mathrm{R}}) d_{\mathrm{M}}^\dagger d_{\mathrm{M}}}$$

Backaction

Fermi's golden rule (bare & + backaction)

$$\Gamma_{if} = \Gamma_{\mathrm{dd}} \int \mathrm{d}\epsilon\, \delta(\epsilon - \epsilon_i + \epsilon_f) n_{\mathrm{F}}(\epsilon) = \Gamma_{\mathrm{dd}} n_{\mathrm{F}}(\epsilon_f - \epsilon_i)$$

$$\Gamma_{if} = \Gamma_{\mathrm{dd}} \int \mathrm{d}\epsilon \boxed{\frac{1}{\pi} \frac{\gamma_{f-i}}{\epsilon^2 + \gamma_{f-i}^2}} n_{\mathrm{F}}(\epsilon_f - \epsilon_i + \epsilon)$$

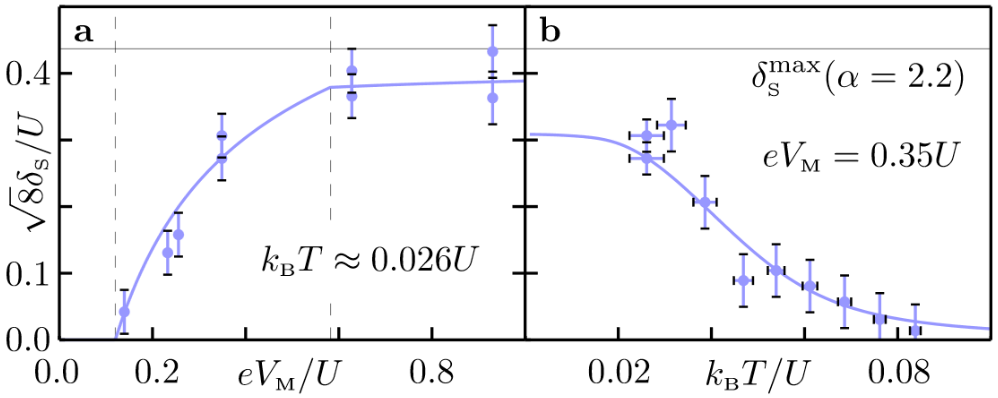
Rate equation for occup. probability

$$\partial_t P_i = \sum_j P_j \Gamma_{ij} - P_i \sum_j \Gamma_{ij}$$

Theory vs Experiment

Extract S-shape and compare

- S-shape strength: Amplitude of sine-function fit
- S-shape evolution vs measurement strength (bias)
- S-shape evolution vs temperature

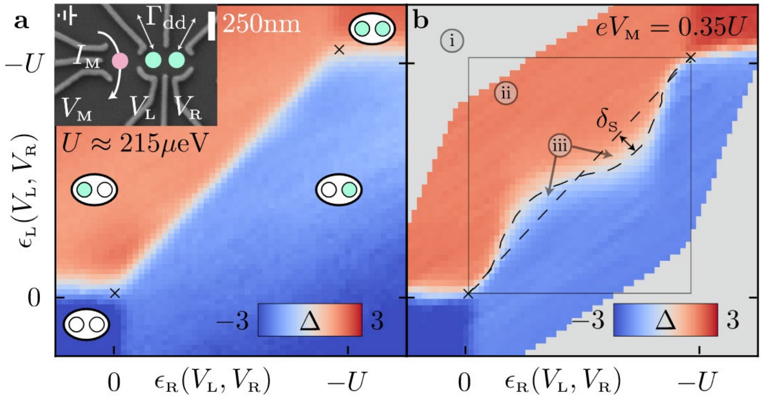


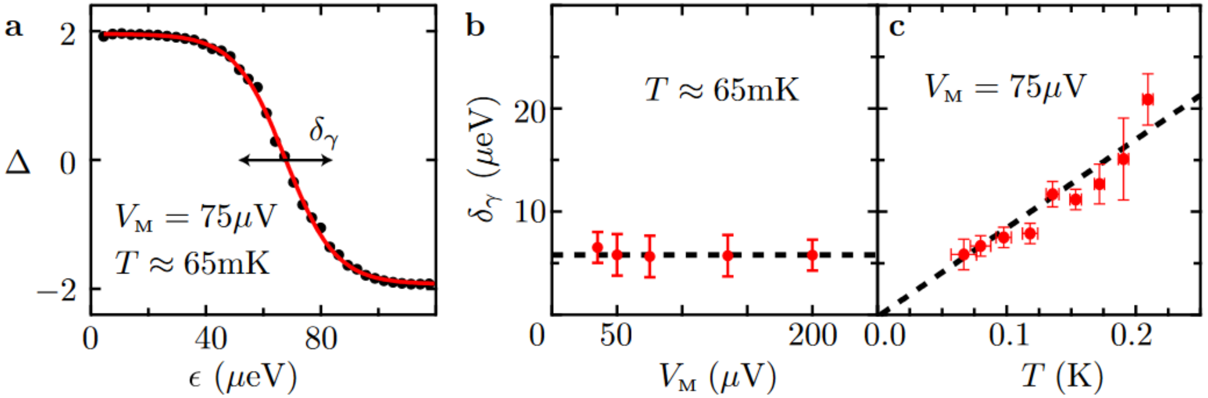
Sanity check

- Bias is not heating the system
- (0,1) – (1,0) transition width not affected by sensor bias
- Width consistent with $k_B T$

