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SMR.998d - 28

Research Workshop on Condensed Matter Physics
30 June - 22 August 1997
MINIWORKSHOP ON
QUANTUM WELLS, DOTS, WIRES
AND SELF-ORGANIZING NANOSTRUCTURES
11 - 22 AUGUST 1997

"Transport Spectroscopy of Artificial Atoms and Molecules"

PART II

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These are preliminary lecture notes, intended only for distribution to participants.

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Transport Spectroscopy
of
Artificial Atoms and Molecules

in collaboration with:

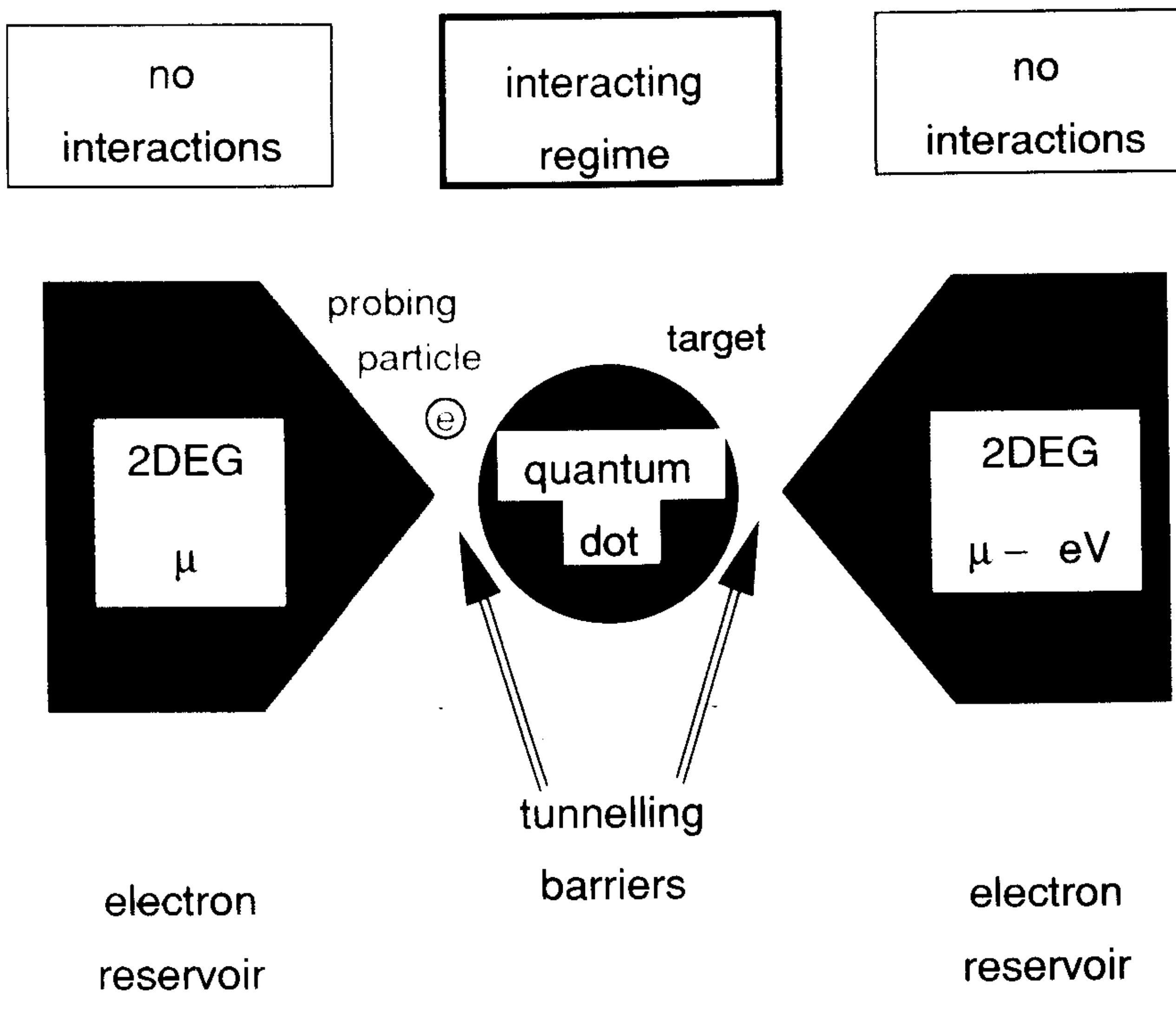
Sergio E. Ulloa	theory
Robert H. Blick Jürgen Weis	experiments

Max Planck Institut für Festkörperforschung, Stuttgart

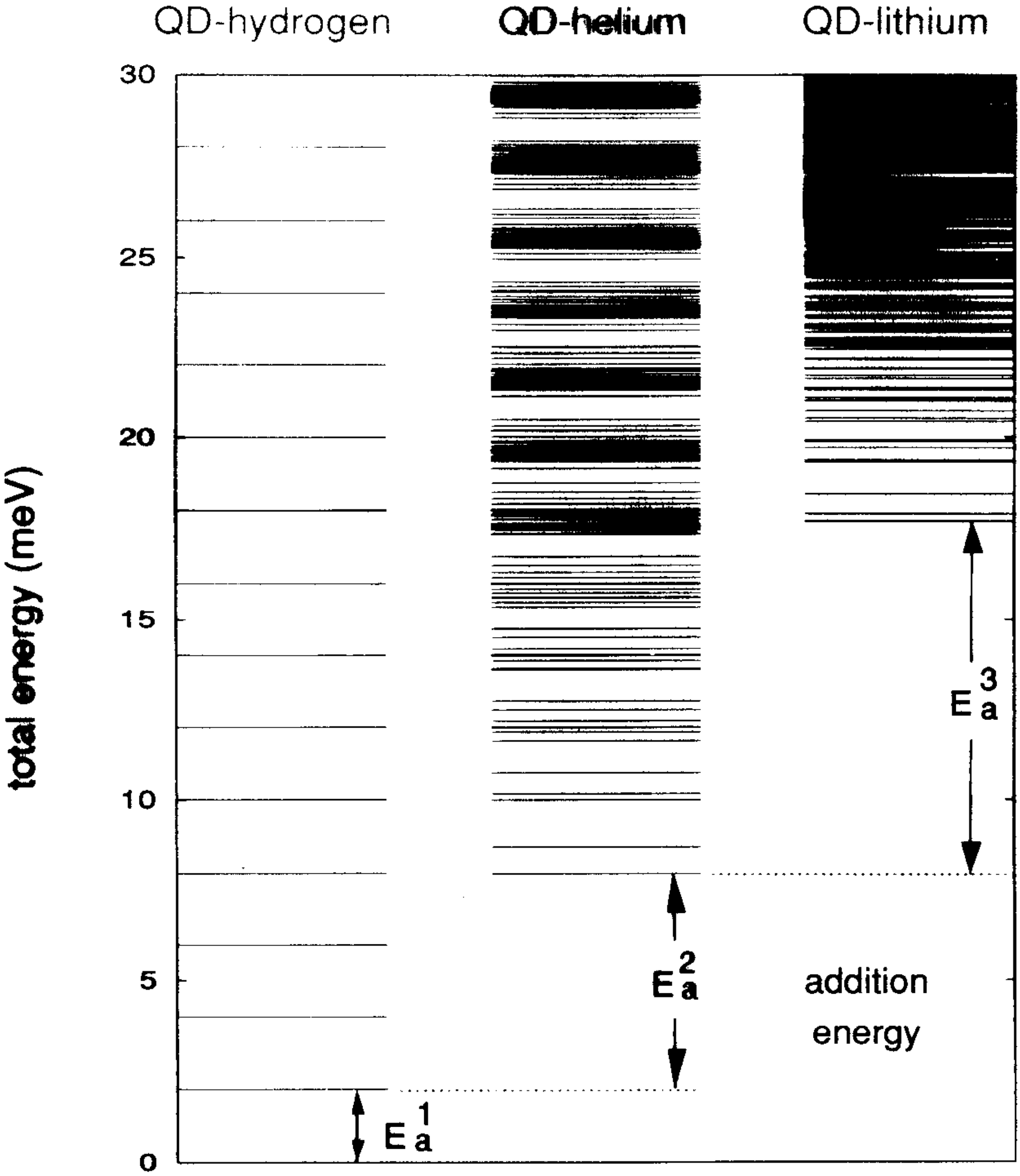
Outline

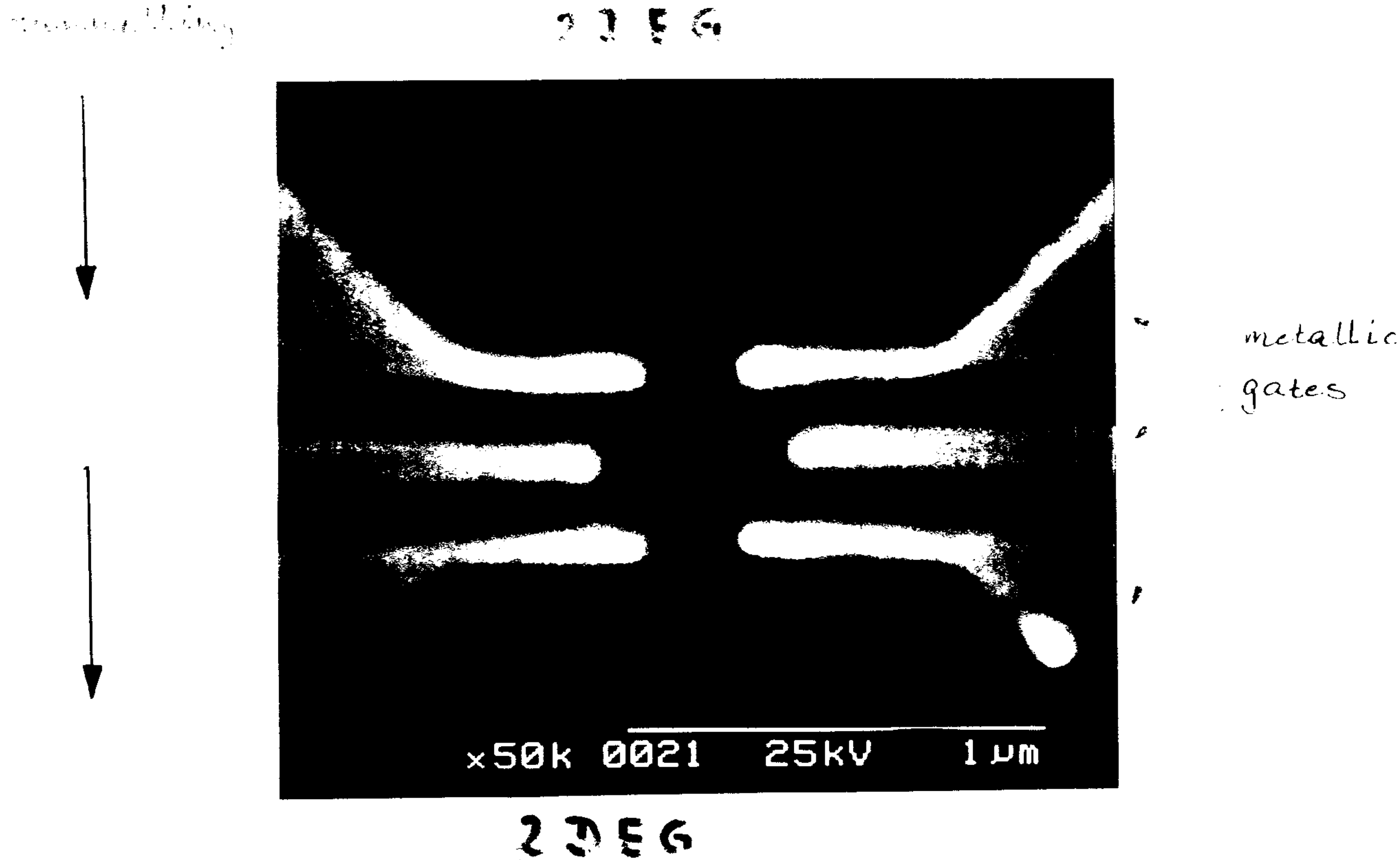
- Transport through Single Quantum Dots:
  - effect of correlations
  - competing channels
- Transport through Double Quantum Dots:
  - electrostatics
  - double-dot eigenstates
  - molecular transport resonances

