Gate-Dependent Orbital Magnetic Moments in Carbon Nanotubes

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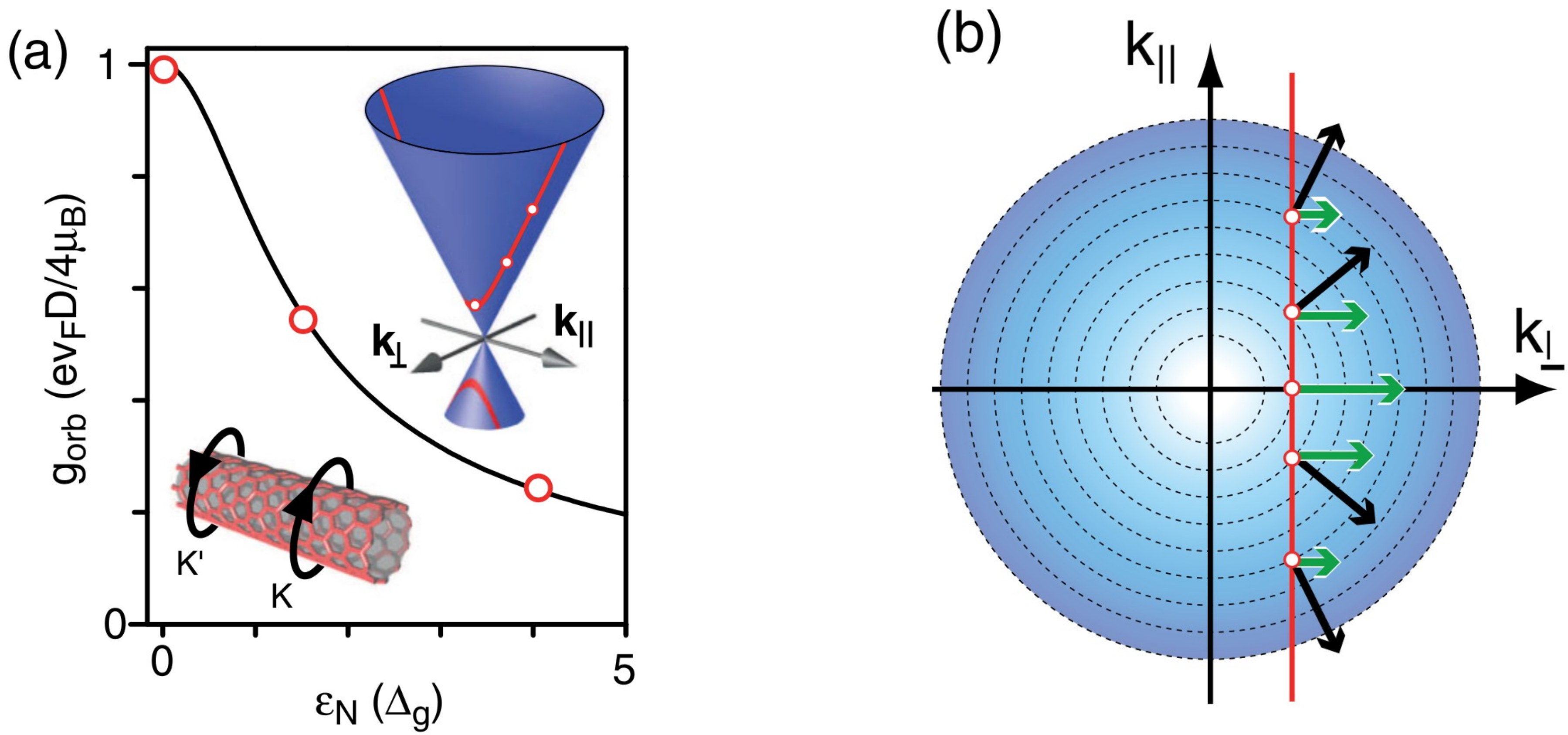
Spectrum and the g-factor

$$E_{(\tau,s)} = \pm\hbar v_F \sqrt{(\tau k_\phi - k_g)^2 + k_\parallel^2} + \frac{1}{2} s g_s \mu_B B$$

