Single-walled carbon nanotube weak links: from Fabry-Pérot to Kondo regime

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We have investigated proximity-induced supercurrents in single-walled carbon nanotubes in the Kondo regime and compared them with supercurrents obtained on the same tube with Fabry-Pérot resonances. Our data display a wide distribution of Kondo temperatures $T_K = 1 - 14$ K, and the measured critical current $I_{CM}$ vs. $T_K$ displays two distinct branches; these branches, distinguished by zero-bias splitting of the normal-state Kondo conductance peak, differ by an order of magnitude at large values of $T_K$. Evidence for renormalization of Andreev levels in Kondo regime is also found.

An odd, unpaired electron in a strongly coupled quantum dot makes the dot to behave as a magnetic impurity screened by delocalized electrons. Such a Kondo impurity creates a peak in the density of states at the Fermi level, thereby leading to characteristic Kondo resonances with enhanced conductance around zero bias, which has been observed in various quantum dot systems during the past decade. In addition, when two normal state conductance, and find smaller critical current than for the same tube with Fabry-Pérot Josephson junctions, normal conductance peaks occur [6]. In the intermediate regime, zero bias conductance peaks alternate with Coulomb blockaded valleys, highlighting the absence of spin in the cotunnelling process between the dot and the leads [3].

Gate-controlled, proximity-induced supercurrents has been reported both in SWNTs [7,8,9,11,12] and in MWNTs [13,14]. Reasonable agreement with resonant quantum dot weak link theories [15] has been reached in best of the samples (see e.g. Ref. [9]). In some of the experiments, Kondo-restored supercurrents were found [11,16] in otherwise Coulomb blockaded Josephson junction case. In addition, when $T_K < \Delta$, $\pi$ Josephson junctions have been observed [10,11].

Here we report a study of gate-tunable proximity-induced supercurrents of an individual SWNT. We compare supercurrents in Fabry-Pérot and Kondo regimes at the same normal state conductance, and find smaller critical currents in the Kondo regime up to $T_K \sim 10\Delta$. In addition, we find that not just $T_K$ but also the shape of the Kondo resonance conductance peak affects the magnitude of the supercurrent: resonances with zero-bias splitting, which appear in about every second of our Kondo peaks, result in a smaller critical current than for the regular Kondo maxima.

Our nanotube samples were made using surfactant CVD growth with Fe catalyst directly on oxidized, heavily-doped SiO$_2$/Si wafer. The electrical conducting substrate works as a back gate, separated from the sample by 150 nm of SiO$_2$. A sample with $L = 0.7 \mu m$ length and $\phi = 2 \mu m$ diameter was located using an atomic force microscope and the contacts on the SWNT were made using standard e-beam overlay lithography. For the contacts, 10 nm of Ti was first evaporated, followed by 70 nm of Al, in order to facilitate proximity-induced superconductivity in Ti. Last, 5 nm of Ti was deposited to prevent the Al layer from oxidation. The width of the two contacts was 200 nm and the separation between the them was 0.3 $\mu m$.

The measurement leads were filtered using an RC filter with time constant of 10 $\mu$s at 1 K, followed by twisted pairs with tight, grounded electrical shields for filtering between the still and the mixing chamber, while the final section was provided by a 0.7-m long Thermocoax cable on the sample holder. In the measurements, differential conductance $G_d=dI/dV$ was recorded using standard lock-in techniques. Voltage bias was imposed via a room-temperature voltage divider. The normal state data were obtained by applying a magnetic field of $B \sim 70$ mT perpendicular to the nanotube. The superconducting gap of the contact material was found to be $\Delta_g = 125 \mu eV$, and gate capacitance $C_g = 1.6 \mu F$ was estimated from the measured gate period of 0.1 V.

The data presented in this paper have been measured in several cool downs, thermal cycles, that have changed the contact conditions on our sample. In the first cool down, the sample showed a strongly asymmetric Fabry-Pérot pattern with one low-transmission (spin-degenerate) channel and another one with high transmission; the zero-bias conductance was limited to $2e^2/h$ as a consequence [17]. A scan of differential conductance $G_d(V_{ds}, V_g)$ versus bias voltage $V_{ds}$ and gate voltage $V_g$ is shown in Fig. 1(a) at $B \sim 70$ mT. In the absence of magnetic field, a gate-voltage-dependent supercurrent...
FIG. 1: (Color online) Normal state differential conductance $G_d$ on the plane spanned by bias voltage $V_d$ and gate voltage $V_g$ in (a) Fabry-Pérot regime, and (b) Kondo regime both at $T = 30$ mK. Normal states were achieved in all the cases with a magnetic field of $B = 70$ mT. Red and blue arrows in (b) refer to two types of resonance peaks, which have one magnitude difference in $I_{CM}$ with similar Kondo temperature $T_K$. See text for more details.

is observed in the SWNT. The measured critical supercurrent $I_{CM}$ varies periodically with the gate voltage $V_g$, reaching a maximum of 4.8 nA at zero bias normal state conductance $G_N = G_d|_{V_d=0} = 2.03e^2/h$. The $I_{CM}R_N$ product is $V_g$-dependent and it changes in a similar fashion as $I_{CM}$ and the inverse of the normal state resistance $G_N$. This result is similar to what has been observed in a superconducting SWNT in Fabry-Pérot regime [3].