Transport-Spectroscopy

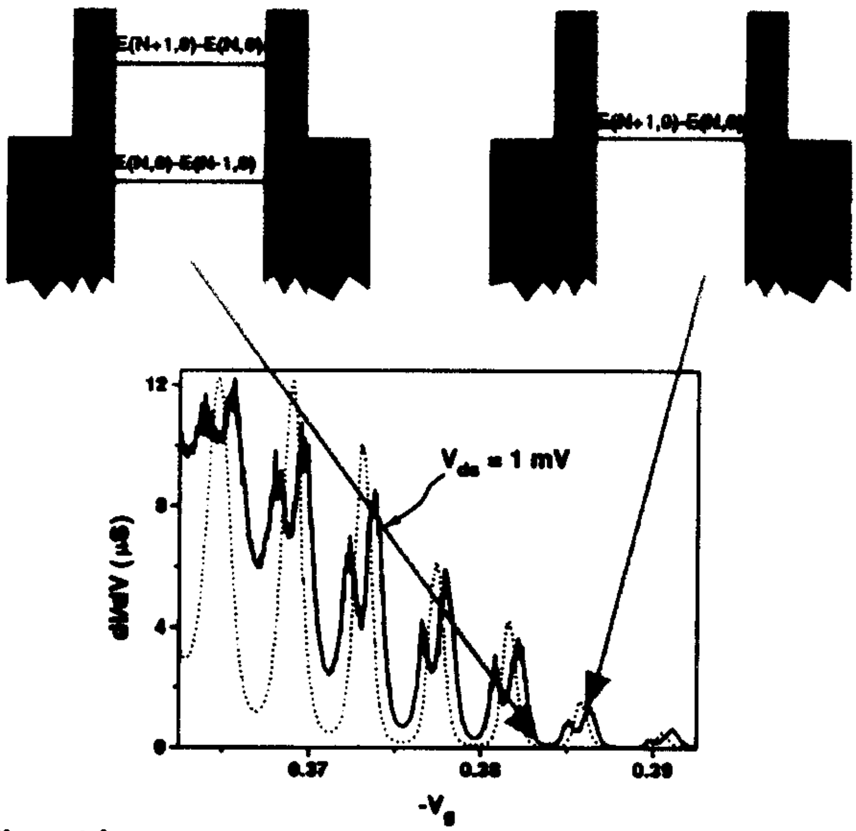


Spectra of different QD-Elements




2DEG
metallic gates
×50k 0021 25kV 1 µm
2DEG

Transport in Single Quantum Dots



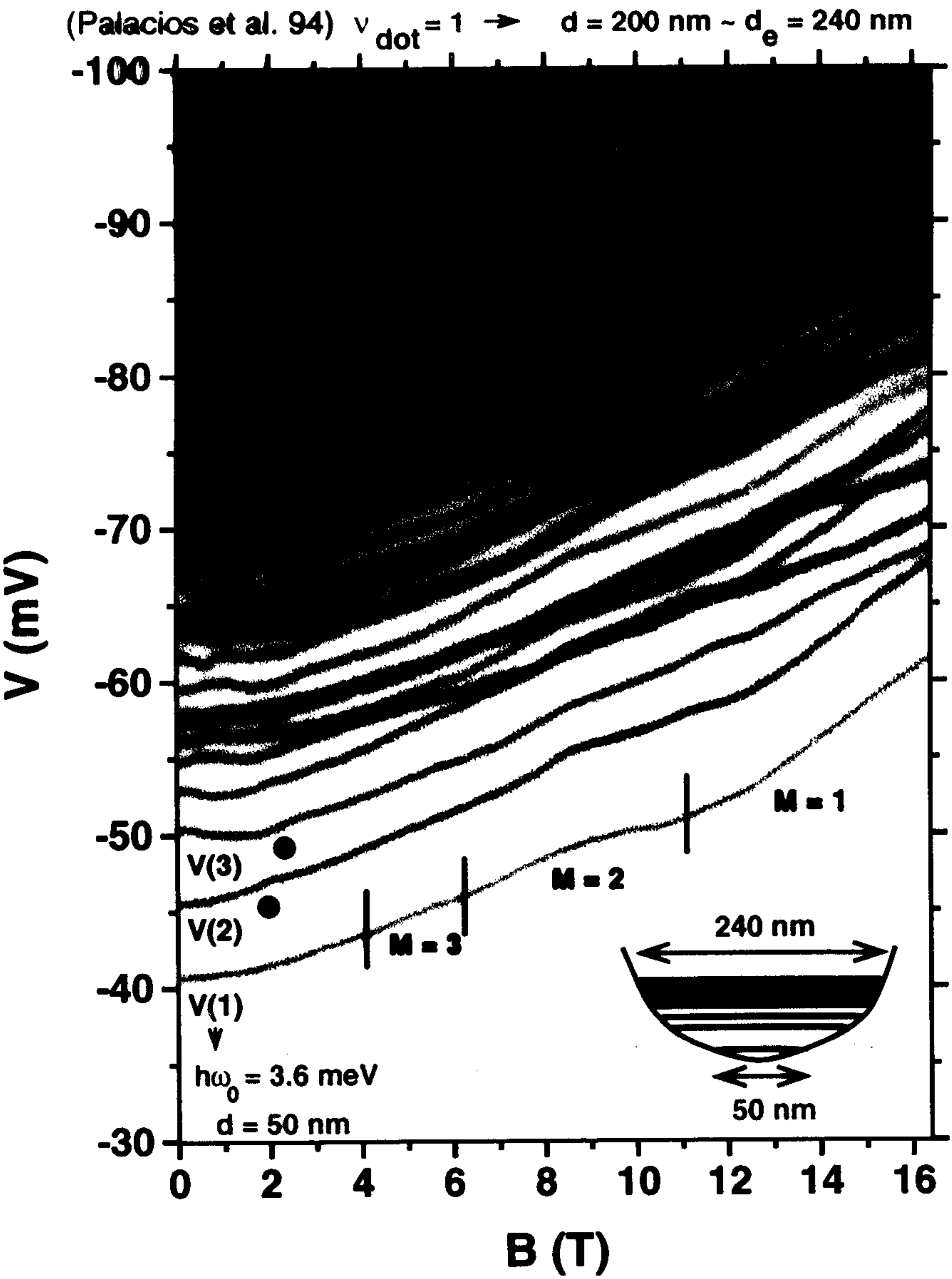
simplification:

$$E(N,\alpha) = \frac{1}{2C}N^2e^2 - \lambda_g e N V_g + \sum_k \epsilon_k$$

conductance resonances at:

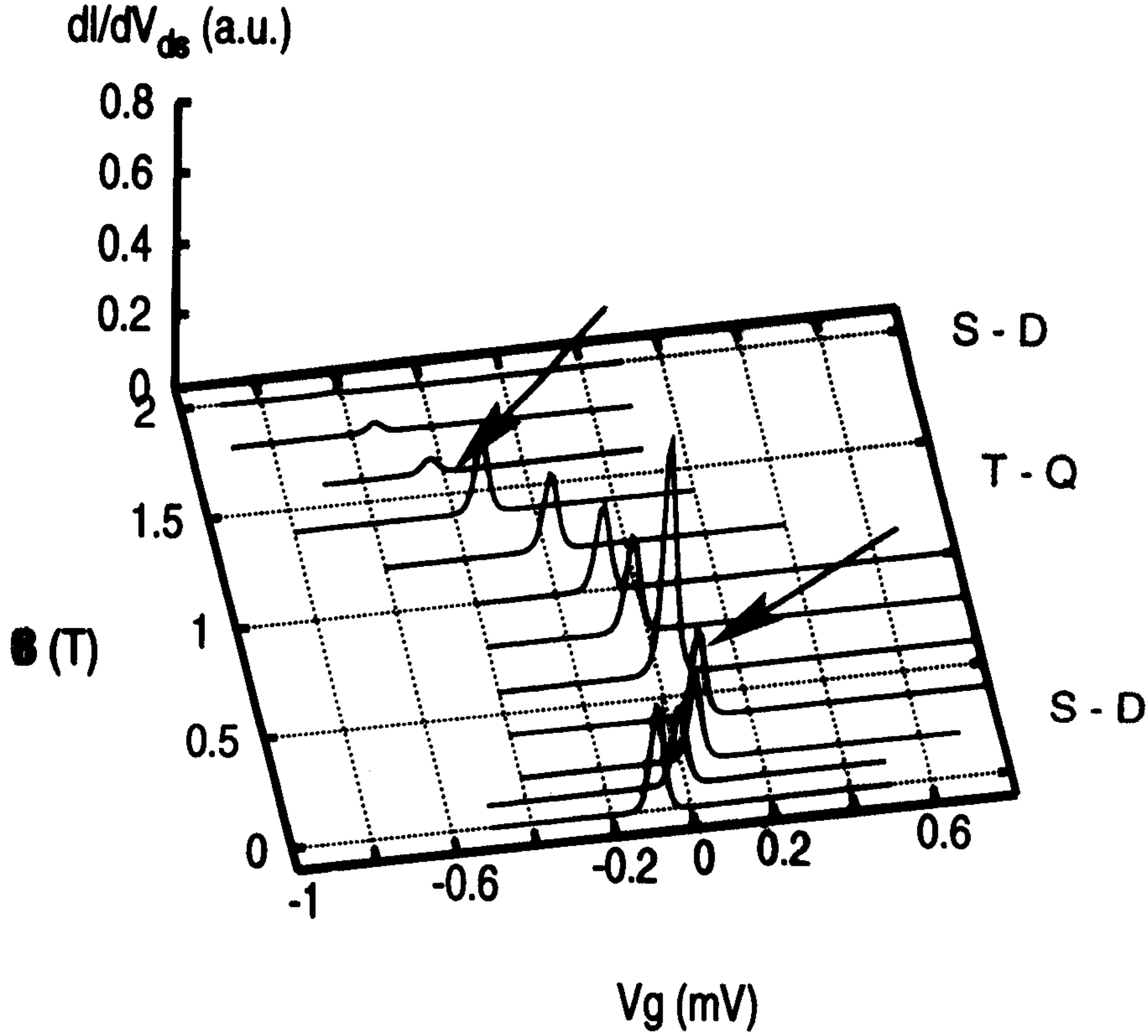
$$\mu = E(N+1,\alpha') - E(N,\alpha) = \frac{e^2}{2C}(2N+1) - \lambda_g e V_g + \epsilon_{k_F}$$

Coulomb Blockade Oscillations

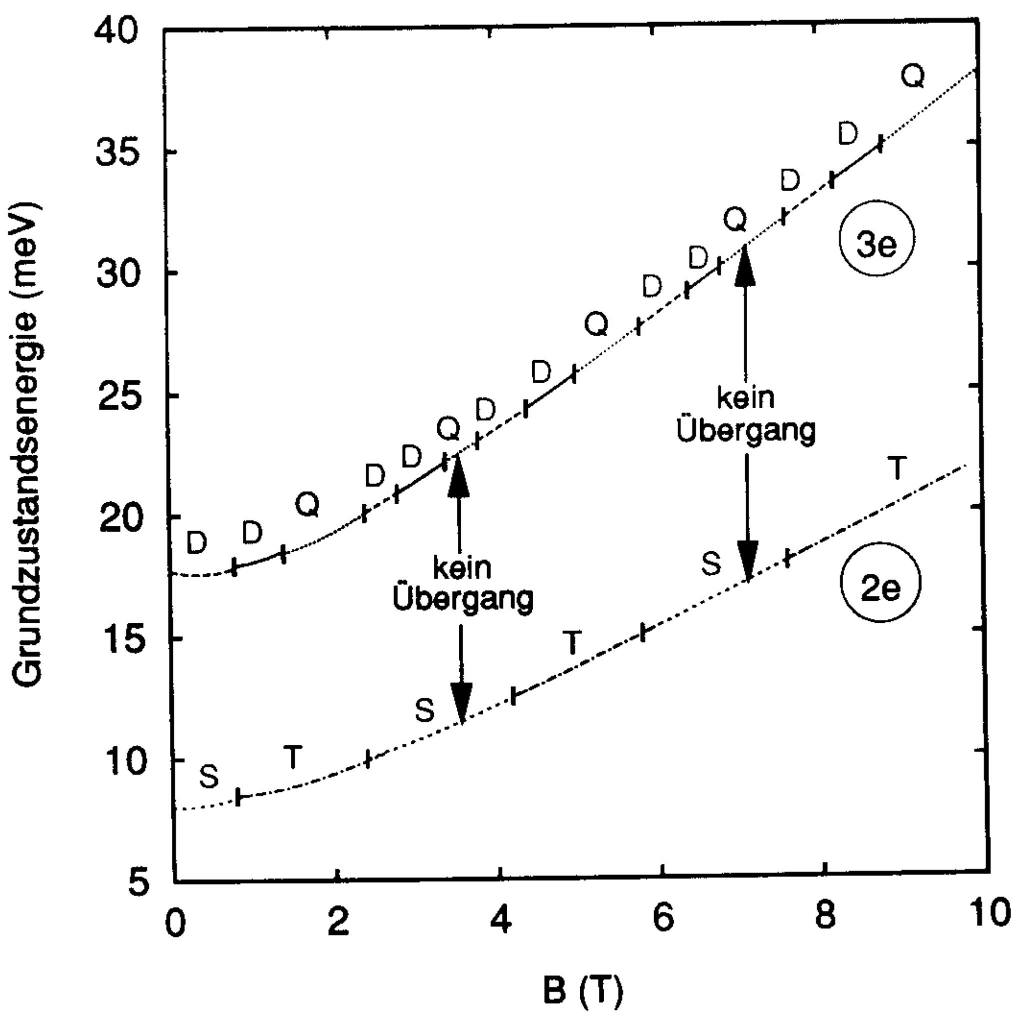


(Palacios et al. 94) ν_{dot} = 1 → d = 200 nm ~ d_e = 240 nm
-100
-90
-80
-70
-60
-50
-40
-30
V (mV)
0
2
4
6
8
10
12
14
16
B (T)
V(3)
V(2)
V(1)
M = 1
M = 2
M = 3
$h\omega_0$ = 3.6 meV
d = 50 nm
240 nm
50 nm

