TT 26: Transport: Graphene and Carbon Nanotubes

Time: Wednesday 14:00–19:00 Location: HSZ 03

Invited Talk TT 26.1 Wed 14:00 HSZ 03
Nanotube and Graphene ElectroMechanics — •Adrian Bachtold — CIN2 (CSIC-ICN) Barcelona, Campus UAB, Spain

Carbon nanotubes and graphene have attracted a lot of attentions as high-frequency mechanical resonators. For instance, nanotube resonator devices hold promise for ultralow mass detection or quantum electromechanical experiments. However, the detection of the mechanical vibrations remains very challenging. In this talk, I will present a novel detection method of the vibrations of nanotubes and graphene, which is based on atomic force microscopy. This method enables the detection of the resonances up to 3.1 GHz with subnanometer resolution in vibration amplitude. Importantly, it allows the imaging of the mode-shape for the first eigenmodes. I will also report on a new artificial nanofabricated motor in which one short nanotube moves relative to another coaxial nanotube. The motion is shown to be controlled by how the atoms are arranged within the two nanotubes. The motion is actuated by imposing a thermal gradient along the device, allowing for sub-nanometer displacements. This is, to our knowledge, the first experimental demonstration of displacive actuation at the nanoscale by means of a thermal gradient.

TT 26.2 Wed 14:30 HSZ 03
Quantum spin Hall state in gapless graphene? — •Martina Hentschel and Grigory Tkachov — MPI für Physik komplexer Systeme, Dresden

We demonstrate the possibility of a quantum spin Hall state in a two-dimensional gas of massless Dirac fermions as is realized in graphene [1]. To this end we use a generalized zigzag-confinement model that admits a spin-orbit interaction. At a certain critical strength the spin-orbit coupling induces a phase transition of the quantum-spin-Hall type. It is characterized by the existence of a novel type of edge states consisting of a Kramers pair of counter propagating modes with opposite spin orientations (i.e. exhibiting spontaneous quantum Hall effects of opposite signs). These edge states are capable of accumulating an integer spin. They exist without any excitation gap in the bulk, due to which our system stands out among other quantum spin Hall systems studied earlier [2-4]. We show that the local density of states is discontinuous at the transition and its energy dependence reflects the phase diagram of the system.

[1] G. Tkachov and M. Hentschel, arXiv: 0803.0713.
[2] C. L. Kane and E. J. Mele, Phys. Rev. Lett. **95**, 226801 (2005).
[3] B. A. Bernevig and S. C. Zhang, Phys. Rev. Lett. **96**, 106802 (2006).
[4] M. König, S. Wiedmann, C. Brüne, A. Roth, H. Buhmann, L. W. Molenkamp, X.-L. Qi, and S.-C. Zhang Science **318**, 766-770 (2007).

TT 26.3 Wed 14:45 HSZ 03
Transport properties of the graphene edge state — •Michael Wimmer, Inanc Adagideli, and Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg

A graphene edge in zigzag configuration supports a localized state, the graphene edge state. Despite being localized at the graphene boundary, recent numerical studies within the nearest-neighbor tight-binding model found that transport in the graphene edge state is influenced little by edge defects [1].

We investigate systematically the transport properties of the graphene edge state for corrections to the nearest-neighbor tight-binding model. In particular we find that the nearest-neighbor tight-binding model—the paradigm model of graphene—is not suitable for describing edge state transport, as exponentially small corrections (such as next-nearest neighbor hopping, see also Ref. [2]) alter the transport properties of the edge state fundamentally.

[1] F. Muñoz Rojas *et al.*, Phys. Rev. B **74**, 195417 (2006), L. Zârbo *et al.*, Europhys. Lett. 80, 47001 (2007).
[2] M. Wimmer *et al.*, Phys. Rev. Lett. **100**, 177207 (2008).

TT 26.4 Wed 15:00 HSZ 03
Exchange phenomena in transport across graphene armchair nanoribbon quantum dots — •Sonja Koller[1], Leonhard Mayrhofer[1,2], and Milena Grifoni[1] — [1]Universität Regensburg — [2]Fraunhofer IWM Freiburg

Taking into account interaction effects, we have investigated spectrum and transport properties of finite size graphene armchair nanoribbons (ACNRs). In wide ribbons, the long-ranged part of the Coulomb interaction dominates, yielding charging and spin-charge separation effects. For narrow ribbons, short-ranged processes become relevant. Those can involve not only two bulk electrons, but also one bulk electron and one electron localized in an edge state, which arises at both zig-zag ends of the stripe. In particular, this edge-bulk interaction strongly influences spectrum and transport properties of the system. In transport, the most prominent feature is the occurrence of a pronounced negative differential conductance for a completely symmetric, unpolarized setup. Further, we discuss the transport characteristics of ACNRs in magnetic field and with collinearly polarized contacts.

