Magnetic field control of the Franck-Condon coupling of few-electron quantum states[1]

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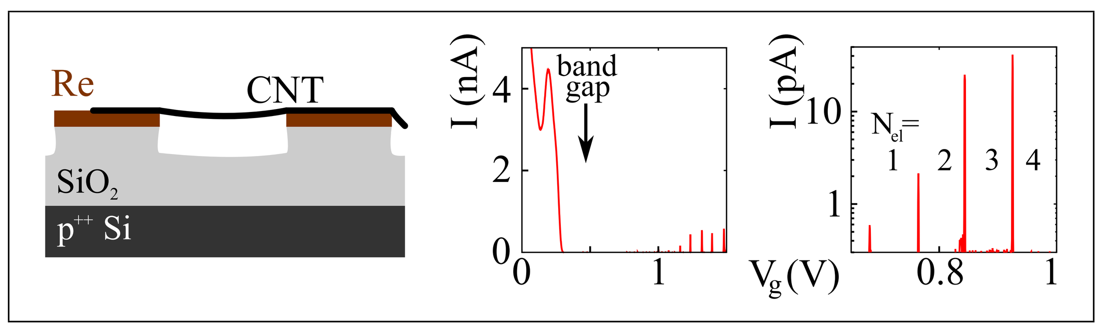
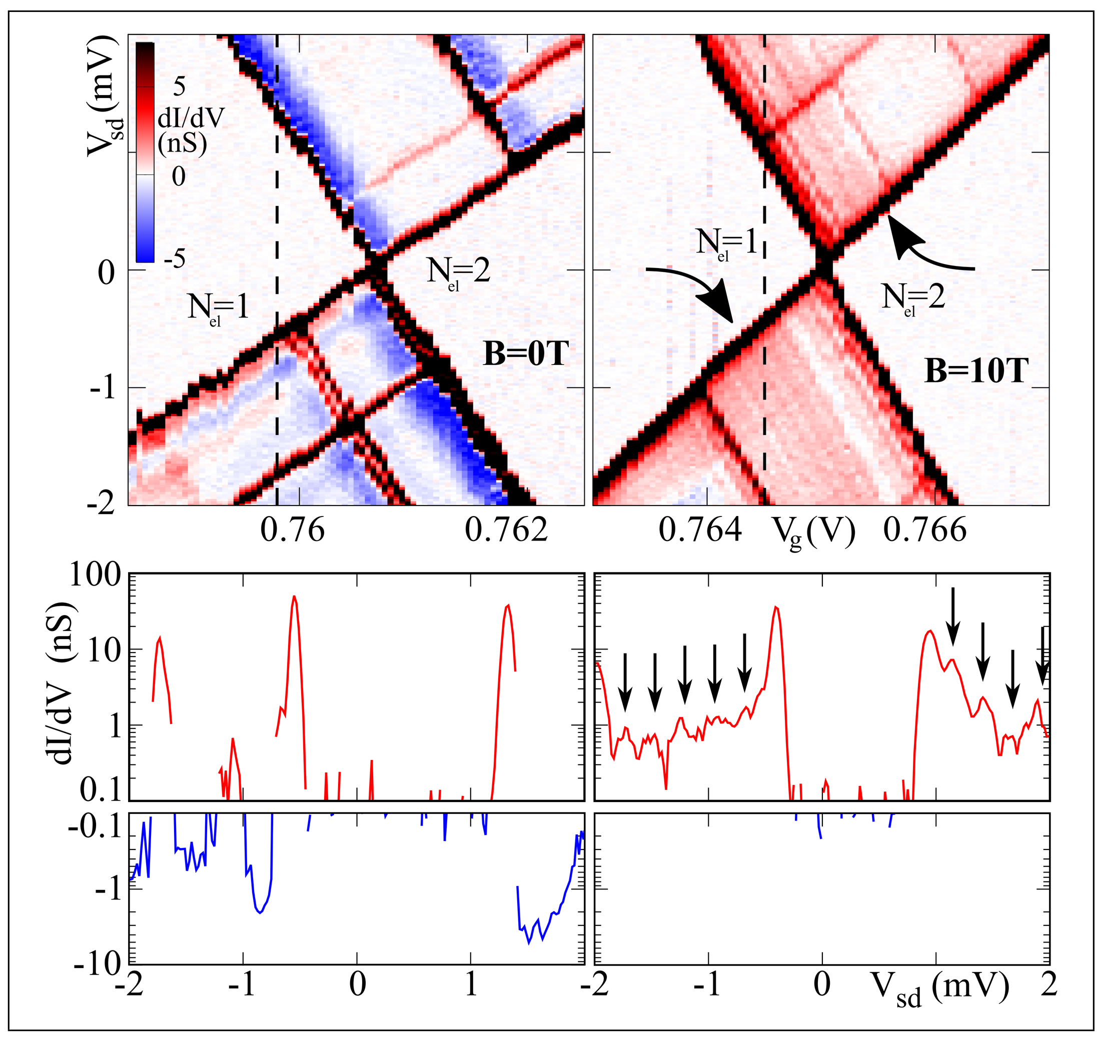
Clean, regular CNT quantum dot



