Comment on "Magnetoresistance and differential conductance in mutliwalled carbon nanotubes"

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Jeong-O Lee *et al.* [Phys. Rev. B **61**, R16 362 (2000)] reported magnetoresistance and differential conductance measurements of multiwalled carbon nanotubes. The observed aperiodic conductance fluctuations and the negative magnetoresistance was interpreted to originate exclusively from changes in the density of states at the Fermi energy. We show that this interpretation is questionable and not supported by their measurements.

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In a recent paper Jeong-O Lee *et al.* discuss measurements of the electrical resistance R of multiwalled carbon nanotubes (MWNTs).[1] In perpendicular magnetic field H the resistance decreases with field, i.e., displaying a negative magnetoresistance (MR). In addition, aperiodic resistance fluctuations are superimposed. The fluctuations and the negative MR increase in magnitude at lower temperature T. These characteristic features have been seen before by several groups and were successfully interpreted within the framework of quantum interference corrections to the diffusive motion of electrons.[2–7] In this interpretation the negative MR is caused by weak localization, while the aperiodic conductance fluctuations resemble so-called universal conductance fluctuations (UCF's).

As the authors mention, there is a disagreement between the theoretical prediction and these previous experiments. For a defect-free (and undoped) metallic carbon nanotube with ideal electrical contacts the electrical conductance $G = 1/R$ is predicted by theory to be *twice* the quantum conductance $G_0 = 2e^2/h$ due to two propagating one-dimensional (1D) modes at the Fermi energy.[8] This is not observed in experiments. Instead, R is temperature dependent; it increases if T is decreased. Also, R is strongly magnetic field dependent, both in previous experiments as well as in the experiments of Lee *et al.* However, for an ideal (and undoped) metallic carbon nanotube the number of 1D subbands at the Fermi energy does not change if a perpendicular magnetic field is applied. Hence, R should be independent of H. Any dependence on H and T for temperatures below the 1D-subband separation points to physics which is beyond the simple and extremely idealized picture of a 1D ballistic wire with zero back scattering and noninteracting electrons. This should hold for the equilibrium (linear response) resistance *and* for the differential resistance, as long as the applied voltage is smaller than the 1D-subband separation. There is only a disagreement between theory and experiments if one sticks to the assumption that nanotubes are ideal. This poses no problem to theory, for which an ideal nanotube is the most simple model to work with. But why should a *real* nanotube be perfect in the experiment? Nanotubes may have defects, adsorbates may play a role, the evaporated metallic contacts most likely add additional back scattering and electrons in 1D strongly interact. There is a large body of experiments showing that all necessary ingredients for ballistic transport are not realized in MWNT's.[2,5,6,9]

Though Lee *et al.* measured MR dependences similar to previously published work, they decided to explain their data along a different line of thinking. They set out to prove that the negative MR and the aperiodic fluctuations have nothing to do with conventional interference corrections (WL, UCF), but mainly originate from the change in the density-of-states (DOS) near the Fermi energy E_F. In order to support their statement, they not only measure the equilibrium conductance but study the differential conductance $dI/dV(V)$ as a function of applied bias V, too. Any change in dI/dV is assumed to originate from a change of the DOS. This interpretation is very problematic, because of the low-Ohmic contacts to the nanotubes and the four-terminal measurements. Only in the opposite limit with *high-Ohmic* contacts is it possible to measure exclusively the DOS. One has to make sure that the contacts (or at least one contact) act as tunneling contacts determining the total resistance locally.

Lee *et al.* find in two MR measurements particular field values at which the measured resistance is practically temperature independent (7 T for sample S1 and 4 T for sample S2). It is quite interesting that the corresponding resistance value are close to the predicted value of 6.4 kΩ for a perfect nanotube. However, this cannot be taken as a proof for ballistic transport in the nanotubes in agreement with the prediction $G = 2G_0$ for an ideal tube. Following the arguments of Lee *et al.*, we could equally well take another data point of the S2 data (see inset of Fig. 2 of Lee *et al.*), where R is also practically T independent at 1.8 T. According to Lee *et al.* this would mean metallic (and ballistic) behavior, this time, however, with a resistance of 7.2 kΩ in contradiction with $G = 2G_0$.

Measuring dI/dV, Lee *et al.* have observed pseudogaps of order 1.5 mV for certain field values. The authors realize that these gaps are an order of magnitude too small to be explained by theory (i.e., the separation between 1D subbands of an ideal nanotube). Moreover, they conclude their paper by mentioning that "the most unusual observation is the existence of aperiodic fluctuations of the MR in perpendicular field totally absent in the theoretical predictions." In our opinion, the conclusion should have been that the measurements of Lee *et al.* cannot be explained by simple DOS features obtained from a tight-binding band-structure calculation.

In view of the authors' own summary, their main claim that ''the aperiodic fluctuations and negative magnetoresistance mainly originate from the change of the density of states near the Fermi level with magnetic field, rather than a quantum interference effect'' is quite speculative. The authors provide no support for this claim, they have not even tried to demonstrate that their data cannot be understood in the framework of conventional quantum interference corrections.

In conclusion, the paper by Lee *et al.* does not prove that the observed MR in MWNT's is mainly due to DOS effects, it is rather in support of previous interpretations which proved that interference corrections are important in MWNT's.[2–7] Finally, let us emphasize that we do not claim that DOS effects are unimportant in nanotubes at all. According to the Einstein relation the conductance is a product of the DOS and the diffusion coefficient D. In the conventional theory of quantum corrections to the Drude resistance, the main effect of interference is to change D, while the interaction enters in to the DOS. This is only an approximation valid for small corrections. Because corrections are large in MWNT's, the two contributions cannot easily be separated anymore.

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