$$\Delta_g = \hbar v_F k_g$$



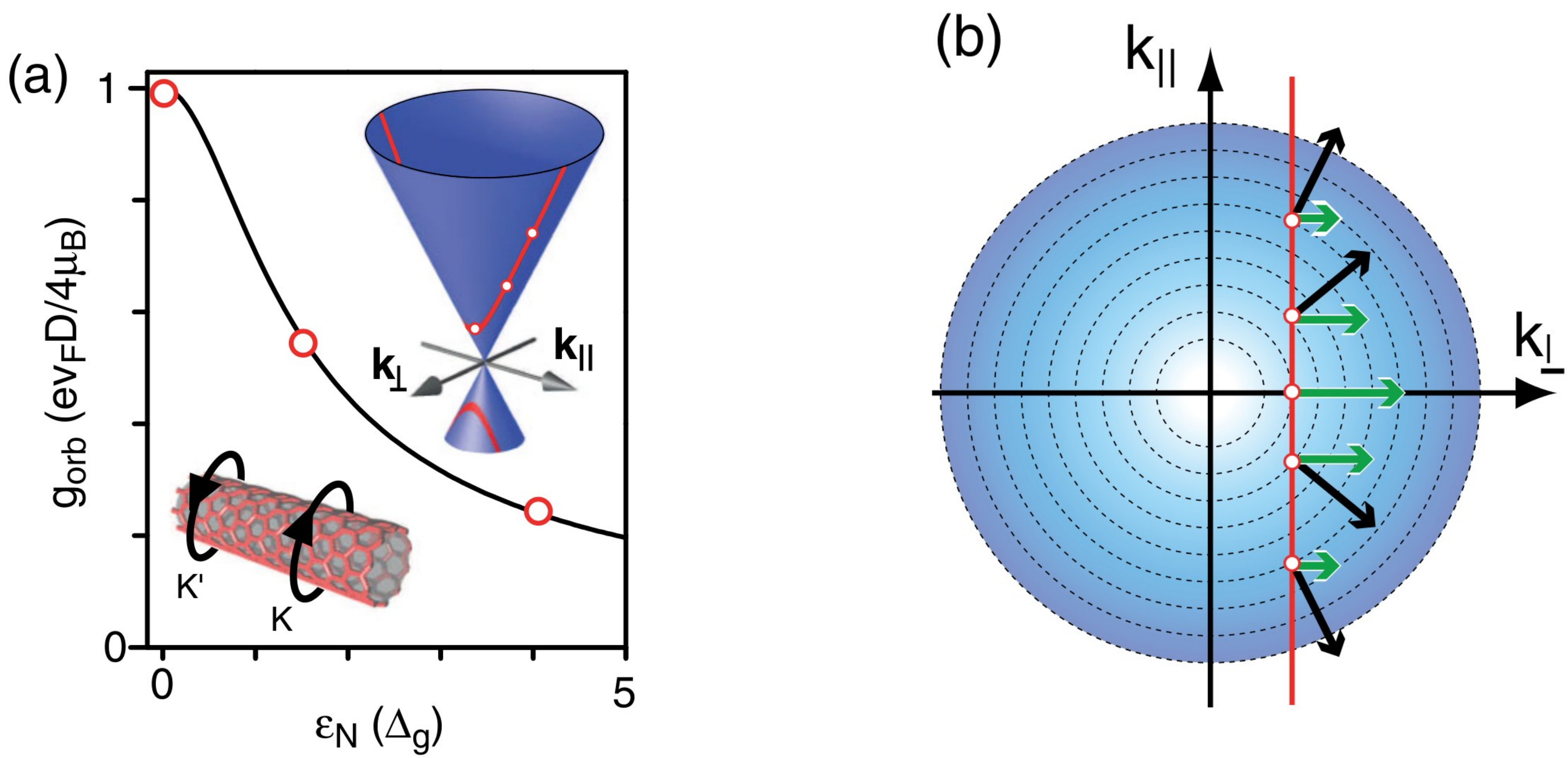
Spectrum and the g-factor

$$E_{(\tau,s)} = \pm\hbar v_F\sqrt{(\tau k_\phi - k_g)^2 + k_\parallel^2} + \frac{1}{2}sg_s\mu_B B \qquad k_\Phi = eB_\parallel D/4\hbar$$

