From Fabry-Pérot Interference to Coulomb Blockade at Fixed Hole Number

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We present a complex set of transport spectroscopy data on a clean single-wall carbon nanotube device in high magnetic fields. At zero axial field, the device displays in hole conduction a fast transition to Fabry-Pérot interference of conductance at high contact transparency. When increasing the axial field component up to $B_\parallel = 17\, T$, the contact transparency and the overall conductance are reduced all the way to Coulomb blockade. The continuous transition between the two transport regimes is dominated by a rich spectrum of Kondo-like resonances, with distinct features in the stability diagrams.

I. INTRODUCTION

Carbon nanotubes provide a prototypical, highly versatile system for quantum transport, which has been the topic of extensive research over the last decades [1]. They have allowed the observation of electronic transport regimes as different as Coulomb blockade [2, 3], Kondo effect-dominated tunneling [4, 5], and electronic Fabry-Pérot interference [6, 7]. A striking property of suspended, so-called “ultraclean” nanotube devices [3, 8] is that the effective transparency of contacts can be tuned over a large range by application of a gate voltage alone, while maintaining the regularity of the confinement potential. In combination with analysis of the repetitive shell filling, this has led to studies on the evolution of transport regimes with tunnel coupling [9–11].

When the absolute number of electrons or holes, as opposed to the shell filling, is relevant, investigating the dependence of the spectrum on barrier transparencies becomes more challenging. Approaches that have been pursued here include comparing hole and electron spectrum [12] (which utilizes electron-hole symmetry) or introducing additional barrier gates [13] (which requires more complex fabrication).

Here, we present data on the transport spectrum in the few-hole regime, where the contacts are typically transparent and a transition to Fabry-Pérot interference of conductance is observed [6, 7]. Application of an axial magnetic field of up to $B_\parallel = 17\, T$ reduces the conductance in our device, leading via multiple Kondo-like transport resonances [4, 5, 14–16] all the way to strong Coulomb blockade [2, 3], for constant applied bias voltage $V_{sd} = 0.2\, mV$; $T \approx 300\, mK$.

II. DEVICE AND MEASUREMENT

Figure 1(a) displays a schematic of the central part of the nanotube device, with a suspended carbon nanotube grown in situ across rhenium contacts. (b) Overview of current measurement $I_{dc}(V_g)$ as function of gate voltage $V_g$, for constant applied bias voltage $V_{sd} = 0.2\, mV$; $T \approx 300\, mK$. (c) Differential conductance $G(V_{sd}, V_g)$ in the few-hole region, numerically differentiated from a dc current measurement; pre-characterization measurement at $T \approx 300\, mK$.

FIG. 1. (a) Sketch (not to scale) of the central part of the nanotube device, with a suspended carbon nanotube grown in situ across rhenium contacts. (b) Overview of current measurement $I_{dc}(V_g)$ as function of gate voltage $V_g$, for constant applied bias voltage $V_{sd} = 0.2\, mV$; $T \approx 300\, mK$. (c) Differential conductance $G(V_{sd}, V_g)$ in the few-hole region, numerically differentiated from a dc current measurement; pre-characterization measurement at $T \approx 300\, mK$.

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The device was very stable, surviving multiple cool-downs in different cryostats with only minor changes, and very clean in the sense of highly regular transport spectra. Its characteristics in parameter ranges other than discussed here have already been presented in several publications [3, 5, 20, 21]. Figures 1(b) and 1(c) show pre-characterization measurements performed in the vacuum of a helium-3 cryostat, i.e., at $T \approx 300\, mK$.

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A measurement of the dc current $I(V_g)$ as function of gate voltage $V_g$, at zero magnetic field and constant low bias $V_{sd} = 0.2 \text{mV}$, is plotted in Fig. 1(b). Here the typical behaviour of a small-bandgap carbon nanotube is visible. For positive gate voltages $V_g > 0.6 \text{V}$, i.e., in electron conductance, strong Coulomb blockade with a repetitive shell filling pattern can be observed; the tunnel barriers here are formed by a wide p-n junction within the carbon nanotube [3, 22, 23]. The electronic band gap is observed at a low positive gate voltage. Hole conductance, for $V_g < 0.5 \text{V}$, shows a rapid onset towards wide Fabry-Pérot interference oscillations.