TT 26.5 Wed 15:15 HSZ 03
Time dependent transport in graphene nanosystems — •Viktor Krückl[1], Christoph Kreisbeck[1], and Tobias Kramer[1,2] — [1]Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg — [2]Department of Physics, Harvard University, Cambridge, MA 02138, USA

In recent experiments the Quantum Hall Effect in graphene is measured for high magnetic fields leading to numerous different filling factors. In order to characterise these effects, we investigate the local density of states for the massless Dirac Hamiltonian in crossed electric and magnetic fields. We predict a unique substructure for each Landau level and present analytical expressions to describe their composition. For more complex setups we present an algorithm which solves the time dependent problem. The numerical data corresponds up to a very high accuracy to the aforementioned analytically solvable problem. Within this computational scheme also other phenomena like the Zitterbewegung can be studied.

15 min. break

TT 26.6 Wed 15:45 HSZ 03
Functional RG on graphene nanodisks — •Michael Kinza, Jutta Ortloff, and Carsten Honerkamp — Universität Würzburg, Institut für Theoretische Physik und Astrophysik

Graphene-nanodisks are nanometer-sized graphene structures with a closed edge. They are promising candidates for future nanoelectronic devices. In a tight-binding approximation trigonal zigzag nanodisks with size N (which is proportional to the number of edge atoms) have 2N-fold degenerated zero-energy-states. By using the functional renormalization group an effective Hamiltonian for these zero-energy-states is derived and used to explore spin-resolved transport through the nanodisks coupled to metallic electrodes in the coulomb blockade regime.

TT 26.7 Wed 16:00 HSZ 03
A theory of ballistic transport in disordered graphene — •Alexander Schuessler[1], Pavel Ostrovsky[1], Igor Gornyi[1], and Alexander Mirlin[1,2] — [1]Institut für Nanotechnologie, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany — [2]Institut für Theorie der Kondensierten Materie, Universität Karlsruhe, 76128 Karlsruhe, Germany

We develop an analytic theory of ballistic electron transport in disordered graphene in a "short-and-wide"geometry [1]. Considering a sample of a large width W, we analyze the evolution of the conductance, the shot noise, and the full statistics of the charge transfer with increasing length L, both at the Dirac point and at a finite gate voltage. The transfer matrix approach combined with the disorder perturbation theory and the renormalization group is used. We also discuss the crossover to the diffusive regime and construct a "phase diagram" of various transport regimes in graphene. Our analytical results are in agreement with experimental observations [2,3].

[1] A. Schuessler et al., arXiv: 0809.3782.
[2] R. Danneau et al., Phys. Rev. Lett. **100**, 196802 (2008).
[3] L. DiCarlo et al., Phys. Rev. Lett. **100**, 156801 (2008).

TT 26.8 Wed 16:15 HSZ 03
Tomonaga-Luttinger liquid parameters of magnetic waveguides in graphene — •W. Häusler[1,2], A. De Martino[1,3], T. K. Ghosh[1,4], and R. Egger[1] — [1]Institut für Theoretis-

che Physik, Heinrich-Heine-Universität, D-40225 Düsseldorf, Germany — [2]Physikalisches Institut, Albert-Ludwigs-Universität, D-79104 Freiburg, Germany — [3]Institut für Theoretische Physik, Universität zu Köln, Zülpicher Strasse 77, D-50937 Köln, Germany — [4]Department of Physics, Indian Institute of Technology-Kanpur, Kanpur 208016, India

Electronic waveguides in graphene formed by counterpropagating snake states in suitable inhomogeneous magnetic fields are shown to constitute a realization of a Tomonaga-Luttinger liquid. Due to the spatial separation of the right- and left-moving snake states, this non-Fermi liquid state induced by electron-electron interactions is essentially unaffected by disorder. We calculate the interaction parameters accounting for the absence of Galilei invariance in this system, and thereby demonstrate that non-Fermi liquid effects are significant and tunable in realistic geometries.

