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Consistent picture of strong electron correlation from magnetoresistance and tunneling conductance measurements in multiwall carbon nanotubes

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Both the magnetoconductance and the nonlinear differential conductance of multiwall carbon nanotube ropes have been studied at low temperture. Suppression in the differential conductance was observed at low bias voltages and at low temperatures, indicating the formation of a Coulomb gap. The magnetoconductance was found to follow a scaling law at both high and low temperatures, but with different mechanisms. The analysis of the data provides a sign of a non-Fermi-liquid-like behavior through magnetotransport measurement.

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While it has been clear that the electrons in a single wall carbon nanotube form a Luttinger liquid,[1] it remains unclear as to what picture should be used to describe the electrons in a multiwall carbon nanotube (MWNT). There are two kinds of experiment pointing toward two different pictures. The tunneling conductance of a MWNT exhibits a power-law-like suppression at low energies,[2] showing the sign of electron-electron (*e*-*e*) strong correlation. The intepretation of the power law might need a nonperturbative treatment on the effect of *e*-*e* interaction in a disordered environment.[3,4] In the second kind of experiment probing the magnetotransport properties of MWNT,[5–7] however, many aspects, including the Aharomov-Bohm oscillation, the universal conductance fluctuation, etc., all point indicate that electrons in a MWNT form a comventional diffusive system, describable within the framework of weak-localization theory, wherein the effect of *e*-*e* interaction can be treated as a perturbation. To clarify the controversy regarding the role of *e*-*e* interaction between the two kinds of experiments, further investigation is needed.

In this paper, we report our magnetoresistance (MC) and nonlinear differential conductance measurements on MWNT ropes. The nonlinear differential conductance measurement would mimic to a certain extent the tunneling conductance measurement. We will show that the MC data at high temperatures can be scaled to a single functional form as predicted by the theory of weak localization. The MC data at low temperatures, although they can also be scaled to the same form, bear a slightly different mechanism in which the electron motion is via hopping instead of diffusion. We believe that the mechanism change is caused by the formation of a Coulomb gap at low temperatures. The scaling law of MC in the presence of the Coulomb gap is a consequence of quantum interference of the electron's wave function in the variable range hopping regime.

The MWNTs used in this study were synthesized by chemical vapor deposition.[8] High-resolution transmission electron microscopy analysis shows that the MWNTs are around ∼30 nm in diameter. They are aligned, and reach several millimeters in length. Thin bundles of MWNTs were selected and laid down on a sapphire substrate. Then three gold wires of diameter ∼10 μm and interval distances of also ∼10 μm were placed perpendicular to the bundle, serving as the mask. After evaporating a gold film onto the substrate, four electric contacts were obtained. The resistance of the samples was measured by using a standard lock-in technique in a magnetic field roughly parallel to the tube axis (note that the tubes in the bundle are only roughly aligned).

Figure 1(a) show the conductance as a function of magnetic field at several different temperatures. In agreement with earlier results,[6,7] we observed a positive MC, i.e, the conductance increases with increasing magnetic field.

In the theory of weak localization, the positive MC is ascribed to the dephasing effect of the electron's wave function by a magnetic field, i.e., the magnetic field breaks down the weak localization. For the case of two-dimensional weak localization (2DWL), the MC is given by:

$$\Delta\sigma(H,T)=\sigma(H,T)-\sigma(0,T)=\frac{e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{1}{x}\right)+\ln x\right], \tag{1}$$

where ψ is the digamma function, $x=H/H_\phi$, and H_ϕ is the characteristic "phase breaking field" which is defined as

$$H_\phi=\frac{\hbar}{4eD\tau_\phi}, \tag{2}$$

with D, the elastic diffusive constant, and τ_ϕ the phase coherence time related to the inelastic and spin-spin scattering processes.

Since in Eq. (1) H_ϕ is the only parameter depending on temperature, the MC data at different temperatures are expected to collapse onto a single functional form of $\Delta\sigma(H,T)=F(H/H_\phi)$ as defined in Eq. (1), if a proper H_ϕ is chosen for the data at each temperature. Fig. 1(b) shows that our data do follow a scaling law.