Figure 1(c) displays the differential conductance $G(V_{sd}, V_g)$ as function of bias voltage $V_{sd}$ and gate voltage $V_g$, recorded during the same pre-characterization cooldown at $T = 300 \text{mK}$. While at this temperature close to the band gap edge Coulomb blockade appears to be still visible, the transition into electronic Fabry-Pérot interference with a strongly broadened, oscillatory pattern is obvious for $V_g < 0 \text{V}$.

### III. LARGE AXIAL MAGNETIC FIELD

In the following, all presented data has been recorded at base temperature $T \approx 30 \text{mK}$ of a top-loading dilution refrigerator, with the device immersed into the diluted phase of the liquid $^3\text{He} / ^4\text{He}$ mixture. The dilution refrigerator was equipped with a 17T superconducting magnet and a rotateable sample holder, such that the relative orientation of the magnetic field and the carbon nanotube could be adjusted within the chip surface plane.

Our central observation is shown in Fig. 2. It plots the zero-bias conductance $G(B_{\parallel}, V_g)$ in the few-hole regime, as function of both gate voltage $V_g$ and magnetic field in the direction of the carbon nanotube axis $B_{\parallel}$. At low magnetic field, left edge of the plot, the transition into Fabry-Pérot interference [6, 7] with overall high conductance is visible. For further clarity, the conductance trace $G(0T, V_g)$ of the data set has been overlaid as a white line plot; $G$ exceeds $3e^2/\hbar$ around $V_g = -0.2 \text{V}$.

Conversely, at high axial magnetic field, up to $B_{\parallel} = 17 \text{T}$ at the right edge of the plot, the overall conductance is significantly lower, and the nanotube device displays well-separated Coulomb oscillations of conductance. A careful search at the edge of the band gap region has not shown any indications of further features in hole conductance at more positive $V_g$. This allows to identify the absolute number of holes $N$ in the system in Coulomb blockade, see the numbers at the right edge of the plot.

The transition between Fabry-Pérot and Coulomb blockade behaviour, filling the central area of the plot, displays an extraordinary degree of complexity. Kondo-like resonances cross Coulomb blockade areas, with different levels of background (cotunneling) conductance on either side of them. They merge into diagonal features in the plot, for lower field passing to more positive gate voltages. From a theory perspective, the transition has to involve a reduction of the charging energy per hole from being the dominant energy scale to nearly zero, giving an indication of the expected complexity of phenomena.

Extending the data of Fig. 2, Fig. 3 plots stability diagrams, i.e., the differential conductance $G(V_{sd}, V_g)$ as function of bias voltage $V_{sd}$ and gate voltage $V_g$, for fixed values of the magnetic field $B_{\parallel}$ in each panel. At comparatively low magnetic field $B_{\parallel} = 5 \text{T}$, only strongly broadened patterns can be observed, see Fig. 3(a). At $B_{\parallel} = 10 \text{T}$, Fig. 3(b), first features resembling diamond-shaped Coulomb blockade regions emerge. They are strongly distorted and broadened, overlaid by a wide zero-bias ridge of enhanced conductance at $V_g \approx -0.2 \text{V}$, and by strongly bias-dependent resonances as, e.g., at $V_g \approx 0.17 \text{V}$. The trend towards lower conductance and more regular Coulomb blockade regions continues with $B_{\parallel} = 15 \text{T}$, Fig. 3(c), where except for the region near $V_g \approx -0.25 \text{V}$ the zero-bias conductance anomalies are nearly gone, and $B_{\parallel} = 17 \text{T}$, Fig. 3(d).
IV. DETAIL OBSERVATIONS

To gain insight into the nature of the “diagonally running resonances” in the magnetoconductance spectrum of Fig. 2, in Fig. 4 we plot selected line traces both from Fig. 2 and Fig. 3. We chose gate voltages such that at the magnetic fields $B_{||}$ of the stability diagrams of Fig. 3 such a resonance is observed. The corresponding gate voltages are marked in Fig. 2 and Fig. 3 with dashed lines.

