



Interference and interactions in multiwall nanotubes

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Abstract

The electrical properties of single multiwall nanotubes (NTs) have been investigated in parallel and perpendicular magnetic field. Quantum interference phenomena like weak localization, Aharonov–Bohm effect, UCF, and nonlocal resistance contributions prove that NTs are mesoscopic (phase-coherent) objects at low temperature. The relatively large elastic-scattering length, inferred from our data, suggests that our NTs are 1d quasi-ballistic conductors where long-range coulomb interactions should be important. This is further substantiated by the temperature dependence of the resistance and by tunneling spectroscopy displaying a pronounced zero-bias anomaly. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Aharonov–Bohm effect; Carbon nanotubes; Luttinger liquid

We report electric transport measurements for single multiwall nanotubes (MWNTs). Earlier experiments have revealed quantum interference effects like weak localization (WL) and universal conductance fluctuations in the magnetoresistance (MR) of MWNTs [1,2]. However, the phase-coherence length l_ϕ was found to be small amounting to only ≤ 20 nm at 0.3 K, in strong contrast to ballistic transport expected for a perfect nanotube.

Low-ohmic contacts (< 10 k Ω) are used for measuring the equilibrium (two- or four-terminal) conductance G . Fig. 1 shows the MR of a single MWNT in parallel magnetic field. Several equidistant peaks are observed in the accessible field range which we interpret as Aharonov–Bohm (AB) oscillation in MWNTs (see also Ref. [3]). The AB-MR agrees with the WL theory only, if the current is assumed to flow through one or at most two graphene cylinders with a diameter corresponding to the measured outer diameter of the NT. This result has given compelling evidence that l_ϕ can exceed the circumference of the tube so that large coherence lengths are possible for MWNTs. Because the magnetic-flux modulated resistance agrees with an AB flux of $h/2e$ the effect is supposed to be caused by weak-localization for

which backscattering is essential. Hence, the transport in the MWNTs cannot be perfectly ballistic.

From the width of the zero-field resistance peak of Fig. 1 l_ϕ is estimated to be $l_\phi \approx 200$ nm. The expected 1d WL contribution to $\delta G = 44$ μ S for $L = 350$ nm and $l_\phi = 200$ nm is in reasonable agreement with the measured conductance change of $\delta G = \delta R/R^2 = 59$ μ S in Fig. 1. From MR measurements in perpendicular field similar coherence lengths are deduced.

The observed temperature-dependence $l_\phi(T)$ roughly agrees with the expected Nyquist-type dephasing and the comparison with theory allows to infer the elastic-scattering length l_e . We obtain $l_e = 90$ –180 nm. Furthermore, the resistance contains a length-dependent contribution of ≈ 6.4 k Ω/μ m at 300 K. Using the Landauer formula, one obtains an effective transmission coefficient of $T = 0.5/\pi d$ corresponding to a large mean-free path. Because $l_e \geq \pi d$, our MWNTs should be classified as 1d *quasi-ballistic* conductors. The low resistances (≈ 1 –10 k Ω) at low T are indeed incompatible with a 2d DOS [4].

Further information on the electronic structure of the MWNTs can be extracted from the density of states. A high-ohmic contact (> 100 k Ω) is employed in a tunneling spectroscopy experiment in which the differential conductance dI/dV is measured as a function of V and temperature T . Most of our samples display spectra in with a pronounced zero-bias anomaly (ZBA) on a small

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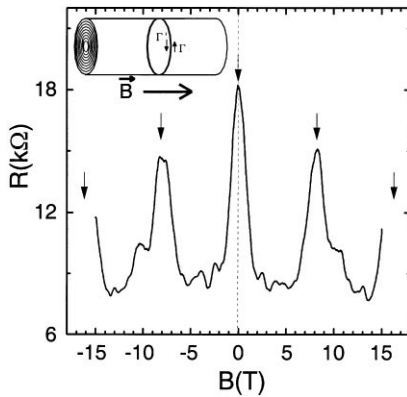


Fig. 1. Electrical resistance R as a function of magnetic field B of a MWNT aligned parallel to B . Arrows denote the resistance maxima corresponding to multiples of $h/2e$ in magnetic flux through the nanotube taking the *outer* diameter.

energy scale of 1–10 meV. For larger energies, a peak-structure develops in dI/dV on the scale of the 1d subband separation (0.1 eV) which may be associated with (broadened) van-Hove singularities. A typical ZBA is shown in Fig. 2 for six temperatures ranging from 2–20 K. A suppression of the tunneling DOS is expected for a strongly correlated electron gas [5]. The Luttinger liquid (LL) theory predicts power laws both for the voltage and temperature dependence with the same exponent α . A power law with $\alpha \approx 0.36$ is deduced from $dI/dV(T, V = 0)$; see the inset of Fig. 2. For comparison with the observed dI/dV -voltage dependence, the dashed-dotted curve $\propto V^{0.36}$ has been plotted. Similar anomalies have recently been observed by Bockrath et al. for SWNTs [6], who found the same exponent $\alpha = 0.36$. Very recent theoretical calculations indicate that the LL behavior should survive in *multiwalled* nanotubes since the screening is weak up to rather high diameter [7]. Consequently, an interpretation of our results in terms of the LL theory appears justified.

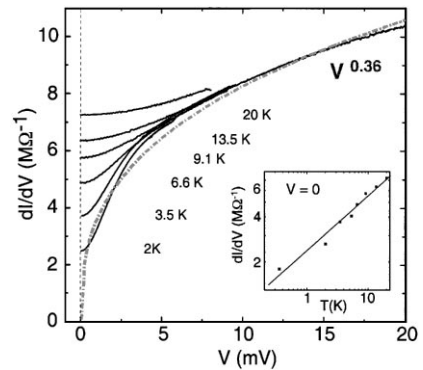


Fig. 2. Differential tunneling conductance dI/dV measured on a single MWNT at different temperatures T displaying a pronounced zero-bias anomaly. Inset: log-log representation of dI/dV versus T for $V = 0$. The dashed-dotted curve displays the power-law $dI/dV \propto V^\alpha$ with $\alpha = 0.36$ deduced from the inset.

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