Evolution of Kondo Effect in Carbon Nanotubes

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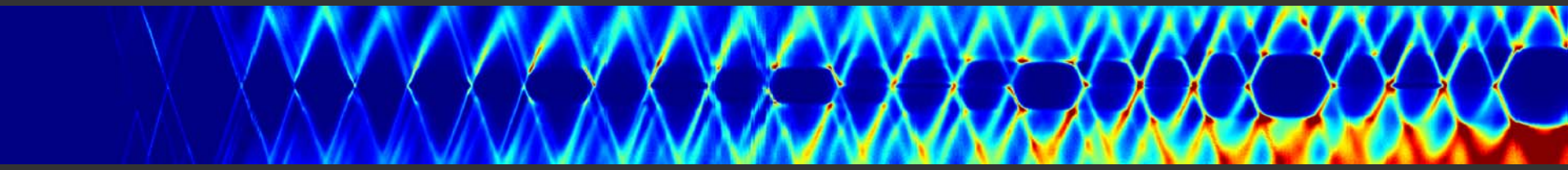


Discussions: I. Aleiner, H. Baranger, A. Chang, L. Glazman, B. Halperin, K. Matveev, M. Pustilnik, D. Ullmo

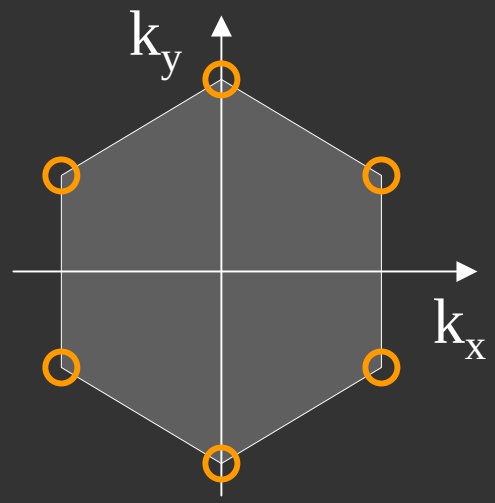
Support: NSF DMR-0239748

Introduction: Electronic properties of nanotubes

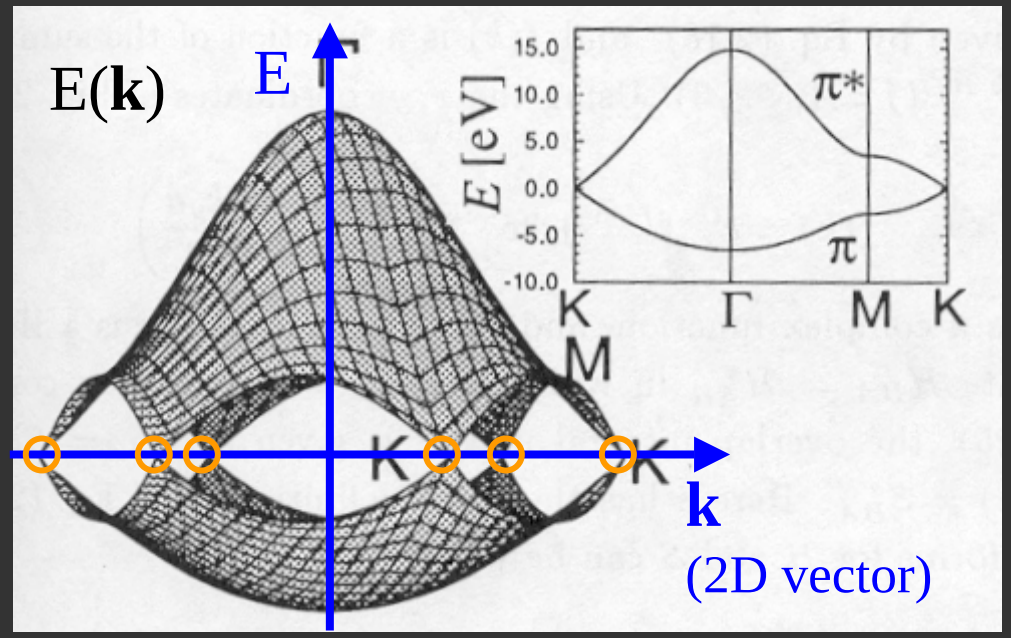
Coulomb blockade in nanotubes: orbital degeneracy

Kondo effect with orbital degeneracy

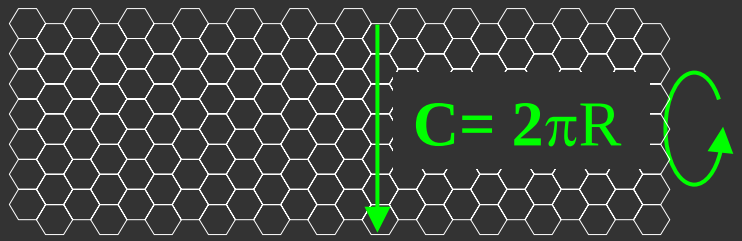
2D graphite: semi-metal



Brillouin zone

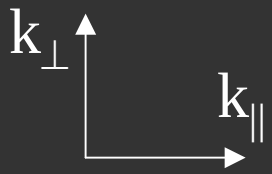


From "Physical Properties of Carbon Nanotubes" by Saito *et al., 1998.*

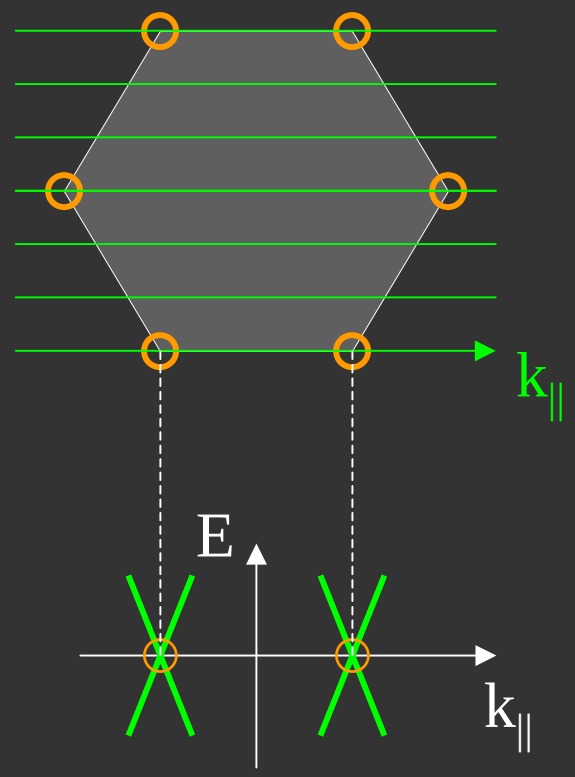


$k_{\parallel}$ - arbitrary

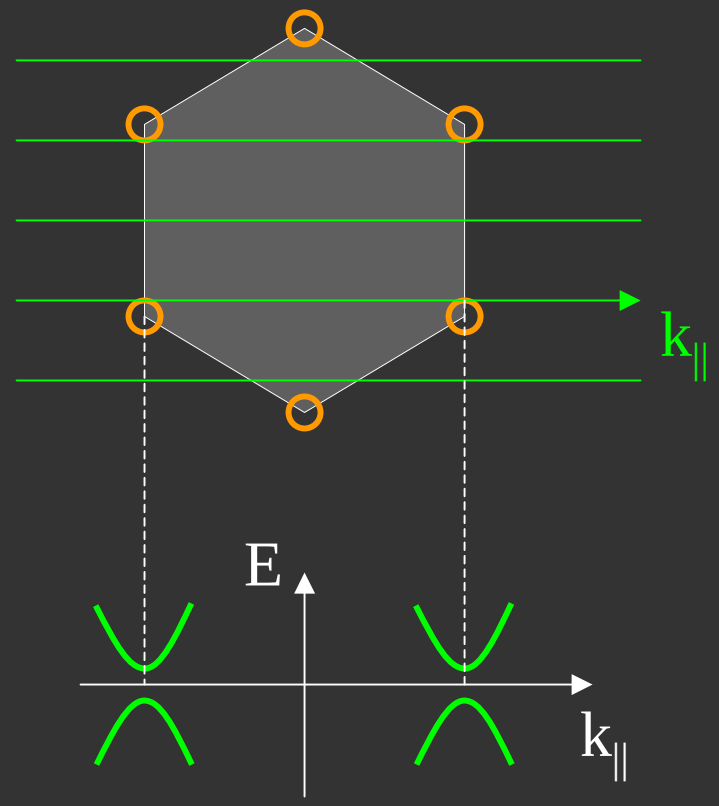
$k_{\perp} = 2\pi N/C = N/R$



Nanotubes: metallic and semiconducting



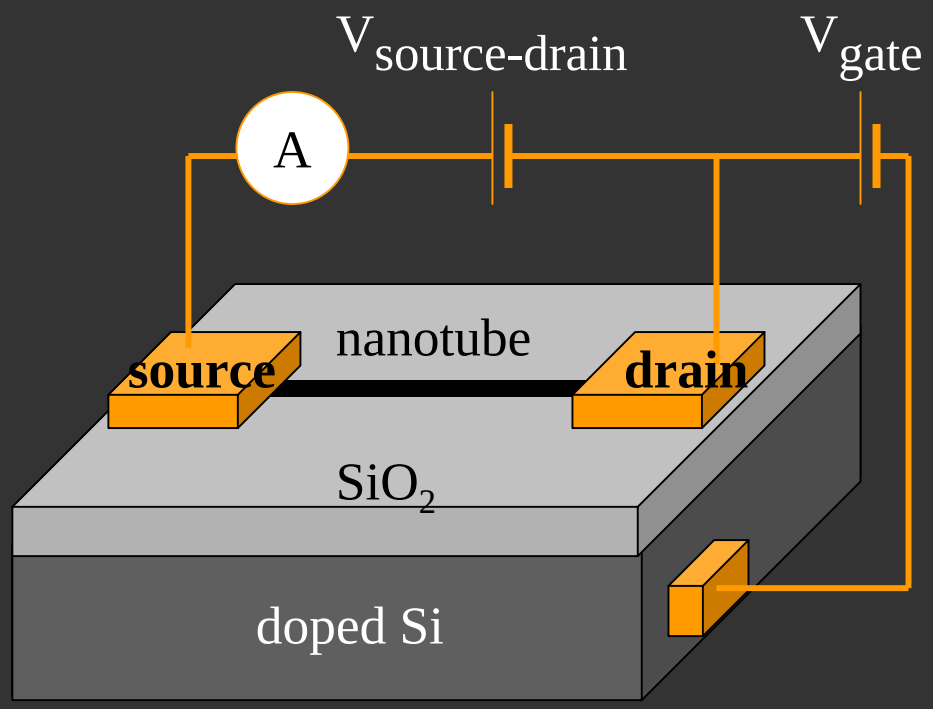
metal

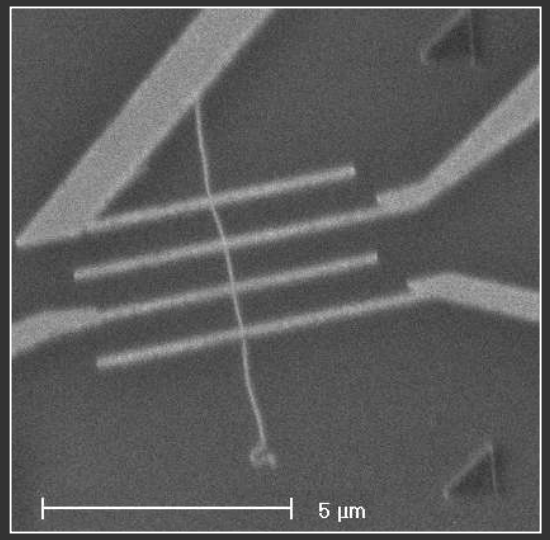


semiconductor

- Metallic or semiconducting
- Two bands

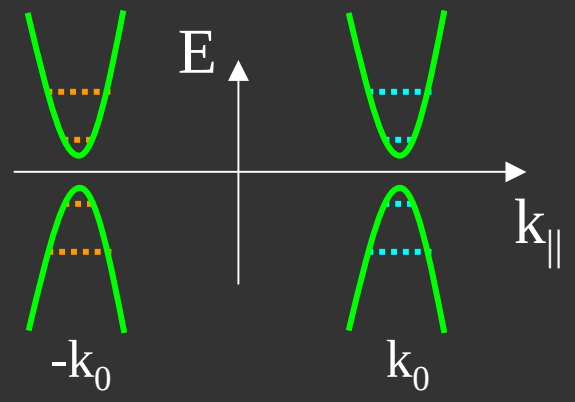
Measurement setup



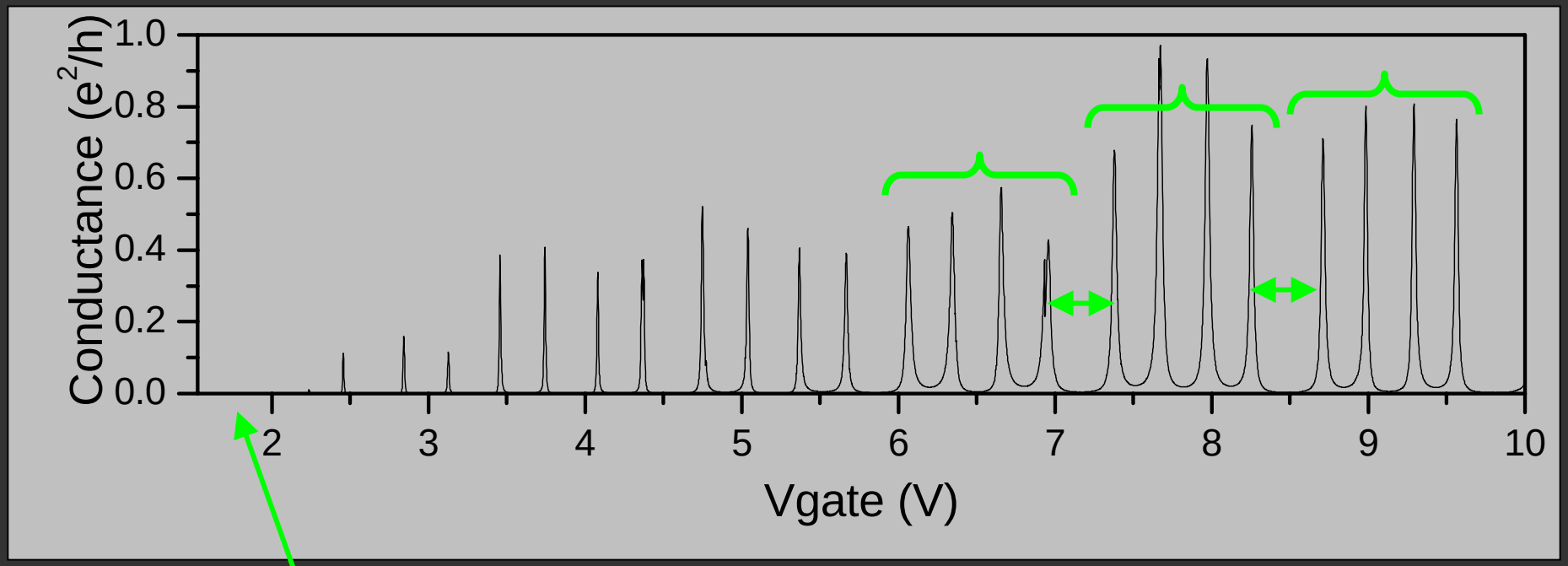


Differential conductance dI/dV (Vgate)