$$E_{(\tau,s)} \approx E_0^\pm \mp \left(\frac{1}{2}g_s s \mp \tau g_{orb}\cos\theta\right)\mu_B B$$

$$\varepsilon_N = \hbar v_F N\pi/L \qquad E_0^\pm = \pm\sqrt{\Delta_g^2 + \varepsilon_N^2}$$

Angular dependence



Spectrum and the g-factor

$$E_{(\tau,s)} \approx E_0^{\pm} \mp \left(\frac{1}{2}g_s s \mp \tau g_{orb} \cos\theta\right)\mu_B B$$

$$E_0^{\pm} = \pm\sqrt{\Delta_g^2 + \varepsilon_N^2}$$

$$\varepsilon_N = \hbar v_F N\pi/L$$

Measurement results are reported as g-factor
(even when they measure the spectrum)

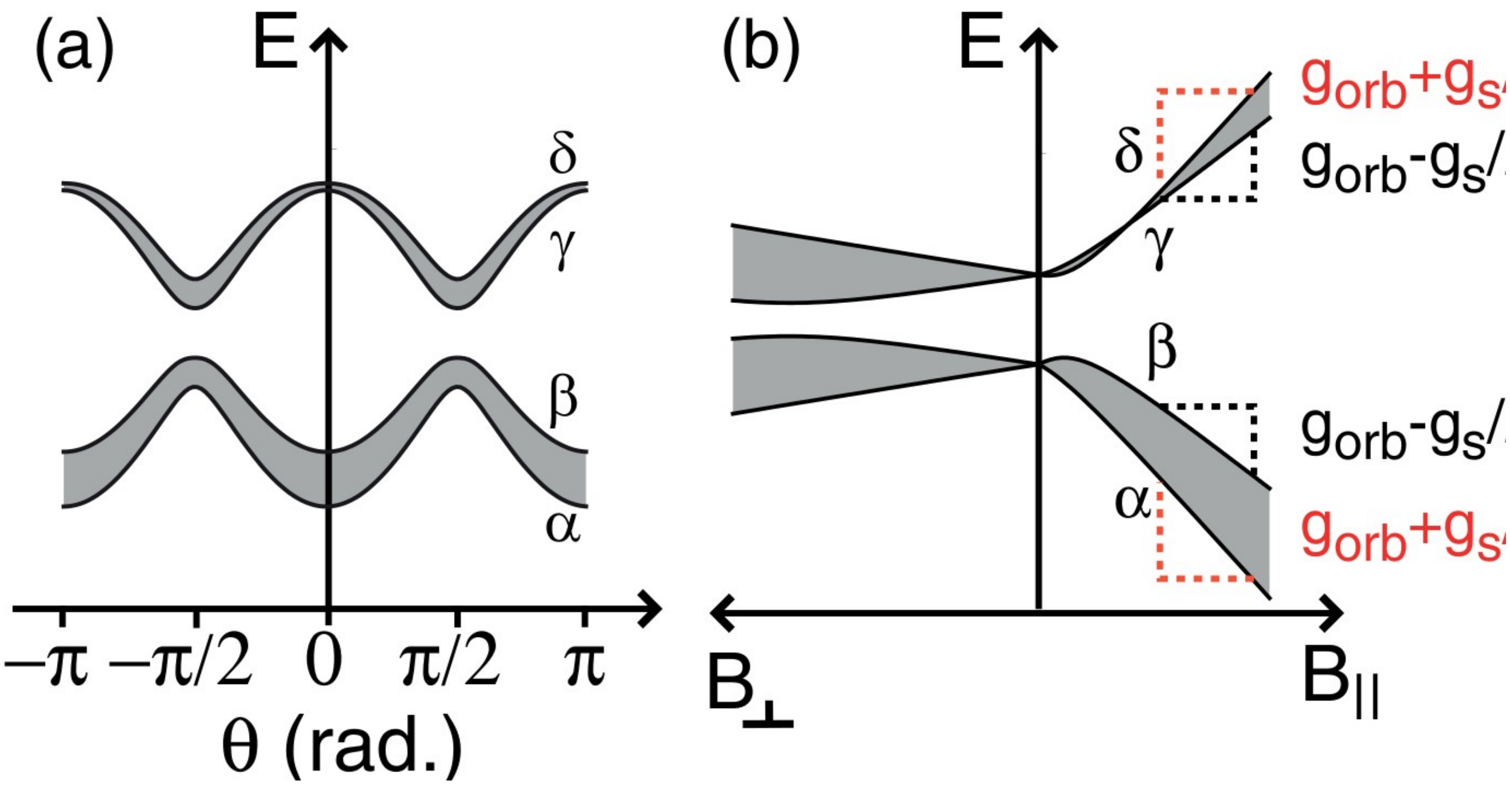
$$g_{orb} = \frac{e v_F D}{4\mu_B\sqrt{1 + \left(\frac{\varepsilon_N}{\Delta_g}\right)^2}}$$