TT 26.9 Wed 16:30 HSZ 03

Universal conductivity and shot noise in graphene quantum billiards — •Adam Rycerz[1,2] and Michael Wimmer[1] — [1]Institut für Theoretische Physik, Universität Regensburg, D-93040, Germany — [2]Marian Smoluchowski Institute of Physics, Jagiellonian University, Reymonta 4, PL-30059 Kraków, Poland

We study the ballistic electron transport through two types of quantum billiards in undoped graphene: a finite section of the Corbino disc, and a long insulating nanoribbon attached to the leads in a way that the current is flowing *perpendicularly* to the main ribbon axis. We found such a *closed* and an *open* billiard behave similarly when changing geometrical parameters. Namely, both billiards show the *pseudodiffusive regime*, in which the conductance is equal to that of the dissipative medium characterized by the conductivity $\sigma_0 = 4e^2/\pi h$, whereas the Fano factor $\mathcal{F} = 1/3$. In the opposite *tunneling regime*, the conductance shows power-law decay with a distance between leads, and the shot-noise is Poissonian ($\mathcal{F} = 1$). Additionally, in the crossover region between tunneling and pseudodiffusive regimes, the conductance $G \approx (1-\mathcal{F})\times 4e^2/h$, what shows the transport is dominated by a single evanescent mode with the fourfold (*spin* and *valley*) degeneracy.

TT 26.10 Wed 16:45 HSZ 03

Conductance of graphene ribbons in the presence of chemical adsorbates — Petra Dietl[1], •Georgo Metalidis[1], Pablo San-Jose[1,2], Dmitri Golubev[1], Elsa Prada[1,2], Henning Schomerus[2], and Gerd Schön[1] — [1]Institut für Theoretische Festkörperphysik and DFG-Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany — [2]Department of Physics, Lancaster University, Lancaster, LA1 4YB, United Kingdom

Chemical adsorbates on a graphene sheet have a large influence on its transport properties, making graphene a candidate system for chemical sensors. The influence of adsorbates on the graphene conductivity is twofold. On one hand they can dope the graphene sheet, thus increasing its conductance, while on the other hand the adsorbates form scattering centers that will decrease the conductance. We have investigated the interplay between these competing effects and observed some interesting properties, one of them being an extremely long localization length for certain types of adsorbates.

TT 26.11 Wed 17:00 HSZ 03

Band gap engineering of carbon nanotubes using pulsed high magnetic fields — •Sungho Jhang[1], Yurii Skourski[2], Dominik Preusche[1], Joachim Wosnitza[2], and Christoph Strunk[1] — [1]Institute of Experimental and Applied Physics, University of Regensburg, Germany — [2]Dresden High Magnetic Field Laboratory, Forschungszentrum Dresden-Rossendorf, Germany

Due to the Aharonov-Bohm (AB) phase generated around the nanotube circumference, the band structure of carbon nanotubes is expected to be strongly influenced by the magnetic field. We report magnetotransport experiments on ballistic carbon nanotubes up to 60 Tesla. We present that the band gap of carbon nanotubes is modulated with the application of magnetic field parallel to the tube axis, and show how initially metallic (or semiconducting) tube evolves into semiconducting(or metallic) tube as we increase the magnetic field. In addition, we find fine structures in the magnetoconductance and explain the phenomena due to the beating effect in the AB interference between clockwise and counterclockwise electronic motions around the tube.

15 min. break

TT 26.12 Wed 17:30 HSZ 03

Exchange effects in single wall carbon nanotube quantum dots — •Christoph Schenke, Sonja Koller, Leonhard Mayrhofer, and Milena Grifoni — Institute for Theoretical Physics, University of Regensburg

Various transport experiments have been performed on single wall carbon nanotube quantum dots (SWNTs) in recent years. Some of them revealed exchange effects - as predicted in a mean-field approach by [1]. Using the powerful technique of bosonization we were able to derive the full spectrum of interacting finite-size SWNTs. The long- and short-range parts of the Coulomb interaction are responsible for charging and exchange effects, respectively. In particular we find that the ground state of a SWNT with two electrons in the last shell can be a triplet or a singlet, depending on the magnitude of the exchange coupling. The latter is at largest for small diameter SWNTs [2].

An additionally applied parallel magnetic field induces a Zeeman-splitting between the energy levels of the system. We evaluated the current - bias voltage - gate voltage characteristics for zero and finite magnetic fields. We found a quantitative agreement with the experimental results in [3] where, in particular, a singlet-triplet crossing by sweeping the magnetic field was observed.

[1] Y. Oreg, K. Byczuk and B.I. Halperin, Phys. Rev. Lett. 85, 365 (2000).

[2] L. Mayrhofer and M. Grifoni, Eur. Phys. J. B63, 45 (2008).

[3] S. Moriyama et al., Phys. Rev. Lett. 94, 186806 (2005).