- Nanotube grown in situ across contacts
- No lithography or wet chemistry afterwards
- Highly regular small bandgap behaviour [2, 3, 4]

$1 \le N \le 2$ electrons at finite field

- Detailed low-energy spectrum measurement



- Multiple equidistant lines develop at finite $B_\parallel$

Franck-Condon sidebands

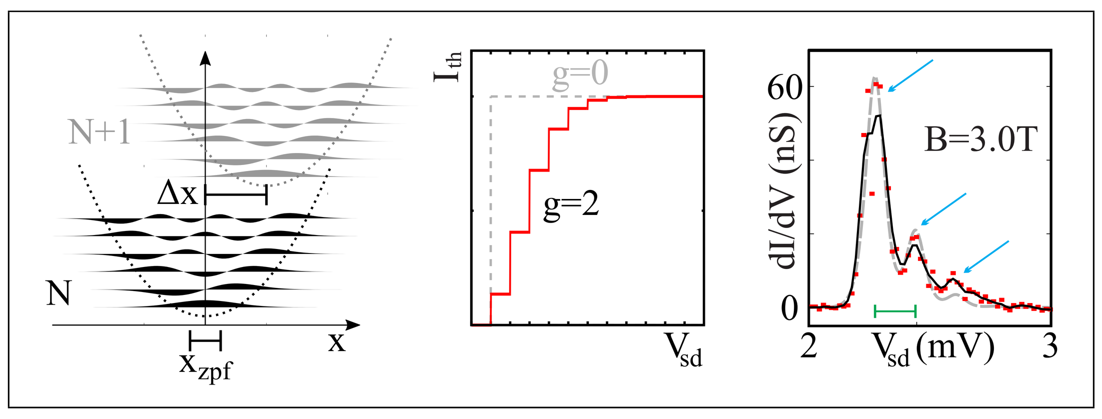
- Equilibrium location of a vibration mode depends on number of trapped electrons N
- Single electron tunneling: $N \leftrightarrow N+1$ transition
- Tunnel rates are modified by overlap of displaced harmonic oscillators [5, 6, 7]