Groups of 4 peaks: orbital degeneracy

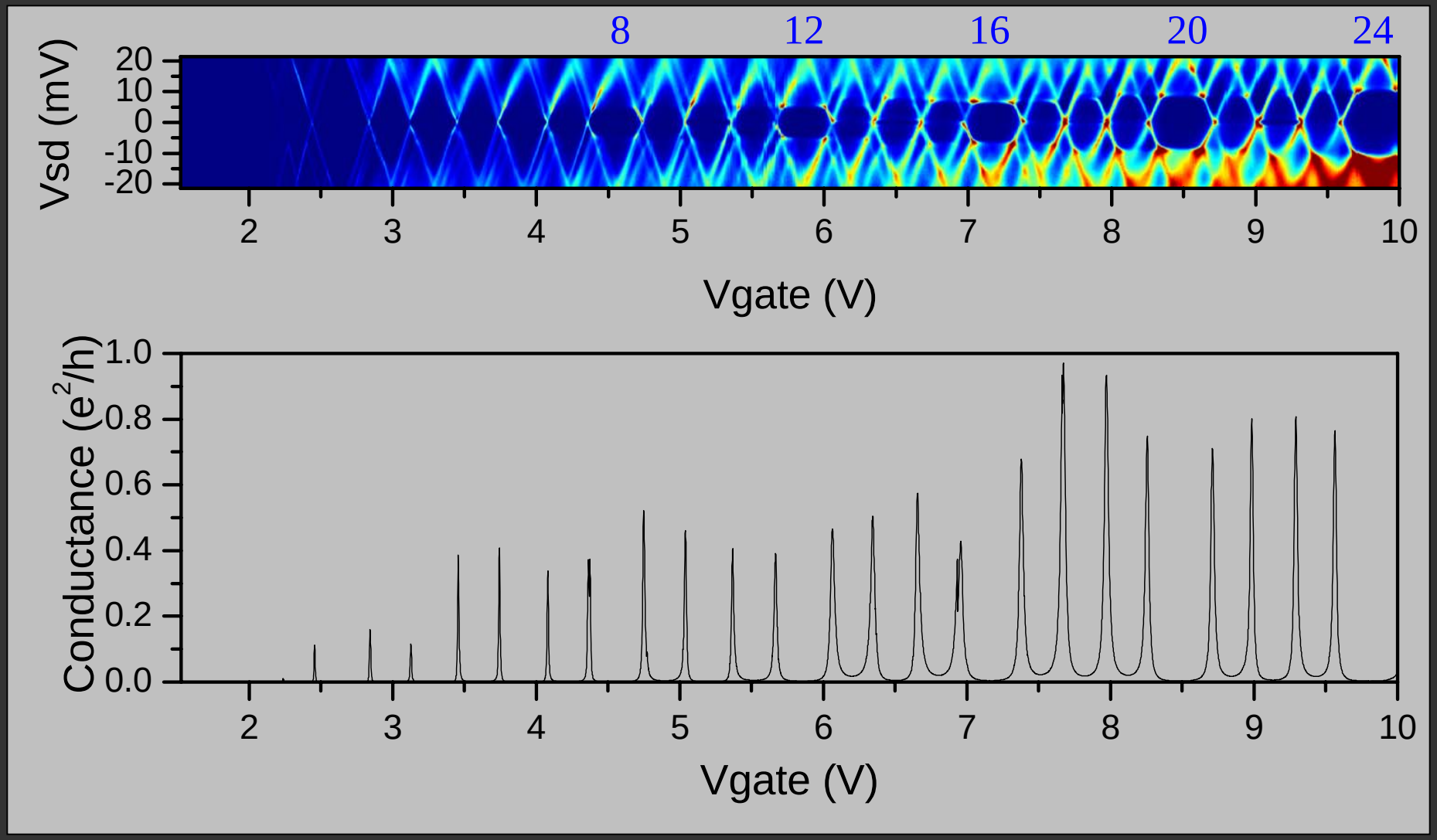


4 degenerate states:
2 degenerate orbitals x 2 spin projections

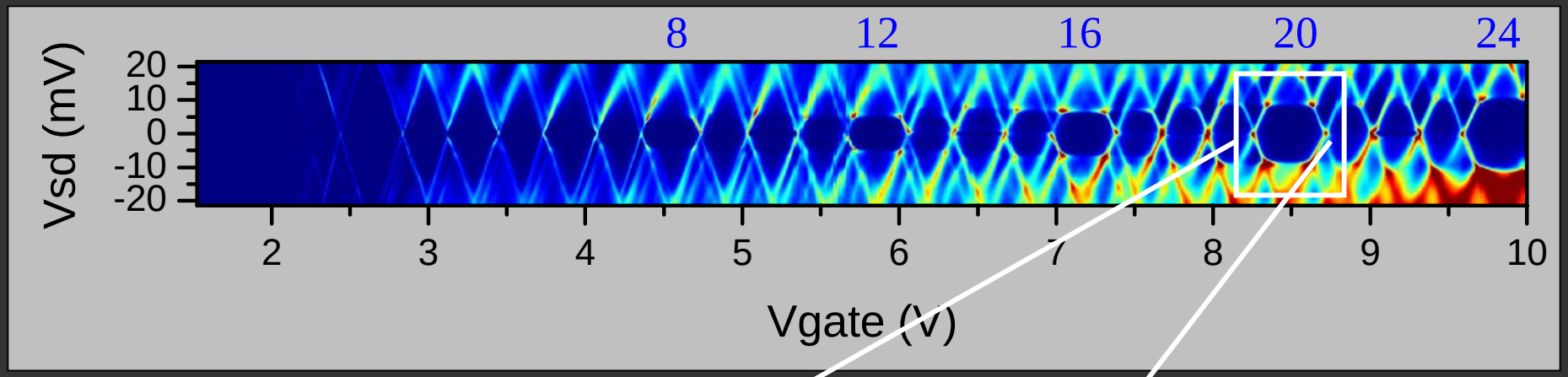


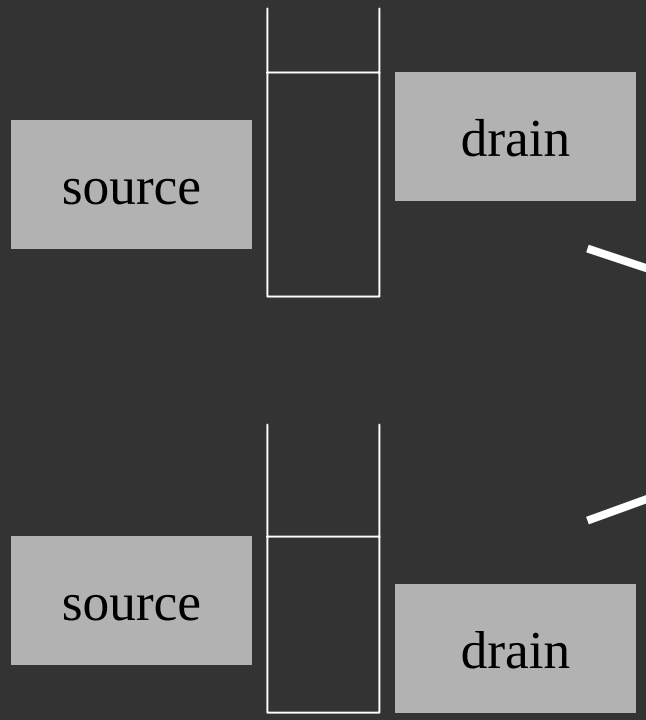
Energy gap (semiconducting tube)

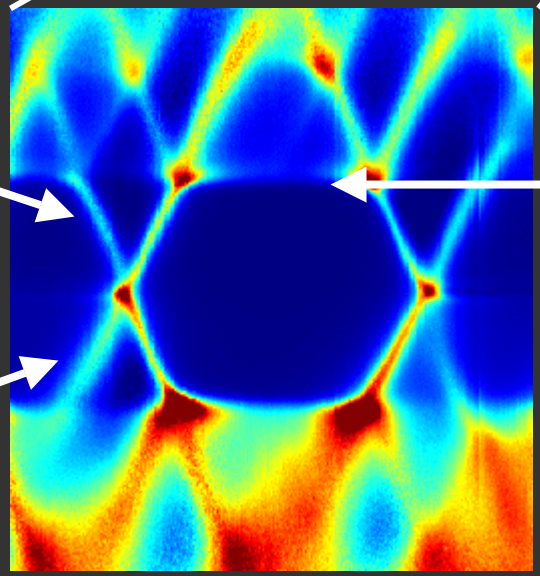
Conductance map: G(Vgate, Vsd)

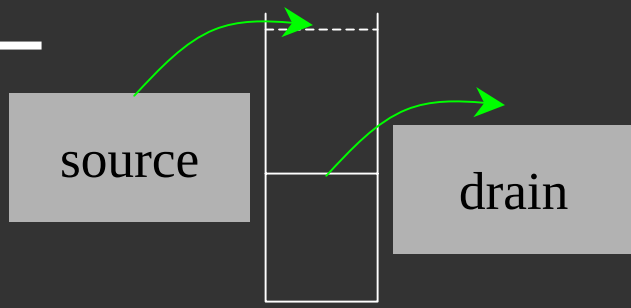


Conductance map: G(Vgate, Vsd)

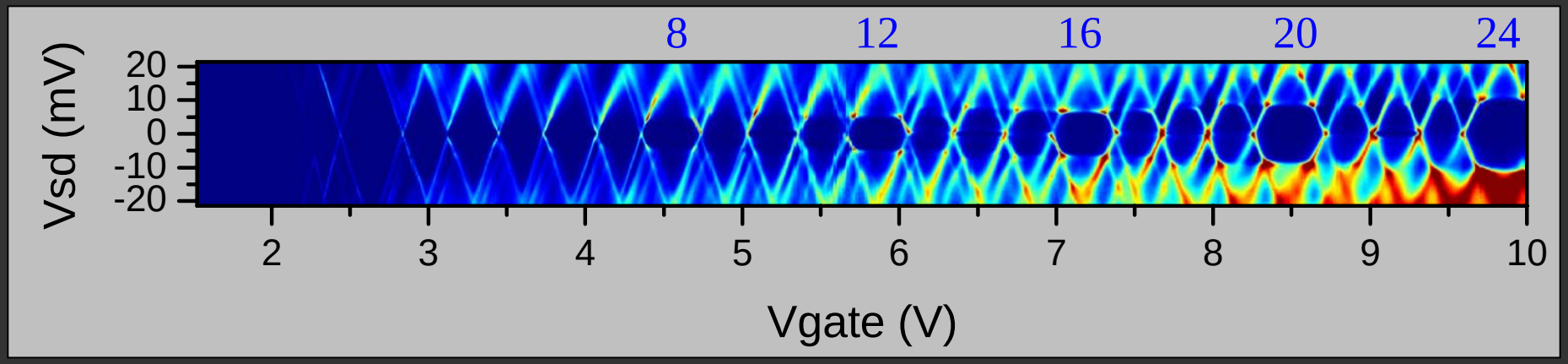


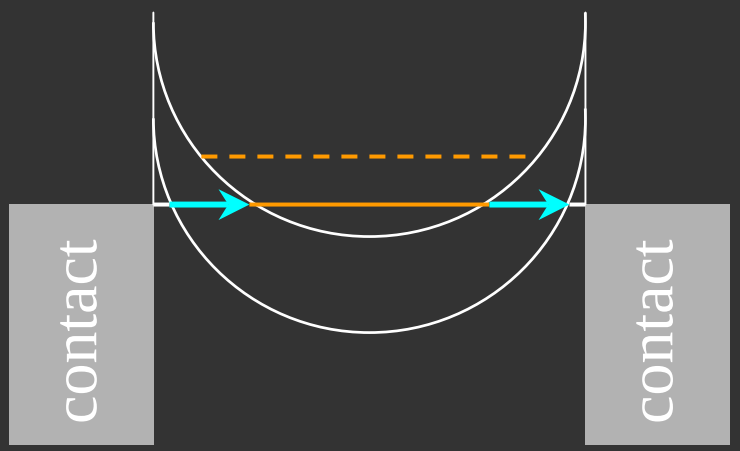


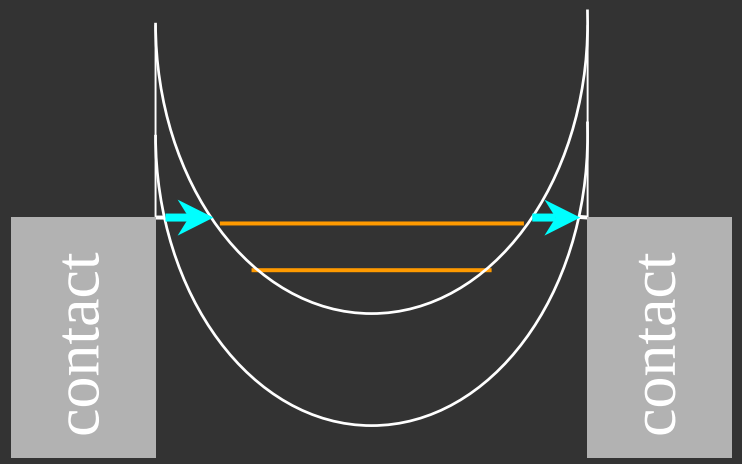




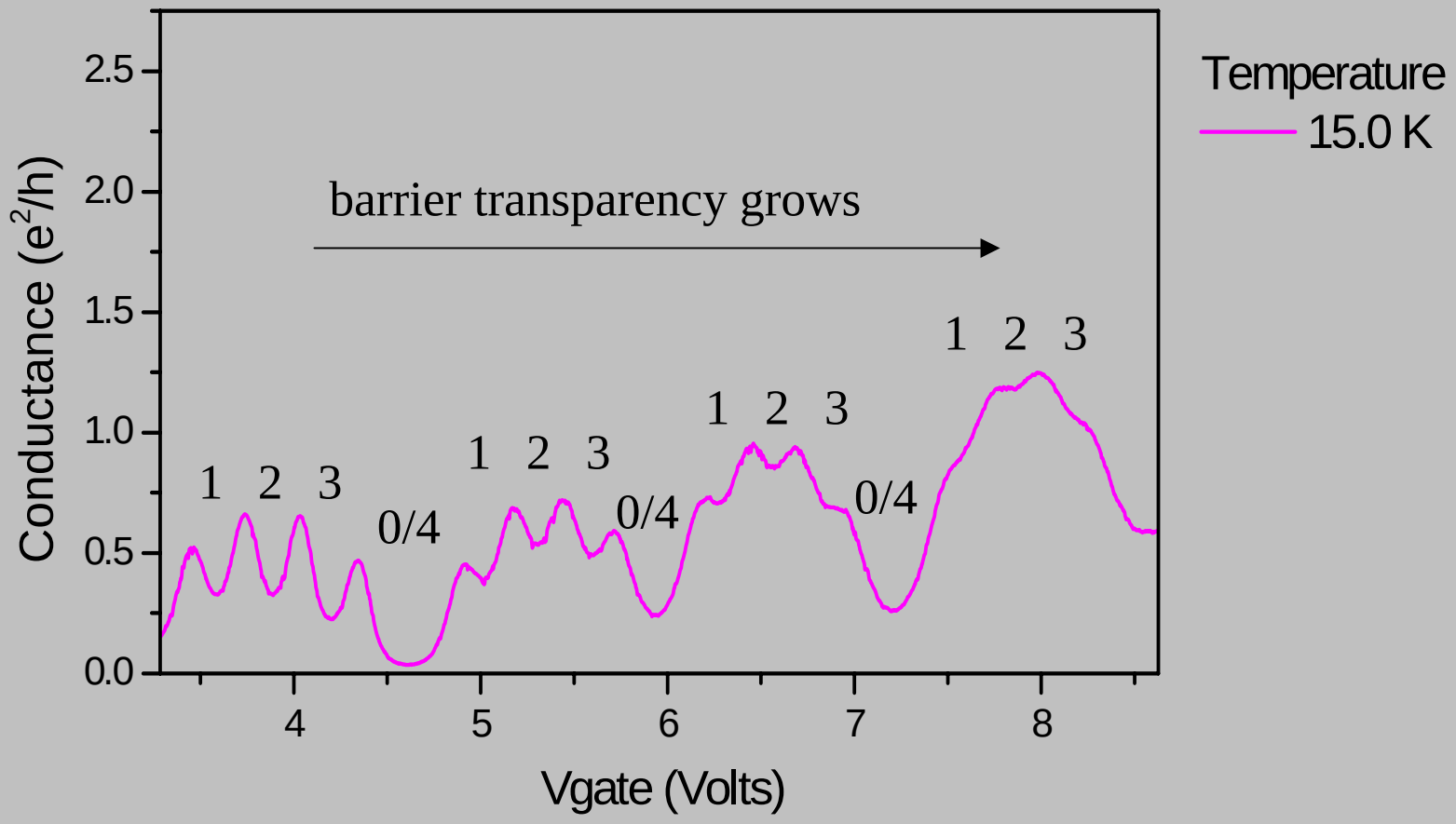
Barrier transparency grows with Vgate







Temperature dependence of conductance



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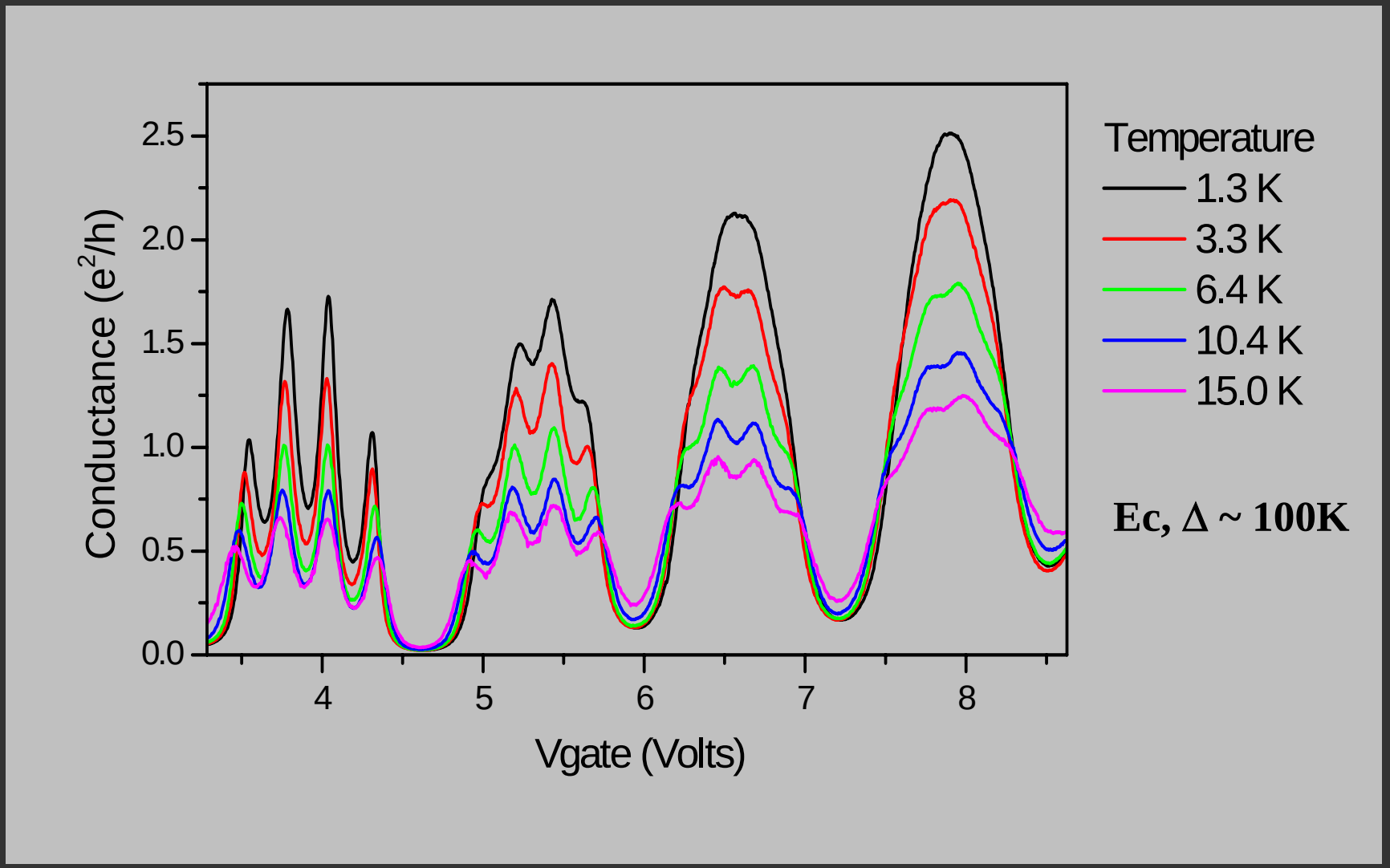
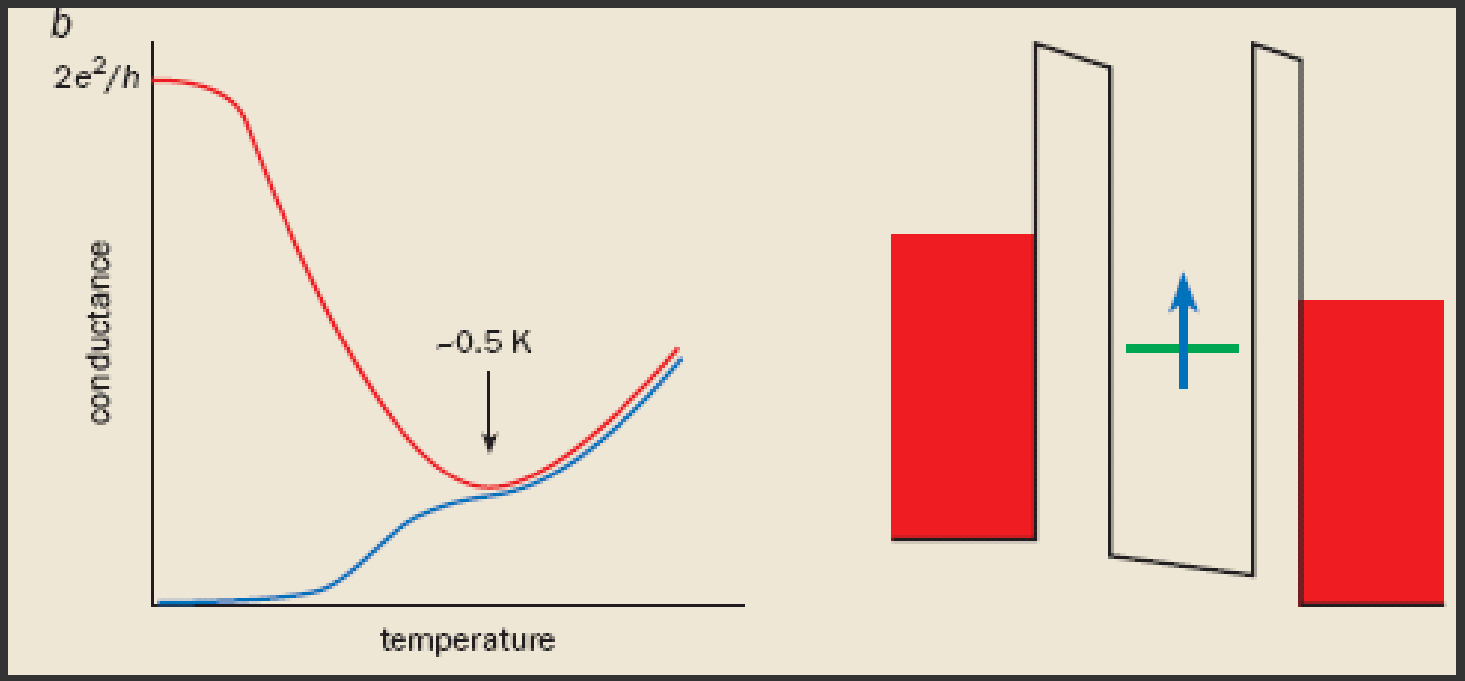