$$g_{orb} \approx e v_F D/4\mu_B \qquad \varepsilon_N \ll \Delta_g$$

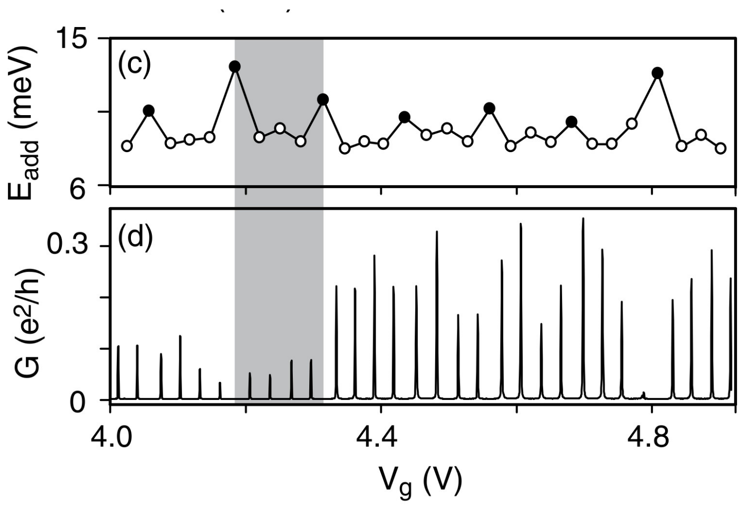
Orbital g-factor decreases as the carriers are added