Magnetic Field Dependence of Conductance Resonances



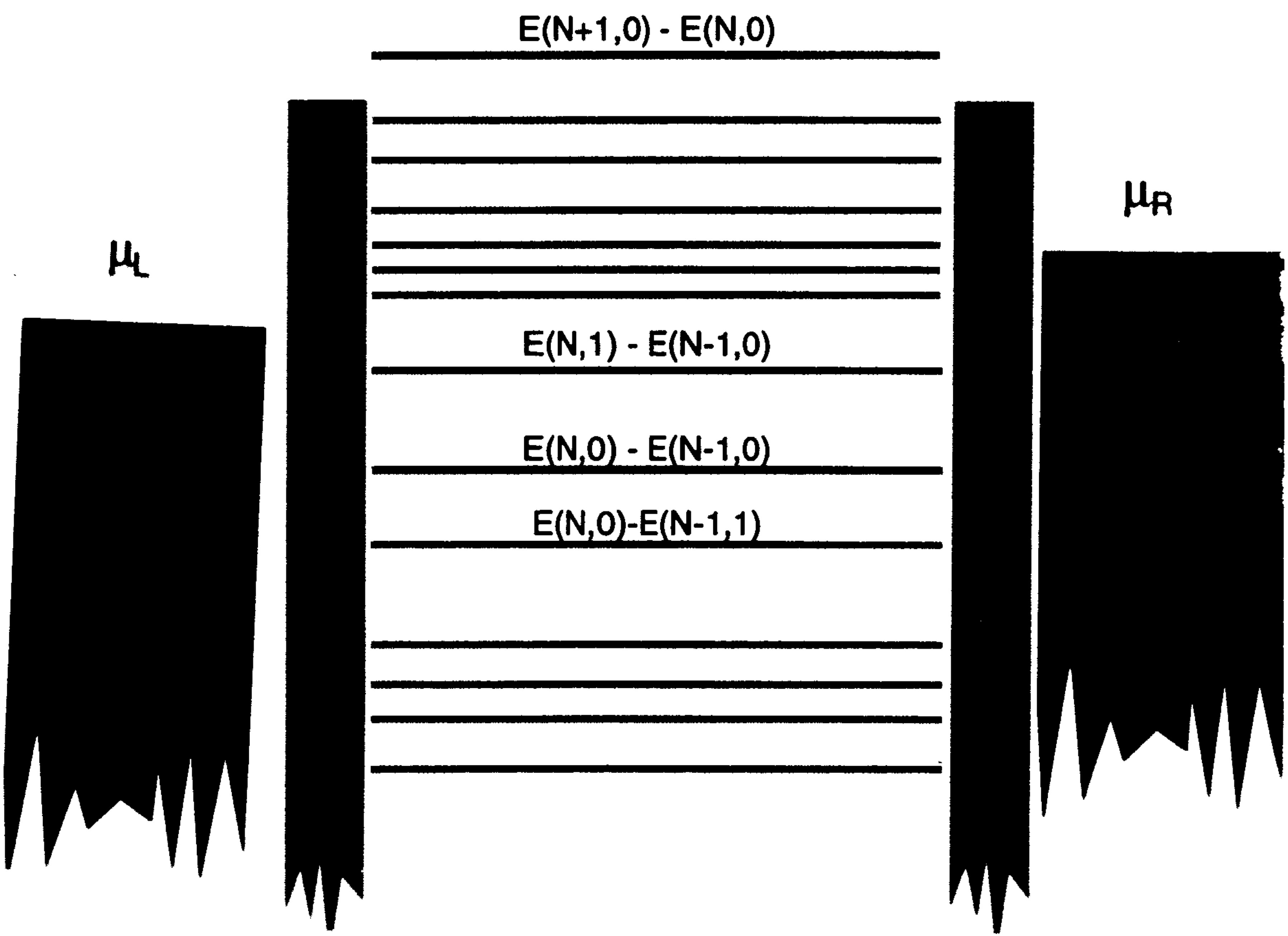
Spin-Auswahlregeln



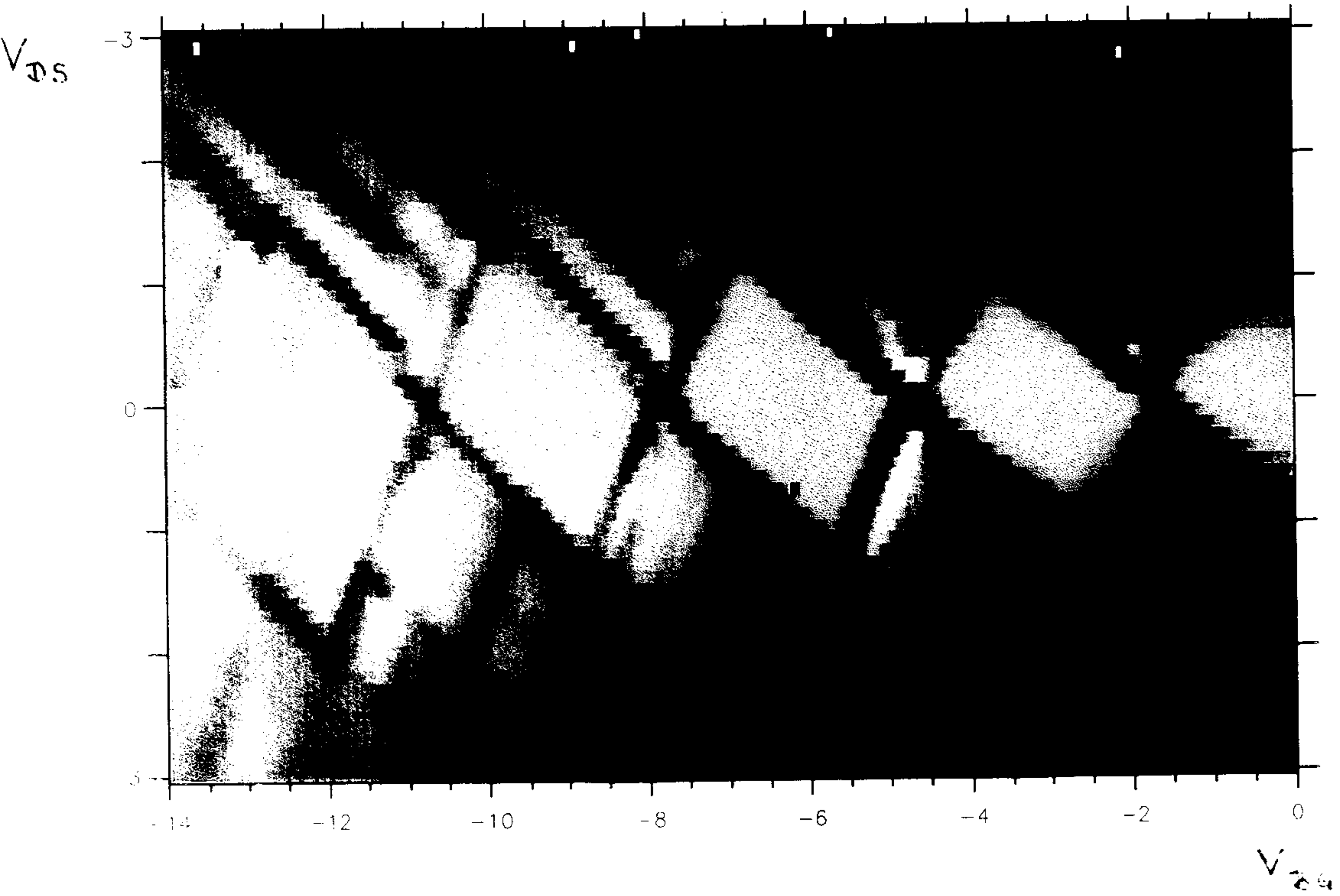
Kein Übergang zwischen Spin-Singulett- und Spin-Quadruplett- Zuständen

Verallgemeinerung auf beliebige Spins:
Weinmann et al., Europhys. Lett., 26, 467 (1994

Non-linear Transport

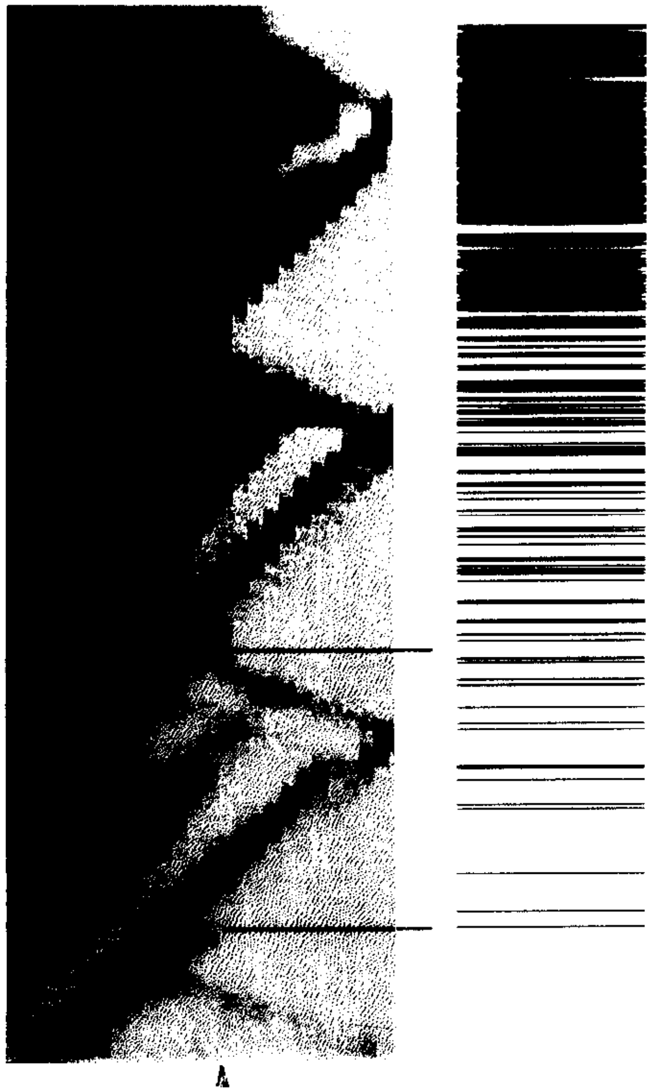


Conductance



B=0T

Vergleich: Experiment - Spektrum (Lithium)

3 Resonanzen  13 Niveaus

Experiment:

erheblich weniger Resonanzen als erwartet

Sequential Tunneling - Current

Fermi-Distribution of
electrons in left reservoir
$f^L_{\alpha\alpha'} = f_{FD}(E_{N,\alpha} - E_{N-1,\alpha'} - \mu^L)$

$$I = -e \sum_N \sum_{\alpha\alpha'} \Gamma^L_{\alpha\alpha'} \left[P_{\alpha'} f^L_{\alpha\alpha'} - P_\alpha (1 - f^L_{\alpha\alpha'}) \right]$$

probability for
dotstate $|N, \alpha\rangle$
→ kinetic equations

[illegible]

Γ [illegible] $\langle N, \alpha | c_n^+ | N-1, \alpha' \rangle$

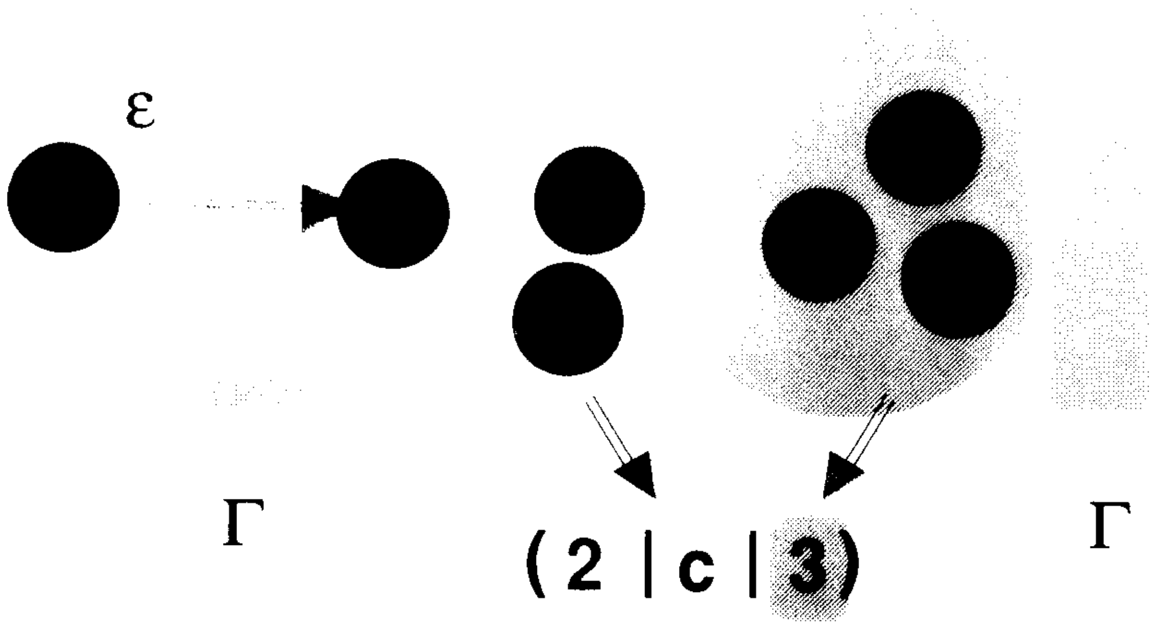
spectral weight [illegible]

limit: linear response ($\mu^L \simeq$ [illegible])

$$\frac{dI}{dV_{DS}} = \frac{e^2}{h} \frac{\Gamma^L \Gamma^R}{\Gamma^L + \Gamma^R} \left| \langle N, \alpha | c_n^+ | N-1, \alpha' \rangle \right|^2 \left(-\frac{\partial f_{00'}}{\partial E} \right)$$