Growth of the signal in the valleys due to the Kondo effect

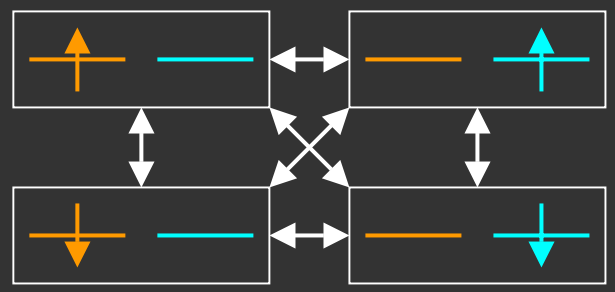
Kondo effect in Quantum Dots



From: Revival of the Kondo effect
L. Kouwenhoven and L. Glazman
Physics World 2001

SU(4) Kondo in nanotubes

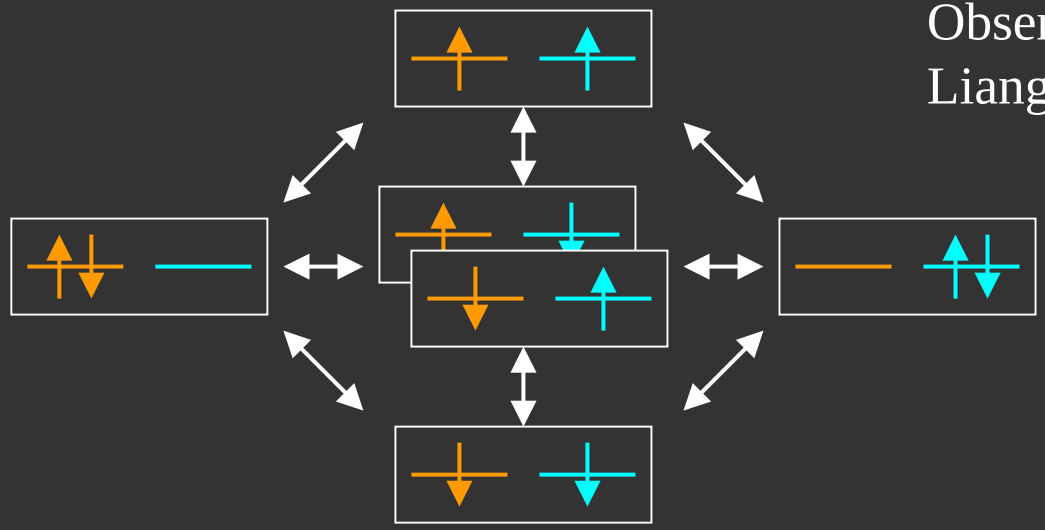
1e valley - 4 degenerate states



Investigation in nanotubes:
Jarillo-Herrero, Nature (2005)

Many theory papers
(primarily on double dots)
Gmax=$2e^2/h$

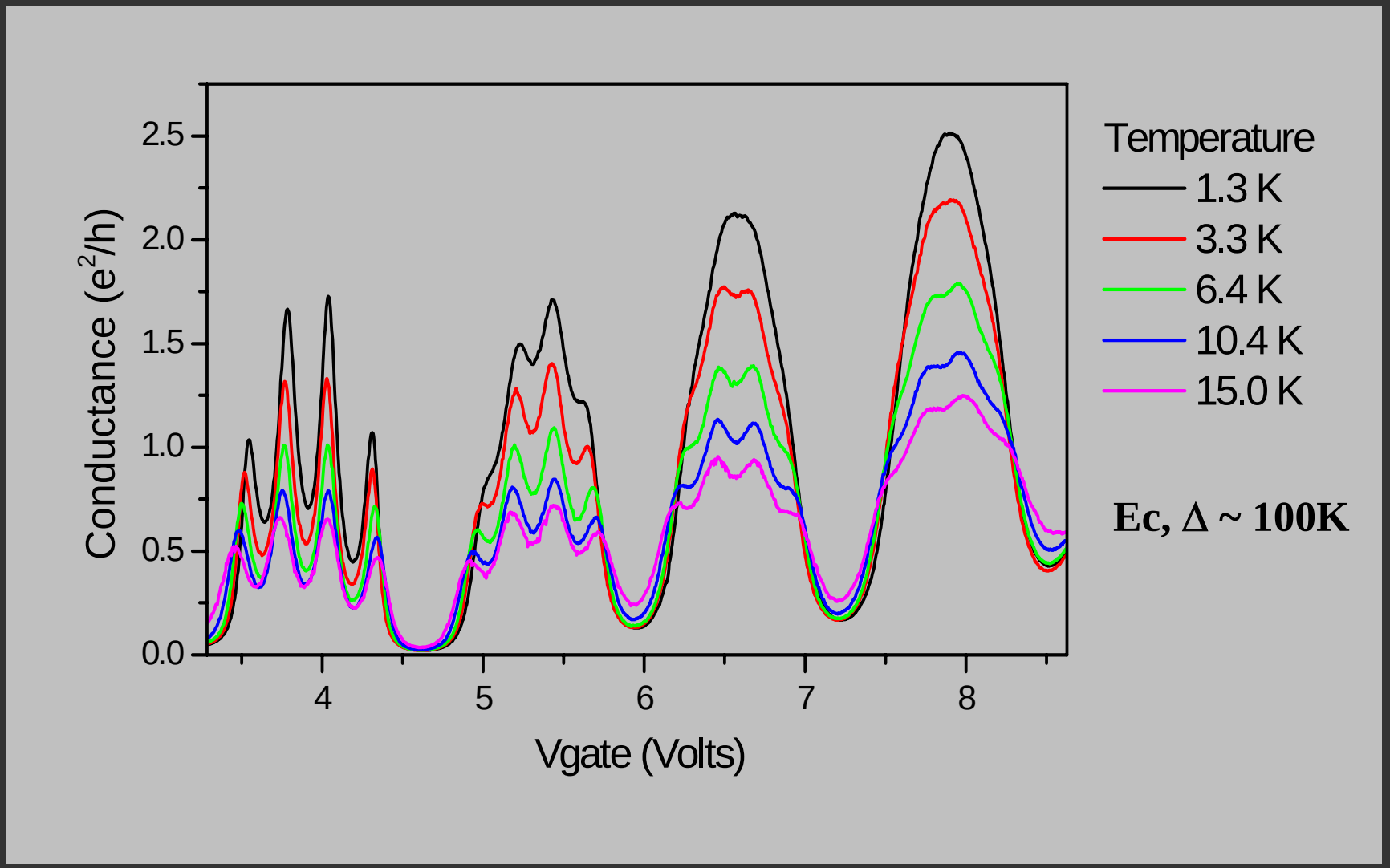
2e valley - 6 degenerate states



Observation in nanotubes:
Liang PRL 2000, Babic PRB 2004

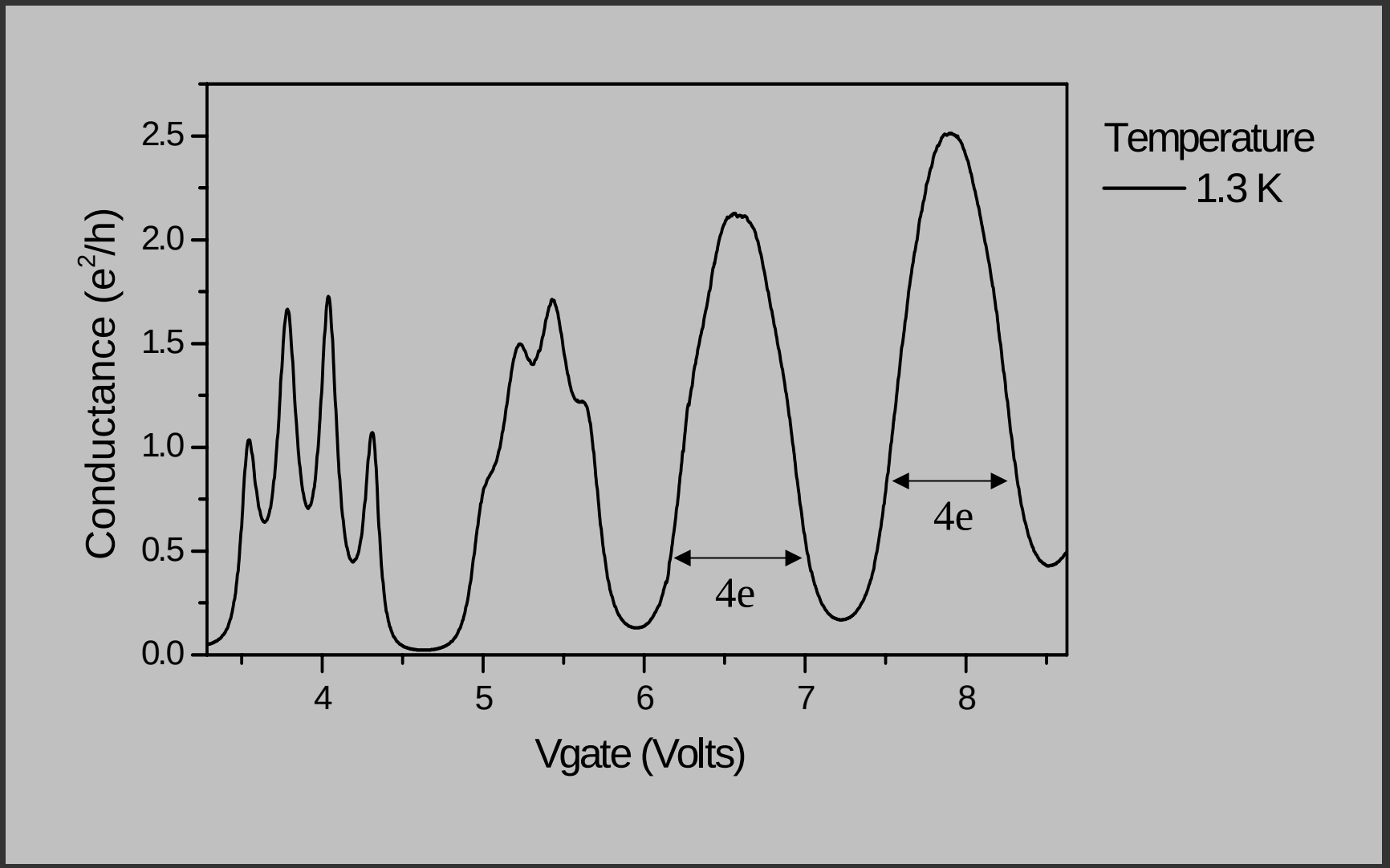
Gmax=$4e^2/h$

Temperature dependence of conductance



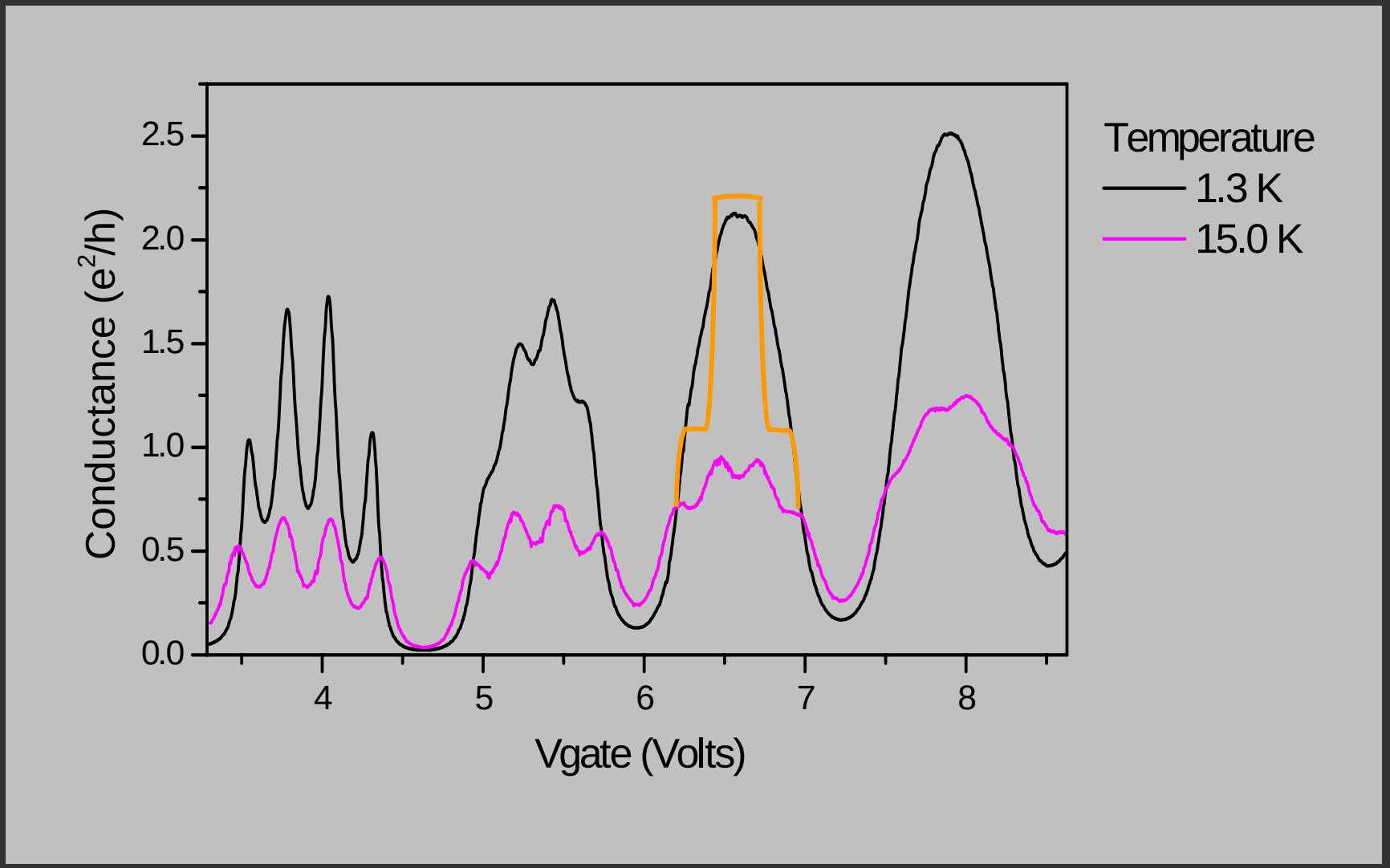
Growth of the signal in the valleys due to the Kondo effect

Shape of the 4-electron clusters at low T and high transparency



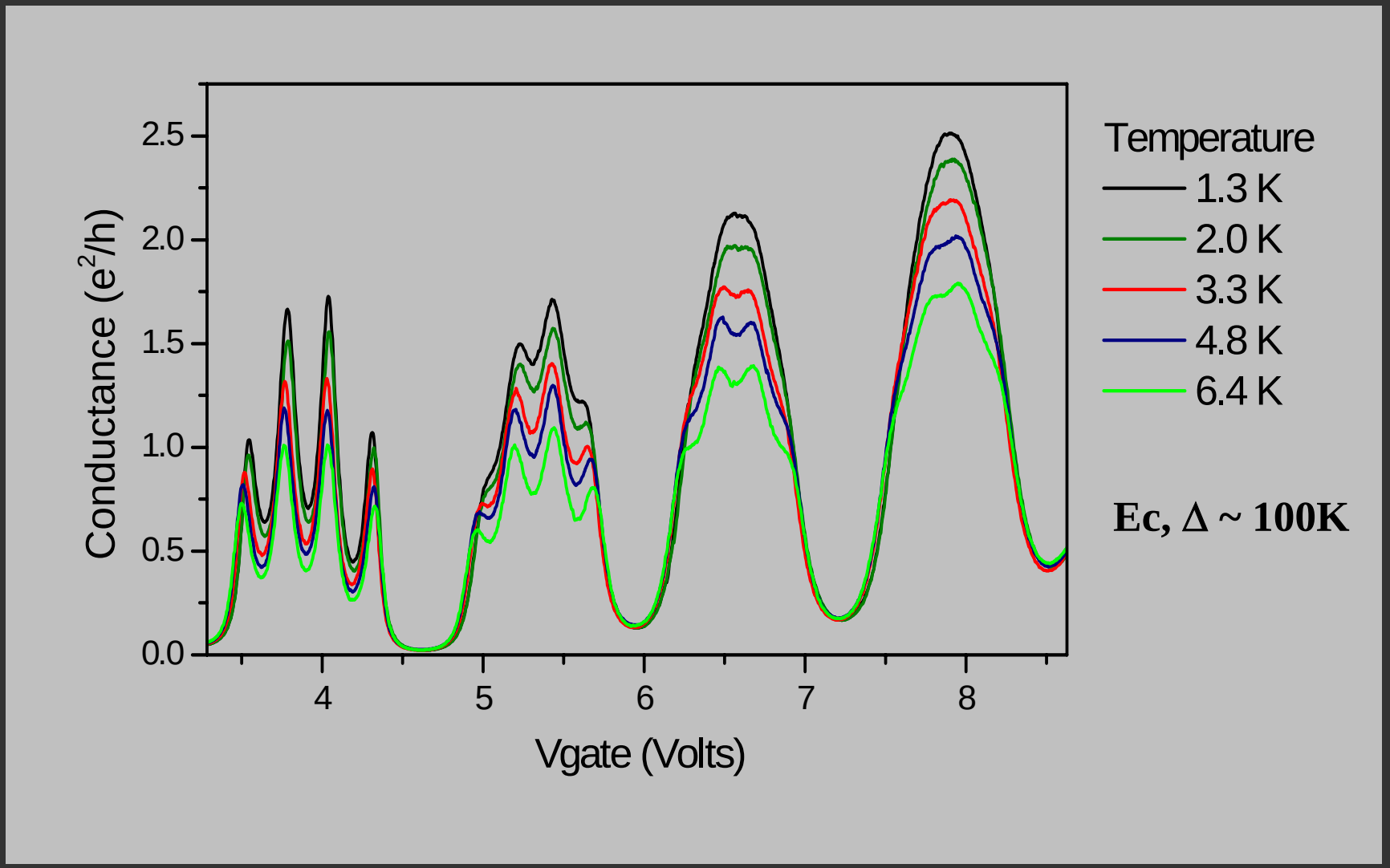
Single-electron features are washed out at low temperature