TT 26.13 Wed 17:45 HSZ 03

Ultra-sensitive carbon nanotube resonant tunneling transistor — Soren Andresen[1,3], •Lorenz Lechner[2], Fan Wu[2], Romain Danneau[2], and Pertti Hakonen[2] — [1]Niels Bohr Institute, Copenhagen, Denmark — [2]Low Temperature Laboratory, Helsinki University of Technology, Helsinki, Finland — [3]Nanoscience Center, University of Copenhagen, Copenhagen, Denmark

We have studied resonant tunneling field-effect transistors (RTFET) made from single-walled carbon nanotube quantum dots in the Fabry-Pérot regime. We show excellent charge sensitivity of $8.0 \cdot 10^6$ e/Hz$^{1/2}$ with a carrier frequency of 719 MHz at 4.2 K. This resolution is comparable to the best values so far reported for radio frequency single electron transistors (RF-SET). Unlike RF-SETs operating in the Coulomb blockade regime our device can work as an electron interferometer up to temperatures of 23 K.

TT 26.14 Wed 18:00 HSZ 03

Coupling between chirality and pseudospin in a 2D Dirac fermion semi-confinement: New type of polarization and electronic functionalities — •Grigory Tkachov and Martina Hentschel — Max Planck Institute for the Physics of Complex Systems, Dresden

We introduce a novel type of polarization - chiral pseudospin polarization (CPP) - that represents a nonmagnetic analogue of electron spin polarization [1]. It can be realized in two-dimensional carbon or semiconductor systems exhibiting massless Dirac fermions of two opposite chiralities. The CPP occurs as a boundary effect arising from a correlation between the chirality and effective spin degrees of freedom, which is unique to time-reversal invariant Dirac fermion confinement. The CPP can be probed by tunneling, resulting in a zero-bias conductance anomaly and a singular particle-hole asymmetric local density of states. We use our findings to interpret recent scanning tunneling experiments on monoatomic graphite steps and outline possible applications motivated by the search for new functionalities brought by Dirac quasiparticles into nanoelectronics.

[1] G. Tkachov and M. Hentschel, arXiv: 0810.0632.

TT 26.15 Wed 18:15 HSZ 03

Ballistic electrons in graphene antidot lattices - a numerical study — •Jan Bundesmann, Jürgen Wurm, Michael Wimmer, Inanc Adagideli, and Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany

Motivated by recent experiments at the University of Regensburg we study quantum transport properties of charged carriers in graphene antidot lattices. To this end we perform numerical quantum transport simulations on a tight-binding honeycomb lattice with antidots cut out of the lattice using recursive Greens function methods.

Our main focus lies on magnetoconductance and weak localization due to scattering from antidots. We find that the magnetic field profile of the weak localization curve is similar to results from semiclassics and random matrix theory of chaotic cavities.

We further discuss the relevance of intervalley scattering on the magnitude of the weak localization peak.

TT 26.16 Wed 18:30 HSZ 03

Symmetry Classes in Graphene Quantum Dots — •Jürgen Wurm[1,2], Adam Rycerz[1,3], Inanc Adagideli[1], Michael Wimmer[1], Klaus Richter[1], and Harold Baranger[2] — [1]Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg — [2]Department of Physics, Duke University, Durham, NC 27708, USA — [3]Marian Smoluchowski Institute of Physics, Jagiellonian University, 30059 Krakow, Poland

In view of the recently increased experimental activity in the field of graphene quantum dots [1-2], the need of a theoretical description of these systems is apparent. In this work we study the symmetry classes of open and closed graphene quantum dots through the conductance and energy level statistics [3]. For an abrupt lattice termination, these properties are well described by the standard orthogonal and unitary ensembles of random matrix theory. For a smooth mass confinement, the Hamiltonian and the scattering matrix are block diagonal in the valley degree of freedom. While the effect of this structure is clearly visible in the conductance of open dots, it is suppressed in the spectral statistics of closed dots, because the intervalley scattering time is shorter than the time required required to resolve a level spacing in the closed systems but longer than the escape time of the open systems.

[1] L.A. Ponomarenko et. al., Science 320, 356 (2008)

[2] C. Stampfer, et. al., Appl. Phys. Lett. 92, 012102 (2008)

[3] J. Wurm, Adam Rycerz, Inanc Adagideli, M. Wimmer, K. Richter, H.U. Baranger, arXiv:0808.1008 (2008)

TT 26.17 Wed 18:45 HSZ 03

Few electrons in magnetic graphene quantum dots — •Wolfgang Häusler[1,2] and Reinhold Egger[1] — [1]Institut für Theoretische Physik, Heinrich-Heine-Universität, D-40225 Düsseldorf, Germany — [2]Physikalisches Institut, Albert-Ludwigs-Universität, D-79104 Freiburg, Germany

We consider inhomogeneous magnetic fields to design quantum islands on graphene structures. Following the well known case of semiconducting quantum dots we investigate two interacting electrons. Without further consideration the Dirac Hamiltonian is ill defined for more than one particle. We solve this issue by projecting on positive energy states as physically justified by the presence of a chemical potential. Results of relatively demanding numerical diagonalizations will be presented for artificial graphene helium.