only ground states thermally occupied

Tunneling Probability



energy conservation: $\varepsilon + E_2 = E_3$

tunneling through barrier: Γ

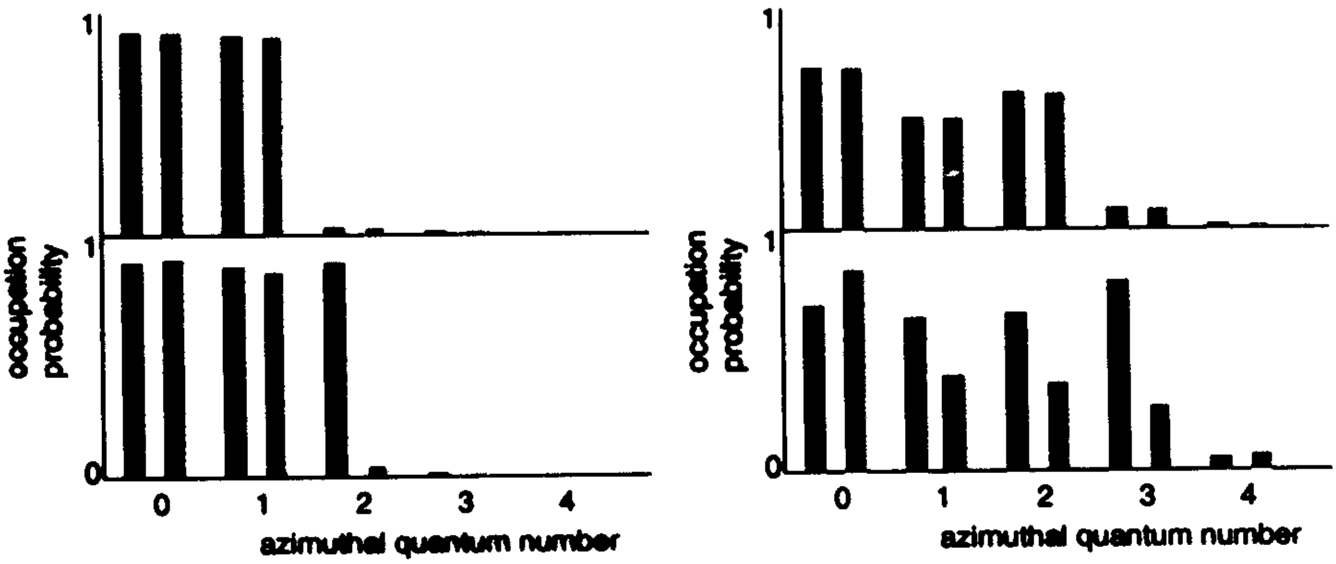
overlap matrix element: $(2 | c | 3)$

uncorrelated system: $\sum_n \left| (2 | c_n | 3) \right|^2 = 1$

Orbital Overlap

uncorrelated strongly correlated

states

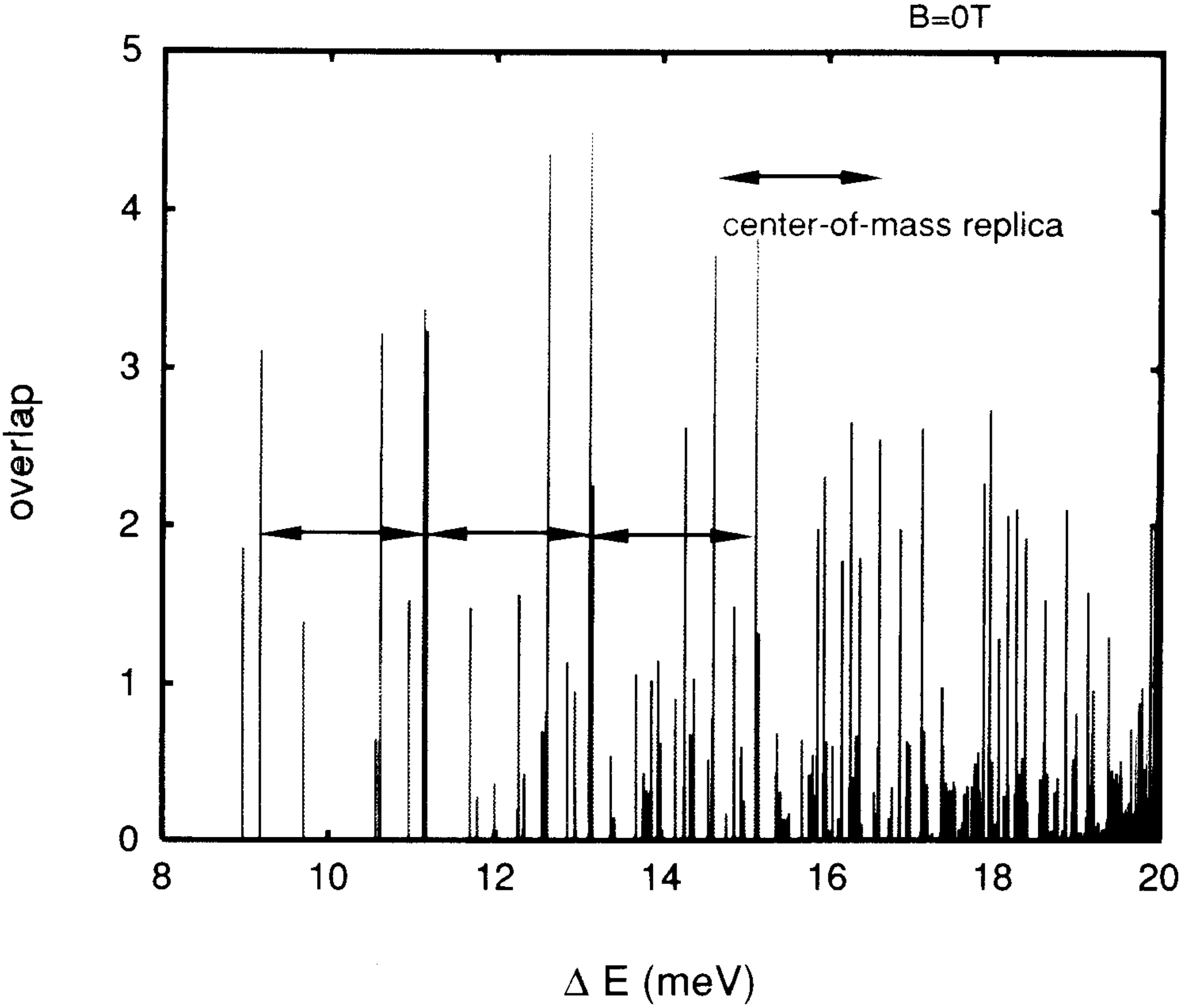


from Palacios et al., Superlattices..., **15**, 91,(1994)

$$\sum_n |\langle 4|c_n|5\rangle|^2 = 1$$

$$\sum_n |\langle 4|c_n|5\rangle|^2 \ll 1$$

Overlap

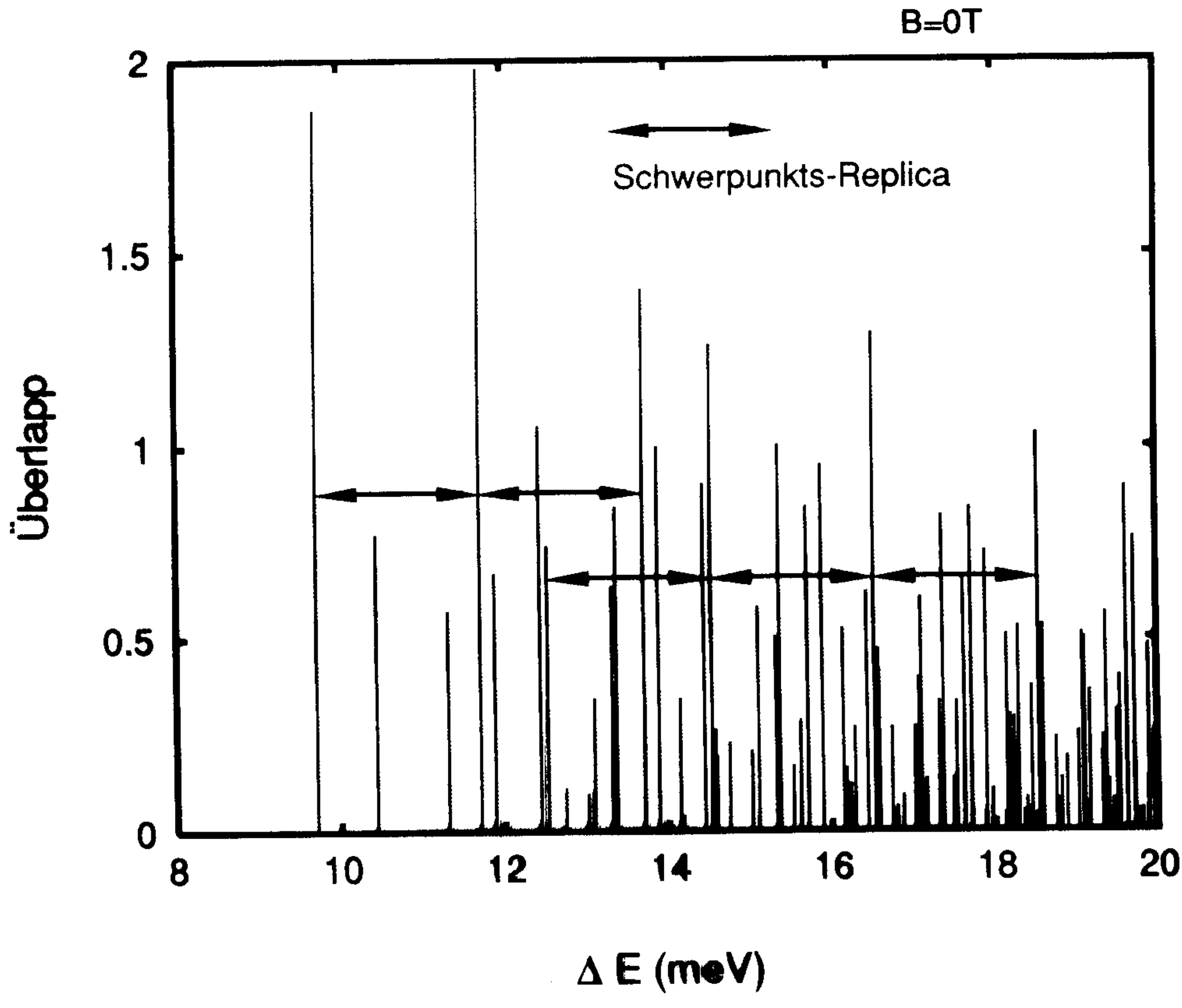


transition:

2-particle lowest triplet to 3-particle state

quasi-selection rules due to correlations

orbitaler Überlapp

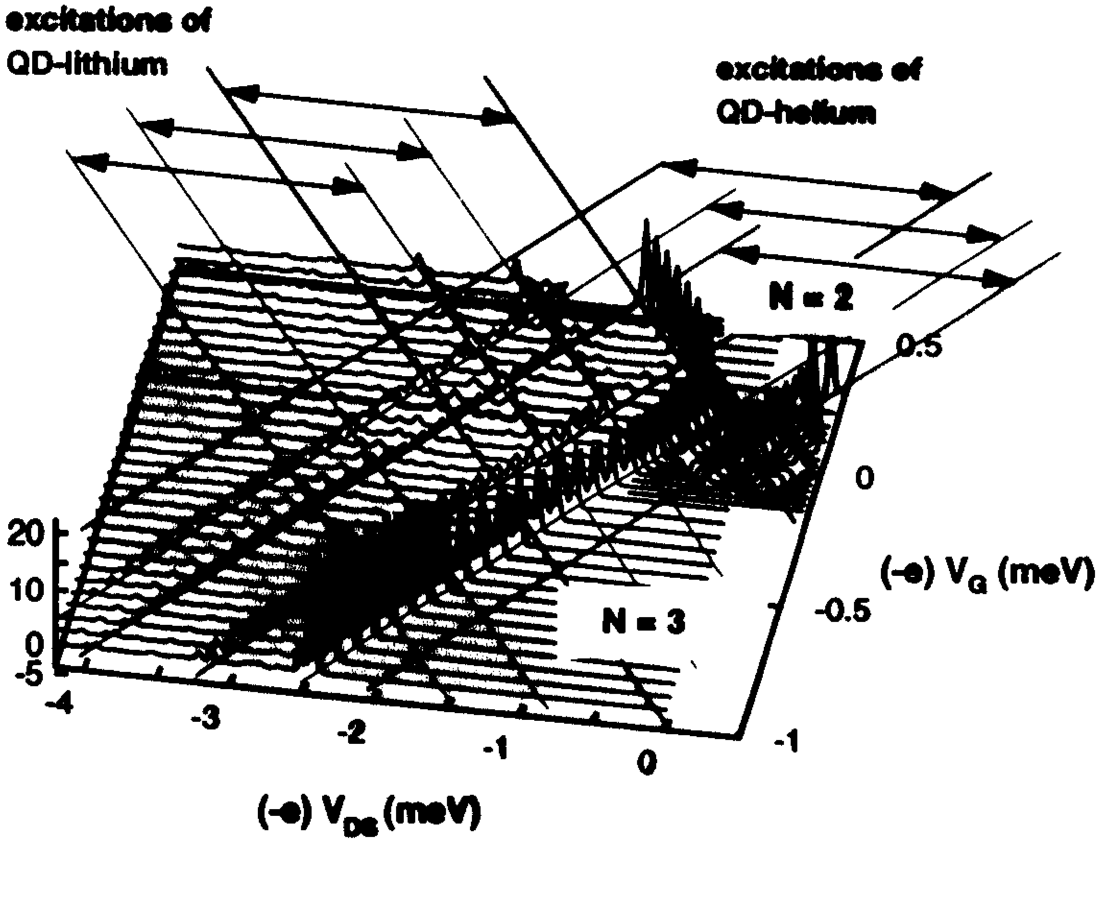


Übergang:

2-Teilchen-Grundzustand in 3-Teilchen-Zustände

Quasi-Auswahlregeln auf Grund von Korrelationen

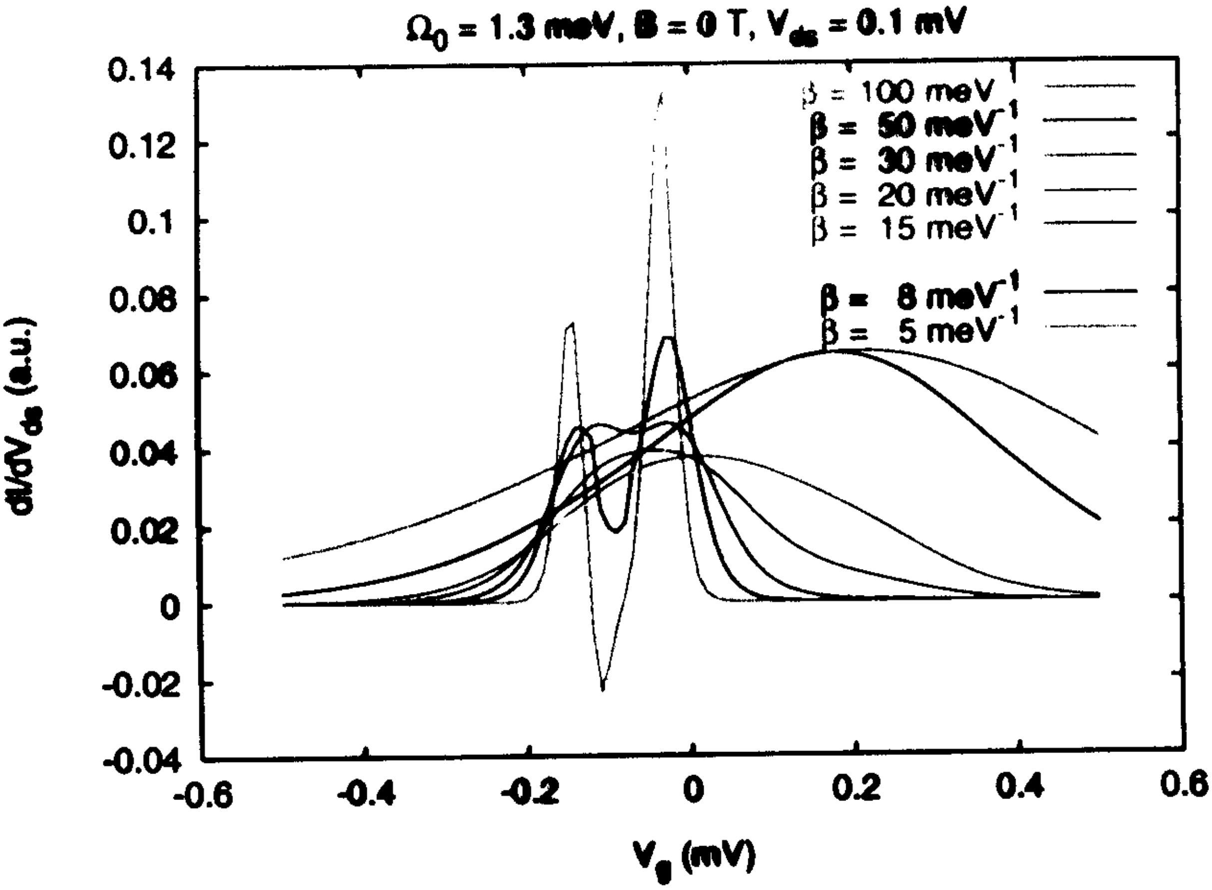
Tunneling spectrum of a Single Quantum Dot



collective excitations

Anomalous Temperature Dependence

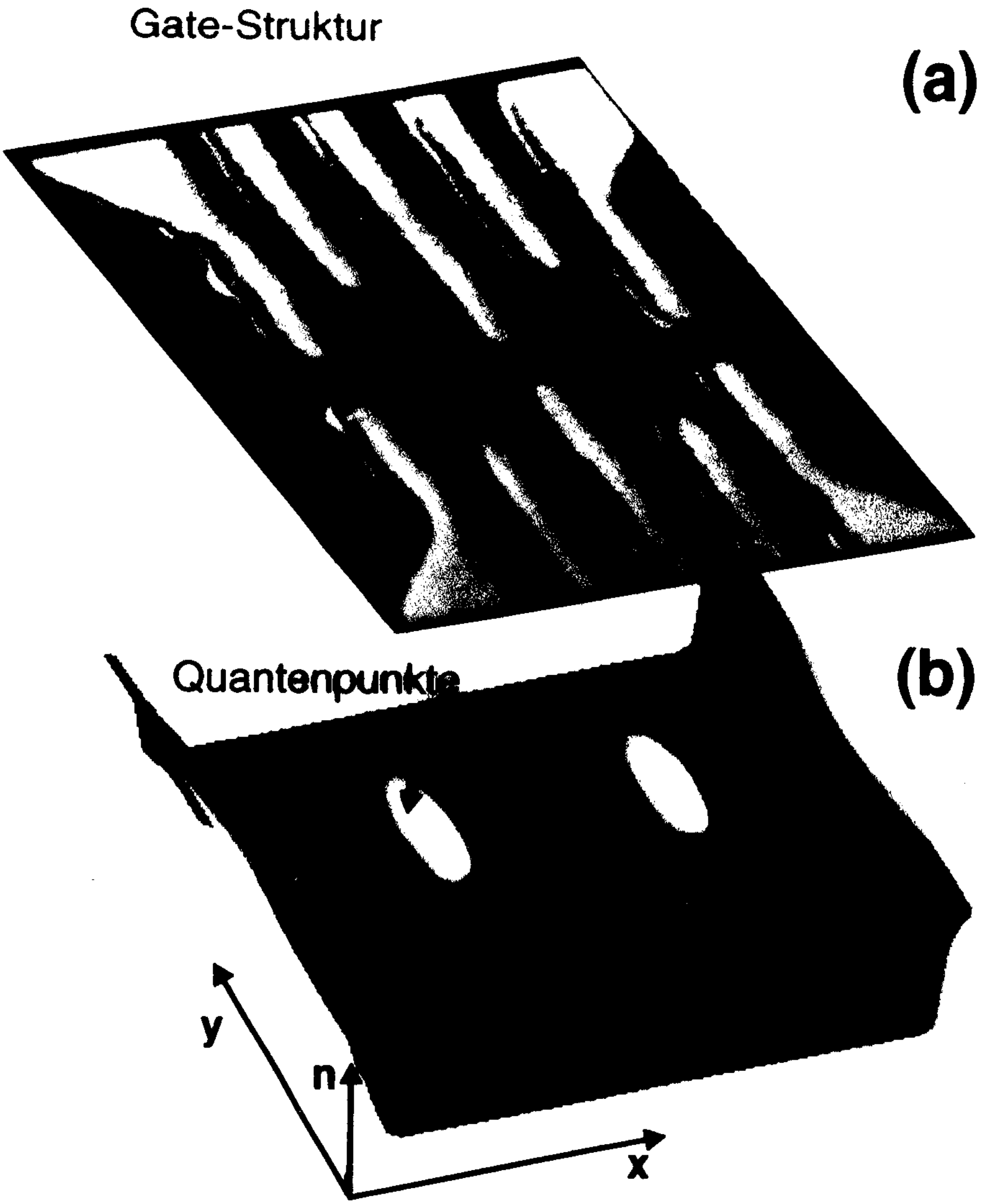
single transition: $1/T$-behavior

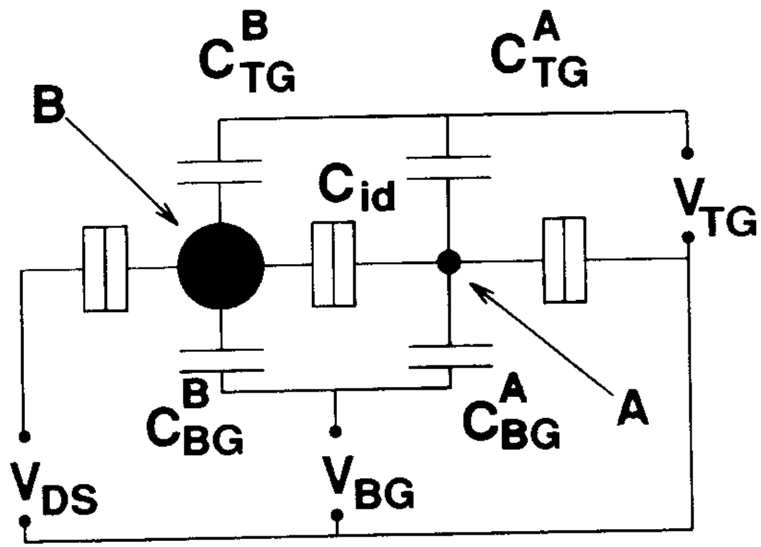


competition between:

- non-spin polarized transition with small tunneling rate
- spin-polarized transition with large tunneling rate