According to the theory of 2DWL, we can determine the phase coherence length $L_\phi=\sqrt{D\tau_\phi}$ from the scaling parameter H_ϕ, thus determining the inelastic scattering time τ_ϕ. In such a theoretical framework, τ_ϕ should vary with temperature in a power law of $\tau_\phi\sim T^{-p}$, with p depending on the dominant mechanism of dephasing scattering. The ob-

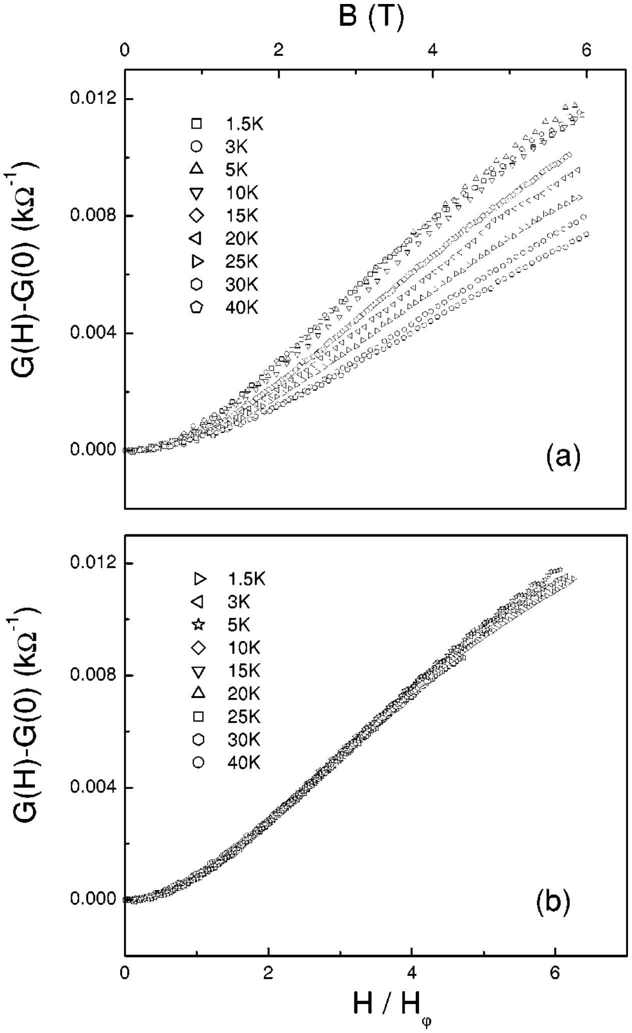

FIG. 1. (a) The magnetoconductance (MC) of multiwall carbon nanotube samples as a function of the magnetic field parallel to the ropes at different temperatures. (b) The data as a function of H/H_ϕ. Above 15 K, the MC for different temperatures is scaled onto a universal curve over the entire field range.

tained H_ϕ are plotted against T in Fig. 2, showing a linear temperature dependence above 10 K, in agreement with the previous experimental results.[6] This result, i.e., $p=1$, implies that *e-e* scattering is the dominant scattering mechanism above 10 K.

We obtained $L_\phi \sim 10$ nm even at 10 K, being comparable to the magnetic length $L_B = \sqrt{\hbar/eB}$ at 6 T. Thus this can well explain why the data of MC can be well described by the theory of WL even at high magnetic field above 10 K. However, the 2DWL picture is correct only at temperatures above ~ 10 K. Below 10 K, the temperature dependence of H_ϕ deviates from its high-temperature $p=1$ trend. In the raw MC data, a downward deviation from the temperature-dependent trend can also be noticed below ~ 10 K, as shown in Fig. 3.

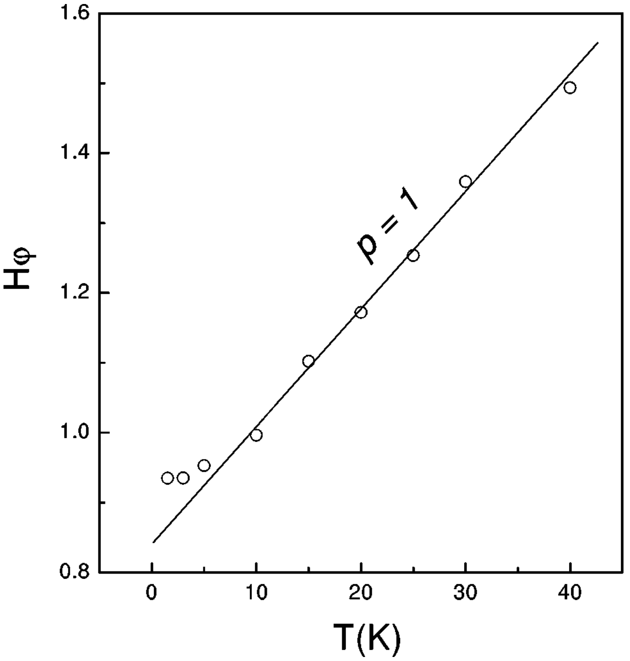

FIG. 2. The scale parameter H_ϕ obtained from the fitted magnetoconductance as a function of temperature. Below 10 K, the H_ϕ deviate from the linear dependence.