Naïve expectation: plateaus of different height



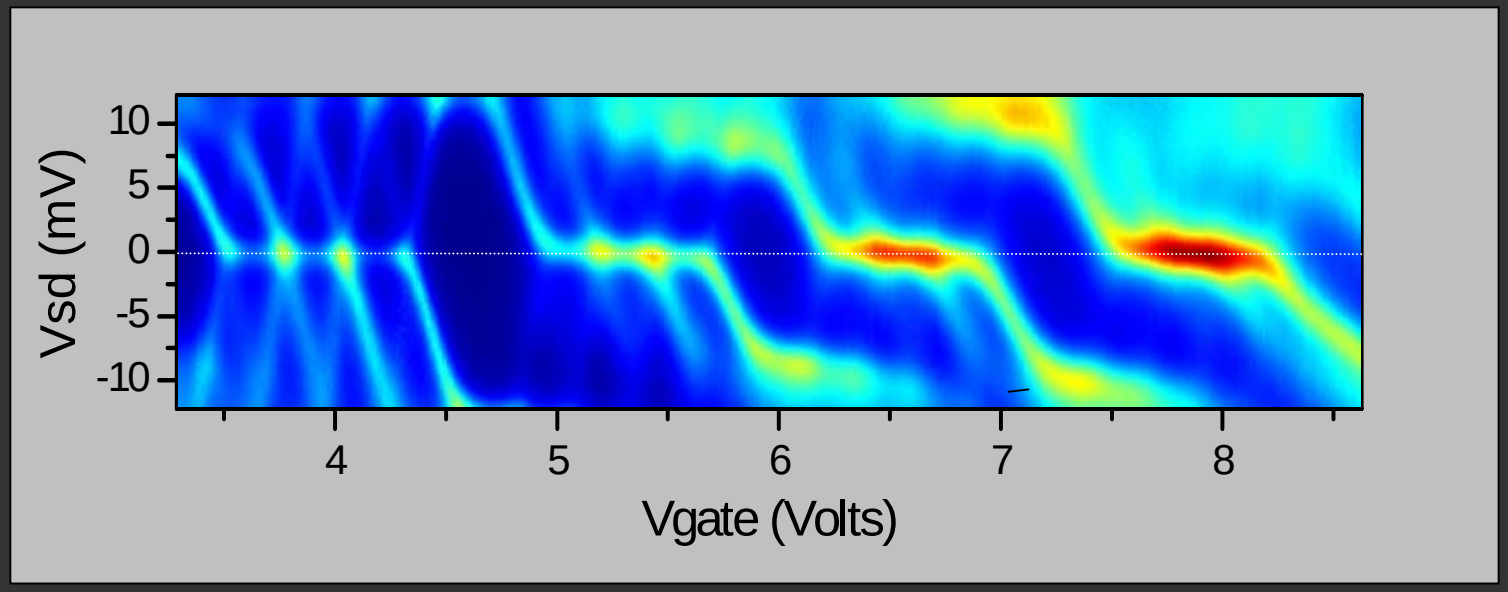
No individual Kondo plateaus of various heights

Temperature dependence of conductance



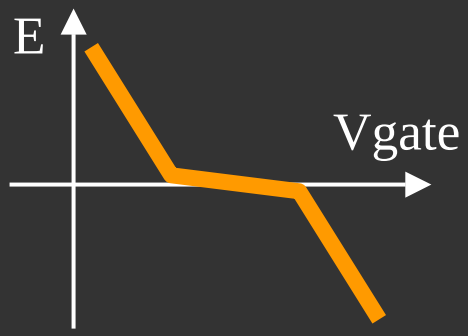
Growth of the signal in the valleys due to the Kondo effect

Positions of the resonances



"Usual" Coulomb blockade at small transparency (left cluster)
Kondo ridge the most prominent feature (right clusters)

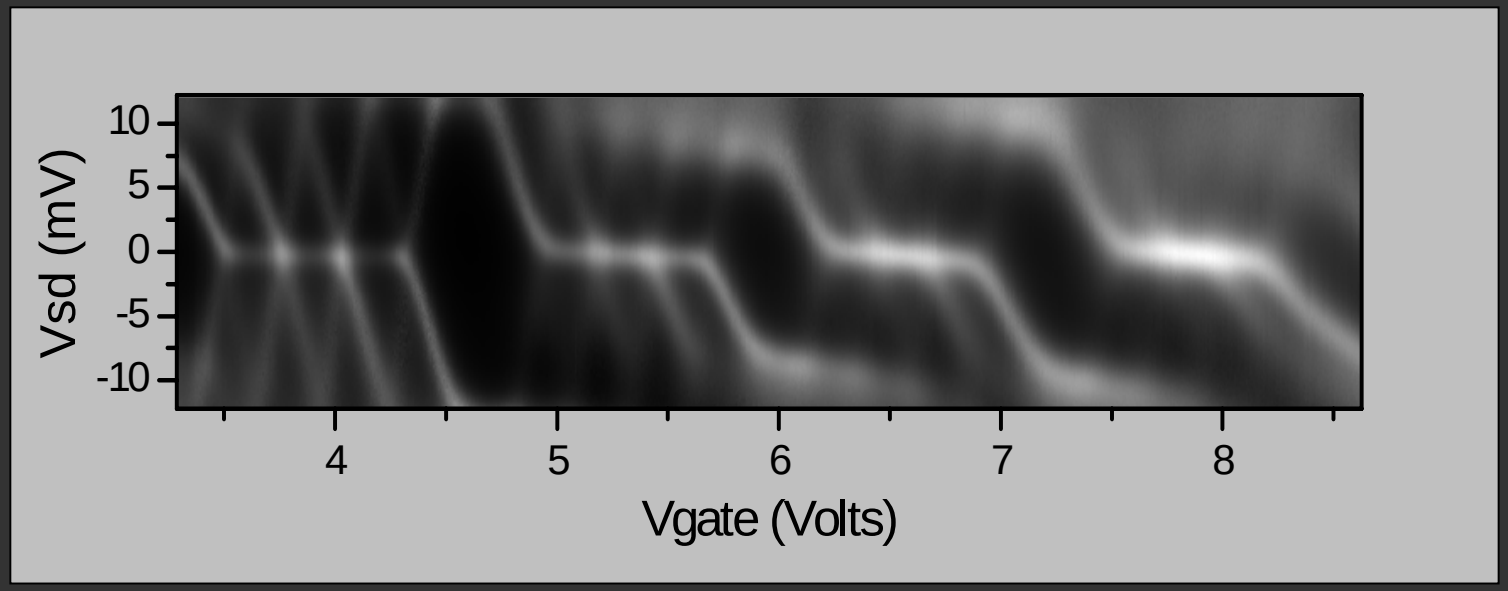
$\Gamma_L >> \Gamma_R$



One contact much better couples to the nanotube: Tunneling from the weak contact probes the density of states in the nanotube + lead system

Behavior different from both Coulomb blockade and single-particle interference

Positions of the resonances



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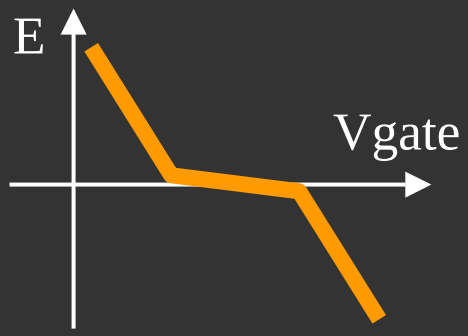
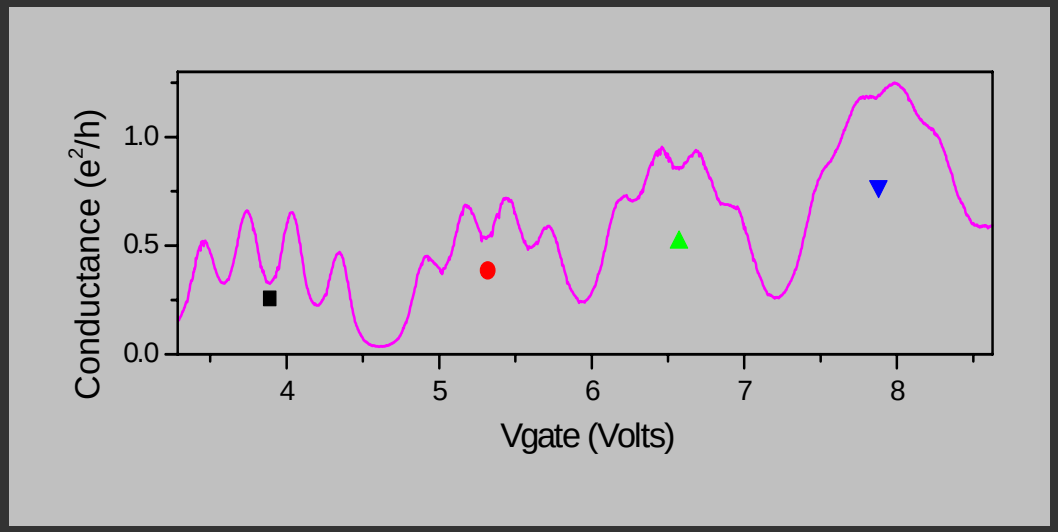
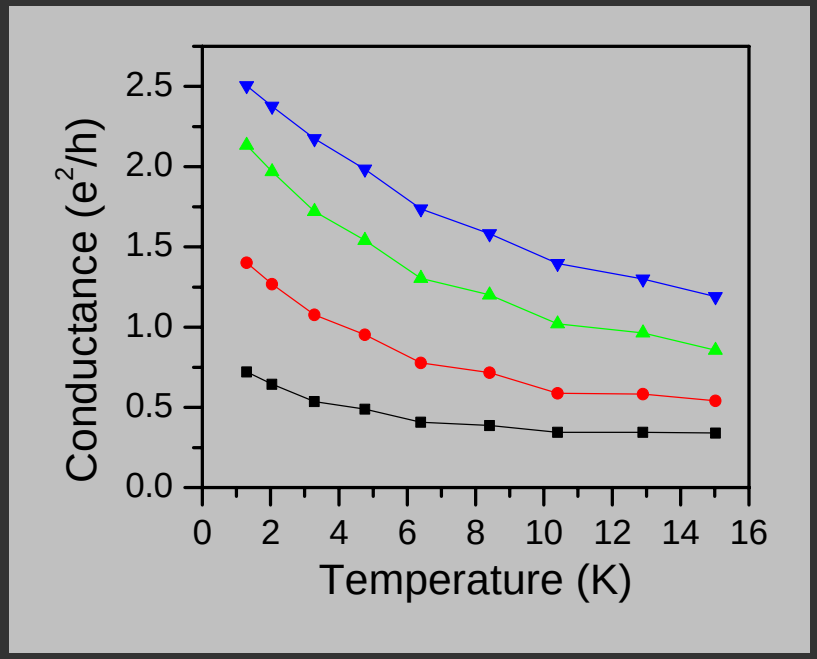


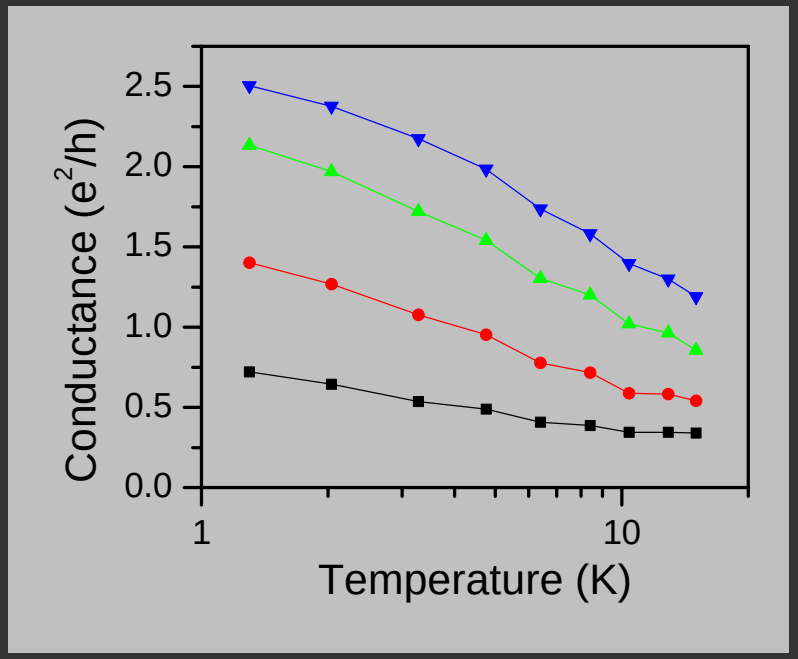
One contact much better couples to the nanotube: Tunneling from the weak contact probes the density of states in the nanotube + lead system

Behavior different from both Coulomb blockade and single-particle interference

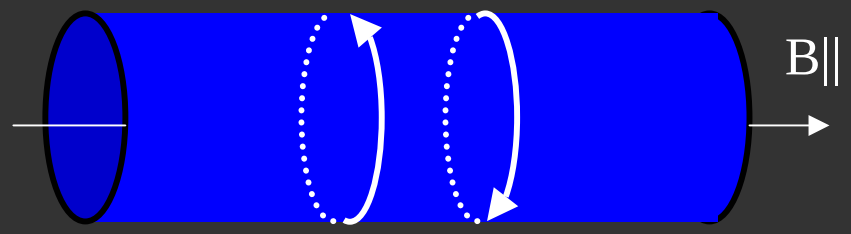
Temperature dependence of the 2-electron valleys