Doppelquantenpunkte

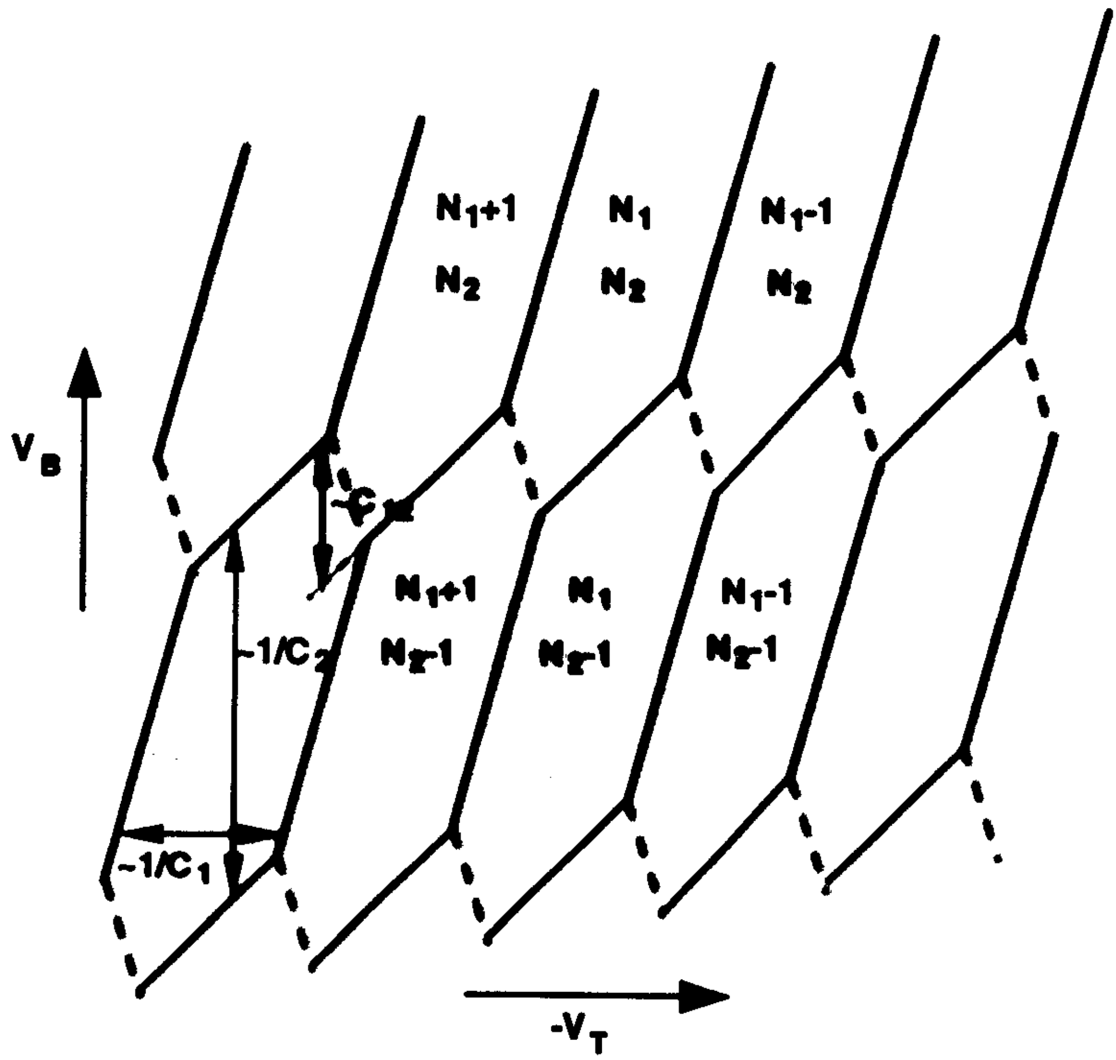



B
C_{TG}^{B}
C_{TG}^{A}
C_{id}
V_{TG}
C_{BG}^{B}
C_{BG}^{A}
A
V_{DS}
V_{BG}

Charging Diagramm

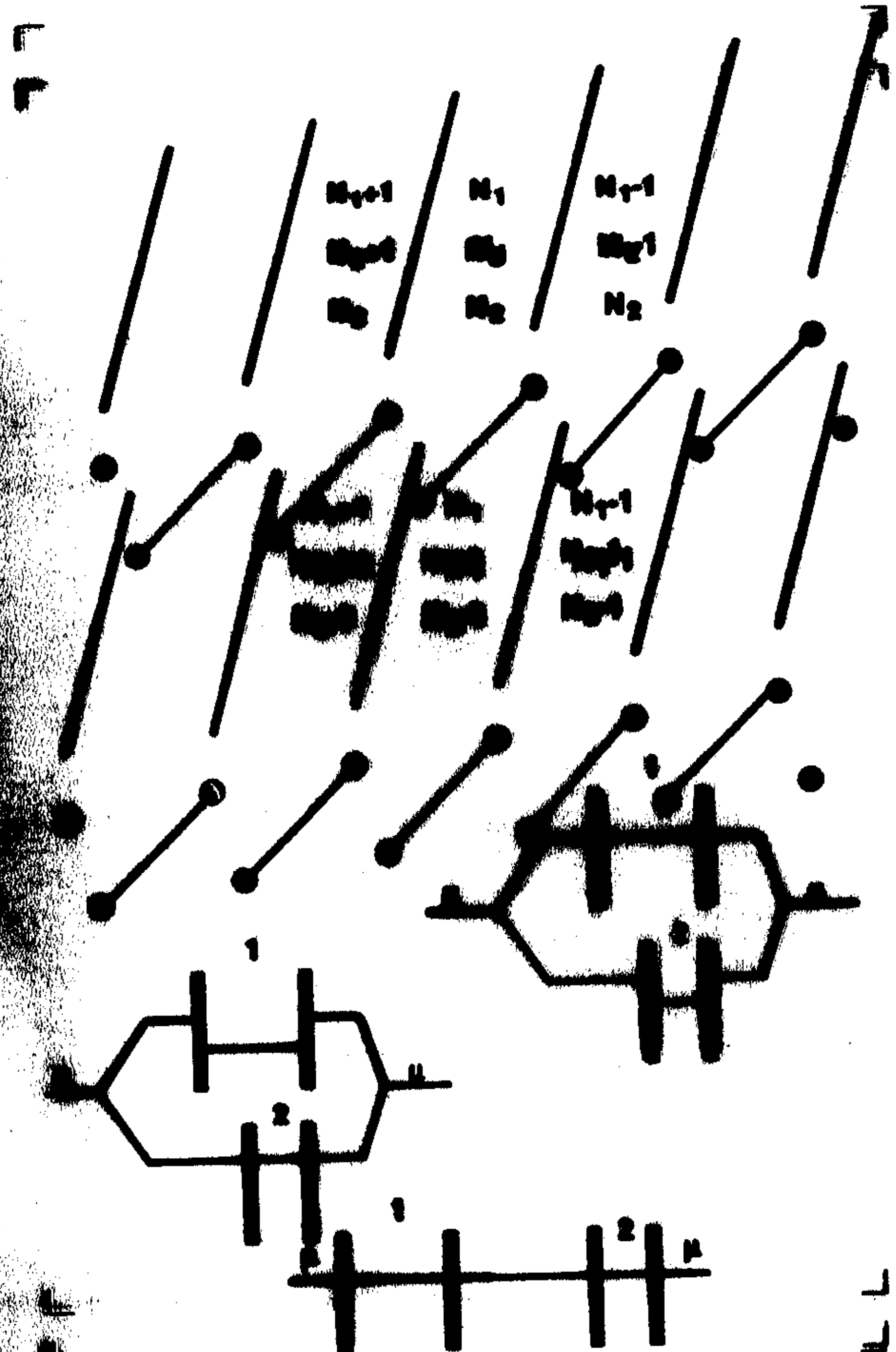
electrostatic energy:

$$E^{el} \simeq \frac{1}{2C_1}(N_1 e)^2 + \frac{1}{2C_2}(N_2 e)^2 + \frac{C_{12}}{C_1 C_2}(N_1 e)(N_2 e) - (\lambda_{1T} N_1 + \lambda_{2T} N_2) e V_T - (\lambda_{1B} N_1 + \lambda_{2B} N_2) e V_B$$

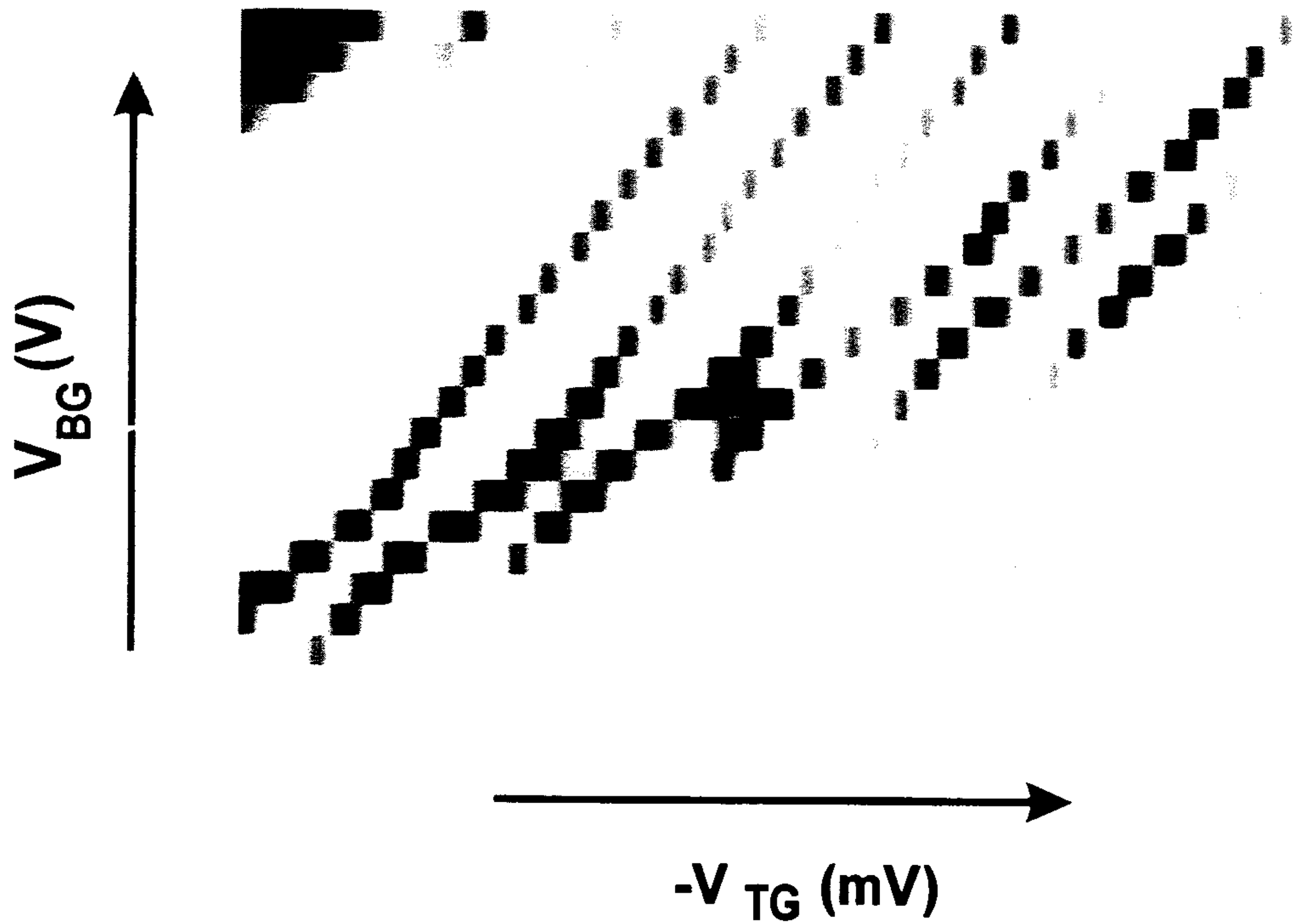


Transport in Double Quantum Dots

sequential



Charging Diagram of the Double Quantum Dot:



Hamilton Operator

$H = \quad H^{el}$	electrostat. energy
$+ \quad H^{L} + H^{L\leftrightarrow 1}$	left reservoir + tunneling L $\leftrightarrow$ 1
$+ \quad H^{1\leftrightarrow 2}$	interdot tunneling
$+ \quad H^{2\leftrightarrow R} + H^{R}$	tunneling 2 $\leftrightarrow$ R + right reservoir

coherent interdot tunneling: $H_{DD} = H^{el} + H^{12}$

artificial molecule

Interdot Tunneling

weak coupling **between** both dots

Double Dot Eigenstates:

$$|N\rangle = \lambda_1 |N_1, N_2\rangle + \lambda_2 |N_1 - 1, N_2 + 1\rangle$$

valence electron **shared between** both dots

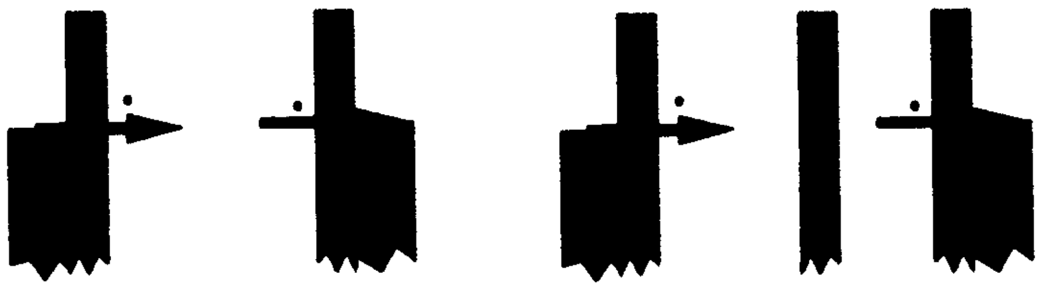
Coefficients depend on:

- interdot barrier transparency t
- $\Delta E = E(N_1, N_2) - E(N_1 - 1, N_2 + 1)$

at triple point:

$\Delta E = 0, \qquad \lambda_1 = \frac{1}{\sqrt{2}} = \lambda_2$

Coupling to Reservoirs



modified tunneling rates:

$$\Gamma^L_{a,a'} = \Gamma^L |\langle N, a| c_1^+ |N-1, a'\rangle|^2$$

$$\Gamma^R_{a,a'} = \Gamma^R |\langle N, a| c_2^+ |N-1, a'\rangle|^2$$

intrinsic asymmetry of outer barriers

for single product state:

$$\langle N_1, \alpha; N_2, \beta | c_1^+ | N_1', \alpha; N_2', \beta\rangle \propto \delta_{N_1, N_1'+1} \delta_{N_2, N_2'}$$

$$\langle N_1, \alpha; N_2, \beta | c_2^+ | N_1', \alpha; N_2', \beta\rangle \propto \delta_{N_1, N_1'} \delta_{N_2, N_2'+1}$$

never simultaneously $\neq 0$

Differential Conductance of artificial molecules

for energetically isolated transitions between ground states:

$$\sigma = \frac{e^2}{h} 2\pi \Gamma^{eff}_{0,0'} \left(-\frac{\partial f_{0,0'}}{\partial \epsilon} \right)$$

energy conservation

$$\frac{1}{\Gamma^{eff}_{0,0'}} = \frac{1}{\tilde{\Gamma}^{L}_{0,0'}} + \frac{1}{\tilde{\Gamma}^{R}_{0,0'}}$$