Spectrum and the g-factor

Spectrum as a function of the magnetic field direction



Measurements



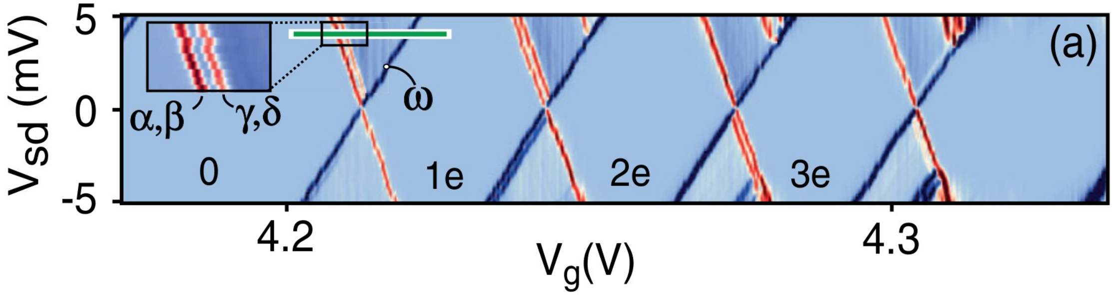
Addition energies

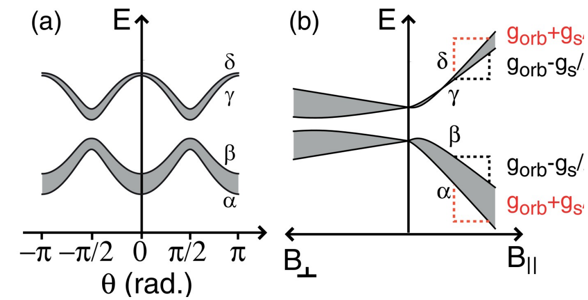
Coulomb blockade peaks

Quasi periodic addition energies show the 4-fold degeneracy

Remaining measurements are done in the shaded region (about hundred electrons)

Measurements





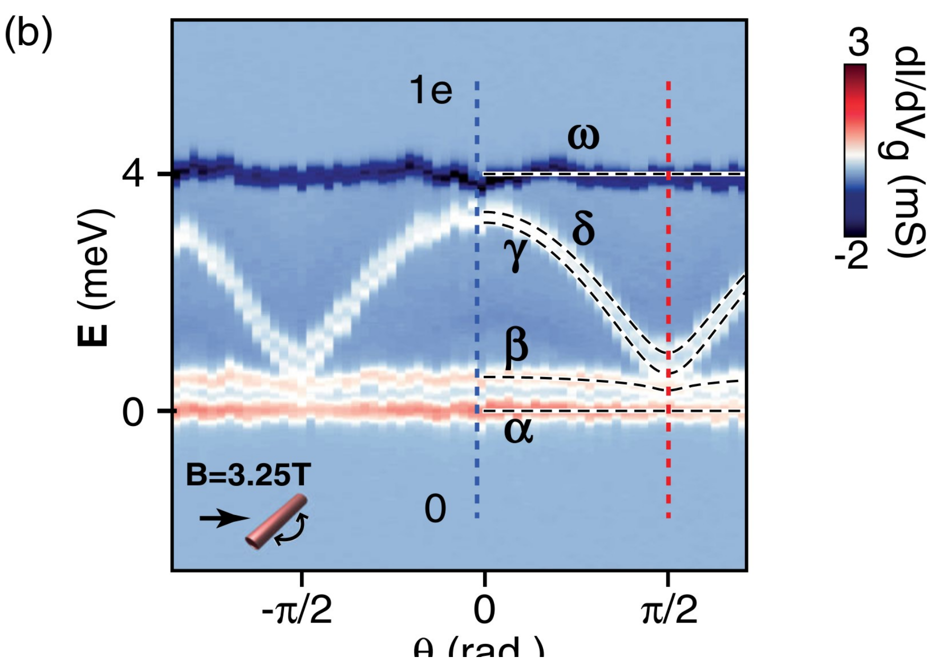
A set of Coulomb diamonds where the conductance is measured.

Electron number has an offset of about 100.

In the inset, the spectrum can be seen quite clearly.

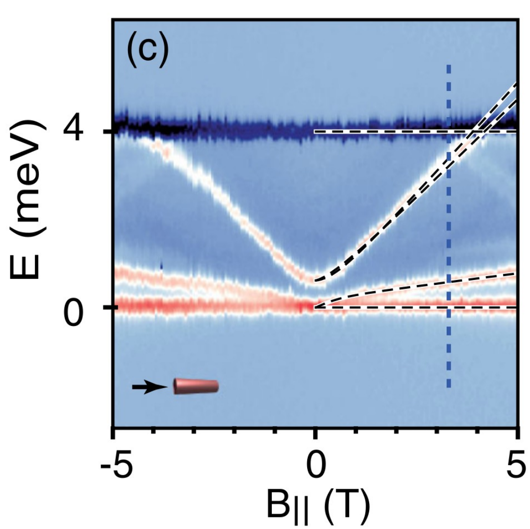
This is simple sequential tunneling spectroscopy