For the first two panels, Fig. 4(a,b), the gate voltage is $V_g = 0.17 \text{ V}$; at this voltage, a resonance crosses $B_{||} = 10 \text{T}$, see the white cross in Fig. 2. This resonance becomes clearly visible again in the line cut of Fig. 4(a) as a distinct local maximum of conductance. Fig. 4(b) shows the corresponding bias traces of the panels of Fig. 3, at $B_{||} = 5, 10, 15, 17 \text{T}$. The trace at $B_{||} = 10 \text{T}$ immediately stands out with a (near) zero bias anomaly of conductance, suggesting a Kondo-like behaviour of the observed phenomenon. Surprisingly, the conductance maximum displays a strong gate voltage dependence in Fig. 3(b).

Similar behaviour of the line traces is observed in Fig. 4(c,d) at $B_{||} = 5 \text{T}$ and in Fig. 4(e,f) at $B_{||} = 10 \text{T}$. For Fig. 4(c,d), $B_{||} = 5 \text{T}$ and $V_g \approx 0.07 \text{ V}$, the corresponding region in the stability diagram of Fig. 3(a) resembles a Coulomb blockade degeneracy point; it also evolves at higher magnetic field into the $3 \leq N \leq 4$ transition. In the case of Fig. 4(e,f) at $B_{||} = 10 \text{T}$ and $V_g \approx -0.23 \text{ V}$, the zero-bias conductance maximum corresponds to a wide region in Fig. 3(b) similar to merged Kondo ridges. In addition, in the latter panels, also the conductance feature near but not exactly at $B_{||} = 15 \text{T}$ translates into a conductance maximum in bias dependence. Note that the data indicates a global shift of all features in bias on the order of $\Delta V_{sd} \sim +0.1 \text{ meV}$, most likely due to an input offset of the current amplifier. On close observation the same offset is also visible in Fig. 3.

A surprising detail of the stability diagrams of Fig. 3 is the presence of several sickle-shaped features of positive, low, or even strong negative differential conductance, see the arrows in the figure. Two of the corresponding regions are enlarged in Fig. 5, each accompanied by the simultaneously measured dc current.

The precise origin of these features is unknown; their shape does not correspond to typical single electron tunneling or cotunnelling phenomena. Given that the measurement took place with the device immersed in liquid helium, and that a high magnetic field was present, mechanical self-activation is unlikely to be the cause [20, 21, 24–26]. A self-driving mechanism would need to overcome both viscous damping and dissipation due to induction. An unambiguous decision whether the sharpest such features here in our measurement are sudden switching events, as expected for the onset of mechanical instability, is not possible from the data set due to the averaging times of lock-in amplifier and multimeter. Some of the sickle-shaped features in Fig. 3 are, however, clearly broadened, see, e.g., the region enlarged in Fig. 5(c,d), also speaking against a vibrational instability phenomenon.
FIG. 4. Conductance traces for fixed gate voltage (a,b) $V_g = 0.17V$, (c,d) $V_g = 0.07V$, and (e,f) $V_g = -0.23V$. (a,c,e) are trace cuts from Fig. 2, plotting the differential conductance $G(V_{sd})$ as function of parallel magnetic field, at constant $V_{sd} = 0$. (b,d,f) are the corresponding sections of the panels of Fig. 3, plotting the conductance $G(V_{sd})$ as function of bias, for constant $B_\| = 5, 10, 15, 17T$. In (b), the lock-in amplifier reached its resolution limit in the 15T trace, leading to step-like measurement artifacts.

V. FURTHER DATA

In Fig. 6(a), the magnetic field is kept constant at its maximum value, $B = 17T$, but the sample holder is rotated step-wise; the magnetic field remains in the chip surface plane, but the relative orientation of nanotube axis and field changes. The plot shows the differential conductance as function of gate voltage and axial magnetic field component $B_\| = B \cos(\phi)$, with $\phi$ as the angle between field direction and nanotube axis. The overall similarity between Fig. 6(a) and Fig. 2 immediately confirms that the axial field component is crucial for the suppression of overall conductance and for most of the observed spectrum features. On closer observation, however, there are subtle deviations in the conductance resonance pattern between the figures, indicating that the large angle-independent Zeeman energy here modifies the transport spectrum. Three particularly clear cases where resonance lines visible in Fig. 2 are absent in Fig. 6(a) are marked with dashed rectangles in the figure.

