Molecular states in a one–electron double quantum dot

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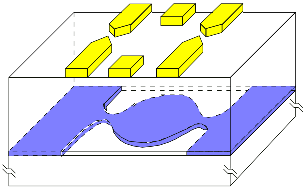
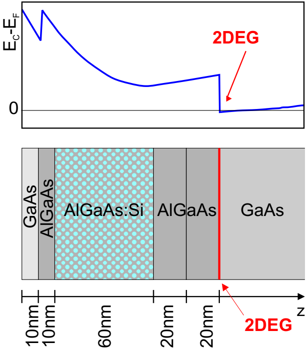
The material system – lateral quantum dots

- GaAs/AlGaAs heterostructure
- two-dimensional electron gas
- SEM lithography
- split–gate technique

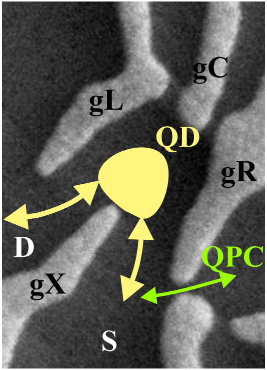


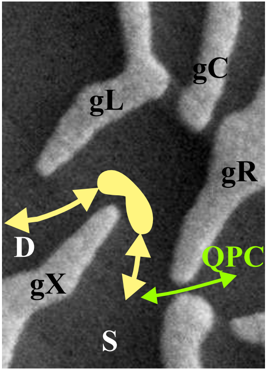


2DES depth $z \simeq 120\,\text{nm}$, e^- mean free path $l \simeq 5\,\mu\text{m}$, Fermi wavelength $\lambda_F \simeq 60\,\text{nm}$,

e^- sheet density $n \simeq 1.8 \cdot 10^{15}\,\frac{1}{\text{m}^2}$, e^- mobility $\mu \simeq 75\,\frac{\text{m}^2}{\text{Vs}}$

Deforming a single quantum dot





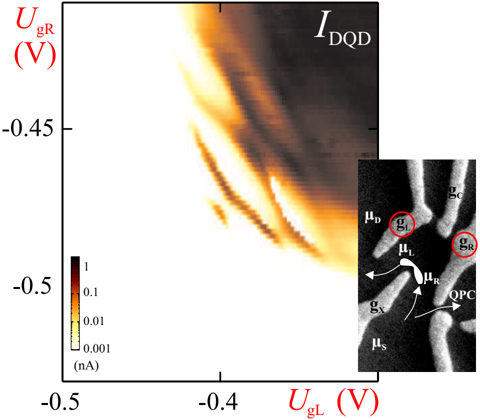
- triangular gate geometry
  (M. Ciorga *et al.*, PRB **61**, R16315)
- single quantum dot
- $N = 1$ electrons

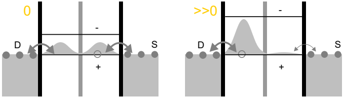
- U_{gC}, U_{gX} more negative
- U_{gL}, U_{gR} less negative

$\longrightarrow$ double well potential

Measured stability diagram

Side gates used to tune potentials!





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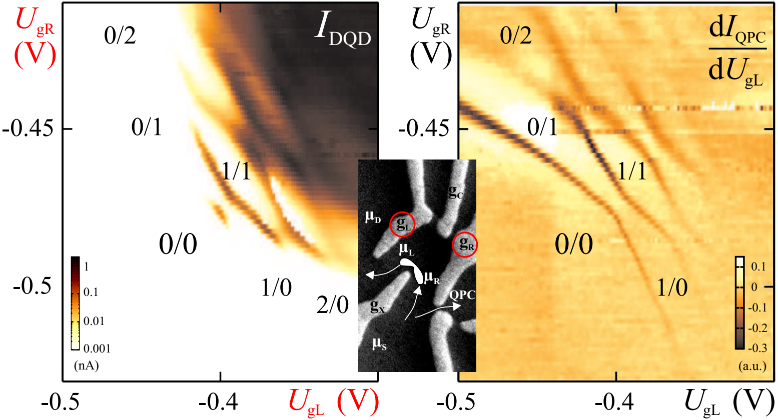
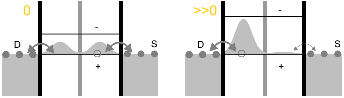