Let us see if the low-temperature deviation is an effect of *e-e* interaction. In conventional perturbation theory, the suppression in MC due to *e-e* interaction, $\Delta\sigma_{e-e}$, is a function of the dimensionless parameter $h=(g\mu_B B/k_B T)$, i.e.,[9]

$$\Delta\sigma_{e-e} = -\frac{e^2}{2\pi^2\hbar}\frac{F}{2}g(h), \tag{3}$$

where F is the Coulomb Screening constant, and $g(h)$ is

$$g(h) = \int d\omega \frac{d^2}{d\omega^2}\left[\omega\frac{1}{e^\omega - 1}\ln\left|1-\frac{h^2}{\omega^2}\right|\right] \tag{4}$$

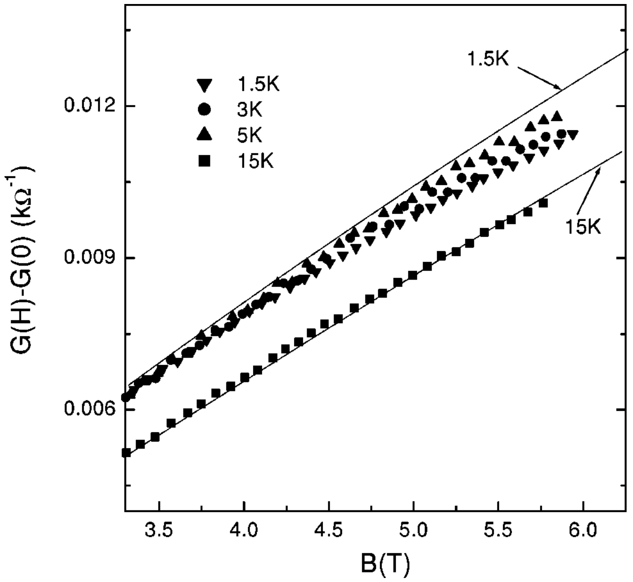

FIG. 3. Magnetoconductance (MC) as a function of magnetic field for MWNTs samples at different temperatures T=1.5, 3, 4.2, and 15 K. Lines are the fits by Eq. (2) to data at low magnetic field, $T=1.5$ and 15 K. At low temperature and higher magnetic field, the negative MC contribution from the *e-e* interaction produced a downturn deviating from the weak localization theory results.

We find that this functional form cannot account for our MC data at low temperatures and in high magnetic fields, In fact, the MC at 1.4 K is even smaller than that at 4 K (Fig. 3), despite that these data in low magnetic fields can still be scaled after properly choosing the H_ϕ [as shown in Fig. 1(b)].

In the following we will show that the deviation represents a crossover of the electron system from weak to strong localization due to strong e-e interaction. Electron-electron interaction is a very interesting and important issue in disordered systems that affects the transport properties of the electrons. Two factors can usually enhance the Coulomb interaction: low dimensionality and disordering. In particular, when the localization length of the electron wave function ξ becomes smaller than the phase-coherence length L_ϕ, the electron's motion will crossover from diffusion to hopping. Pollak[10] and Srinivasan[11] first showed that the unscreened Coulomb interaction in localized systems would deplete the single particle's density of states near the Fermi level E_F. Effros and Shklovskii[12] pointed out that this depletion would cause the formation of a Coulomb gap and lead to a hopping resistance of the form $R \propto \exp(T_0/T)^{1/2}$. The low-temperature resistance of our MWNTs seems to follow this behavior,[13] indicating that the electrons undergo a crossover from weak to strong localization below $\sim$15 K.

For comparison, and also to clarify the seemingly discrepant roles of *e*-*e* interaction in magneto-transport and tunneling measurements, we have measured the differential conductance dI/dV on the same sample as used for the MC measurement, thinking that such a measurement would involve the tunneling processes across the defects and at the contacts. Figure 4(a) shows a series of dI/dV versus V curves measured at different temperatures. Below 10 K, we observed an obvious zero-bias anormaly, i.e., a suppression in differential conductance at low bias voltages. The depletion of the density of states at low energies is always regarded as a signature of *e*-*e* interaction,[14] in accordance with the gradual opening of a Coulomb gap at low temperatures. At some fixed temperatures, we have also measured the dI/dV versus V curves in several different fields. The results are shown in Fig. 4(b). It seems that, while the whole curves shift with the magnetic field, the overall feature of the Coulomb gap remains unchanged. For the MC data taken at fixed bias voltages, therefore, the effect of *e*-*e* interaction will be largely eliminated so long as the zero-field conductance is subtracted, though a deviation of H_ϕ from its high temperature $p=1$ trend can still be seen. Our results indicate that the *e*-*e* interaction and the dephasing by a magnetic field are two nearly independent mechanisms that affect the electron properties of MWNT's. This gives us a consistent picture to understand the seemingly contradictory behaviors of *e*-*e* interaction on magnetotransport and tunneling measurements as mentioned in the introduction.