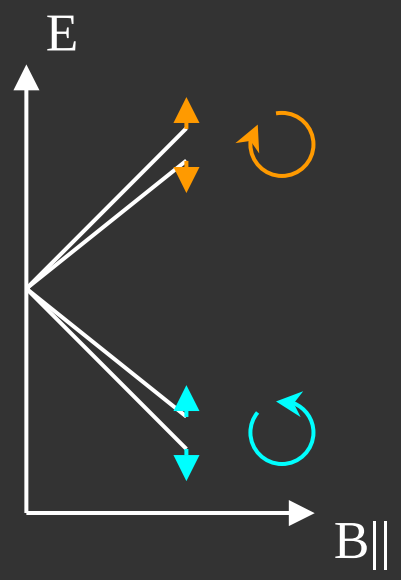


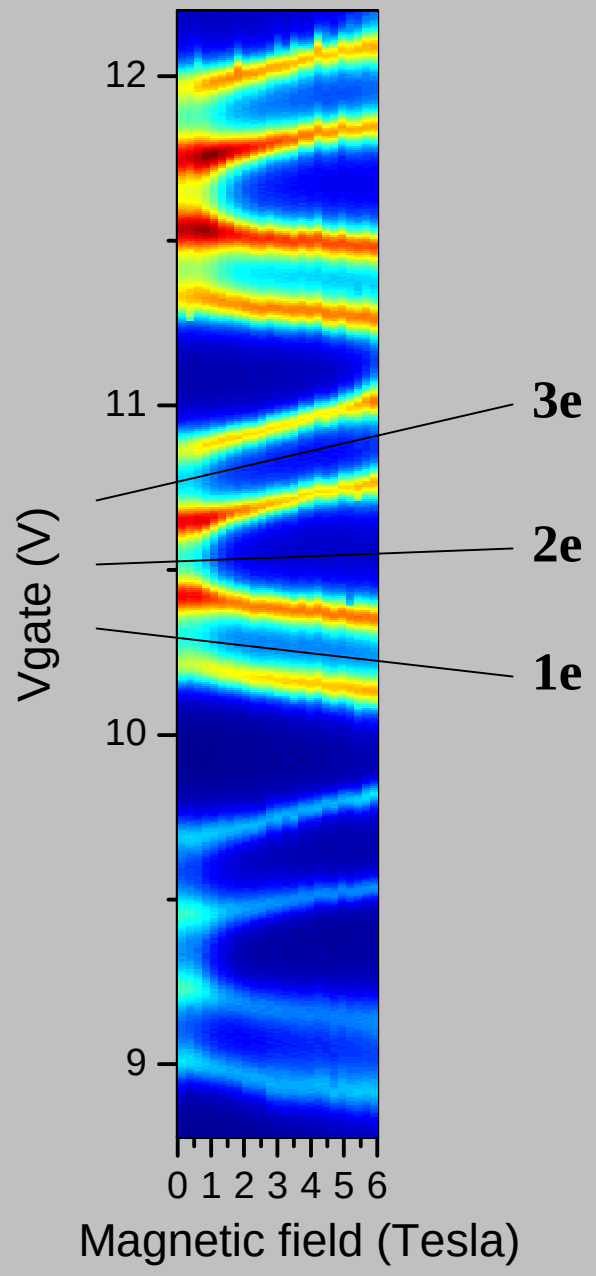


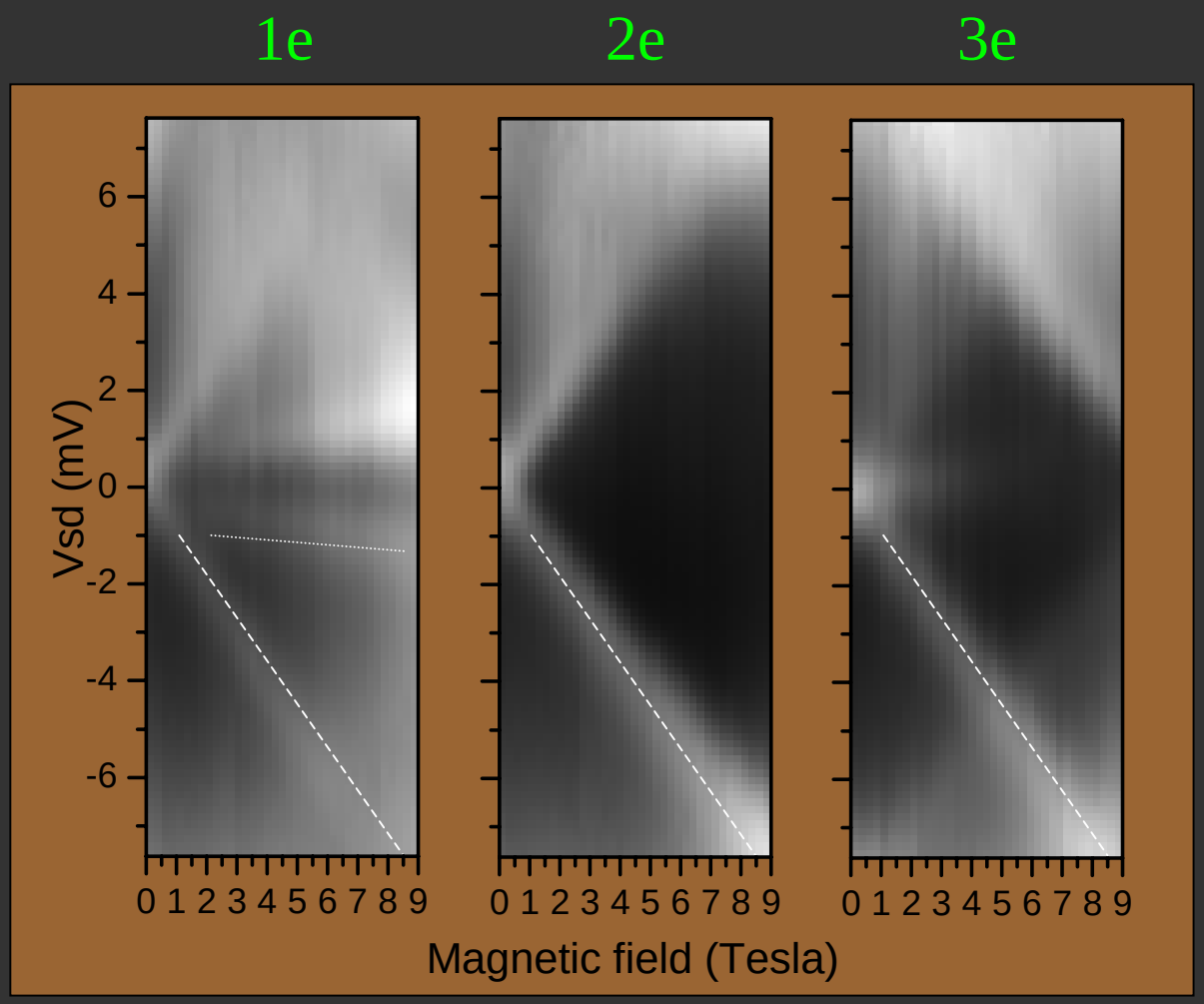


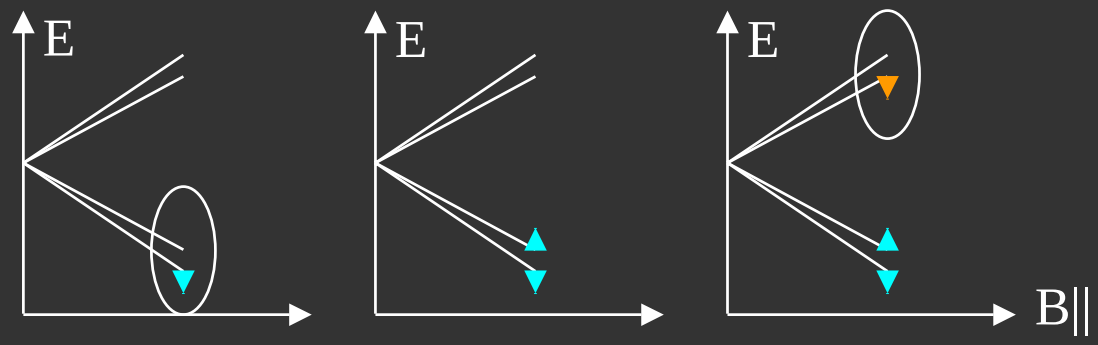
Nanotube in B||





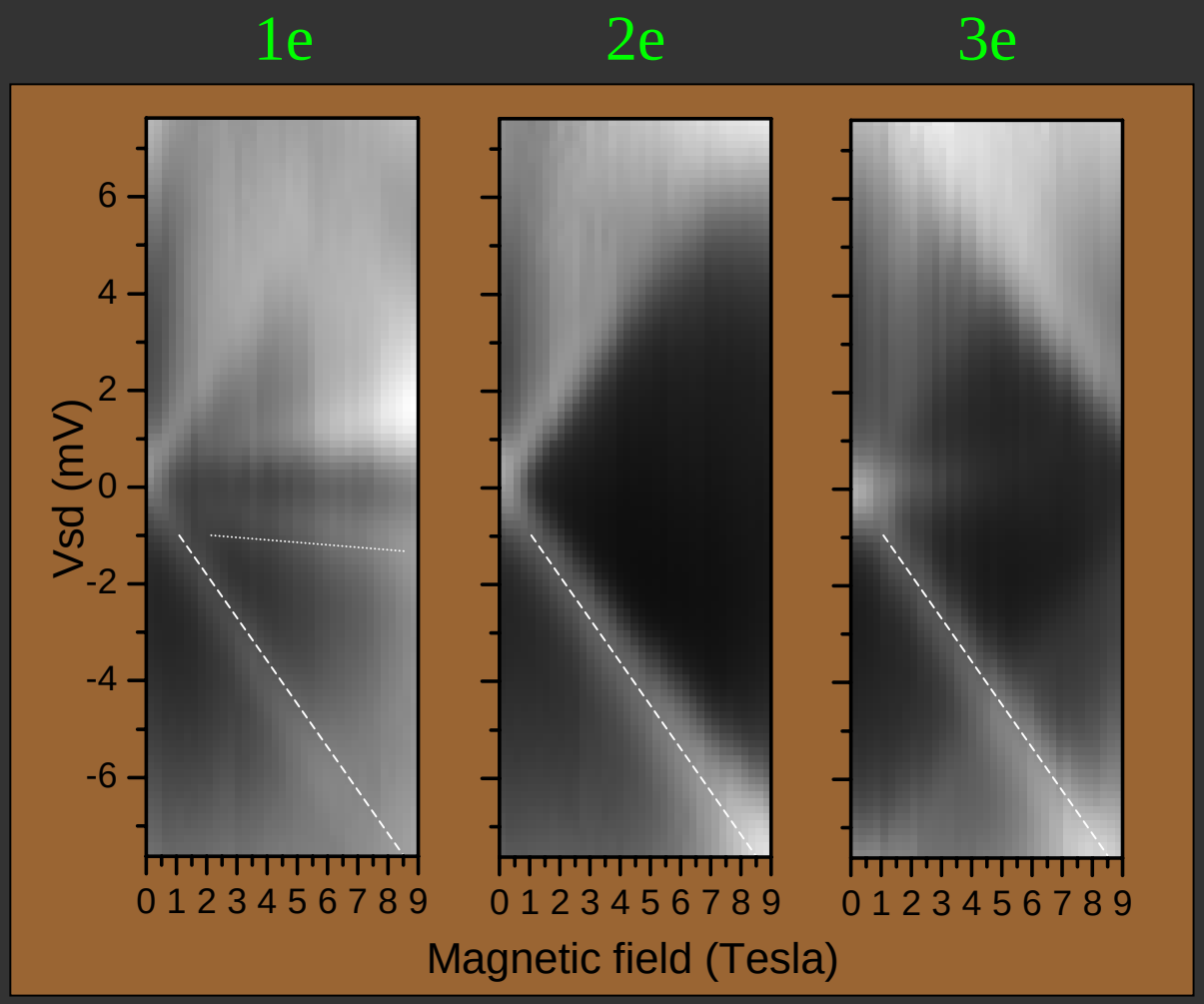


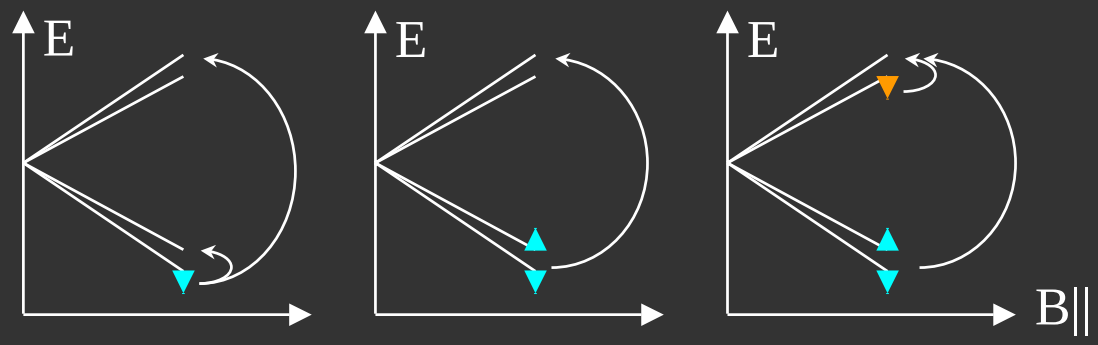




Kondo signal disappears in the 2e valley as the orbitals are split

"Usual" SU(2) Kondo may still possible in the 1e and 3e valleys





Co-tunneling energy:

2e valley:
orbital

1e valley:
orbital and Zeeman

3e valley
orbital + SU(2)
Kondo feature at
zero energy

Conclusion

- Low temperature regime is featureless;

Single electron peaks are recovered at higher temperature

- No individual plateaus at 1e, 2e, 3e occupation

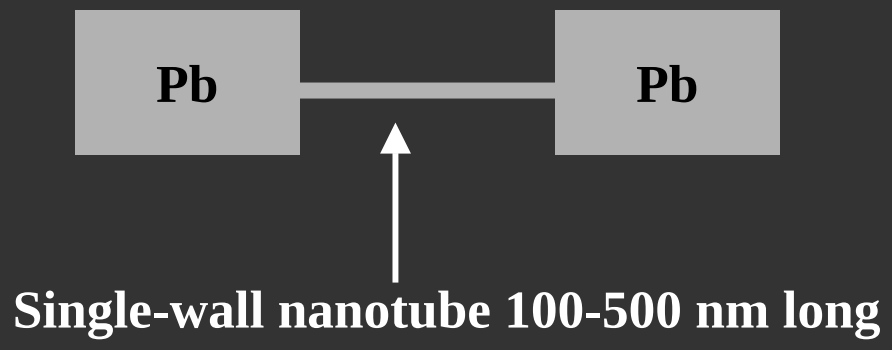
=> The different charge states are hybridized by Kondo processes at low temperature

- 1e and 3e Kondo features behave very differently in B||

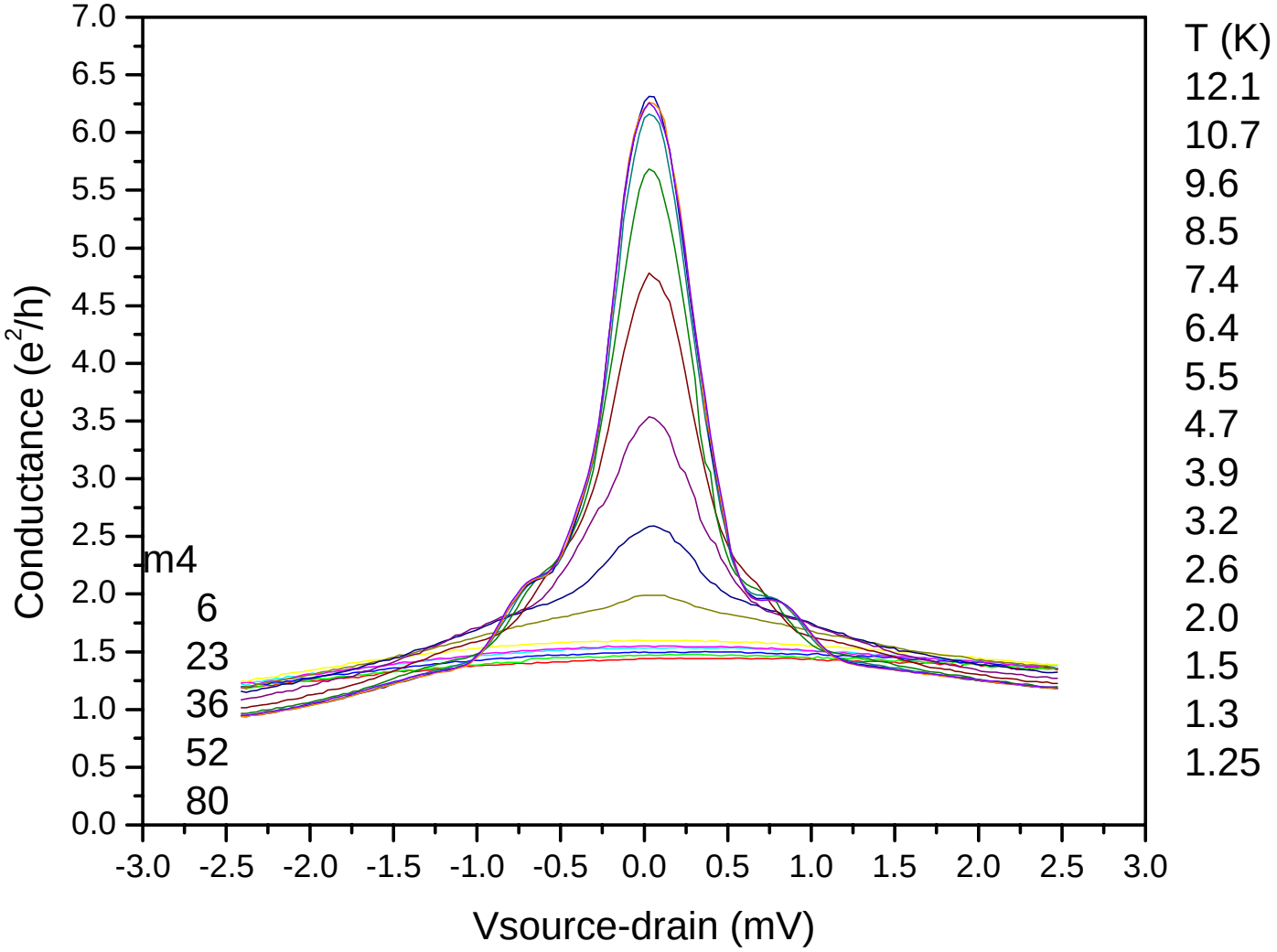
=> Electron-hole symmetry is apparently absent

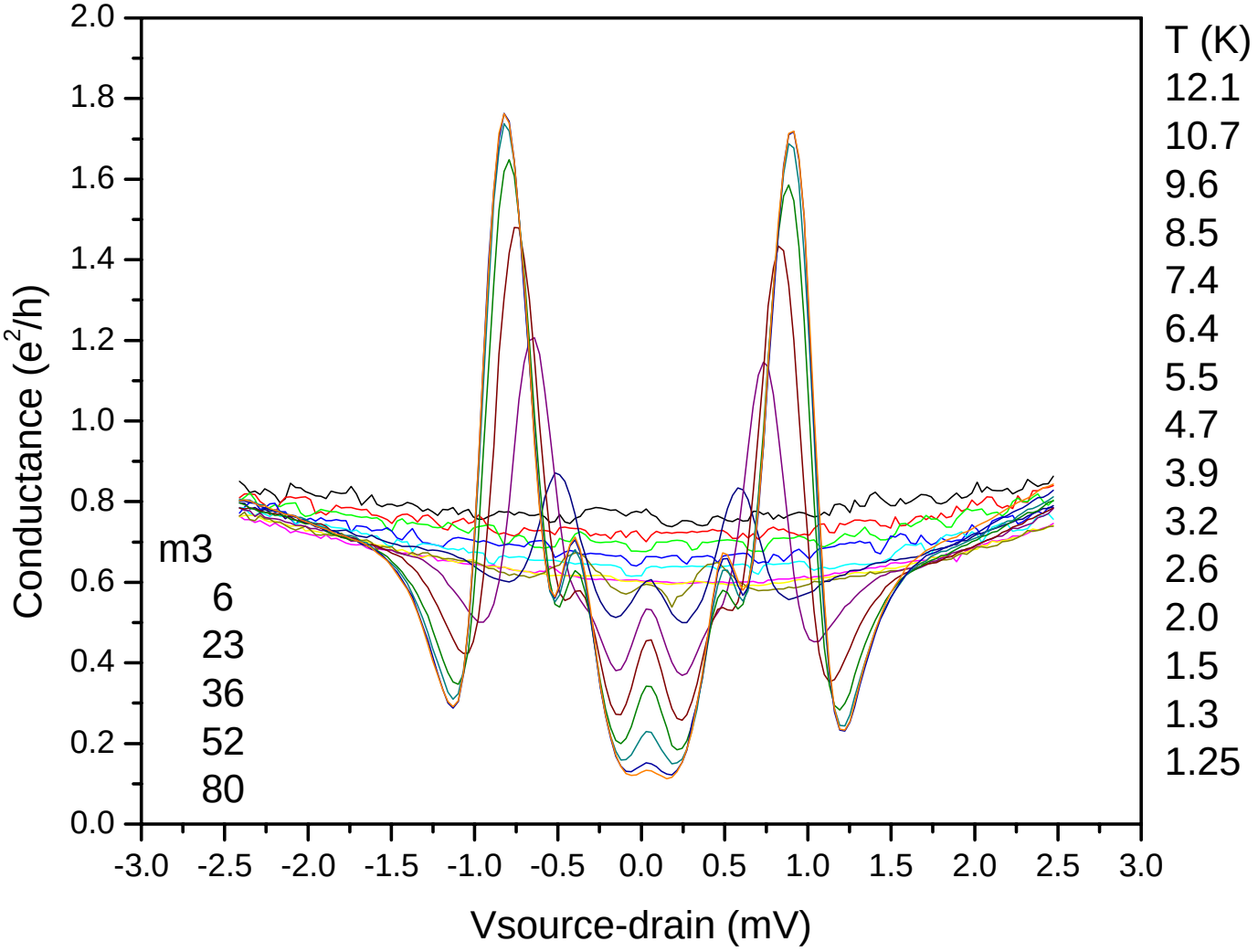
Superconducting contacts

Enhancement of conductance at small bias
in multi-wall or multi-tube geometry
Morpurgo et al. 1999
M. R. Buitelaar et al. 2002, 2003



