TT 39: Transport: Graphene 1 (jointly with MA, HL, DY, DS, O)

Time: Thursday 9:30–13:00 Location: BH 334

TT 39.1 Thu 9:30 BH 334

Spin relaxation in graphene induced by adatoms — •Jan Bundesmann and Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany

By means of a recursive Green's function method we study diffusive spin-dependent transport through graphene and graphene nanostructures. Diffusion in graphene mainly originates from charges trapped in the substrate. In addition we assume the presence of adsorbed atoms or molecules. These are the origin of a locally fluctuating spin-orbit coupling. While both intrinsic spin-orbit interaction and spin-orbit coupling induced by electric fields or curvature are rather weak (typically $\mathcal{O}(\mu eV)$), underneath adatoms these values can reach the height of meV. Our results show that adatoms clearly reduce the spin relaxation time in graphene. The ones we obtain are on the order of magnitude as the ones found in experiments ($\mathcal{O}(ns)$).

Depending on the type of adatom, the effect on intrinsic and extrinsic spin-orbit interaction is of different strength. We study how this influences the relaxation of in-plane or out-of-plane polarized spins.

Lastly we plan to address the questions if adatoms tend to relax spins via the Elliot-Yafet or rather via the Dyakonov-Perel mechanism.

TT 39.2 Thu 9:45 BH 334

Emergent Gauge Fields in Bilayer Graphene — •Roland Winkler[1,2,3] and Ulrich Zülicke[4] — [1]University of Basque Country and IKERBASQUE Foundation, Bilbao, Spain — [2]Northern Illinois University, DeKalb, Illinois 60115, USA — [3]Argonne National Laboratory, Argonne, Illinois 60439, USA — [4]School of Chemical and Physical Sciences and MacDiarmid Institute for Advanced Materials and Nanotechnology, Victoria University of Wellington, Wellington 6140, New Zealand

We present a detailed study of the electronic properties of bilayer graphene. Group theory is used to derive an invariant expansion of the Hamiltonian for electron states near the **K** point taking into account the effect of electric and magnetic fields, strain and spin-orbit coupling. We obtain several new gauge fields for band electrons in bilayer graphene, resulting in novel orbital and spin-related effects.

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TT 39.3 Thu 10:00 BH 334

Single-parameter pumping in graphene — •Sigmund Kohler[1], Pablo San-Jose[2], Elsa Prada[1], and Henning Schomerus[3] — [1]Instituto de Ciencia de Materiales de Madrid, CSIC, 28049 Madrid, Spain — [2]Instituto de la Estructura de la Materia, CSIC, 28006 Madrid, Spain — [3]Department of Physics, Lancaster University, Lancaster, LA1 4YB, United Kingdom

The ratchet or pump effect, which is the induction of a dc current by an ac force in the absence of any net bias, represents one of the most intriguing phenomena in non-equilibrium transport. For graphene, one expects that its gapless and chiral nature negatively affects pumping, because it hinders the confinement of electrons. Despite this expectation, a pump mechanism that is particularly efficient in graphene exists [1]: It is based on barriers in which the, say, left half is modulated by an ac gate voltage. Then electrons entering the barrier in evanescent modes from that side may be excited to propagating modes. Evanescent mode entering from the right, by contrast, decay before reaching the driving region. This mechanism is rather efficient in graphene, because all evanescent modes within a certain energy range contribute. The corresponding mechanism in a two-dimensional electron gas works only with modes that fulfill certain resonance conditions, which leads to a much smaller pump current.

[1] P. San-Jose, E. Prada, S. Kohler, and H. Schomerus, Phys. Rev. B **80**, 155408 (2011)

TT 39.4 Thu 10:15 BH 334

Self-consistent theory of the second-harmonic generation in graphene — •Sergey Mikhailov — Institute of Physics, University of Augsburg, 86135 Augsburg, Germany

A self-consistent-field theory of the second-order nonlinear electromagnetic response of graphene is developed. The second-order polarizability and the corresponding second-order self-consistent dielectric response function of graphene are calculated for the first time. The second harmonic generation in graphene is shown to be about two orders of magnitude stronger than in typical semiconductor structures. Under the conditions of 2D plasmon resonances the second harmonic radiation intensity is further increased by several orders of magnitude.