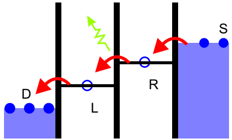
cond-mat/0501012, to appear in PRB

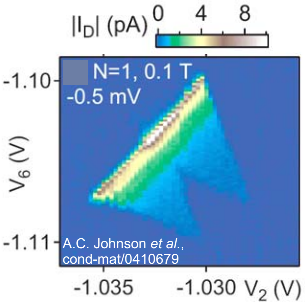
DQD: Finite U_{SD}, weak tunnel coupling

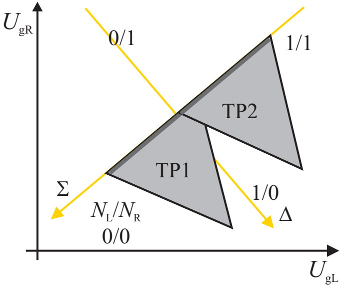
- Transport window

$$\mu_S \geq \mu_R \geq \mu_L \geq \mu_D$$

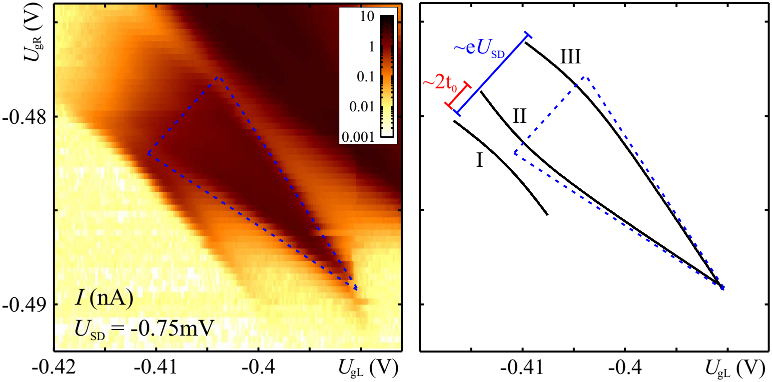
- Triplepoints expand to triangles, size $\leftrightarrow U_{SD}$
- $\mu_R \neq \mu_L \rightarrow$ relaxation required







Finite U_{SD}, strong tunnel coupling — current



curved lines ↔ molecular states

$$\mu_- - \mu_+ = 2\sqrt{\Delta^2 + t_0^2} \qquad \Delta = \frac{\mu_R - \mu_L}{2}$$

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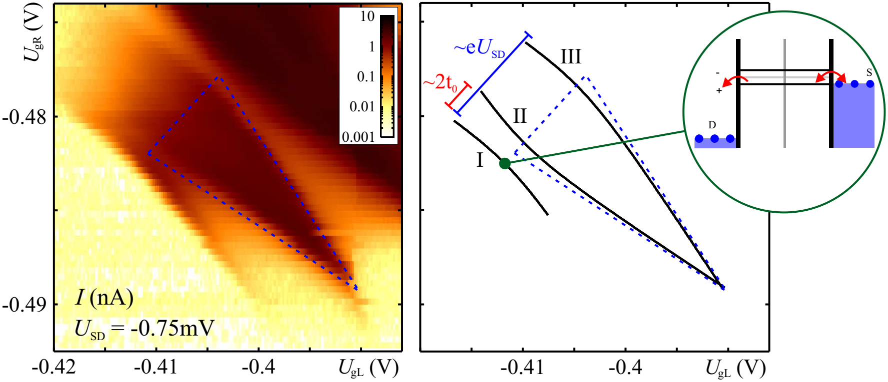

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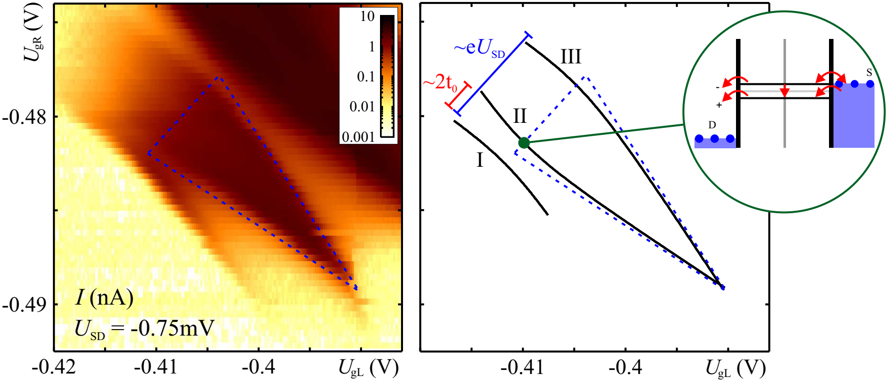