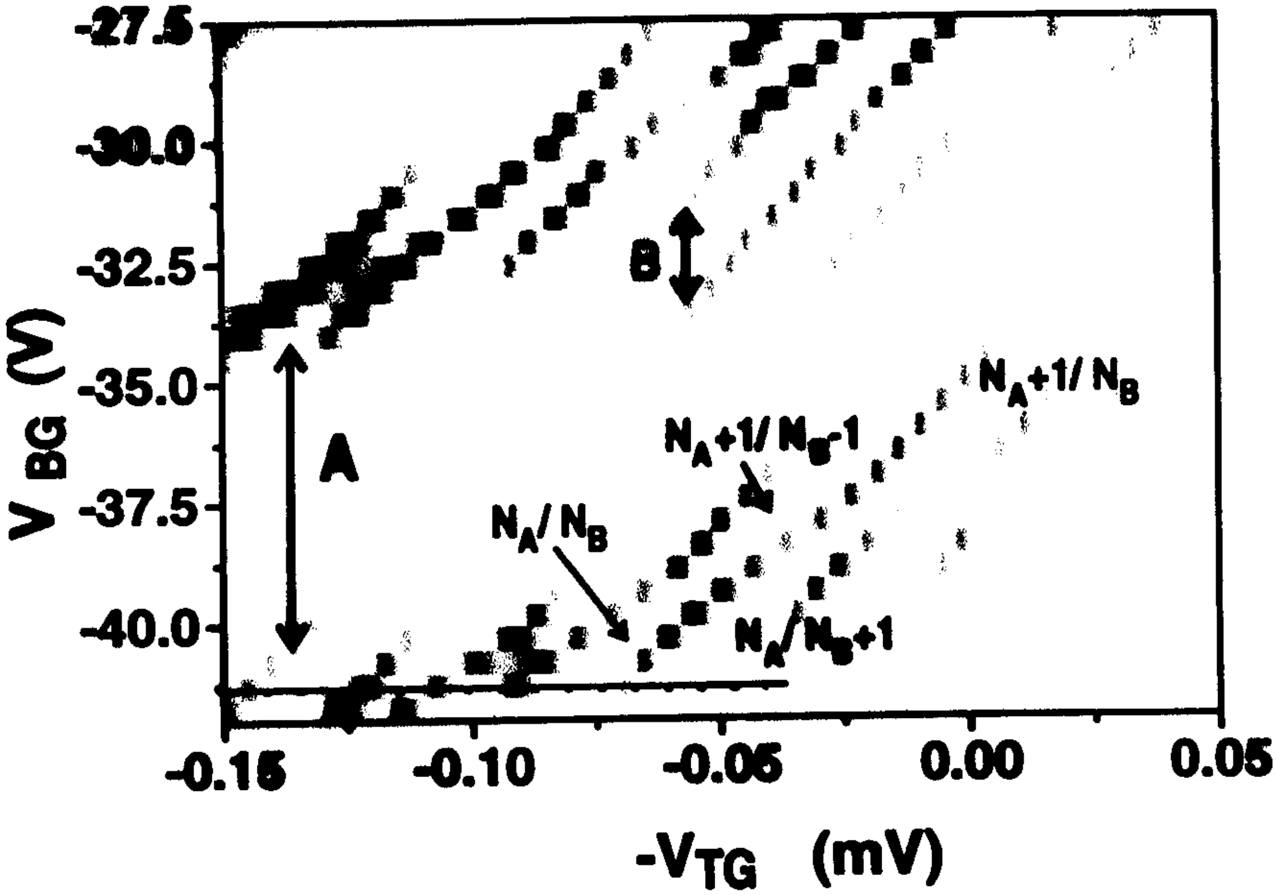
modified tunneling rates

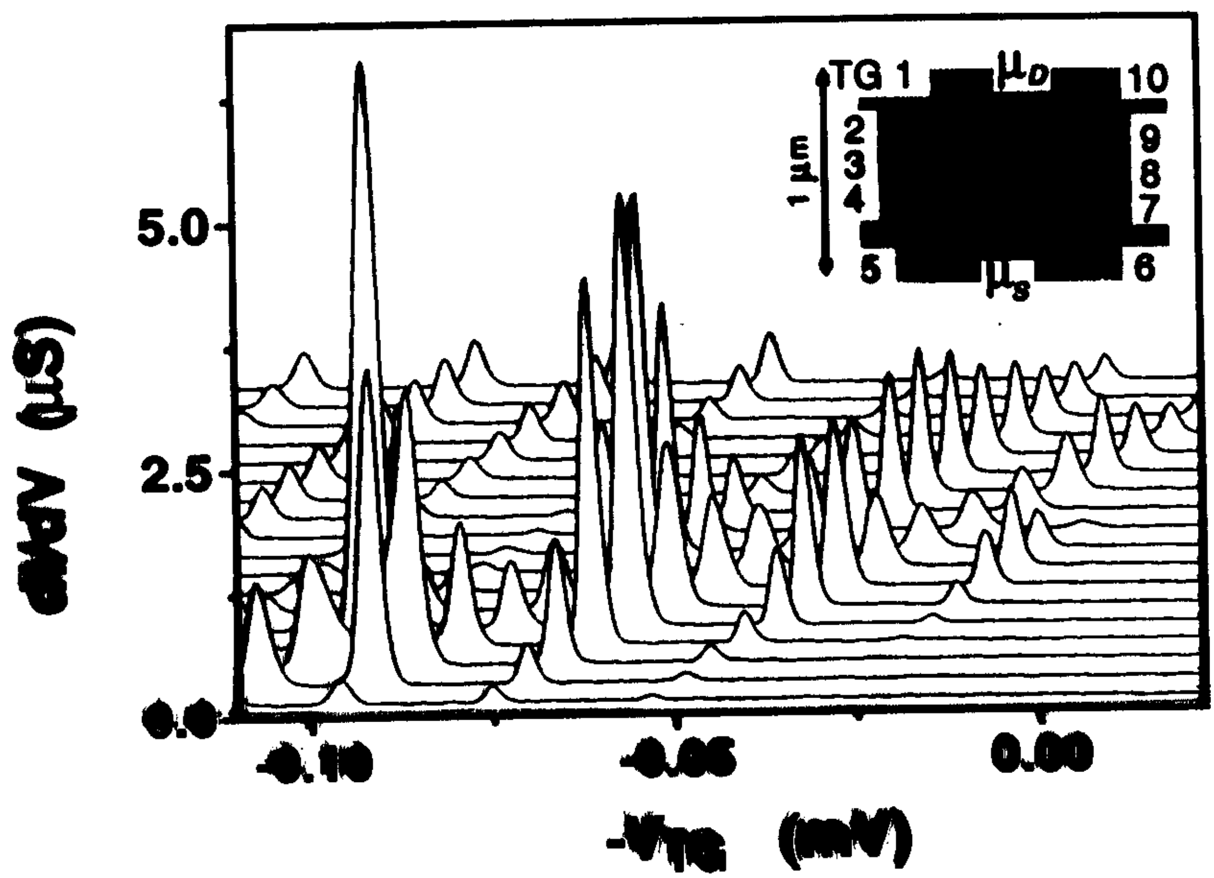
for coherent interdot tunneling:

$$\Gamma^{eff}_{0,0'} = \frac{\lambda_1^2 \lambda_2^2}{\lambda_1^2 + \lambda_2^2} = \Gamma \frac{4|t|^2}{4|t|^2 + (\Delta E)^2}$$

Lorentzian Peakform

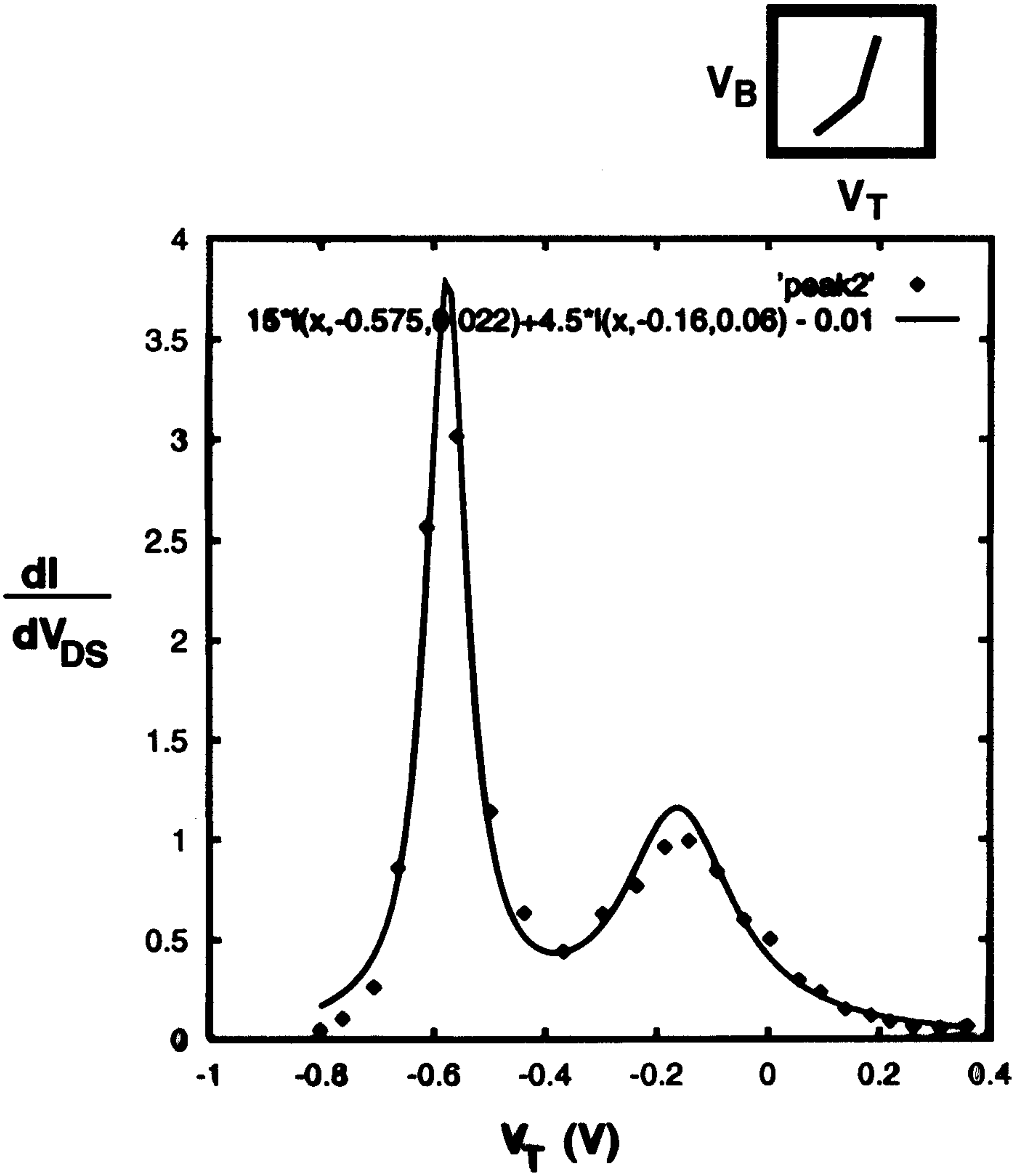
Charging Diagram:





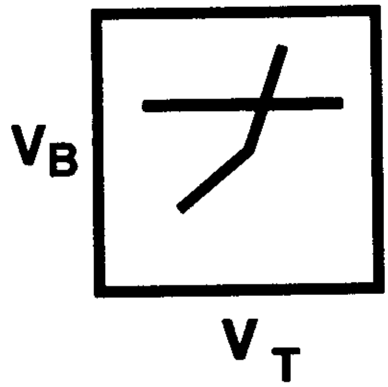
Lorentzian-Lineshape

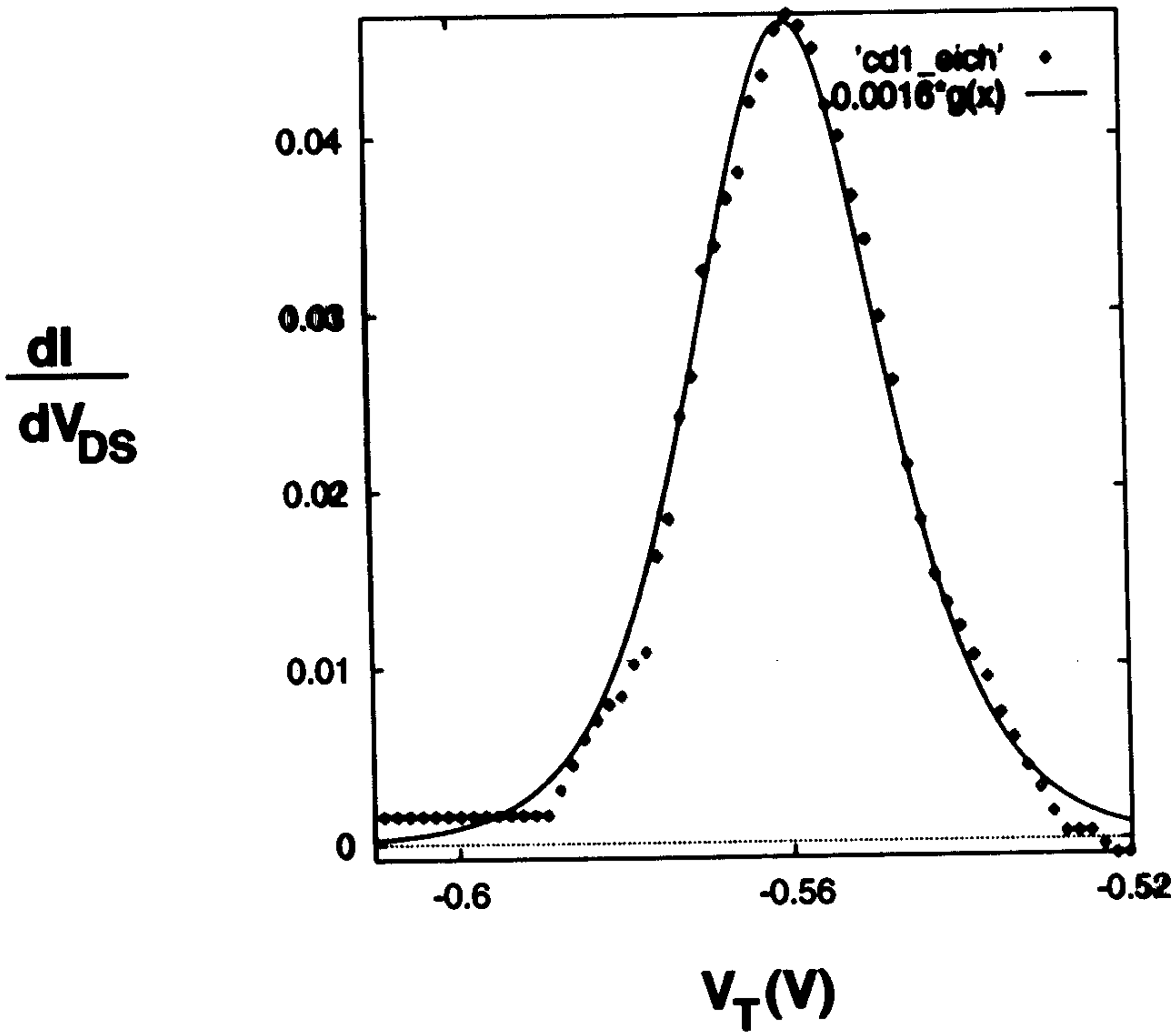
Theory and Experiment



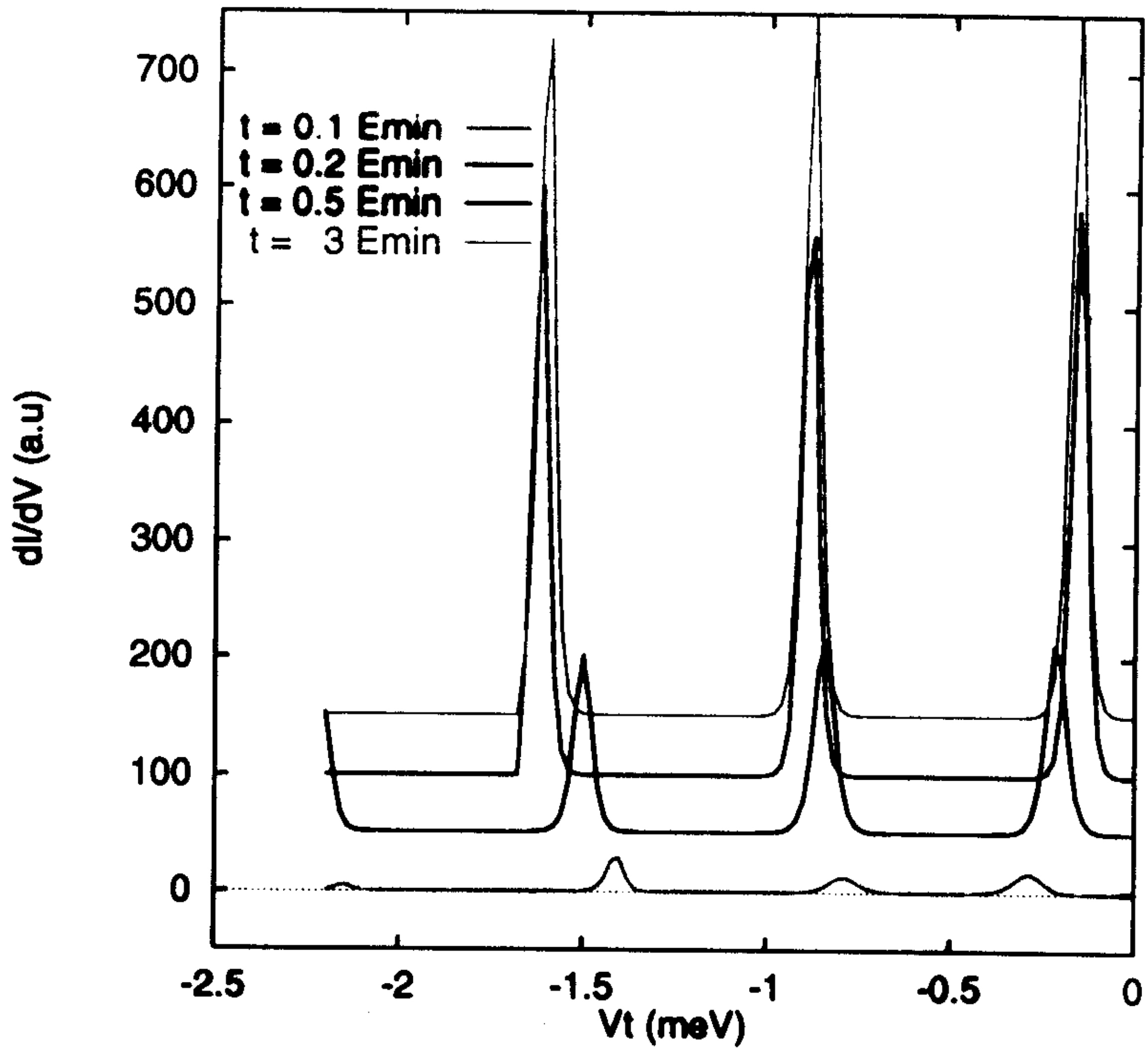
Fermi-Peak

fit: $g(x) \sim (-f'_{FD})$





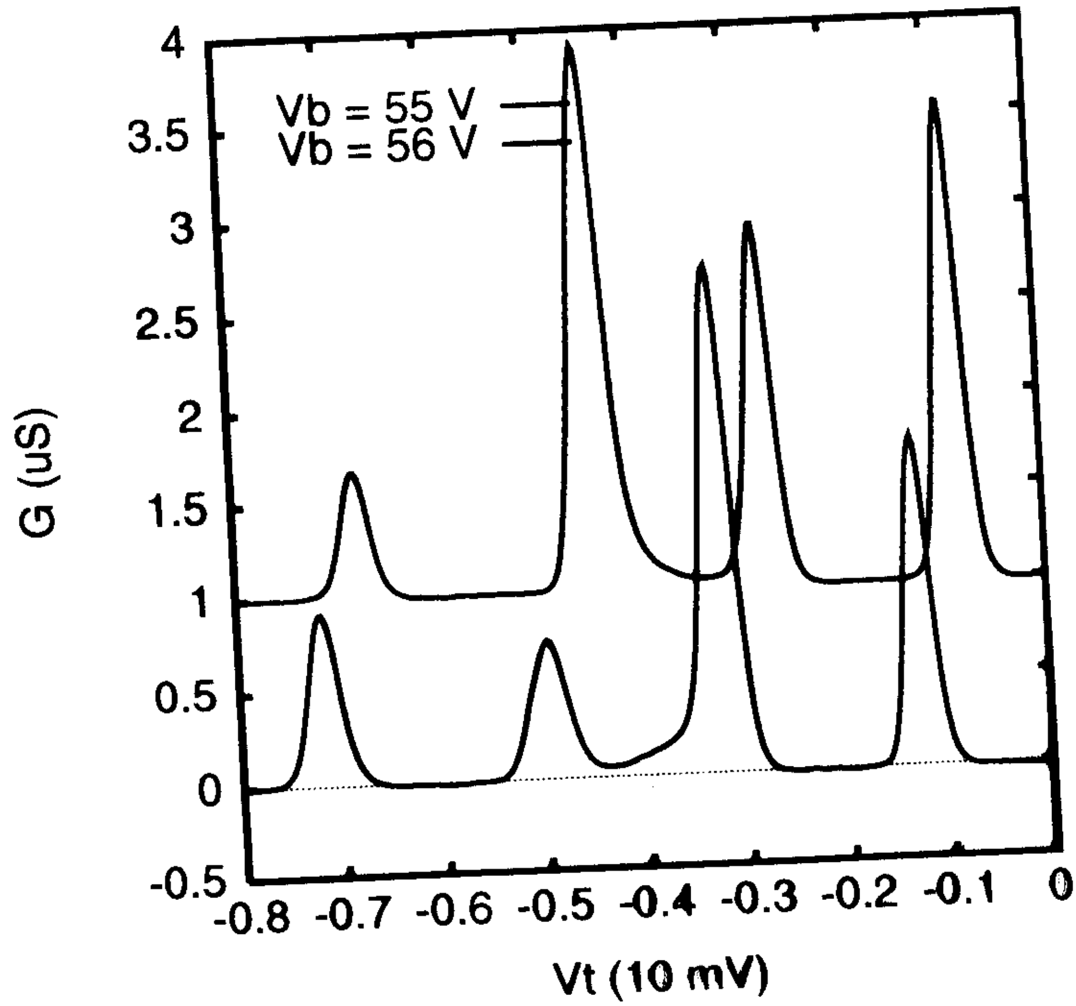
From Double Dot to Single Dot



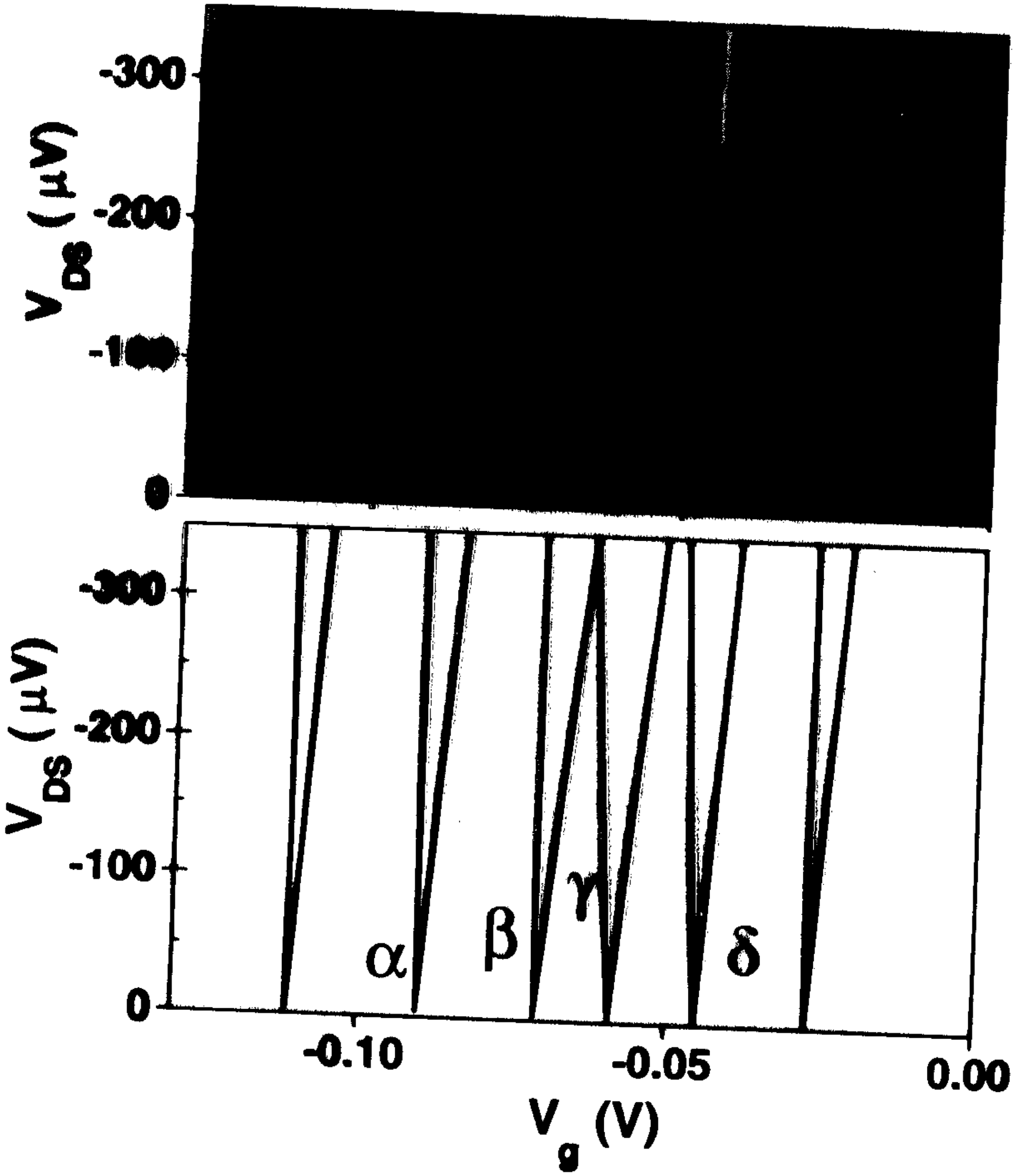
saturation of peak height

vanishing modulation of periodicity

Resonances from Anti-Bonding States



Charging Diagram at Finite Bias



Theory vs Experiment

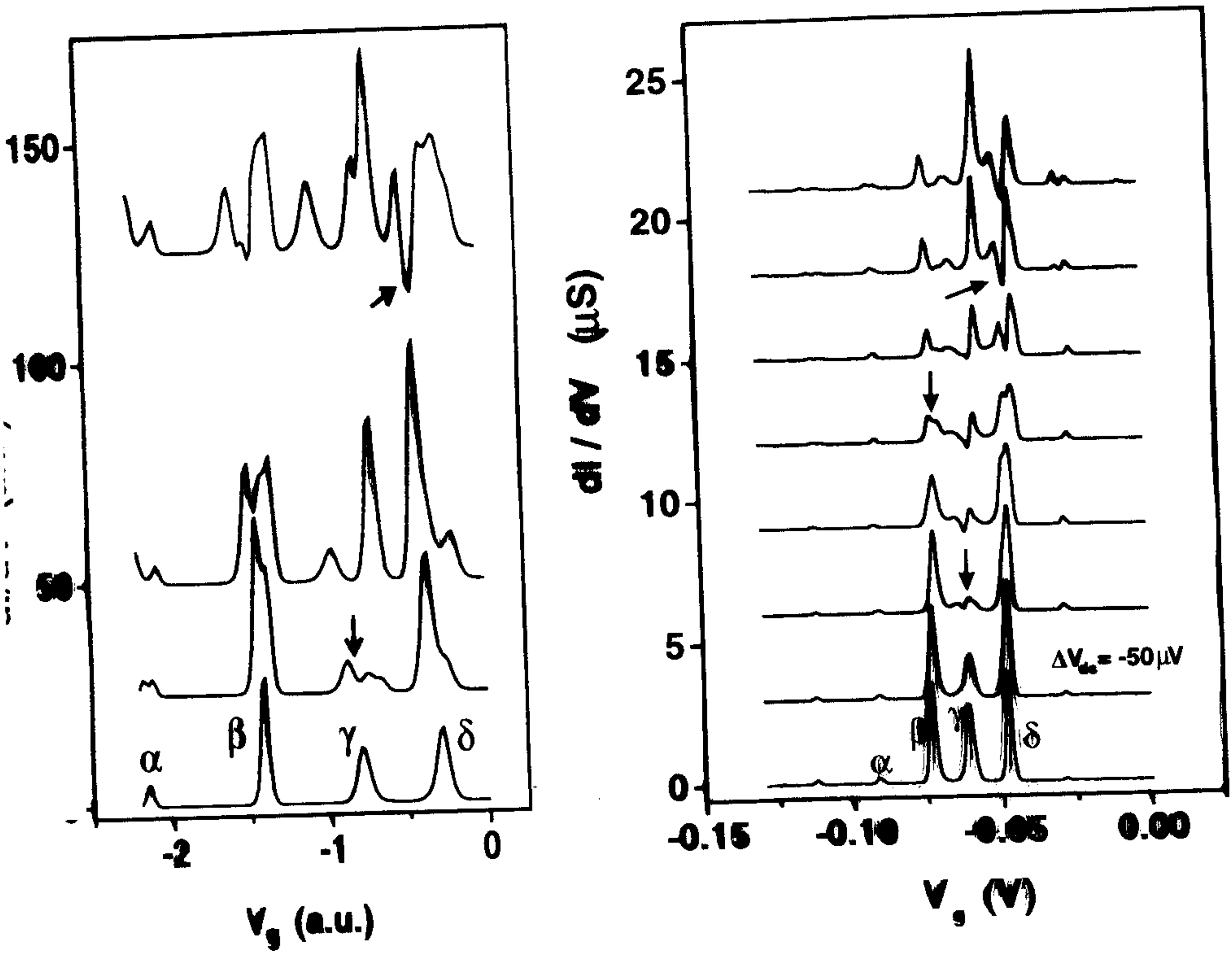


Fig. 4, Blick et al.

Summary

- Single Quantum Dots:
  sequential tunneling

- Coulomb interaction:
  correlations → selection rules

- excitation spectroscopy:
  dominated by collective response

- linear transport in Double Quantum Dots
  coupled in series
  → coherent interdot tunneling

- spectroscopy of artificial molecular states

- resonance shows Lorentzian form
  for electrostatic detuning