$$\Gamma = \Gamma_{\mathrm{el}} |< \Psi(x)|\Psi(x+\Delta x) >|^2$$

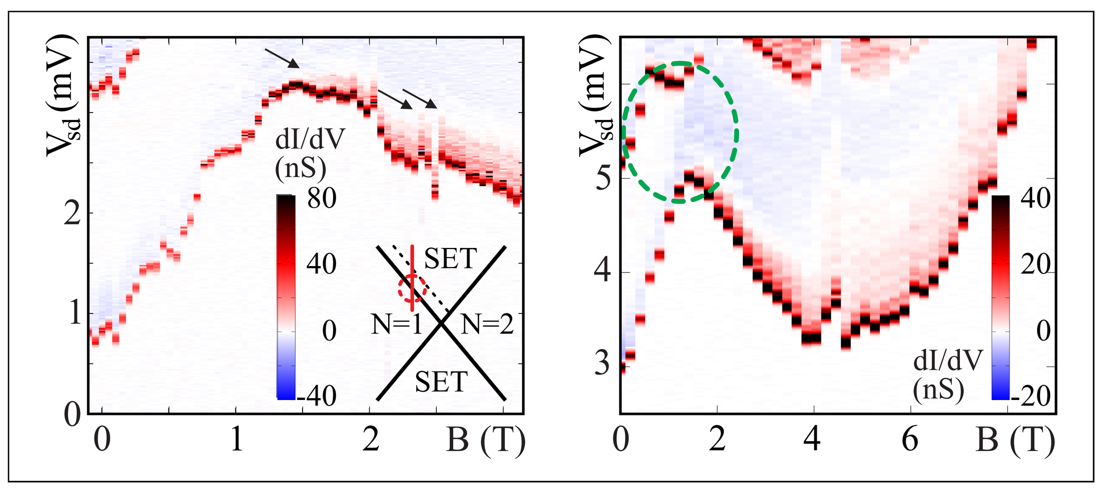
- Electron-vibron coupling parameter:

$$g = \frac{(\Delta x)^2}{2x_{\mathrm{zpf}}^2}, \qquad x_{\mathrm{zpf}} = \sqrt{\frac{\hbar}{m\omega_{\mathrm{vib}}}}$$

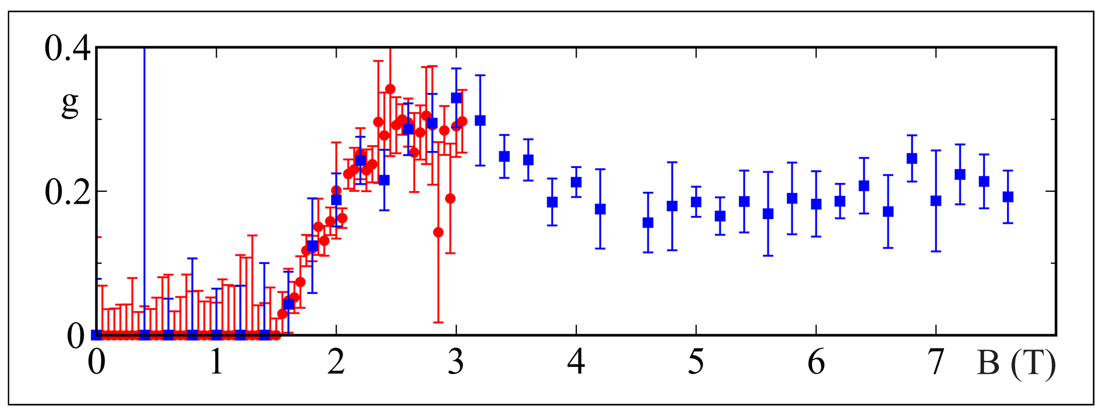
- $T \simeq 0$, strong relaxation: assume initial state is always vibrational ground state
- $I(V_{\mathrm{sd}})$ becomes a step function, $\propto P_n = \frac{e^{-g}g^n}{n!}$
- The conductance $\mathrm{d}I/\mathrm{d}V_{\mathrm{sd}}$ becomes a sequence of equidistant peaks



