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dc Josephson effect in metallic single-walled carbon nanotubes

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Abstract

The dc Josephson effect is investigated in a single-walled metallic carbon nanotube connected to two superconducting leads. In particular, by using the Luttinger liquid theory, we analyze the effects of the electron–electron interaction on the supercurrent. We find that in the long junction limit the strong electronic correlations of the nanotube, together with its peculiar band structure, induce oscillations in the critical current as a function of the junction length and/or the nanotube electron filling. These oscillations represent a signature of the Luttinger liquid physics of the nanotube, for they are absent if the interaction is vanishing. We show that this effect can be exploited to reverse the sign of the supercurrent, realizing a tunable π-junction.

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1. Introduction

Since the discovery by Iijima in 1991 [1], carbon nanotubes have attracted much interest in the community of Mesoscopic Physics. Due to their peculiar electronic and mechanical properties, they are regarded as optimal candidates for nanotechnological implementations, and have been successfully applied to the realization of quantum transistors [2,3], electron waveguides [4], interferometric devices [4,5] as well as nanoelectromechanical systems [6]. Recent experiments have spurred the interest in superconducting properties of these materials: it has been observed indeed that proximity-induced superconductivity can arise in nanotube bundles in contact with superconductors (S); in ropes, intrinsic superconductivity has also been measured [7,8] and explained in terms of combination of electron coupling to the breathing phonon modes and intertube Cooper-pair tunneling [9]. Individual multiwall nanotubes have recently been utilized in the fabrication of superconductor-nanotube-superconductor hybrid structures, allowing to reveal the dynamics of multiple Andreev reflections [10] and to realize a controllable supercurrent transistor [3]. In contrast, the investigation of superconducting properties of *single-walled* nanotubes in hybrid structures has been only partly explored so far.

Metallic Single-walled carbon nanotubes (SWNT) are known to behave as 1D conductors with four conduction channels exhibiting ballistic transport up to several μm [11, 12]. Different from other 1D metals, SWNT preserve their conduction properties even at very low temperature, since the cylindrical lattice geometry prevents the arising of Peierls distorsion. They thus offer promising features for interconnecting components of nanodevices. Due to their 1D character, electronic correlations have dramatic effects on the behavior of SWNT: experimental evidences of a power law behavior for the conductance as a function of temperature [13] indicate that SWNT exhibit a Luttinger liquid (LL) behavior, and that their elementary excitations are not fermionic quasiparticles like that in normal 3D metals [14,15]. It is thus expected that, when an SWNT is in contact with S leads at equilibrium, electronic correlations might significantly modify the behavior of the supercurrent with respect to junctions realized with a normal metal. This issue has been addressed in the literature [16–21] and it has been shown that the effect of interaction is particularly enhanced when the coupling between the LL and the S leads is realized through tunnel junctions.

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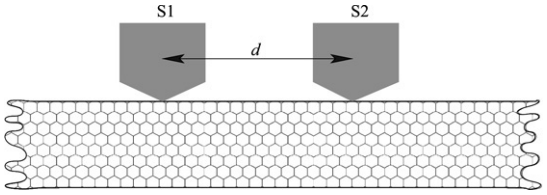

Fig. 1. Schematic set-up of the S-I-SWNT-I-S junction under investigation.

However, most of these investigations focused on the case of a two-channel (i.e. one spinful mode) LL, and cannot be straightforwardly applied to the case of a four-channel SWNT. In this paper we discuss this problem by investigating the dc Josephson effect in an S-I-SWNT-I-S junction, and show that new features arise due to the peculiar band structure of SWNT. The paper is organized as follows: In Section 2 we briefly review the model used to describe SWNT, accounting for the electron–electron interaction within the Luttinger Liquid theory. In Section 3 we present our results about the Josephson current. We find that the interaction yields a two-fold effect on the critical current j_c: on the one hand it modifies the scaling law of j_c as a function of the junction length d; on the other hand, it introduces oscillations of j_c as a function of either the electron filling or the junction length d. The latter oscillations are absent for a non-interacting system, and therefore represent a signature of Luttinger liquid behavior on the supercurrent. Finally, in Section 4 we discuss the results and propose possible implementations to observe this effect.