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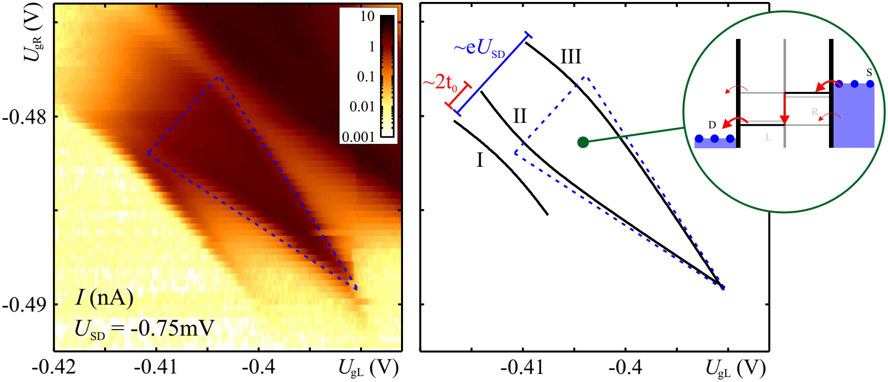

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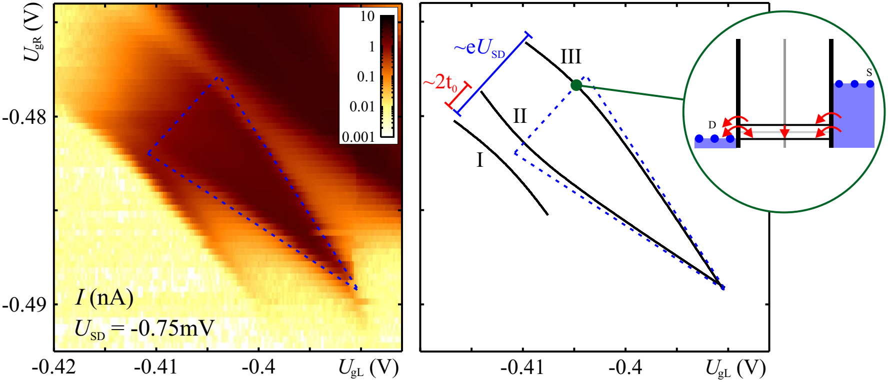

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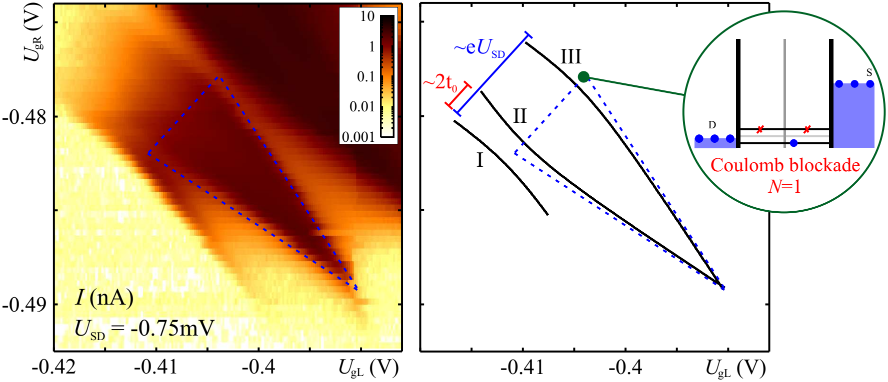

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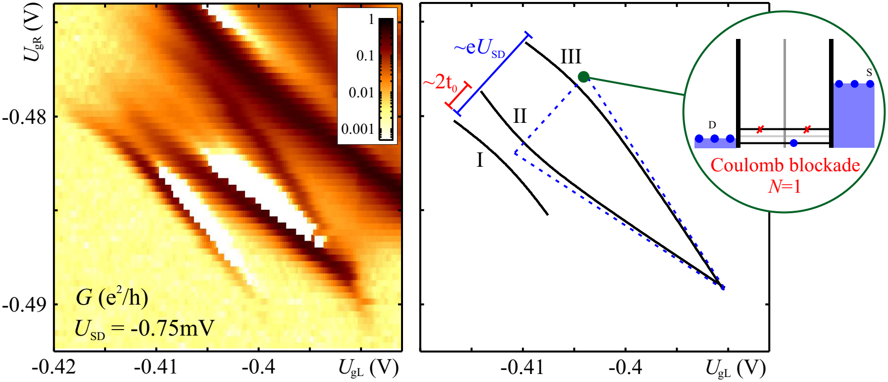
Finite U_{SD}, strong tunnel coupling — conductance