After a few thermal cycles, the transport of SWNT changed from Fabry-Pérot into Kondo type of behavior as seen in Fig. 1(b). The $G_d$ map displays a series of Coulomb blockade diamonds (even number of electrons) alternating with Kondo ridges, marked by the arrows (odd number of electrons). The Kondo ridges are rather wide and the Kondo temperatures, which are deduced from the half width at half maximum of the resonant conductance peaks versus bias voltage $G_d(V_d)$ (see below), range over $T_K = 1 – 14$ K. We find that both the critical current and zero-bias conductance are smaller compared with Fabry-Pérot regime, even in the Kondo resonances with the highest $T_K$.

The superconducting state IV curves in both Fabry-Pérot and Kondo regimes are shown in Fig. 2. As the sample is voltage biased, negative differential resistance (NDR) is observable in Fabry-Pérot regime. However, in Kondo regime, NDR occurs only at small measured critical current $I_{CM}$ and it disappears around the maximum of the Kondo resonance peak where $I_{CM}$ is large. We note that zero bias resistance and the IV curves evolve smoothly with $V_g$ around the Kondo resonance without any sudden jumps, and that $T_K > \Delta_g$. We ascribe the disappearance of NDR to the presence of large MAR-induced subgap current, which is stronger with respect to the supercurrent in the Kondo regime than in the FP case.

The nanotube together with superconducting leads can be considered as a resonant level quantum dot, and thus the two-barrier Breit-Wigner model is applicable to model the behavior [12]. In our case, the measured $I_{CM}$ is nearly one order of magnitude smaller than the theoretical prediction $I_0 = e\Delta_g/h \approx 30$ nA with one resonant spin-degenerate level [13]. Taking into account the phase diffusion in an underdamped, voltage-biased Josephson junction [13], the measured $I_{CM} \propto E_J^2 \propto I_C^2$. With Breit-Wigner model for wide resonance limit $h\Gamma >> I_C$, transmission probability $\alpha_{BW}$, we have $I_C = I_0[1 - (1 - \alpha_{BW})^{1/2}]$, so the $I_{CM} - G_N$ relation can be written as

$$I_{CM} = I_{0M}[1 - (1 - \frac{1}{2}g_n)^2]^2, \quad (1)$$

where $I_{0M}$ denotes the maximum measurable critical current when the scaled conductance $g_n = G_N/(e^2/h) \rightarrow 2$. This equation is written for one spin-degenerate channel (the Kondo case) where the transmission coefficient is obtained from $\frac{1}{2}g_n$, and the prefactor depends on $T_K$; in our case it also applies approximately to the asymmetric FP conduction as one of the spin-degenerate transmission channels is greatly suppressed [17]. The fit of Eq. 1 to our data is displayed in Fig. 2 (c), with $I_{0M} = 5.3$ nA and 3.3 nA corresponding to Fabry-Pérot and Kondo regimes respectively (the latter at $T_K = 14$ K).

As in the FP regime, the largest critical current over a Kondo resonance corresponds to the peak value of the normal state conductance. In addition, the magnitude of $I_{CM}$ depends on the width of the resonance in bias voltage, i.e. on $T_K$. We have fitted the conductance peaks $G_d(V_d)$ with a Lorentzian function in order to extract the Kondo temperature $T_K$. The resulting $I_{CM} - T_K$ correlation is plotted in Fig. 3 which displays two branches, instead of a single-valued correlation as observed by Grove-Rasmussen et al. [16]. The upper and lower branches involve the resonance peaks marked in Fig. 1(b) by red and blue arrows, respectively. Due to the problem of trapped charge fluctuating on the back gate, we have been forced to present only data on which we are sure of the identification between critical current and normal state conductance. As shown in the inset of Fig. 3 in the data of the lower branch, there is a small dip on the zero-bias conductance peak signifying zero-field splitting of the Kondo resonances marked by blue arrows. The Lorentzian fitting on the split peaks is somewhat approximative, and the fitted $T_K$ remains a bit smaller than from the true half width. Nevertheless,
triangles refer to Fabry-Pérot (several resonances) and Kondo data, respectively. Data in (a) were measured in the same cool normal state conductance regime. The circles with different colors show how the measured critical current $I_{CM}$ was determined [20]. $I_{CM}$ versus zero-bias normal state conductance $G_N$, measured for a resonance with $T_K = 14$ K, is displayed in (c) where the black dots and red triangles refer to Fabry-Pérot (several resonances) and Kondo data, respectively. Data in (a) were measured in the same cool down as Fig. 1(a) at $T = 60$ mK; data in (b) were taken from another cool down after Fig. 1(b) at $T = 60$ mK with unchanged $G_N$. The current of the smallest $I_{CM}$ curve in (b) has been amplified by a factor of 5 for clarity. Black and red solid lines in (c) are theoretical fits using Eq. (1).

