Aharonov-Bohm effect in circular carbon nanotubes

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Abstract

We study the interference of interacting electrons in toroidal single-wall carbon nanotubes coupled to metallic electrodes by tunnel junctions. The dc conductance shows resonant features as a function of the gate voltage and the magnetic field. The conductance pattern is determined by the interaction parameter, which in turn can be cross-checked against the exponents governing the transport at high temperatures. The coordinate dependence of the conductance reflects electron correlations in one-dimensional space.

Abstract

Recent experiments [1,2] have revealed ring-shape structures of single-wall carbon nanotubes (SWNTs). The data by Liu et al. [1] suggests that the rings consist of ropes of toroidal SWNTs. Presumably, single toroidal SWNTs have been detected as well. On the other hand, samples produced by a different technique [2] consist of ropes of coiled (non-toroidal) SWNTs.

The Coulomb interaction in one-dimensional (1D) SWNTs leads to non-Fermi liquid electron correlations observed in recent experiments [3]. Toroidal SWNTs is an unique system for studying the interference of interacting electrons. In this work we investigate the Aharonov-Bohm effect in toroidal SWNTs coupled to metallic electrodes by tunnel junctions at the points $x_1 = 0$, $x_2 = x$.

The conductance $G$ of the system can be evaluated in the lowest order in tunneling,

$$ G = \frac{\pi \hbar G_1 G_2 v_F^2}{96 e^2} \sum_s \left| \tilde{G}_s(x, \omega = 0) \right|^2, $$

where $G_{1,2}$ are the conductances of the junctions, $v_F$ is the Fermi velocity in SWNT, and $\tilde{G}_s$ is the Matsubara’s Green’s function for electrons with spin $s$ in SWNT. The latter is determined by the Fermi operators $\psi_{\alpha sd}$ for right/left ($d = \pm$) moving electrons near the Fermi points $\alpha K$ ($\alpha = \pm$),

$$ \tilde{G}_s = - \sum_{ad} e^{i \alpha K x} \langle T_\tau \psi_{\alpha sd}(x, \tau) \psi_{\alpha sd}^\dagger(0, 0) \rangle. $$

The averages (2) are taken over the low-energy phase Hamiltonian of toroidal SWNT [4],

$$ H_{NT} = \int_{-L/2}^{L/2} dx \frac{v_{\delta \delta}}{K_{\nu \delta}} \left( \nabla \theta_{\nu \delta} - \frac{2 K_{\nu \delta}}{v_{\delta \delta}} \mu \delta_{\delta + \delta_{\nu \delta}} \right)^2 $$

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and velocities $v_{\nu\delta}$ of charge/spin ($\nu = \rho, \sigma$) excitations in symmetric/antisymmetric ($\delta = \pm$) modes are introduced. We take into account only the strongest interaction in charged mode, $K_{\rho+} \approx 0.2$, so that $v_{\rho+} = v_F/K_{\rho+}$ and $K_{\rho\delta} = 1$, $v_{\nu\delta} = v_F$ for three neutral modes. The electro-chemical potential $\mu$ (or gate voltage) is coupled to the charge density $\rho \propto \nabla \theta_{\rho+}$ in SWNT. The magnetic flux $\Phi$ is coupled to the current $I \propto \nabla \phi_{\rho+}$.

In order to describe the system with finite number of electrons, the fields $\theta_{\nu\delta}$ and $\phi_{\nu\delta}$ are decomposed into bosonic and topological parts. The averages (2) over the corresponding parts of the Hamiltonian (3) can be evaluated separately.

The conductance of the system displays resonant peaks as a function of the electro-chemical potential $\mu$ (Fig. 1). The map of the peak positions in $\mu - \Phi$ plane depends on the wrapping vector and the length of toroidal SWNT [4]. The map for armchair SWNT of length $L = 3na$ is shown in Fig. 2 (here $a = 2.46$ Å is a lattice constant of graphite). The diagram is periodic in $\mu$ with period $\mu_0 = 2\pi v_{\rho+}/K_{\rho+}L$ and in $\Phi$ with the period $\Phi_0 = h/e$. Eight electrons enters SWNT per period $\mu_0$. The lines with the negative/positive slope correspond to entering of electrons with orbital magnetic moment parallel/antiparallel to the magnetic field. The slope of the lines $d\Phi/d\mu = (\Phi_0/\mu_0)/K_{\rho+}^2$ allows one to determine the interaction in the charged mode [5].

Close to the resonances, $|\Delta \mu| \ll \mu^*$, the conductance scales as $G \propto (a/L)^{2g}/\Delta \mu^2$, $g = \sum_{\nu\delta}(K_{\nu\delta} + 1/K_{\nu\delta})/8$ (cf. Ref. [5]). The divergence at $\Delta \mu \rightarrow 0$ is an artifact of the perturbation theory. At $x \ll L$, in the energy range $\mu^* \ll |\Delta \mu| \ll \mu_0$ the conductance levels off as a function of $\Delta \mu$ and shows power-law dependence on $x$, $G \propto (a/x)^{2g-2}(a/v_{\rho+})^2$. By comparing the two asymptotics of $G$ we obtain, $\mu^* \approx (2\pi v_{\rho+}/L)(2\pi x/L)^{g-1}$. In addition, away from half-filling the conductance shows oscillations as a function of $x$ with the period $\pi/q$ related to the mismatch $q \approx 2\pi \mu/L\mu_0$ of the Fermi vectors of right and left-moving electrons. At finite voltages and/or temperatures we expect the competition of the considered process of coherent electron transfer through SWNT with incoherent sequential tunneling through the junctions.

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References

[1] J. Liu, et. al., Nature 385, 780 (1997).
[2] R. Martel, et. al., Nature 398, 299 (1999).
[3] M. Bockrath, et.al. Nature 397, 598 (1999).
[4] A.A. Odintsov, et. al., Europhys. Lett. 45, 598-604 (1999).
[5] J.M. Kinaret, et. al., Phys. Rev. B 57, 3777 (1998).