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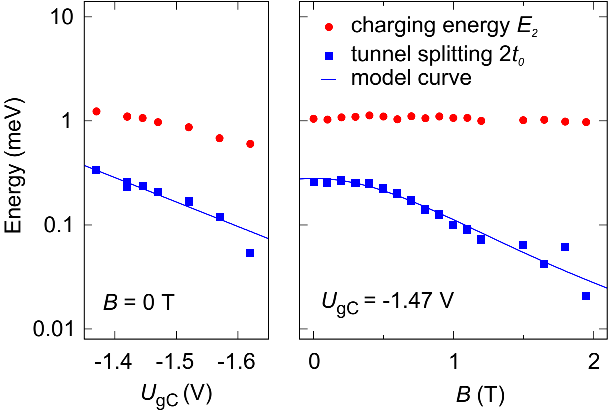
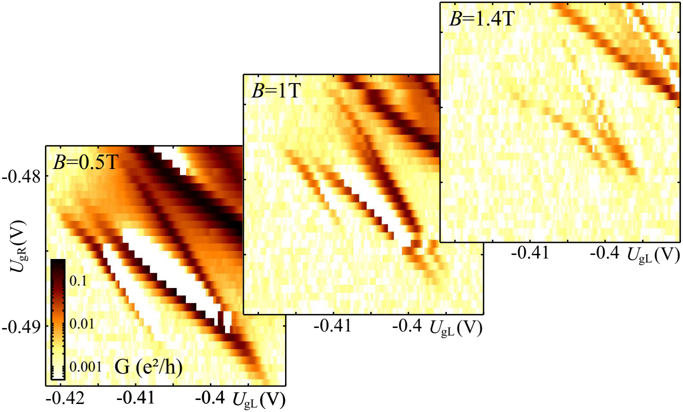
Tuning the tunnel coupling



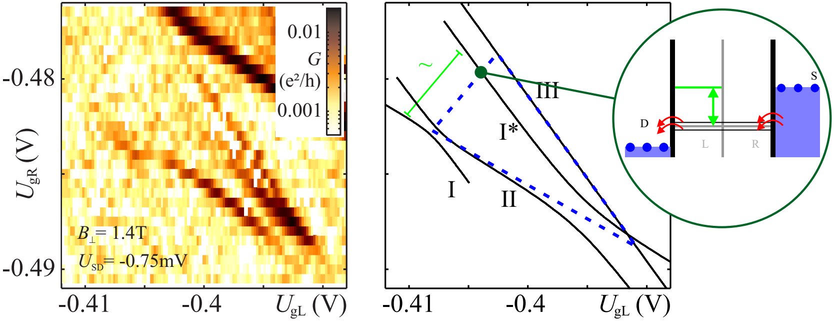
U_{gC} shifts the dots apart, $B_\perp$ compresses the dot states
model $\leftrightarrow$ WKB approximation

Effect of $B_\perp$ on the level structure



- overall G decreases, tunnel coupling at $\Delta = 0$ decreases
- tip of triangle splits, additional line $\leftrightarrow$ excited state

Finite U_{SD}, $B_\perp = 1.4\,$T: second level anticrossing



- ground state – ground state coupling very small
  $2t_0 \simeq 0.06\,$meV
- finite asymmetry $\Delta \longrightarrow$ excited state of left dot couples to ground state of right dot
  $2t_0^* \simeq 0.2\,$meV

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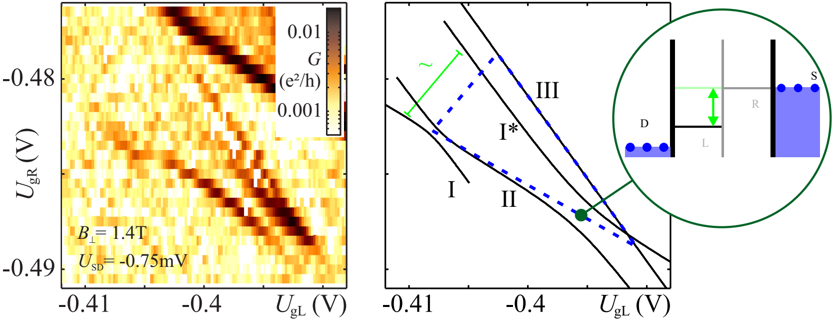