2. Modeling the system

The set-up of the system is depicted in Fig. 1: a metallic SWNT is coupled through tunnel contacts to two superconducting leads to realize an S-I-SWNT-I-S junction. For simplicity, here we limit our treatment to the case of armchair nanotubes; we also assume that the S leads have the same gap $|\Delta|$; the two superconducting order parameters thus read $\Delta_{1,2} = |\Delta| e^{i\chi_{1,2}}$, where χ_i is the superconducting phase of the ith lead. We are interested in the dependence of the critical current on the junction length d; we thus analyze the regime

$$\lambda_c, \xi \ll d \ll L \tag{1}$$

where λ_c represents the width of the contacts, ξ the coherence length of the S electrodes, d the electrode distance, and L the length of the nanotube. The regime (1) is quite realistic in view of customary fabrication of μm long ballistic nanotubes [12], and the recent realization of superconducting tips for Scanning Tunneling Microscope (STM) [22–24] or of 10–20 nm short superconducting finger leads. In order to simplify the mathematical treatment without altering the essential physical features of the regime (1), we shall henceforth assume that the tunnel contacts are point-like, the coherence length ξ is vanishing, and the length of the nanotube is infinite, $L \to \infty$.

In a metallic nanotube the lowest band consists of four electron branches located around two Fermi points αk_F, with $\alpha = \pm 1$; the energy separation to the second band is of the order of eV, so that the latter can be in practice neglected up to a broad range of thermal excitations. Within this energy scale, the energy dispersion of the lower band is linear under quite good approximation, as shown in Fig. 2. SWNT can thus be regarded as four-channel 1D metals. As discussed in the introduction, their 1D character implies that a careful treatment of the electron–electron interaction is needed. It is indeed well-known that transport properties of SWNT cannot be explained in terms of the customary Fermi liquid theory, since their elementary excitations are bosonic plasmon modes, rather than fermionic quasi-particles. A model for SWNT based on the Luttinger liquid theory has been formulated a decade ago [25,26], and applied in a number of problems [27–33]. Here we briefly remind the main aspects that are relevant to our discussion: An SWNT can be ideally obtained by wrapping into a cylinder shape a graphene sheet, whose honeycomb carbon lattice consists of two sublattices $p = \pm$. A nearest-neighbor tight-binding calculation of the π-electrons in the graphite, together with appropriate wrapping boundary conditions, leads to express the electron field in the nanotube as

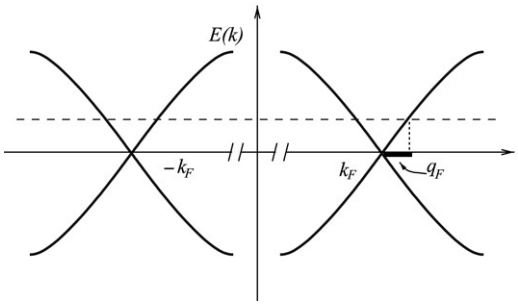

Fig. 2. The electron band dispersion relation of an SWNT originates from the two-sublattices honeycomb carbon structure, and is characterized by four Fermi points. The latter can be identified through two Fermi momenta: k_F denotes the band crossing points, whereas q_F accounts for the deviation from k_F, i.e. the electron filling of the SWNT.

$$\Psi_\sigma(x) = \sum_{\alpha=\pm, r=R/L} \sum_{p=\pm} U_{pr} e^{i(\alpha k_F + r q_F)x} \psi_{\alpha r\sigma}(x) \tag{2}$$

where $\sigma = \uparrow, \downarrow$ denotes the spin component and x the longitudinal coordinate in the nanotube. In Eq. (2), U_{pr} are the entries of the matrix

$$U = -\frac{e^{-i\pi/4}}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ i & -i \end{pmatrix} \tag{3}$$

describing the unitary transformation from the sublattice electron fields into the right (left) moving fields description. The exponential terms in Eq. (2) represent the fast oscillating contribution to the electron wave function, where the wave vector q_F is related to the electron filling exceeding the Fermi points $\pm k_F$, as illustrated in Fig. 2. Finally the field $\psi_{\alpha r\sigma}(x)$ varies slowly over the scale of Fermi wavelength.

In order to account for the electron–electron interaction, it is useful to represent the electron fields $\psi_{\alpha r\sigma}$ through the bosonization identity

$$\psi_{\alpha r\sigma}(x) = \frac{\eta_{\alpha r\sigma}}{\sqrt{2\pi a}} \exp\{i\varphi_{\alpha r\sigma}(x)\} \tag{4}$$

where $\varphi_{\alpha r\sigma}(x)$ is the plasmonic field describing the long wavelength fluctuations. The operators $\eta_{\alpha r\sigma}$ are Klein