Rotate data to ϵ_L, ϵ_R basis

$$\begin{pmatrix}\epsilon_{\rm L}\\ \epsilon_{\rm R}\end{pmatrix} = \begin{pmatrix} l_{\rm LL} & l_{\rm LR}\\ l_{\rm RL} & l_{\rm RR}\end{pmatrix}\begin{pmatrix} V_{\rm L} - V_{\rm L}^0 \\ V_{\rm R} - V_{\rm R}^0\end{pmatrix}$$

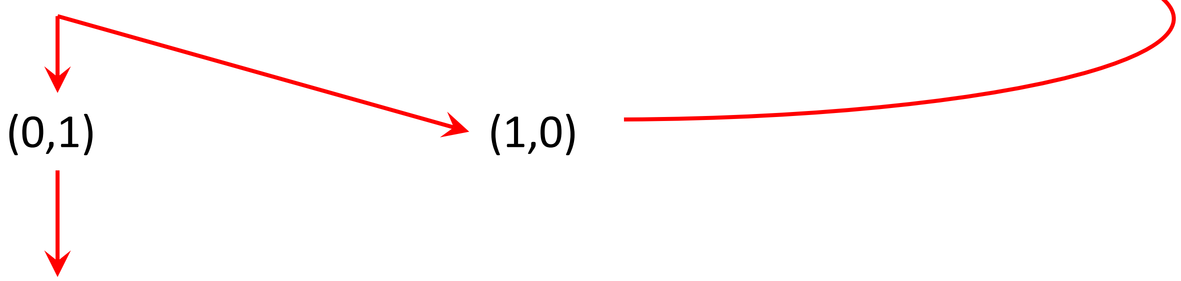




Ground-state transition

Population inversion

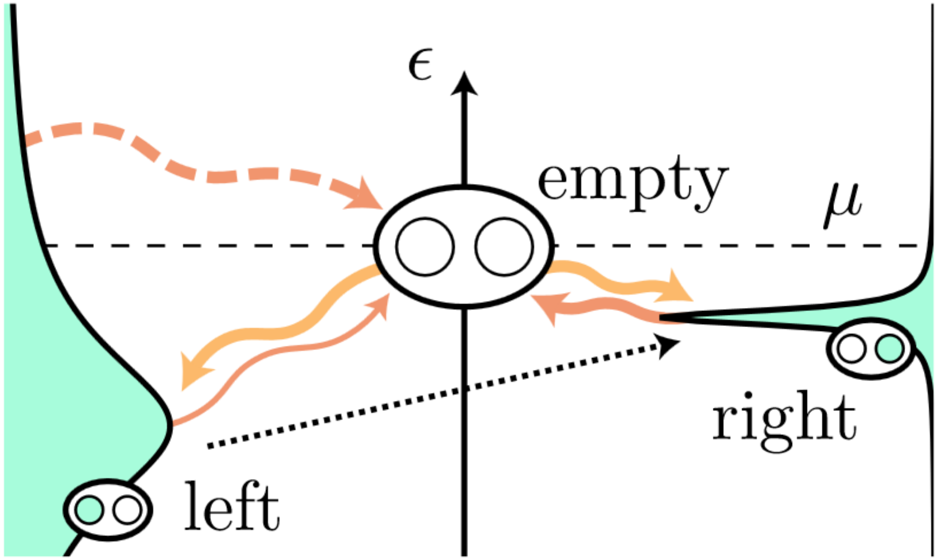
- (1,0) lowest energy state
- Observation of (mainly) the left dot with sensor → level broadening
- Broadened level can be emptied efficiently to (0,0)
- (0,0) decays quickly



(0,1) (1,0)

- right dot far from sensor → very little level broadening
- Broadened (0,1) completely below chem. potential
- (0,1) metastable, electron spends a lot of time here

⇒ low energy level efficiently emptied to high energy level
⇒ Inversion of ground-state population: ground-state transition



Conclusions

- Every detector causes backaction on the measured system
- Charge sensor causes level broadening in adjacent DQD
- Enhanced coupling to reservoirs due to broadened DQD level
- Efficient depopulation of ground-state
- Population of higher energy state $\Rightarrow$ Ground-state transition (inversion)
- Change in measurement paradigm of ideal detectors
- Even weak measurements can drastically affect the state of many body systems
- Simple model (induced level broadening) captures quantitatively experiment