Ground state: in $B_\parallel > 1.5$ T



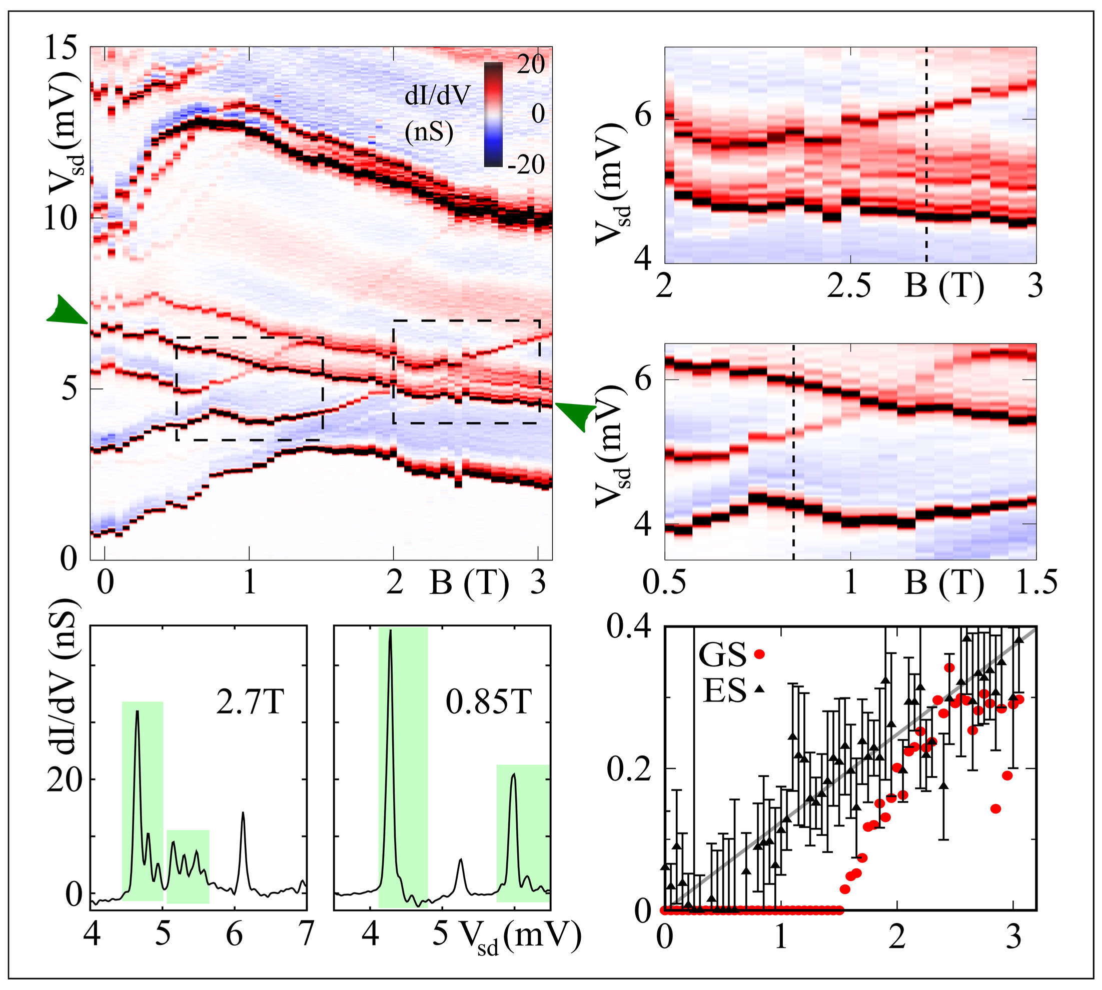
- $N = 1 \rightarrow 2$ electrons ground state transition
- Conductance sidebands visible for $B_\parallel > 1.5$ T
- Consistent with Franck-Condon model?
- Peaks equidistant, $\hbar\omega \simeq 50\,\mu$eV $\simeq$ const. ✓
- In typical range for longitudinal vibration [7, 8, 9]
  (expected: $L = 700$ nm $\rightarrow$ $\hbar\omega_{\mathrm{theo}} \simeq 160\,\mu$eV) ✓