Figure 6(b) explicitly compares the two measurements. Local maxima have been extracted from $G(V_g)$ traces and plotted as points; based on these points, lines have been drawn manually to connect them, also taking account step-like features in the data that did not trigger the maximum search. As last step, the two sets of points and lines have been superimposed. Red points and black lines stem from the data of Fig. 2, where an axial magnetic field of varied strength is applied; green points and green lines stem from Fig. 6(a), where at fixed magnetic field value $B = 17T$ the angle $\phi$ between nanotube and field and with that the axial component is varied. As expected, at the right edge of the plot, with $B_\| = 17T$ (or $\phi = 0$) the patterns coincide. For smaller field or larger angle, the deviations gradually increase; the three resonances missing in Fig. 6(a) are marked again with dashed lines.

Figure 7(a) plots the conductance in the case of a magnetic field perpendicular to the nanotube axis, $G(B_\perp, V_g)$. The overall signal remains large, and only broad features occur. Around zero magnetic field, a gate voltage independent pattern of larger conductance is visible, which may be related to superconductivity in the rhenium contacts.

Finally, Fig. 7(b) shows a detail measurement at low parallel magnetic field $-1T \leq B_\| \leq 2T$. Again, around zero field, larger conductance is observed, consistent with an impact of the contact metal independent of the precise in-plane orientation of the magnetic field.
or even neglected [3, 22]. This is, however, not the case for hole transport (i.e., negative applied gate voltages), where the p-n junction is absent.

Regarding the overall suppression of conductance with increasing axial magnetic field, it has been demonstrated recently that cross-quantization affects in such a field the shape of electronic wave functions along the carbon nanotube axis [3]. This leads to smaller tunnel rates to the contacts in the high field limit. The observation in [3] and the corresponding theoretical analysis was, however, targeted at the case of single electron states in a well-closed off system. It may require extension or modification for transparent contacts and interacting charges.

In [27], also an impact of a magnetic field on the tunnel coupling is discussed, though state-specific for KK’-mixed doublet states and on a smaller magnetic field scale. The mechanism proposed in [27] is that the axial field modifies the circumferential wave function and with that the wavefunction overlap at a side contact. Given that in our device the nanotube lies on top of the contacts, this may well be relevant specifically in the hole regime.

Regarding carbon nanotube transport spectra in magnetic fields, many works have demonstrated complex results including multiple ground state transitions as well as, e.g., Kondo phenomena caused by nontrivial degeneracies [15, 16, 27–29]. The gradual transition between transport regimes has been studied mostly via the impact of a changing gate voltage on a repetitive shell filling pattern in linear response [9–11, 30, 31]. This has allowed to observe and model the emergence of the Kondo effect in its SU(2) and SU(4) manifestation and the transition between Coulomb blockade and Fabry-Pérot oscillations [10, 11]; the interplay of Kondo transport and quantum interference in an open system however still poses conceptual challenges [11].

Finally, features quite similar to the diagonal lines of Fig. 2 can be found in [27], see Fig. 3(c) there. The authors describe their observations as cotunneling corresponding to magnetic-field induced level crossings: a functional renormalization group calculation is used to successfully model many details of their measurements. Similar approaches may be able to cover at least part of the parameter range of our data shown in Fig. 2.

VII. CONCLUSIONS

We present millikelvin transport spectroscopy measurements on a well-characterized carbon nanotube device [3, 5, 20, 21], where in a strong axial magnetic field $B_\parallel \leq 17T$ the entire range of transport regimes from Fabry-Pérot interference to Coulomb blockade can be traced at well-known absolute hole number. A multitude of quantum ground state transitions and Kondo-like resonances emerges in the interacting few-hole system. While similar phenomena have been observed and analyzed for smaller parameter spaces in literature, see, e.g., [27], a theoretical description covering strong Coulomb blockade, the Kondo regime, as well as quantum interference in an open conductor in a consistent way is still

FIG. 7. (a) Conductance $G(B_\parallel, V_g)$ as function of gate voltage $V_g$ and magnetic field $B_\parallel$ parallel to the nanotube axis, in higher resolution for the low-field range $-1T \leq B_\parallel \leq 2T$. (b) Conductance $G(B_\parallel, V_g)$ as function of gate voltage $V_g$ and magnetic field $B_\perp$ perpendicular to the nanotube axis.
lacking. Our raw data is available to the interested reader [17]; we hope to inspire corresponding work.

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