Δ=1.3 meV


Conductance (e²/h)
Vsource-drain (mV)
T (K)
12.1
10.7
9.6
8.5
7.4
6.4
5.5
4.7
3.9
3.2
2.6
2.0
1.5
1.3
1.25
m4
6
23
36
52
80
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Conductance (e²/h)
Vsource-drain (mV)
T (K)
12.1
10.7
9.6
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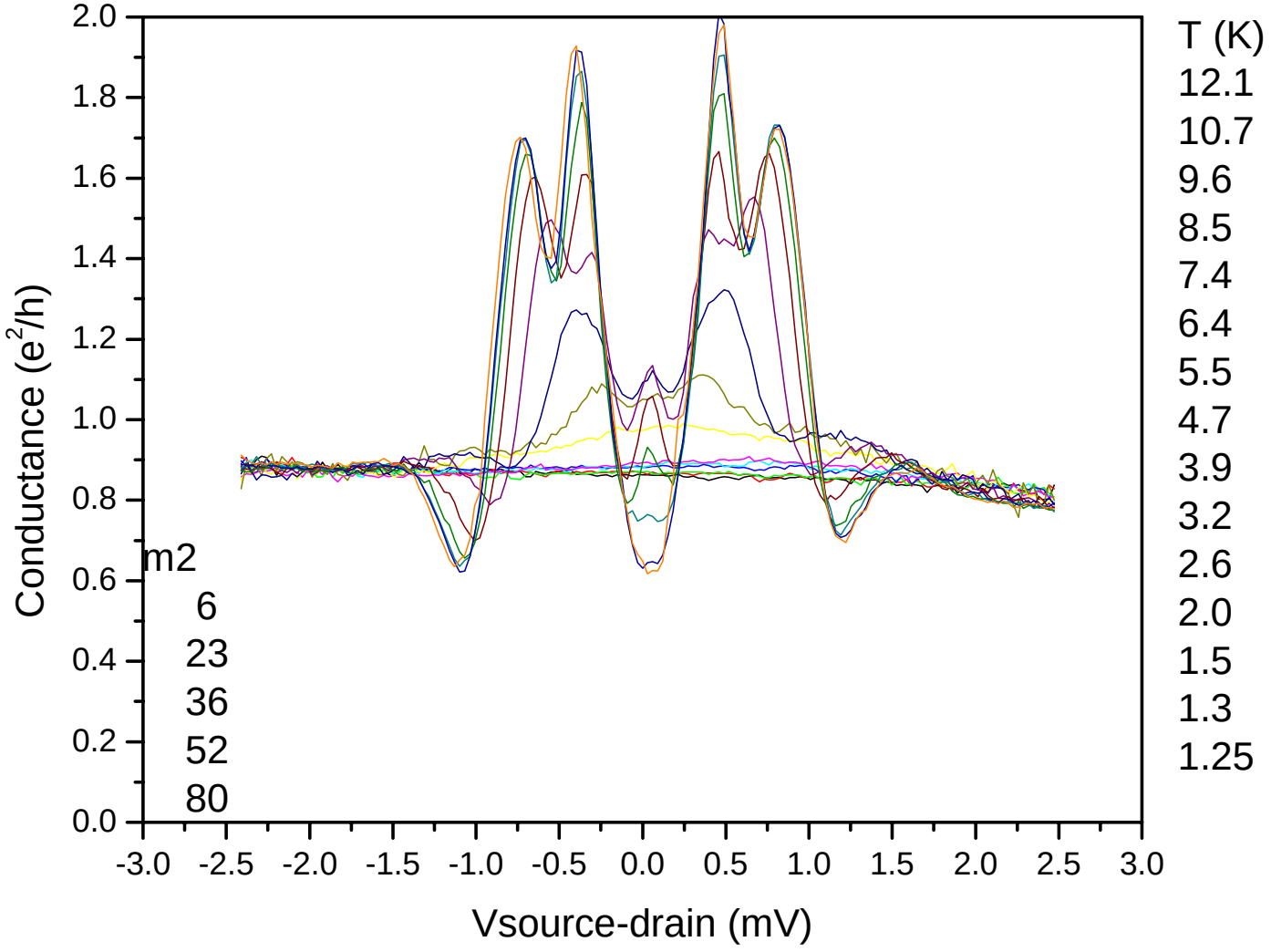
7.4
6.4
5.5
4.7
3.9
3.2
2.6
2.0
1.5
1.3
1.25
m3
6
23
36
52
80
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Conductance (e²/h)
Vsource-drain (mV)
T (K)
12.1
10.7
9.6
8.5
7.4
6.4
5.5
4.7
3.9
3.2
2.6
2.0
1.5
1.3
1.25
m2
6
23
36
52
80
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-3.0
-2.5
-2.0
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-1.0
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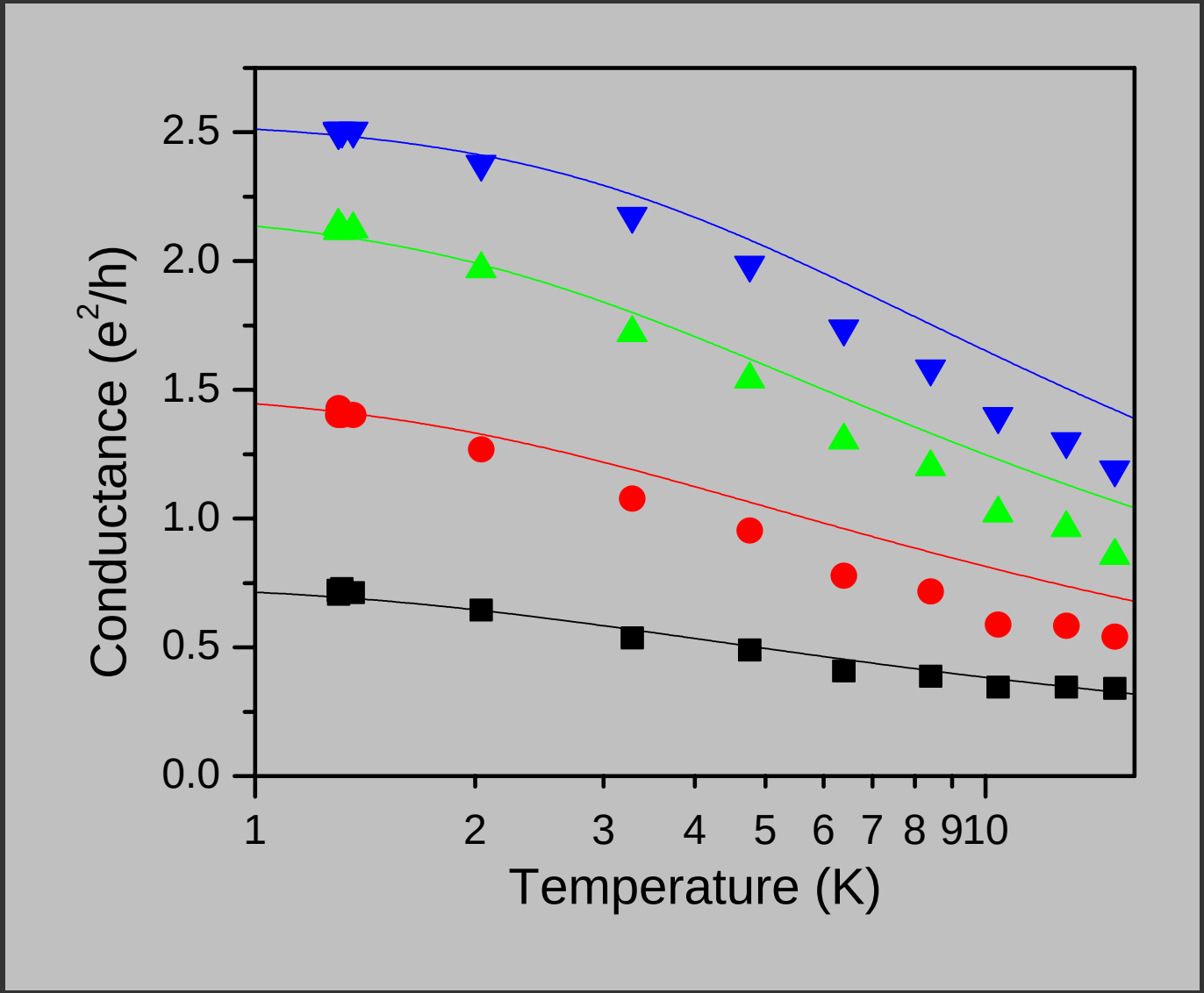
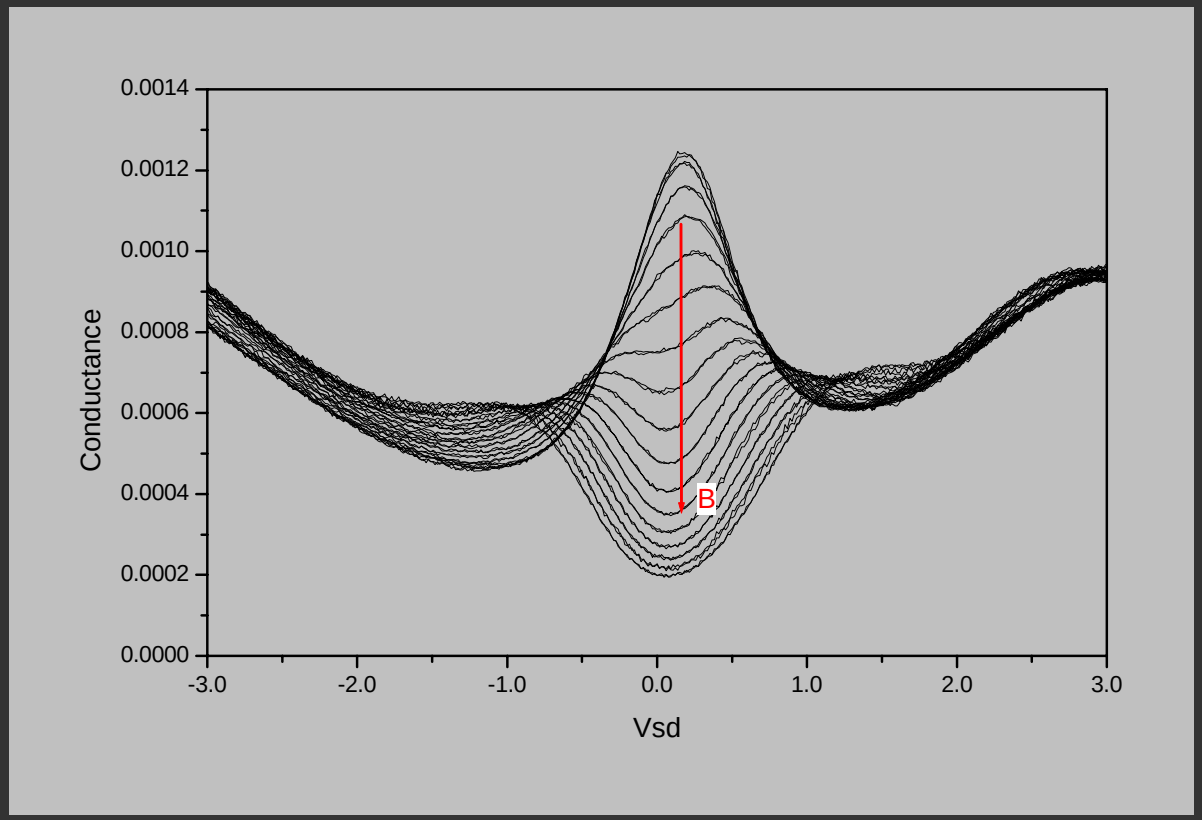
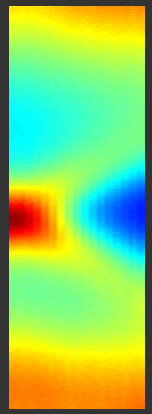
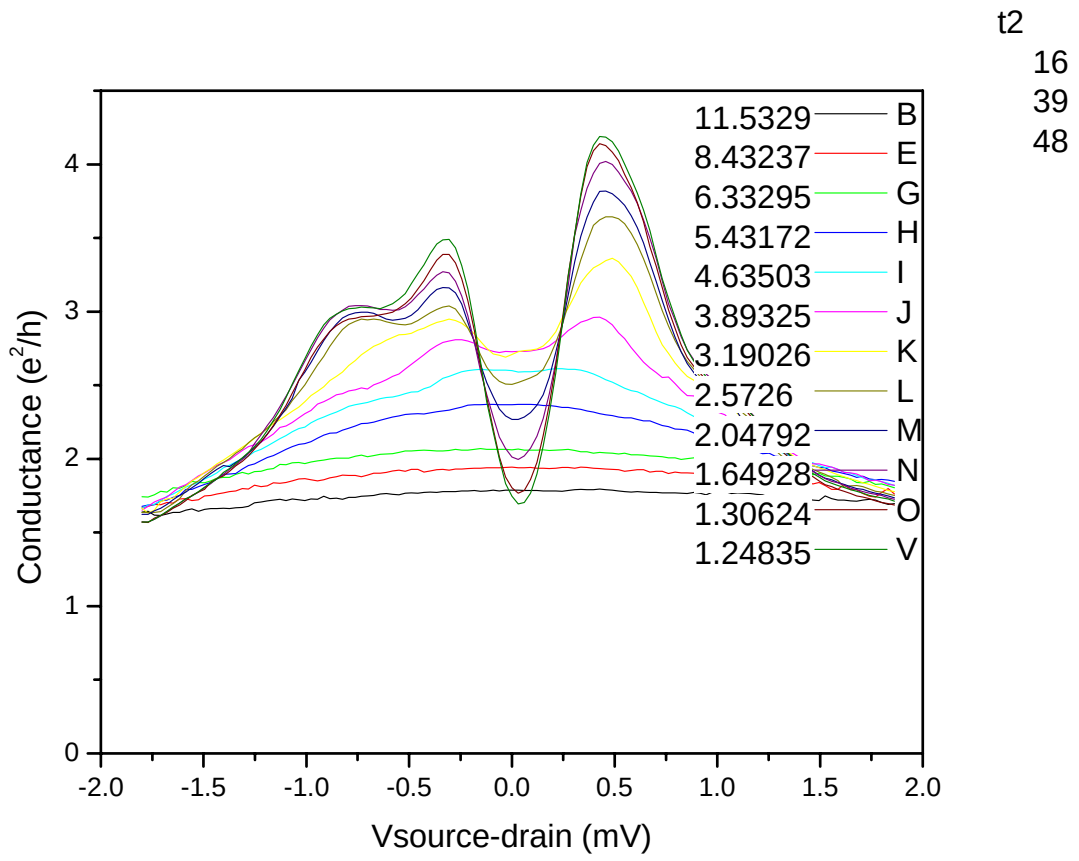
0.5
1.0
1.5
2.0
2.5
3.0

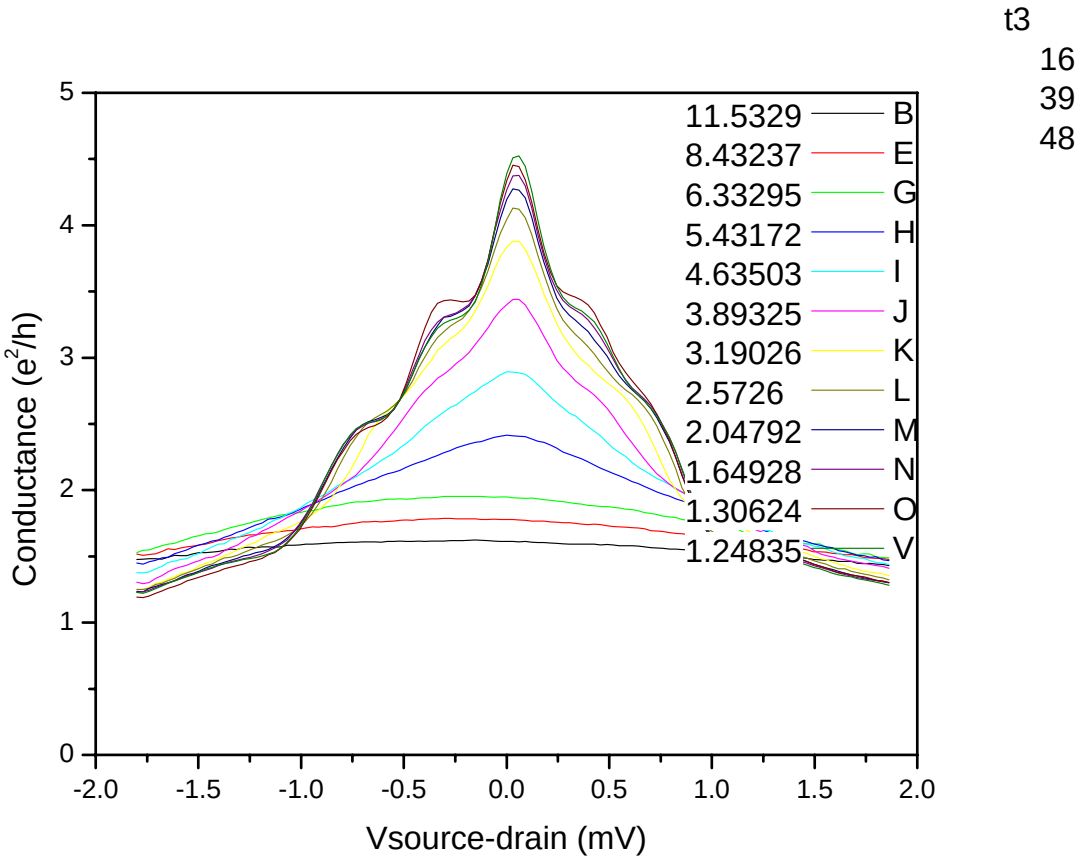

Conductance (e^2/h)
2.5
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
6
7
8
9
10
Temperature (K)

2e Kondo in B⊥


0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
Conductance
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
Vsd
B




t2
16
39
48
11.5329 B
8.43237 E
6.33295 G
5.43172 H
4.63503 I
3.89325 J
3.19026 K
2.5726 L
2.04792 M
1.64928 N
1.30624 O
1.24835 V
Conductance (e2/h)
Vsource-drain (mV)
0
1
2
3
4
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0


t3
16
39
48
11.5329 B
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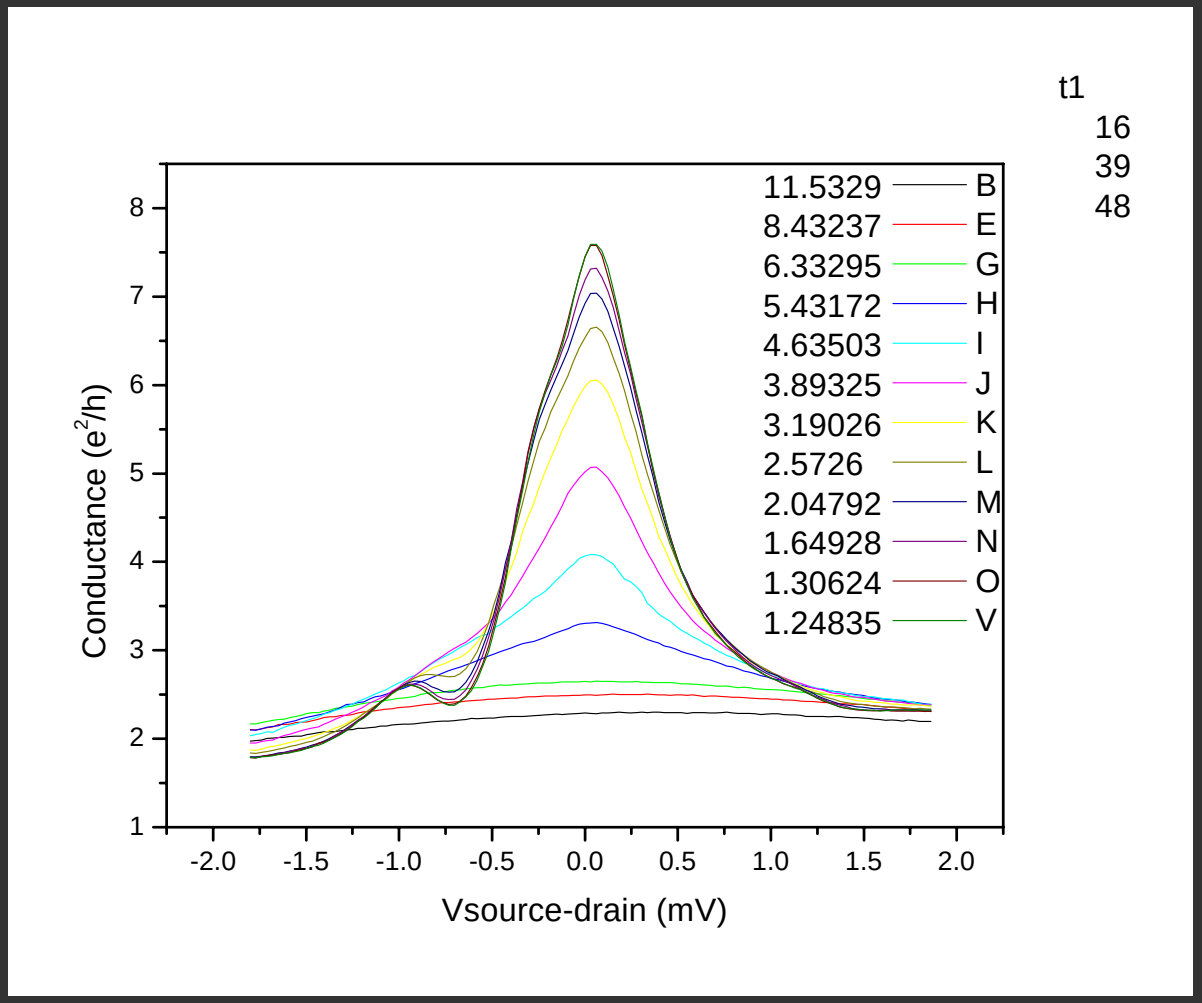
6.33295 G
5.43172 H
4.63503 I
3.89325 J
3.19026 K
2.5726 L
2.04792 M
1.64928 N
1.30624 O
1.24835 V
Conductance (e²/h)
Vsource-drain (mV)
0
1
2
3
4
5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0


t1
16
39
48
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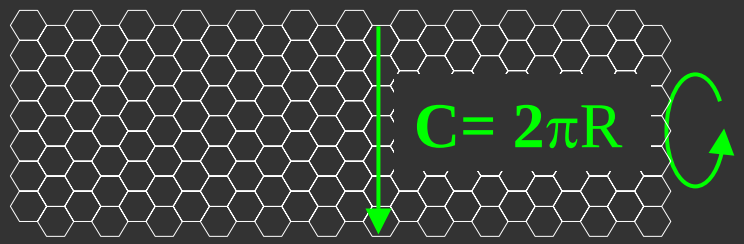
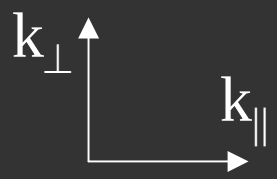
8.43237 E
6.33295 G
5.43172 H
4.63503 I
3.89325 J
3.19026 K
2.5726 L
2.04792 M
1.64928 N
1.30624 O
1.24835 V
Conductance (e2/h)
Vsource-drain (mV)
1
2
3
4
5
6
7
8
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