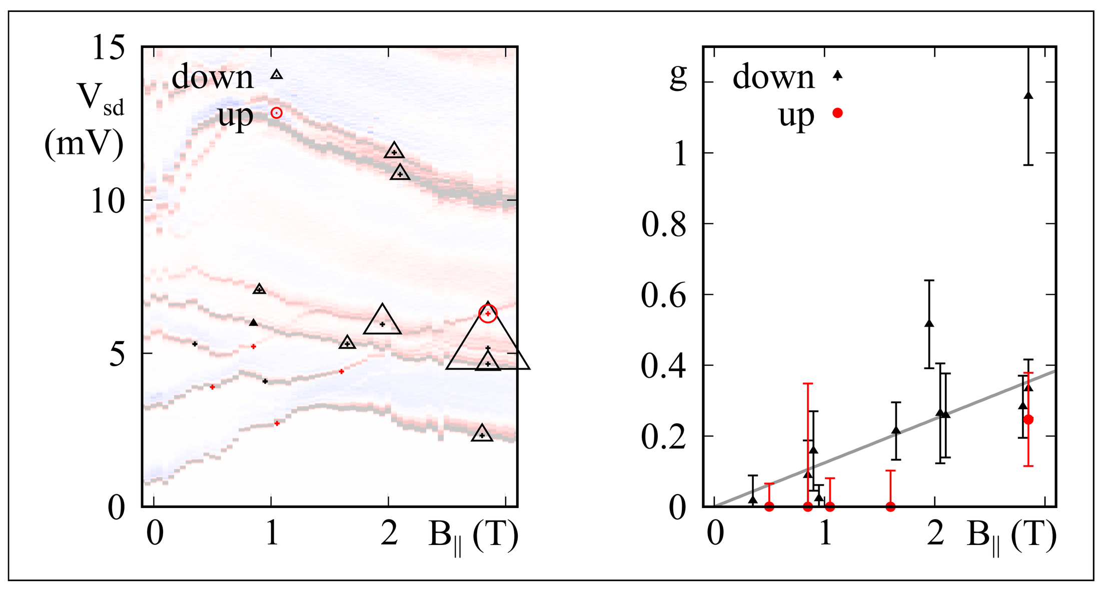
- Extract Franck-Condon coupling g via fits
- Distinct magnetic field dependence

$B_\parallel \lesssim 1.5$ T	$g = 0$
$1.5\,\mathrm{T} \lesssim B_\parallel \lesssim 3$ T	g increases $\sim$ linearly
$3\,\mathrm{T} \lesssim B_\parallel$	slow decrease / constant

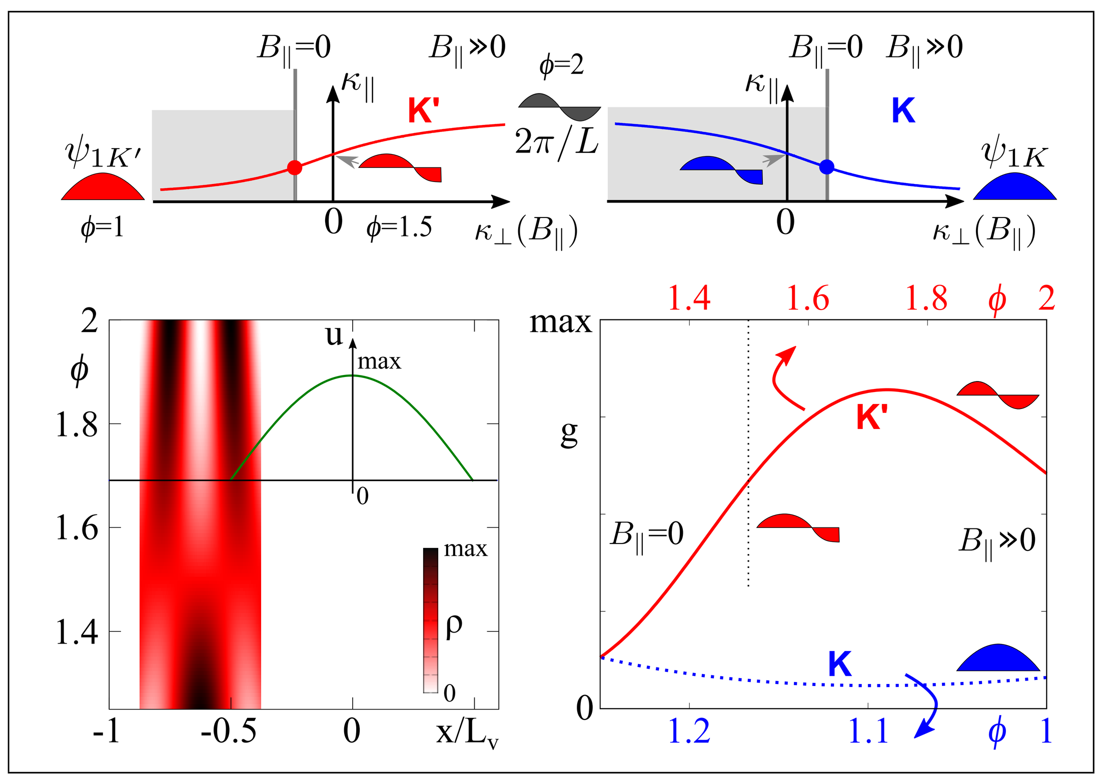
g of excited states?