Zero-field Kondo-peak splitting has previously been reported in Ref. [21], where the the splitting originates from magnetic impurity, which is different from our case as the splitting should then be seen at every Kondo resonance. Using the standard fourfold shell-filling sequence, it is hard to explain our findings. Split Kondo ridges may be observable when the dot is occupied by two electrons ($N = 2$) [8, 22], and the energy scale of the splitting equals to the gap between singlet ground state and triplet excited state. This, however, should be bordered from both sides by standard spin-half Kondo peaks, a sequence that we cannot identify in our data. From the normal state bias maps, the characteristic zero-bias splitting energy can be estimated as $\Delta_{ZBS} \sim 0.4$ meV, which is well above MAR peak of superconducting electrodes $2\Delta_g = 0.25$ meV and the typical singlet-triplet excitation energy as found in Ref. [3]. We conjecture that the observed zero-field splitting is related to the SU(4) Kondo effect which is peculiar to carbon nanotubes [23, 24] and which has been shown to lead to a dip in the density of states at small energies [25]. Alternatively, zero-field splitting may be related with the recent observation of non-negligible spin-orbit coupling in SWNTs [26]. In any case, SU(4) Kondo can explain the unusually high $T_K$ by the enhanced degeneracy of a multiple-level quantum dot [27].

According to theory [28], the width of Andreev levels can be substantially renormalized by the Kondo effect, which would also modify the IV curve. In order to look for the gap renormalization, we have extracted the excess current $I_{ex}$ as a function of normal state transmission coefficient $\alpha$, which is displayed in Fig. 4 with $\alpha$ calculated from $\alpha = G_N/(2e^2/h)$, and $I_{ex}$ determined by the difference of integration from $G_d - V_{ds}$ curves in superconducting/normal state like in Ref. [29]. The relation between $I_{ex}$ and $\alpha$ in a quantum point contact [31, 32] can be

![FIG. 2: (Color online) Superconducting $I - V$ curves at a few gate voltage values in (a) Fabry-Pérot regime, and (b) Kondo regime. The circles with different colors show how the measured critical current $I_{CM}$ versus zero-bias normal state conductance $G_N$, measured for a resonance with $T_K = 14$ K, is displayed in (c) where the black dots and red triangles refer to Fabry-Pérot (several resonances) and Kondo data, respectively. Data in (a) were measured in the same cool down as Fig. 1(a) at $T = 60$ mK; data in (b) were taken from another cool down after Fig. 1(b) at $T = 60$ mK with unchanged $G_N$. The current of the smallest $I_{CM}$ curve in (b) has been amplified by a factor of 5 for clarity. Black and red solid lines in (c) are theoretical fits using Eq. (1).](image)

![FIG. 3: (Color online) Measured critical current $I_{CM}$ versus scaled Kondo temperature $k_B T_K/\Delta$ for Kondo resonances marked by red and blue arrows in Fig. 1. Peaks with zero-bias splitting are denoted by blue circles, while red dots refer to non-split peaks in Fig. 1(b). The solid red and blue curves are to guide the eyes. The inset shows two typical $G_N - V_{ds}$ relations for the different kinds of conductance peaks and their Lorentzian fits. The curve for non-split peak has been shifted downwards by 0.3 units for clarity.](image)
written as \( I_{ex} = I_{ex1} + I_{ex2} \), where
\[
I_{ex1} = \frac{e\Delta}{h} \alpha^2 \ln \left[ 1 + \frac{1}{2\sqrt{1 - \alpha}} \frac{(2\alpha - 1)}{2(1 - \alpha)} \right],
\]
\[
I_{ex2} = \frac{e\Delta}{h} \alpha^2 \left[ \frac{1}{1 - \alpha} + \frac{2 - \alpha}{2(1 - \alpha)^{3/2}} \ln \left( \frac{1 - \sqrt{1 - \alpha}}{1 + \sqrt{1 - \alpha}} \right) \right].
\]  

The blue curve in Fig. 4(a) illustrates Eq. 2 with \( \Delta = 100 \mu\text{eV} \), and the red line in (b) gives linear fit of \( I_{ex}/I_{CM} = 4.3 \).

In summary, we have investigated the proximity-effect-induced supercurrents in SWNTs in the Kondo regime and compared them with results in the Fabry-Perot regime with equivalent conductance. In the Kondo regime, two different types of resonances, either split or non-split at zero-bias, were observed and this behavior reflected also in the magnitude of supercurrent that displayed two branches vs. \( T_K \). The excess current in the Kondo regime was analyzed using MAR theory and renormalization of Andreev levels by 80% was obtained.

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