Nanotubes: quantization of quasi-momentum





$k_{||}$ - arbitrary

$k_\perp = 2\pi N/C = N/R$

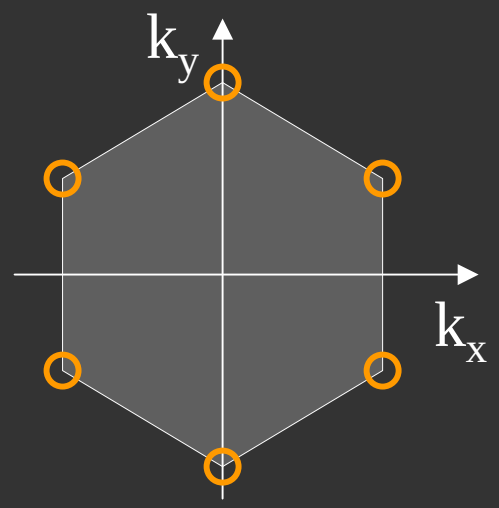
r + C coincides with **r**

$\psi(\mathbf{r} + \mathbf{C}) = \psi(\mathbf{r})$ where $\psi(\mathbf{r}) \sim \exp(i\,\mathbf{k} \cdot \mathbf{r})$

$\Rightarrow \exp(i\,\mathbf{k} \cdot \mathbf{C}) = 1 \Rightarrow \mathbf{k} \cdot \mathbf{C} = 2\pi N$

$k_{||}$ - arbitrary

$k_\perp = 2\pi N/C = N/R$

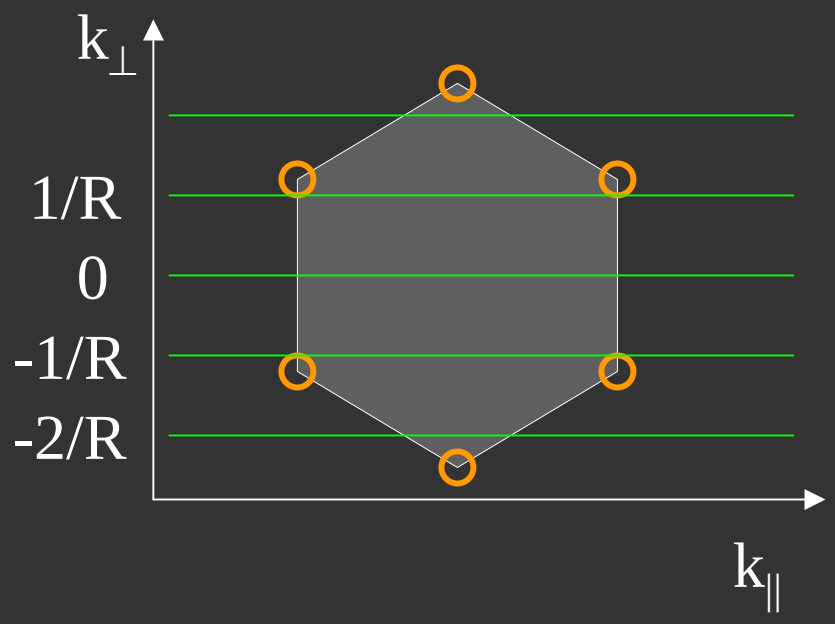


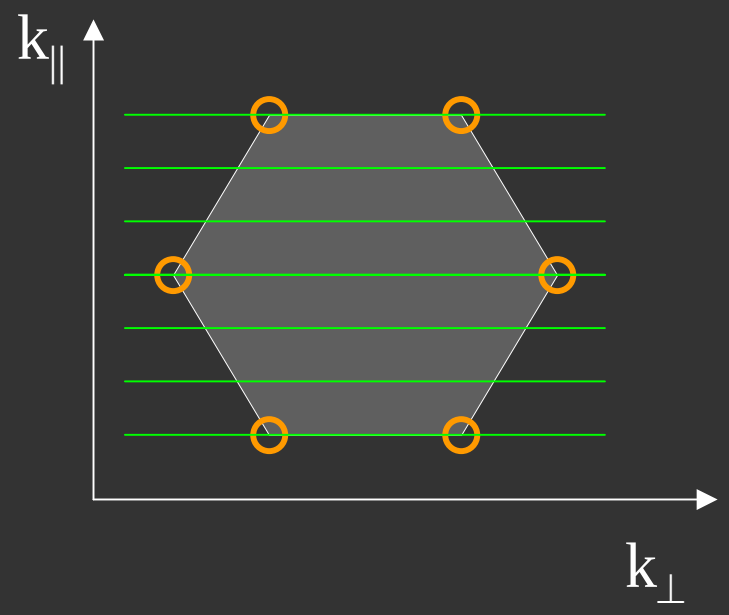
Brillouin zone

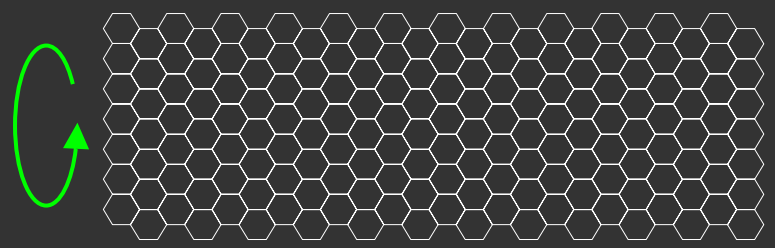
$C = 2\pi R$ – circumference

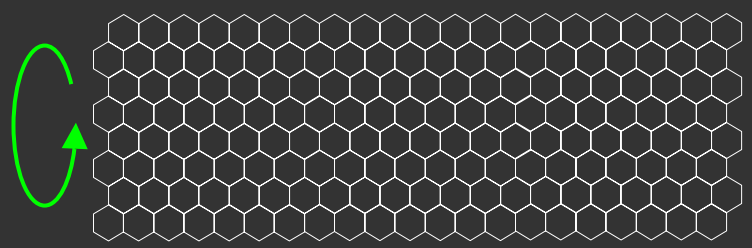
N – arbitrary integer

Nanotubes: quantization of quasi-momentum







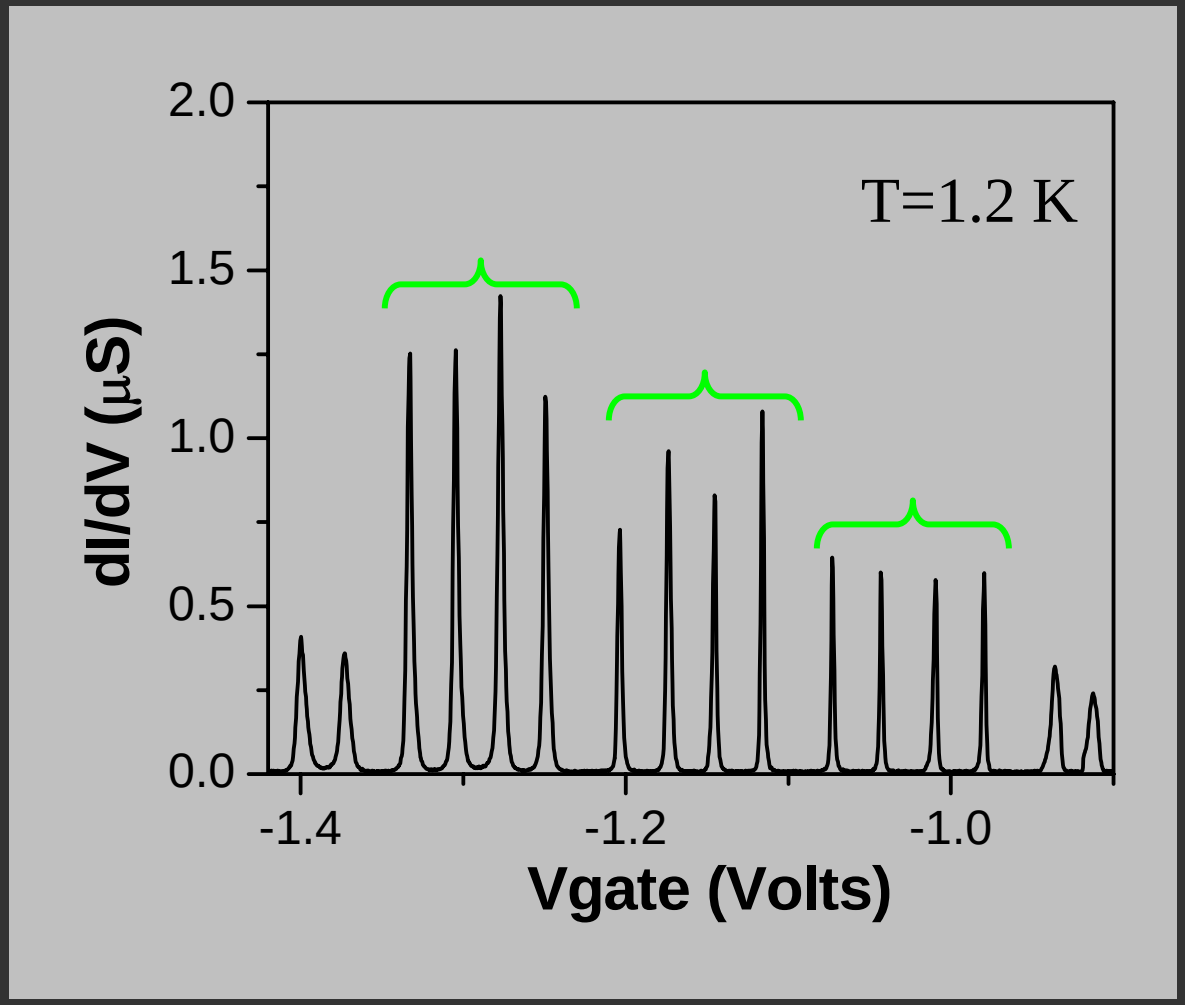


Introduction: Electronic properties

Coulomb blockade: orbital degeneracy

Kondo with orbital degeneracy

Coulomb blockade: groups of 4 peaks

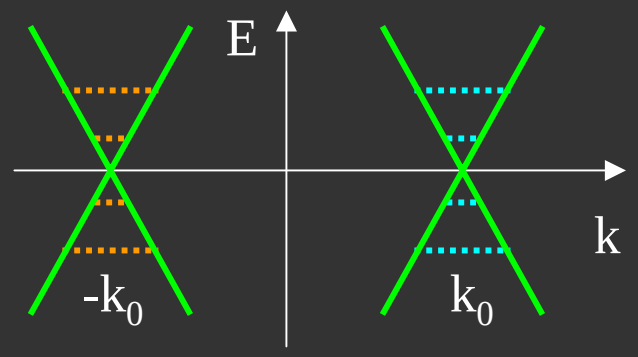


Peaks of similar height are grouped together in Vgate

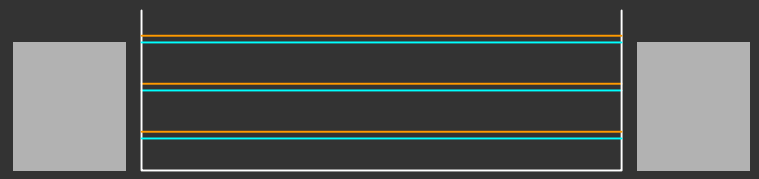
Peak spacing:
small within the group,
larger between the groups

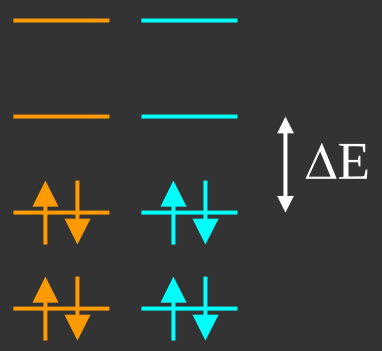
Four-fold degeneracy of the QM energy levels

Groups of 4 peaks: orbital degeneracy



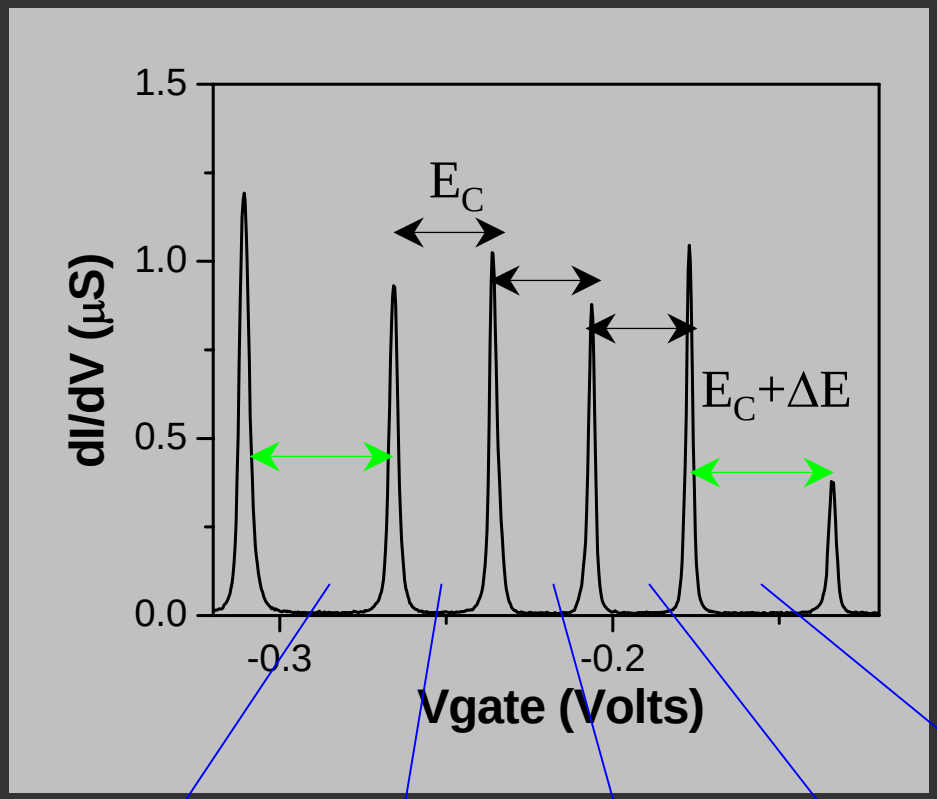
Two subbands
=> Double orbital degeneracy
of the ‘particle in a box’ states





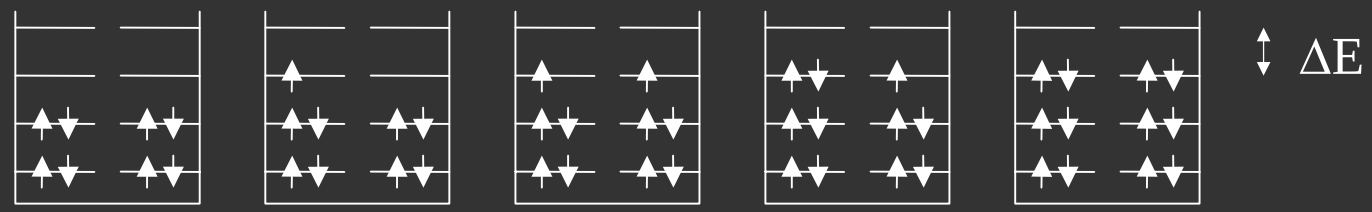
4 degenerate states:
2 degenerate orbitals and
2 spin projections