- Side bands at down- but not up-sloping lines
- Valley-dependent electron-vibron coupling! [10]



Model construction



- Cross-quantization in bipartite lattice [11, 12, 3]
- Axial magnetic field shifts electronic wave function relative to the vibron envelope [3, 14, 15]
- Coupling of the electron density to the deformation potential approximated as [15]

$$g \propto |E_{\mathrm{ev}}|^2, \qquad E_{\mathrm{ev}} \propto \int \rho(x) \frac{\mathrm{d}u}{\mathrm{d}x} \mathrm{d}x$$

- For specific arrangement of electron and vibron, qualitatively reproduces $g(B)$ from experiment

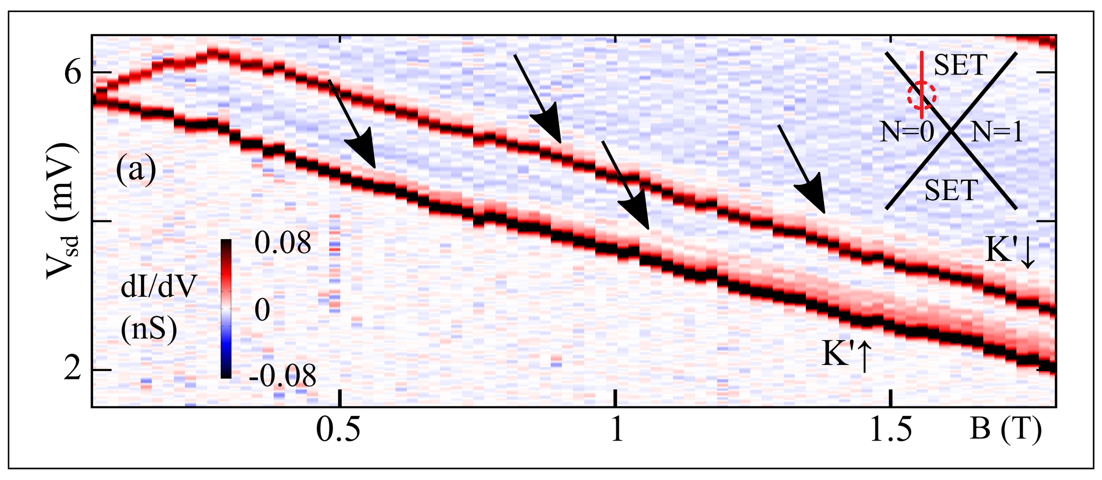
What happens at $B_\parallel \simeq 1.5$ T?

- Two-electron ground state transition
- Field forces both electrons into same valley

$$K\uparrow K'\downarrow + K\downarrow K'\uparrow \quad \longrightarrow \quad K'\uparrow + K'\downarrow$$

- Also $g(B)$ transitions from one case to the other

One-electron spectrum



- Much lower current, but coupling visible!

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PhD positions available!
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We gratefully acknowlegde funding by the DFG via the Emmy Noether grant Hu1808/1, GRK 1570, SFB 689, and SFB 1277, and by the German National Academic Foundation.