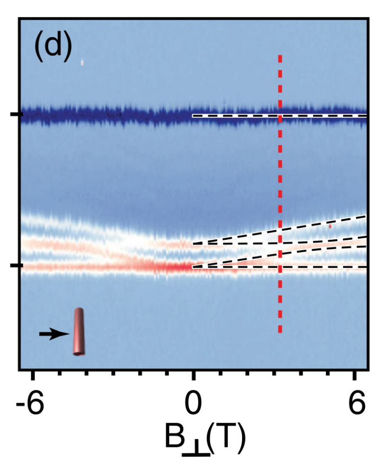
Measurements



Direction of the magnetic field determines the spectrum

Data agrees very well with a simple single-particle model

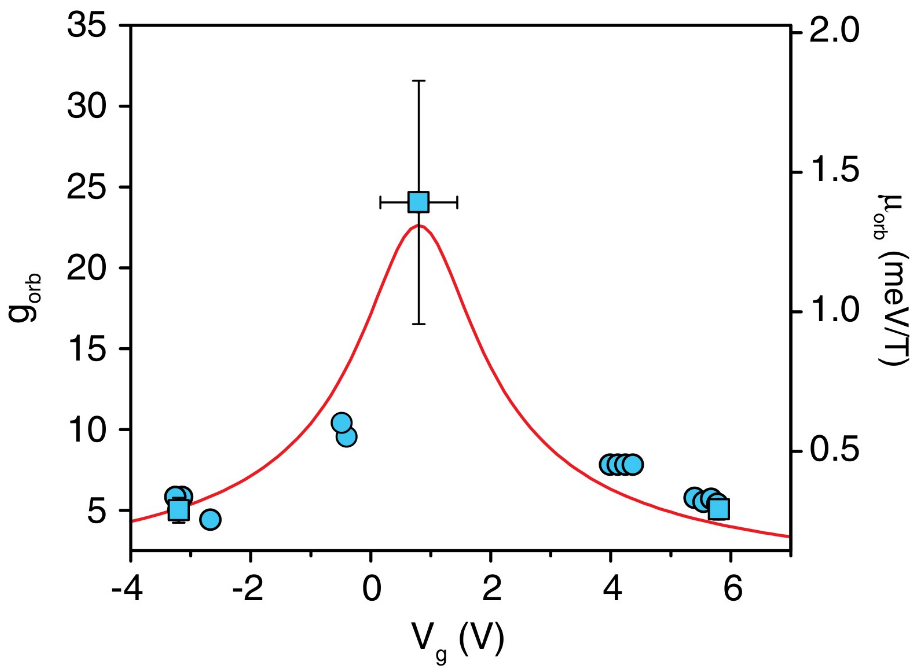




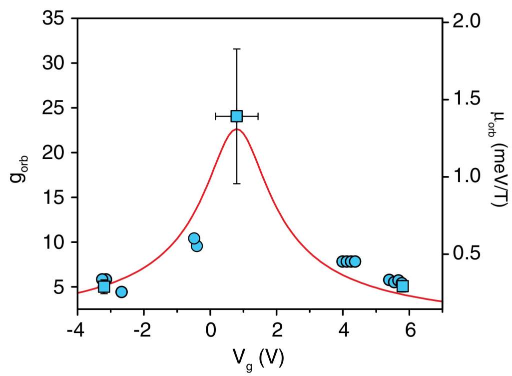
Comparison between the spectrum in parallel and the spectrum in perpendicular field demonstrate the orbital effect and the role of the flux through the tube.

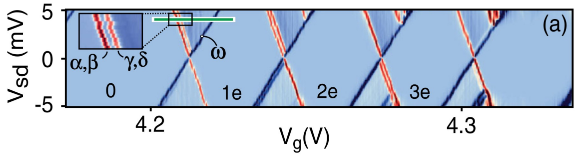
Problem – estimated diameter of the tube is 2-3 times larger than the real one.