4-electron shell filling

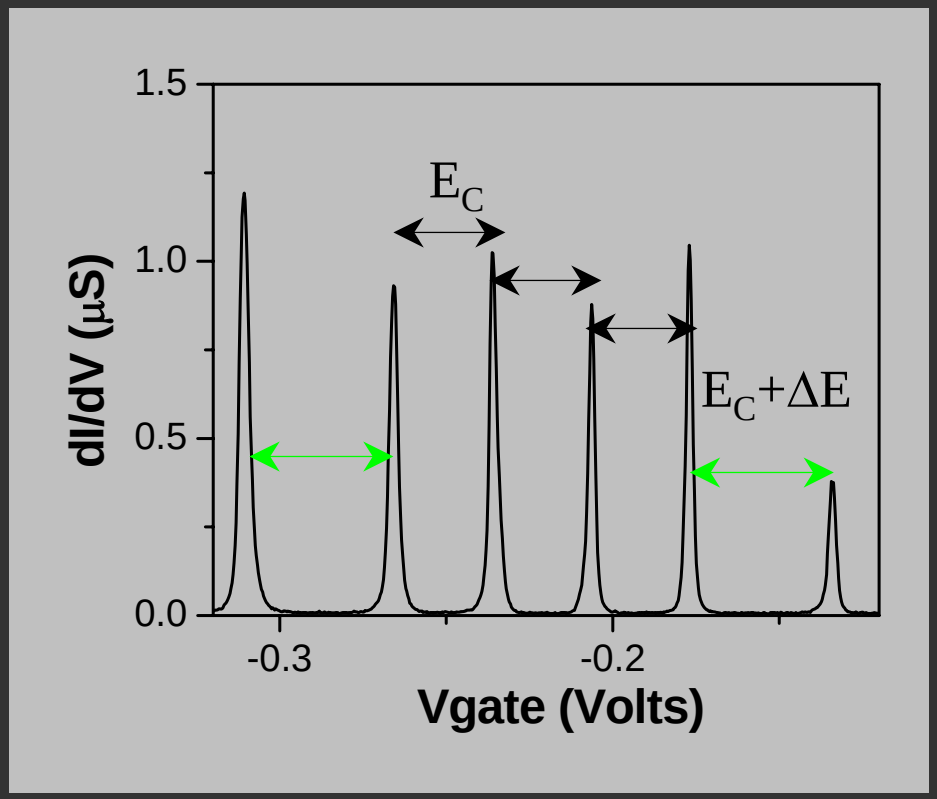


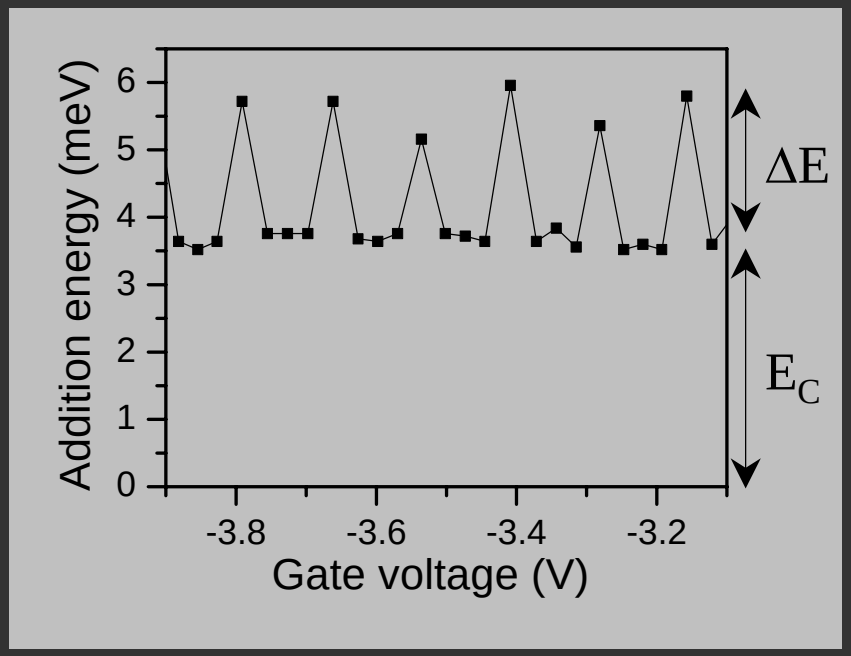
$E_C=e^2/C$ – Charging energy

ΔE – QM level spacing



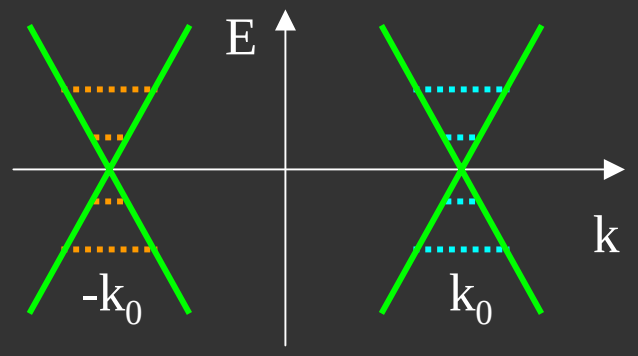
Addition energies

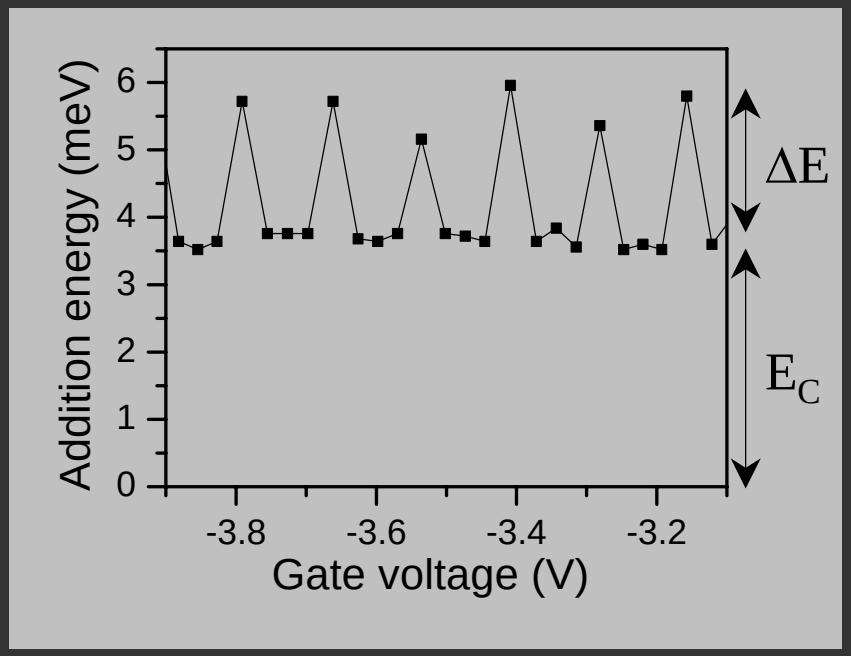




Addition energy – spacing between the conduction peaks converted to the actual energy units

Level mixing?

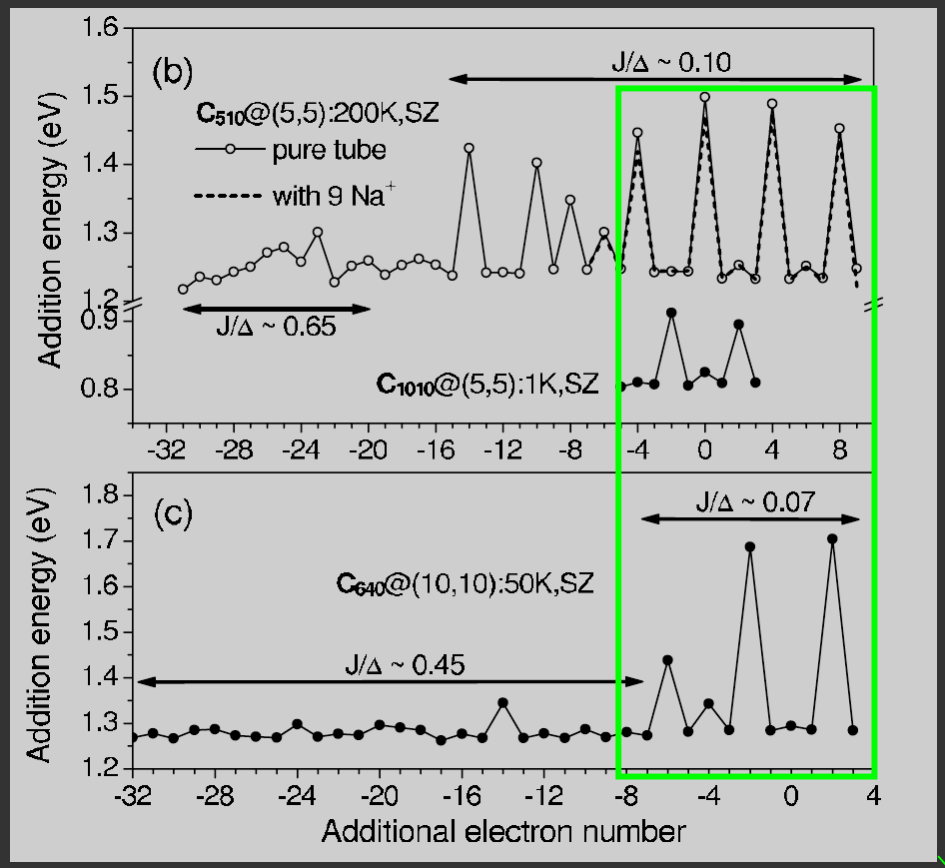


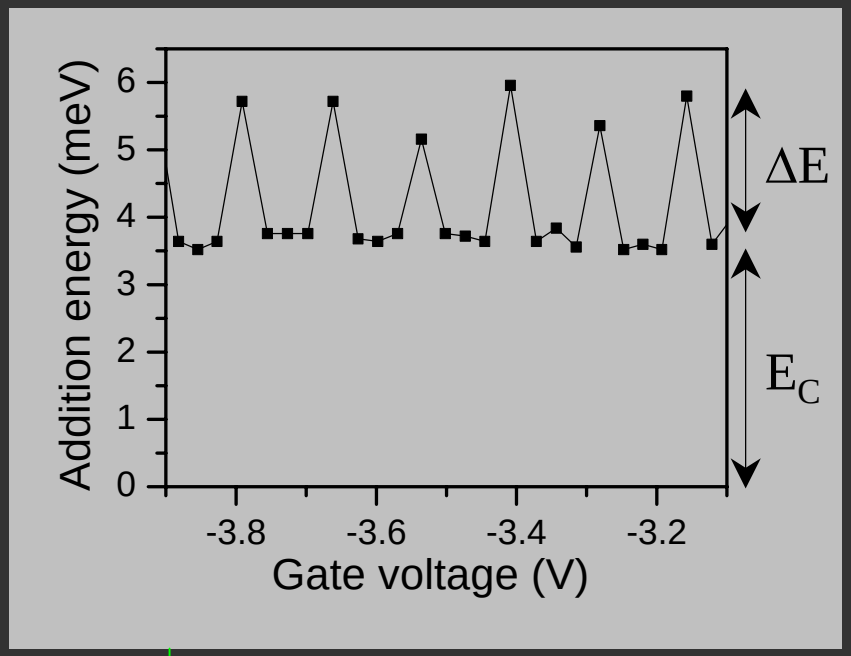


Degeneracy could be destroyed
- by imperfections of the nanotube
- by mixing due to reflections at the contacts

- High quality of the samples
- Contact reflect electrons adiabatically

Addition energies



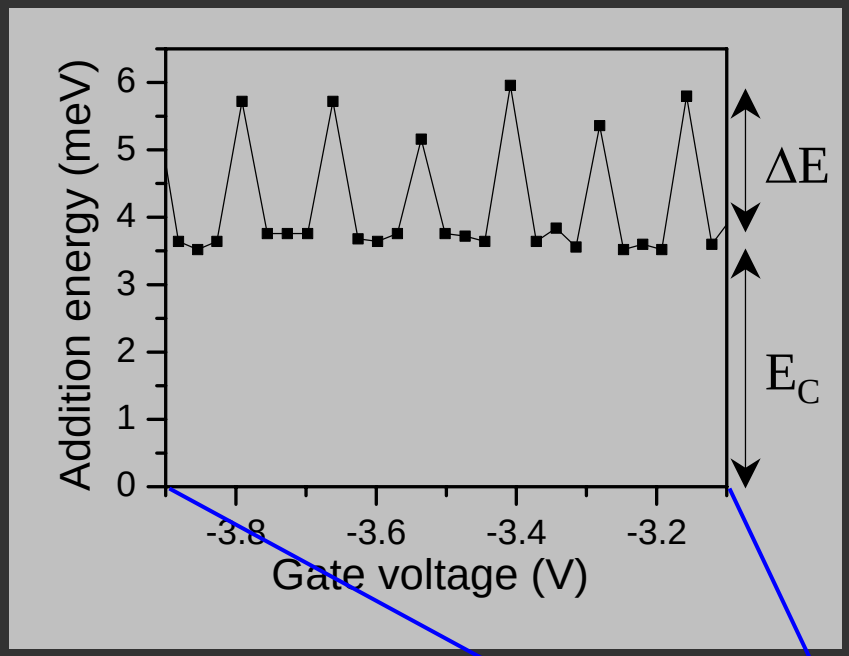


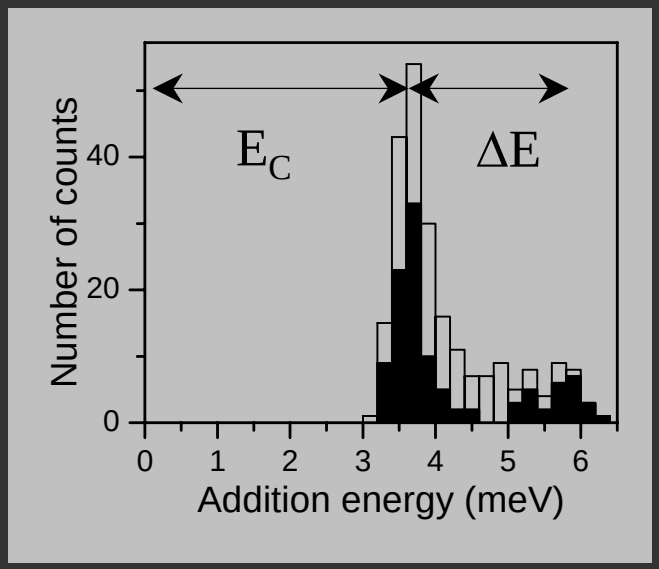
L=750 nm

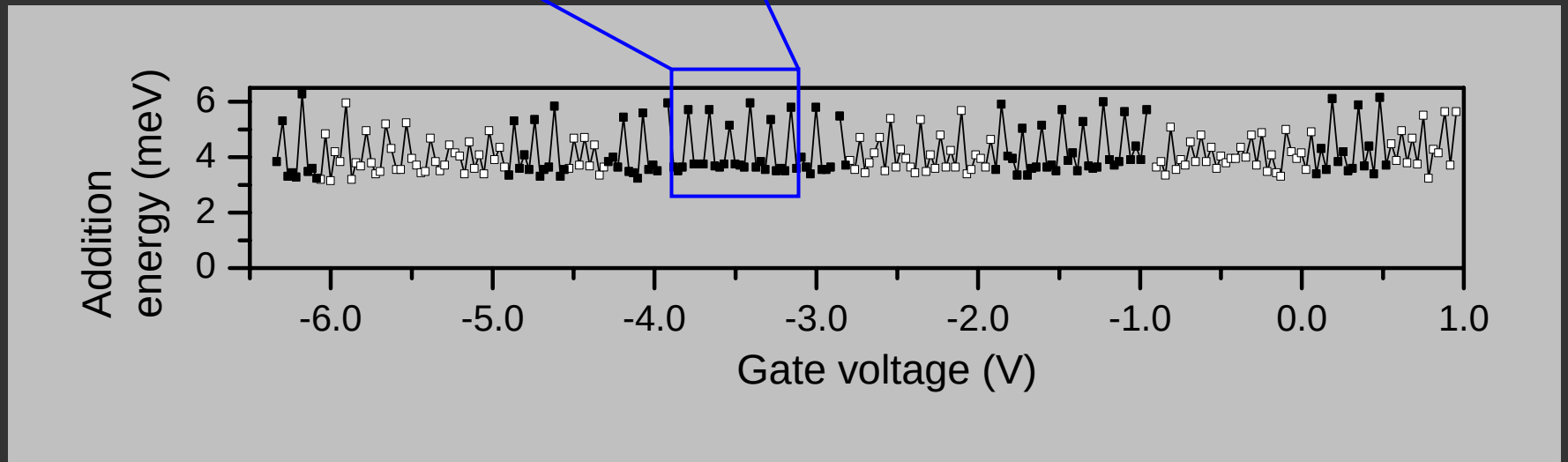
L=5-10 nm

S.-H. Ke, H.U. Baranger, and W. Yang
PRL 91, 116803 (2003)

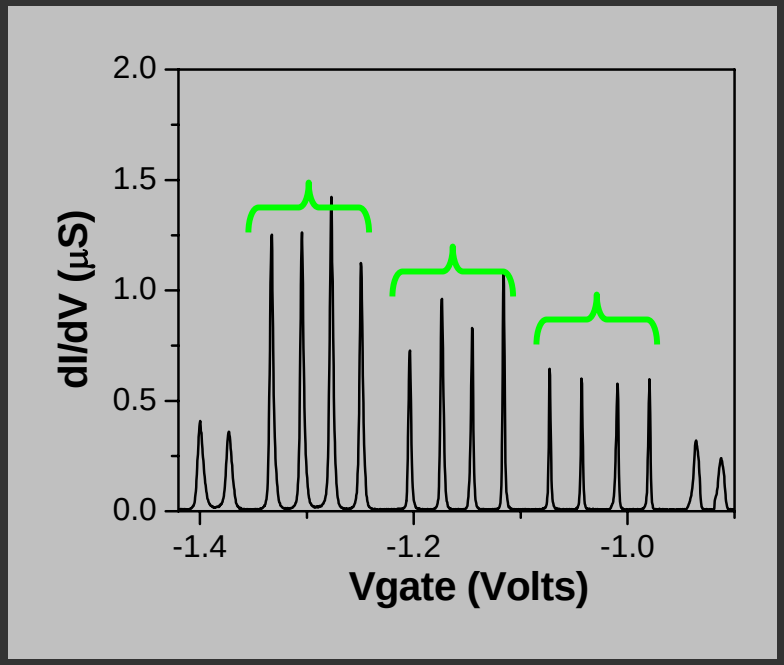
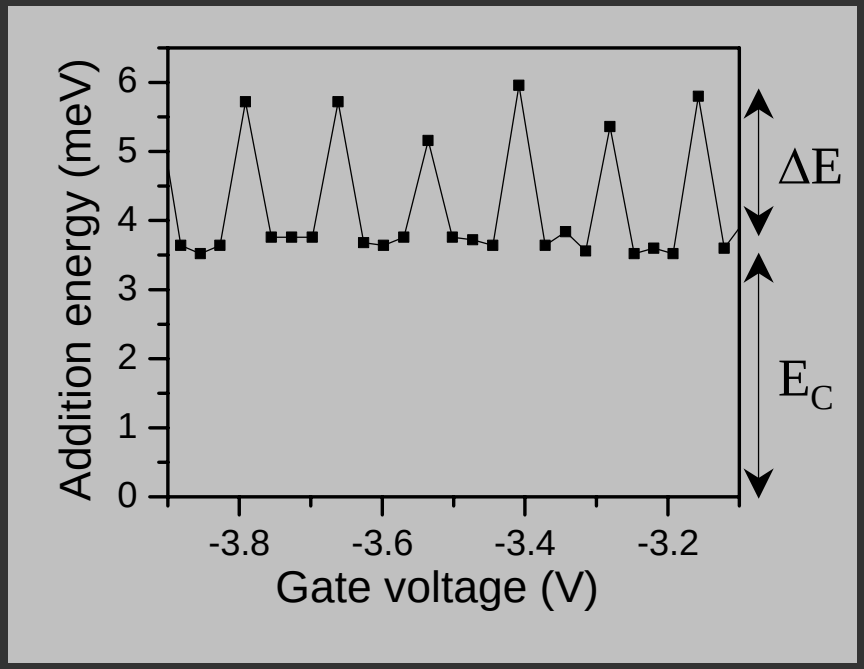
Statistics of addition energies







Conclusions:

- Persistence of the orbital degeneracy

- The degeneracy is insensitive to variations of ΔE