TT 39.5 Thu 10:30 BH 334

The Hubbard model on the bilayer honeycomb lattice with Bernal stacking — •Thomas C. Lang[1], Stefan Übelacker[1], Zi Yang Meng[2], Michael Scherer[1], Carsten Honerkamp[1], Alejandro Muramatsu[3], Fakher F. Assaad[4], and Stefan Wessel[1] — [1]RWTH Aachen, Aachen, Germany — [2]Louisiana State University, Baton Rouge, USA — [3]Universität Stuttgart, Stuttgart, Germany — [4]Universität Würzburg, Würzburg, Germany

Using a combination of quantum Monte Carlo, the functional renormalization group and mean-field theory we study the Hubbard model on the bilayer honeycomb as a model for interacting electrons on bilayer graphene. The free bands consisting of two Fermi points with quadratic dispersions lead to a finite density of states, which triggers the antiferromagnetic instability and spontaneously breaks sublattice and spin rotational symmetry once a local Coulomb repulsion is introduced. We show that the antiferromagnetic instability is insensitive to the inclusion of extended Coulomb interactions and discuss effects on the sublattice magnetization and of finite size systems in numerical approaches.

TT 39.6 Thu 10:45 BH 334

Coulomb drag in graphene via kinetic equation approach — •Michael Schuett[1], Pavel M. Ostrovsky[1,2], Igor V. Gornyi[1,3], Mikhail Titov[4], Boris N. Narozhny[5], and Alexander D. Mirlin[1,5,6] — [1]Institut für Nanotechnologie, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany — [2]L. D. Landau Institute for Theoretical Physics RAS, 119334 Moscow, Russia — [3]A.F. Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia. — [4]School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK — [5]Institut für Theorie der kondensierten Materie, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany — [6]Petersburg Nuclear Physics Institute, 188350 St. Petersburg, Russia.

We calculate the Coulomb drag resistivity at finite temperature for two graphene monolayers within the kinetic equation approach. The emphasis is put on the case of fast electron-electron collisions compared to disorder induced scattering. We obtain the asymptotic behavior of the Coulomb drag resistivity ρ_D both for small chemical potentials (μ_1, μ_2) in the two layers as well as chemical potentials larger than temperature. When only one layer is at the Dirac point the Coulomb drag resistivity is zero. However when approaching the Dirac point of both layers simultaneously, the Coulomb drag resistivity does not vanish as long as $\mu_1 \propto \mu_2 \to 0$. For any finite disorder strength or alternating current Coulomb drag resistivity obeys again $\rho_D(\mu_1 = 0, \mu_2 = 0) = 0$, as expected from the particle hole symmetry argument. When both layers have large chemical potentials we recover the Fermi liquid behavior.

TT 39.7 Thu 11:00 BH 334

Manifestation of electron-electron interaction in the magnetoresistance of graphene — •Johannes Jobst[1], Daniel Waldmann[1], Igor V. Gornyi[2,3], Alexander D. Mirlin[2,4,5], and Heiko B. Weber[1] — [1]Lehrstuhl für Angewandte Physik, Universität Erlangen-Nürnberg, Erlangen, Germany — [2]Institut für Nanotechnologie, Karlsruhe Institute of Technology, Karlsruhe, Germany — [3]A.F. Ioffe Physico-Technical Institute, St. Petersburg, Russia — [4]Inst. für Theorie der kondensierten Materie, Karlsruhe Institute of Technology, Karlsruhe, Germany — [5]Petersburg Nuclear Physics Institute, St. Petersburg, Russia

We investigate the magnetotransport in large area graphene Hall bars epitaxially grown on silicon carbide. In the intermediate field regime between weak localization and Landau quantization the observed temperature-dependent parabolic magnetoresistivity is a manifestation of electron-electron interaction. We can consistently describe the data with a model for diffusive (magneto)transport that covers the crossover to the ballistic regime. We find a temperature-driven crossover related to the reduction of the multiplet modes contributing to electron-electron interaction from 7 to 3 due to intervalley scattering. In addition we find a field-driven crossover from purely diffusive to partially ballistic behavior.

15 min. break.

TT 39.8 Thu 11:30 BH 334

Orbital Magnetism in graphene bulk and nanostructures — •Lisa Hesse, Jürgen Wurm, and Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, Germany

We study the magnetic response of finite and bulk graphene structures due to orbital motion of the charge carriers. Besides a semiclassical approach we use exact quantum mechanical calculus within the Dirac formalism to derive different analytic expressions for the magnetic susceptibility of extended systems at various field regimes. This allows us to study on the one hand edge effects which are accessible through our semiclassical treatment but also to gain profound knowledge of the importance of bulk effects in finite systems. In order to provide an independent confirmation of the theory we also perform numerical calculations on graphene nanostructures based on a tight-binding approximation.