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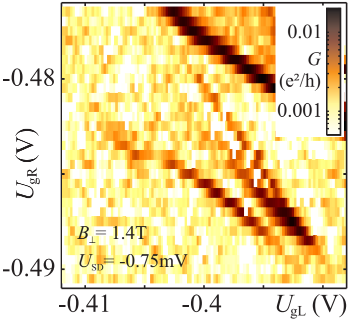

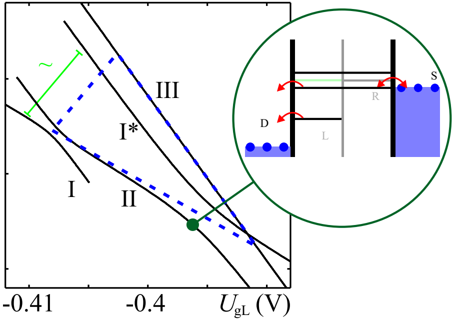

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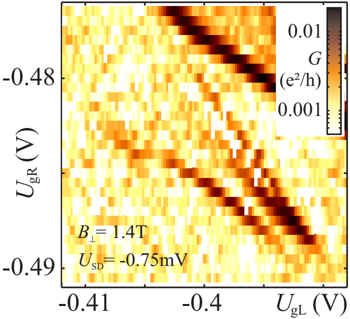

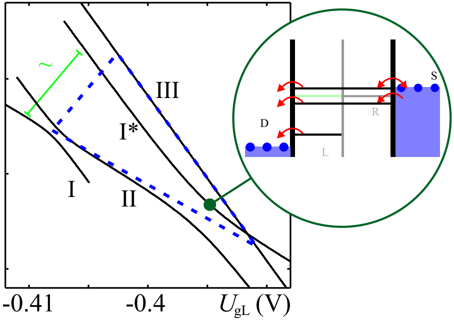

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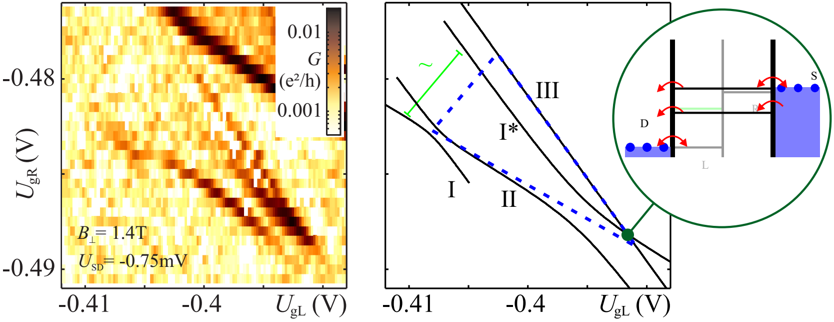

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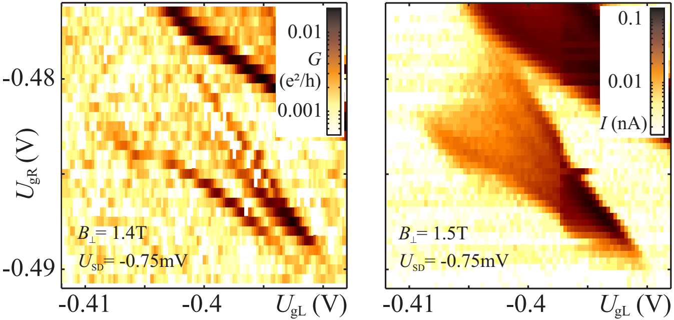

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Summary

- One-electron double quantum dot, strong tunnel coupling
- Tunnel splitting is directly visible as anticrossing in nonlinear transport and can be measured
- Tunnel splitting can be controlled by gate voltages or magnetic field
- At finite $B_\perp$ and finite asymmetry, a hybridization of the ground state of one quantum dot with an excited state of the other quantum dot causes a second level anticrossing

Thanks

Jörg P. Kotthaus

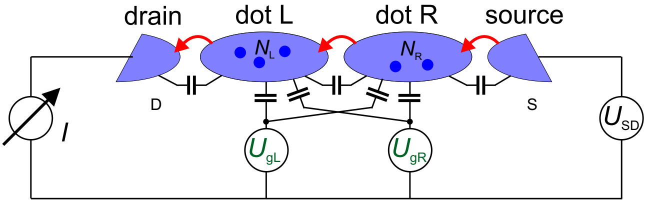
Stefan Ludwig

& Karl Eberl, Robert H. Blick, Jan von Delft & coworkers, ...