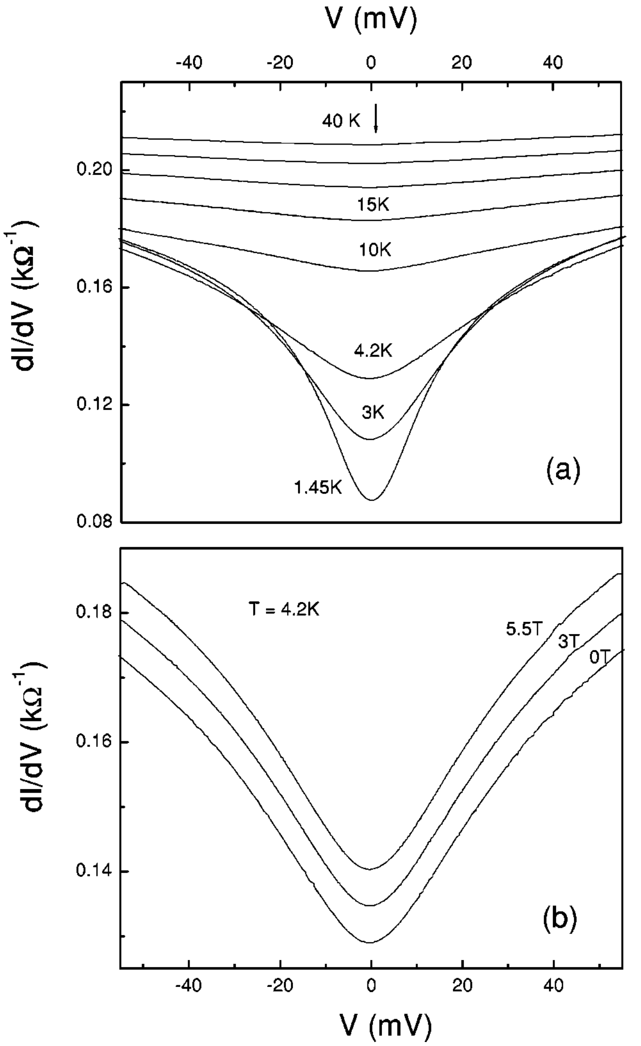

FIG. 4. (a) The dI/dV of multiwall carbon nanotubes samples as a function of V for various temperatures. At low temperatures, the differential conductance at low bias voltages is suppressed, indicating the formation of a Coulomb gap. (b) dI/dV vs V at 4.2 K for different magnetic fields $B=0{,}3$, and 5.5 T, respectively.

Further discussion of the low-temperature MC behavior would involve the effect of *e*-*e* interaction in the variable-range-hopping (VRH) regime. Similar to the MC behavior in 2DWL, the positive MC in the VRH regime is also caused by the dephasing effect of the magnetic field on the quantum interference between many possible hopping paths.[15] By using a critical percolation resistor model, Sivan *et al.*[16] found that the MC in the VRH regime can be scaled if using Φ_M/Φ_0 as the variable, where $\Phi_M = HR_M{}^{3/2}\chi^{1/2}$ is the flux through an effective area of the order $R_M{}^{3/2}\chi^{1/2}$, and R_M is the hopping distance, χ is the distance between impurities, and Φ_0 is the quantum flux. Here the hopping length R_M plays the same role as the phase coherence length L_ϕ does in 2DWL. In the VRH regime, therefore, the MC can also be scaled by a single parameter $H/H_\phi^{VRH}(T)$, where H_ϕ^{VRH} is determined by the hopping length instead of by the phase coherence length. This explains why all of the MC data, below and above $\sim$15 K, can be scaled onto a same functional form as shown in Fig. 1(b), despite that the mechanisms behind them are different.

For an analytic description of our MC data at low temperatures, it would require a nonperturbative theory for the *e*-*e* interaction, similar to that involves in a Coulomb gap[4] or a Coulomb blockade mechanism[3] to explain the non-Fermi-liquid-like behaviors in MWNTs.[2,13]

In summary, we have shown that the MC behavior in MWNTs is modified by the e-e interaction at low temperatures, which is in consistency with the other experimental observations such as the tunneling and thermoelectric power measurements on this kind of material. We have pointed out that the explanation of the detailed MC behavior would probably requires a nonperturbative theory.

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