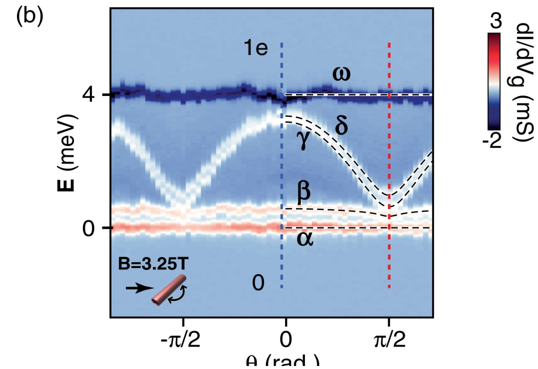
Reporting the g-factor

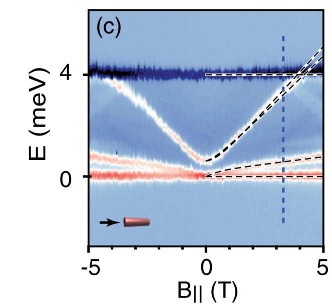


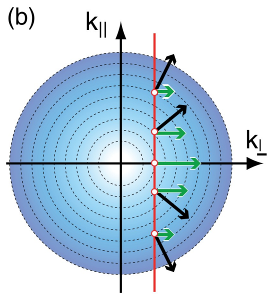
Reporting only the g-factor would not give so much information. Sequential tunneling is a spectroscopy, it measures splittings at the anticrossings, and it is much more than a simple measurement of the g-factor.

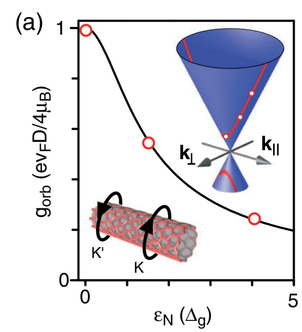

35
30
25
20
15
10
5
g_{orb}
2.0
1.5
1.0
0.5
μ_{orb} (meV/T)
-4
-2
0
2
4
6
V_g (V)

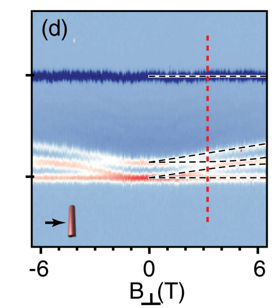

(a)
V_{sd} (mV)
5
0
-5
α,β
γ,δ
ω
0
1e
2e
3e
4.2
4.3
V_g(V)

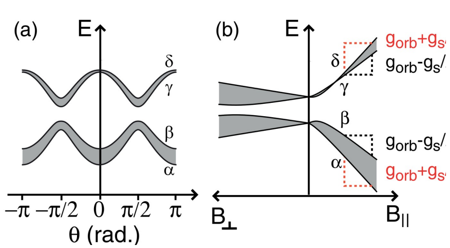

(b)
1e
ω
δ
γ
β
α
0
B=3.25T
E (meV)
4
0
-π/2
0
π/2
θ (rad.)
3
-2
dI/dV_g (mS)

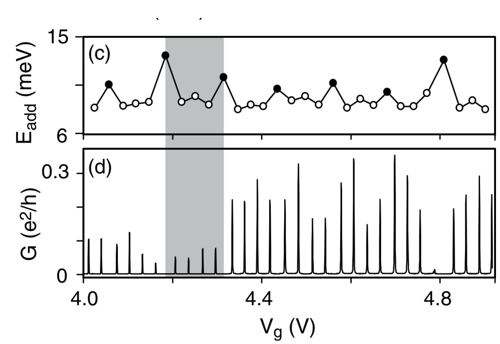

(c)
E (meV)
4
0
-5
0
5
$B_{||}$ (T)