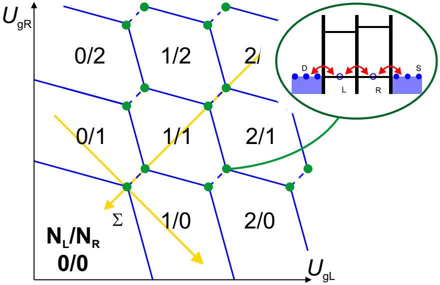
Publications

- ‘Direct control of the tunnel splitting in a one–electron double quantum dot’
A. K. Hüttel, S. Ludwig, H. Lorenz, K. Eberl, and J. P. Kotthaus,
accepted for publication by Phys. Rev. B (Rapid Comm.); cond-mat/0501012
- ‘Molecular states in a one–electron double quantum dot’
A. K. Hüttel, S. Ludwig, H. Lorenz, K. Eberl, and J. P. Kotthaus
EP2DS conference contribution; cond-mat/0507101

DQD: Linear response, weak tunnel coupling



- hexagons of stable charge configuration
- tunnel current only at triplepoints



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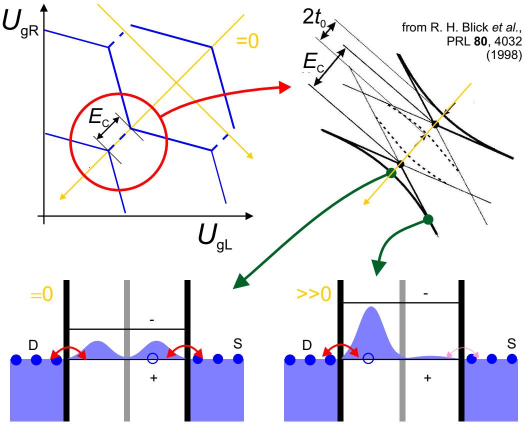
DQD: Linear response, strong tunnel coupling

Hybridized, molecular electron states



hexagons rounded, $\mu_- - \mu_+ = 2\sqrt{\Delta^2 + t_0^2}$

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Tunnel coupling and the WKB–approximation

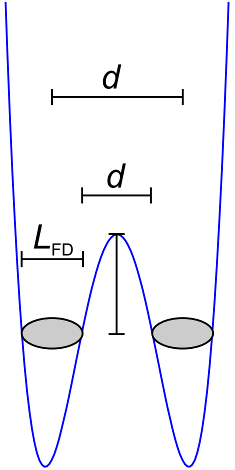
$$2t_0 \simeq \frac{2E_0}{\pi} \exp\left(-\frac{\sqrt{2m^*\phi}\,d}{2\hbar}\right)$$

$$\longrightarrow \log(2t_0) \propto d$$

In a magnetic field $B_\perp$,

$$L_{\mathrm{FD}} = \sqrt{\frac{\hbar}{\omega_c m^*}} \frac{1}{\sqrt[4]{1 + \frac{4\omega_0^2}{\omega_c^2}}}, \qquad \omega_c = \frac{eB}{m^*}$$

$$\longrightarrow d(B) = d_\infty - L_{\mathrm{FD}}(B)$$

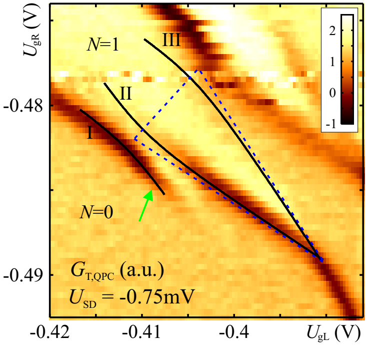


Finite U_{SD}, strong tunnel coupling — $\frac{dI_{QPC}}{dU_{gL}}$

- QPC detects charging:
  - left of dark line, $N \approx 0$
  - right of dark line, $N \approx 1$
- Information on tunnel rates!
- 'Jump' at finite asymmetry
- Line III not visible

  (in triplepoint region)

⟶ Drain–side tunnel rate smaller



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