THEORY OF QUANTUM TRANSPORT IN CARBON NANOTUBES

- Absence of Backscattering and Inter-Wall Conductance -

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A carbon nanotube is a rolled two-dimensional graphite sheets with a nano-meter size diameter discovered by Iijima [1]. Characteristic and essential features of its electronic properties are obtained best in an effective-mass scheme in which the electron motion is equivalent to that of a neutrino or a relativistic Dirac electron with vanishing rest mass [2,3]. In particular, the neutrino description leads to extremely interesting properties of the electron transport.

For potential scattering, in particular, it was shown that in metallic nanotubes there is no backscattering even in the presence of scatterers unless their potential range is smaller than the lattice constant of a two-dimensional graphite [4,5]. When the Fermi level moves away from the energy range where only linear bands are present, interband scattering comes into play because of the presence of several bands at the Fermi level [6]. Even in such a case, a perfectly conducting channel transmitting through the system without being scattered back has been shown to exist and the conductance is always larger than $4e^2/h$.

The absence of backscattering is related to the presence of a topological singularity of Hamiltonian giving rise to Berry's phase under a rotation around the origin in the wave-vector space [5]. It is related also to the special kind of time reversal symmetry present in the effective-mass Hamiltonian [6]. This symmetry can be destroyed by a magnetic field perpendicular to the axis, an Aharonov-Bohm magnetic flux (which is equivalent to finite curvature effects and lattice deformation), the presence of scatterers with potential range much smaller than the lattice constant, a higher-order **k.p** term giving rise to a trigonal warping of the band, inelastic scattering destroying phase coherence, etc.

We performed extensive numerical calculations of the conductance of a metallic nanotube as a function of the length in the presence of such symmetry breaking perturbations such as inelastic scattering [6], a magnetic field and flux [7], short-range scatterers [8], and trigonal warping [9]. The results show that the perfect channel can easily be destroyed even by a very small perturbation when there are several bands at the energy, while it is very robust in the energy range of metallic linear bands. Similar results were obtained for phonon scattering at room temperature [10]. Effects of the symmetry change due to various perturbations were demonstrated also by the study of the degree of the localization in the presence of Aharonov-Bohm magnetic flux [11].

In multi-wall carbon nanotubes the lattice of adjacent tubes is incommensurate as in double-wall tubes [12,13]. One important issue is effects of inter-tube transfer on electronic properties of constituent single-wall nanotubes. Some experimental attempts of the measurement of the inter-tube conductance in telescoping tubes were reported [14,15]. Effects of inter-tube interactions on transport can be studied in model double-wall tubes consisting of metallic outer and inner tubes in a nearest-neighbor tight-binding model including only π orbitals [16-18].

The inter-tube transfer at each lattice site oscillates around zero in a complex plain as a function of position in a quasi-periodic manner and therefore cancels each other when being summed up. The cancellation is not perfect in the presence of sharp edges, giving rise to an inter-tube conductance much smaller than e^2/h (typically 10^{-4} e^2/h) and determined by the structure at edges. The conductance exhibits a wild and almost irregular oscillation as a function of the length with average and fluctuations independent of the length due to the change of the edge structure. The importance of edges can be demonstrated by the fact the conductance decreases rapidly and vanishes when the inter-wall coupling is varied smoothly over the distance of the order of the lattice constant of the two-dimensional graphite. Further, the cancellation becomes incomplete in the presence of scatterers, showing that inter-wall conductance is induced by disorder [19].

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