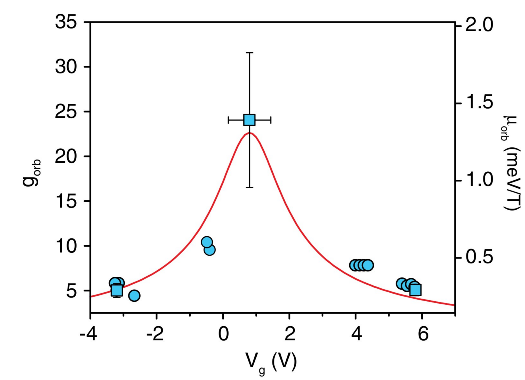

(b)
$k_{||}$
$k_{\perp}$

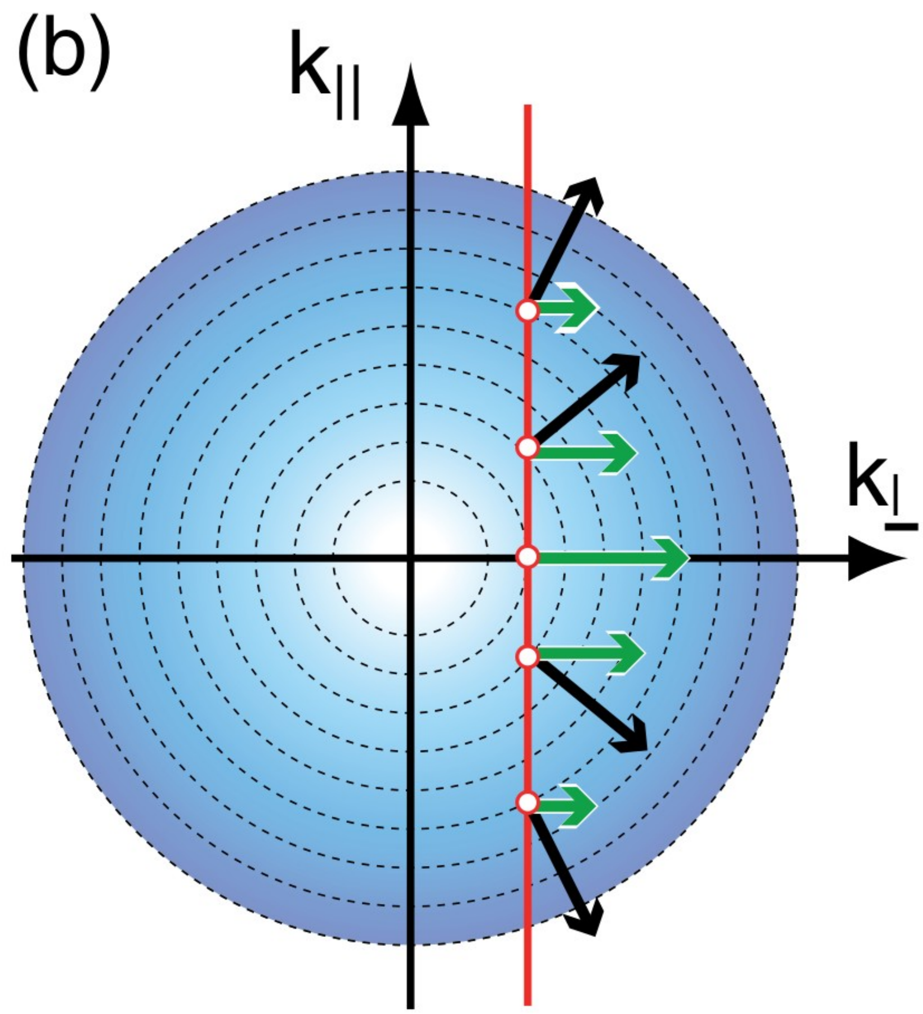

(a)
g_{orb} ($ev_FD/4\mu_B$)
1
0
$k_{\perp}$
$k_{||}$
K'
K
0
5
ε_N (Δ_g)


(d)
-6
0
6
$B_{\perp}$(T)


(a)
E
δ
γ
β
α
−π
−π/2
0
π/2
π
θ (rad.)
(b)
E
δ
γ
β
α
$g_{orb}+g_s$
$g_{orb}-g_s$
$B_{\perp}$
$B_{||}$


(c)
E_{add} (meV)
15
6
(d)
G (e^2/h)
0.3
0
4.0
4.4
4.8
V_g (V)


g_{orb}
35
30
25
20
15
10
5
μ_{orb} (meV/T)
2.0
1.5
1.0
0.5
-4
-2
0
2
4
6
V_g (V)



(b)
k||
k⊥