Coupling of Spin and Orbital Motion of Electrons in Carbon Nanotubes,

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Recommended with a Commentary by Leonid Glazman, Yale University

The spin-orbit coupling till recently was commonly presumed negligible in carbon nanotubes (CNT) due to the lightness of carbon atom and symmetries of flat graphene. Indeed, before the work of Kuemmeth *et al*, the interpretation of the majority of experiments with charge carriers in CNTs assumed the independent spin and orbital degeneracies of the electron states in a CNT.

The approximate four-fold degeneracy of single-particle states was seen in measurements of the spatial quantization of the conductance of a CNT well-connected to the leads, and was inferred also from the electron addition spectra in the Coulomb blockade regime (typical for samples with poor connection of a CNT to the leads – "closed" quantum dots). Observation of the conductance enhanced by orbital Kondo effect, compatible with the $SU(4)$ symmetry of single-particle states in CNT-based quantum dots, was also reported in the recent years.

One should bear in mind though that the addition spectra for quantum dots containing even moderate number of electrons, measure the energy difference between quite complicated many-body states. The enhancement of conductance by Kondo effect may be observed in transport through an "open" quantum dot containing a single electron, but the enhancement actually is not that sensitive to the presence of the exact $SU(4)$ symmetry. [References to the experimental and theoretical works devoted to the addition spectra and Kondo effect may be found, *e.g.*, in V.V. Deshpande and M. Bockrath, Nature Physics **4**, 314 (2008) and A. Makarovski *et al*, Phys. Rev. B **75**, R241407 (2007), respectively.]

Contrary to the previous measurements, the experiment of Kuemmeth *et al* targeted directly the spectra of single-particle states (electrons and holes) in closed quantum dots formed in a high-quality CNT. The experimental results clearly show the presence of spin-orbit interaction due to the curvature of the tube which destroys the four-fold degeneracy of states in the absence of magnetic field.

Kuemmeth *et al* were experimenting with a very clean semiconducting CNT, addressing specifically the states of a single electron or a single hole by means of electron transport spectroscopy of a quantum dot formed within the CNT. Peaks in the differential conductance of the quantum dot as a function of the source-drain bias yielded information about the energies of the excited states in the dot. These energies were affected by a magnetic field applied along the axis of the CNT. The CNT diameter estimated from the spectroscopic data was $d \approx 5$nm.

The first striking observation of Kuemmeth *et al*, as mentioned above, was the absence of the four-fold degeneracy of electron states at zero magnetic field. Instead, two two-fold degenerate states were found. The splitting between the two pairs is an indication of the spin-orbit interaction (which preserves the Kramers degeneracy). The value of the splitting $\Delta_{SO} \approx 0.37$ meV is consistent with the estimates which account for the atomic spin-orbit interaction energy $\Delta_{\rm at}$ and for the curvature of the graphene sheet folded into CNT ($\Delta_{SO} \propto \Delta_{\rm at}/d$).

The magnetic field dependence of the energy levels also allowed the authors to identify two types of states, one with the parallel and another with an anti-parallel orientation of the orbital and spin magnetic moments. These two types have different sensitivity to the magnetic field and different energies due to the spin-orbit interaction.

Further confirmation of the spin-orbit interaction effect came from the observed lack of symmetry between the electron and hole states in the presence of a magnetic field.

The findings of Kuemmeth *et al* may have importance for the many-body physics too: the presence of spin-orbit interaction affects the classification of many-body states. Specifically, it appears from the data of Kuemmeth *et al* that the two-electron ground state is a Slater determinant of two single-electron states each of which have parallel orbital and spin magnetic moments. Clearly this state is different from a spin-singlet or spin-triplet state realized in the absence of spin-orbit interaction.