TT 39.9 Thu 11:45 BH 334

Klein paradox for arbitrary spatio-temporal scalar potential barrier and Josephson-like current in graphene — Sergey E. Savel'ev[1], •Wolfgang Häusler[2], and Peter Hänggi[2] — [1]Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom — [2]Institut für Physik Universität Augsburg, D-86135 Augsburg, Germany

We derive the exact time evolution according to the Dirac-Weyl equation, describing a mono-layer of graphene, in the presence of a scalar potential $U(x,t)$ of arbitrary spatial and temporal dependence at normal incidence, $p_y = 0$. This solution shows that the Klein paradox (the absence of backscattering) persists even for arbitrary temporal modulations of the barrier. Moreover, we identify an unusual oscillating current j_y running along the barrier, despite of the vanishing momentum in y-direction. This current exhibits resemblence to the Josephson current in superconductors, including the occurance of Shapiro steps and its sine-like dependence on the phase difference of wave functions.

TT 39.10 Thu 12:00 BH 334

Relaxation in graphene quantum dots — •Christoph Neumann[1], Christian Volk[1,2], Sebastian Kazarski[1], Stefan Fringes[1], Stephan Engels[1,2], Bernat Terres[1,2], Jan Dauber[1,2], Stefan Trellenkamp[2], and Christoph Stampfer[1,2] — [1]JARA-FIT and II. Institute of Physics B, RWTH Aachen, 52074 Aachen, Germany — [2]Peter Grünberg Institut (PGI-8/9), Forschungszentrum Jülich, 52425 Jülich, Germany

Graphene quantum dots (QDs) have received increasing attention over the last years as interesting candidates for the future implementation of spin qbits. Compared to GaAs-based QDs, their smaller hyperfine and spin-orbit coupling promises more favorable spin coherence times. However, while the preparation, manipulation, and read-out of single spins has been demonstrated in GaAs structures, research on graphene QDs is still at an early stage. Although Coulomb blockade phenomena and excited state spectroscopy is already well established, experimental signatures allowing the identification of relaxation times have been hard to trace. Here we report on pulse gating experiments on graphene quantum devices. We will present measurements of the relaxation rates in single-layer graphene QDs. The investigated devices consist of an island with a diameter of 120 nm, 4 lateral graphene gates and 2 charge detectors. From so-called diamond measurements we extract a charging energy of 11 meV and excited state level spacings of 2-4 meV. The gates enable us to tune the tunnelling rates from the GHz down to the low MHz regime. Finally low-bias pulse gate measurements allow us to extract relaxation rates on the order of 50 ns.

TT 39.11 Thu 12:15 BH 334

Minimal tight-binding model for transport in graphene heterojunctions — •Ming-Hao Liu, Jan Bundesmann, and Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany

A real-space Green's function formalism based on a minimal tight-binding model is adopted to efficiently simulate ballistic transport in graphene heterojunctions. The basic idea is to make use of the Bloch theorem along the transverse dimension of the bulk graphene, which greatly reduces the computation load and hence allows experimental sizes in the longitudinal dimension. Numerically, we will show (i) consistency with the existing results based on the effective Dirac theory for chiral tunneling through *pnp* junctions in monolayer graphene (MLG) and bilayer graphene, (ii) good agreement with recent ballistic experiments on *pnp* junctions in MLG, and (iii) new predictions for spin-dependent tunneling through *pn* junctions in MLG in the presence of the Rashba spin-orbit coupling.

TT 39.12 Thu 12:30 BH 334

Quantum Hall effect in graphene with superconducting electrodes — •Markus Weiss, Peter Rickhaus, and Christian Schönenberger — Departement Physik, Universität Basel, Klingelbergstrasse 82, CH-4056 Basel

We report on the realization of an integer quantum Hall system with superconducting electrodes. Graphene was contacted to niobium electrodes that show a critical field of about 4 tesla, where electronic transport passes mainly through quantum Hall edge-states and bulk transport is largely suppressed. We find a magnetic field range of more than one tesla where well developed quantum Hall plateaus coexist with superconductivity in the leads. In high magnetic fields with the electrodes in the normal state we observe plateaus at $G=\nu e^2/h$ for ν=2, 4, and 10. Reducing the magnetic field to below the upper critical field of the electrodes, the conductance on the plateaus shows a sudden increase. Whereas the conductance on the ν=2 plateau increases only by 10%, the increase on the ν=6 and ν=10 plateau is considerably larger with 60% and 80%, respectively. We attribute this conductance enhancement to multiple Andreev reflection processes along the graphene-superconductor interface, that lead to the formation of Andreev edge-states. The observed conductance enhancement of the ν=6 and 10 plateaus is consistent with a doubling of the conductance contribution of the second and third edge-states. We attribute the small conductance increase on the ν=2 plateau to the special nature of the zero energy Landau level, that makes the corresponding edge-state sensitive to the structure of the graphene edge.

TT 39.13 Thu 12:45 BH 334

Klein paradox for arbitrary spatio-temporal scalar potential barrier and Josephson-like current in graphene — Sergey E. Savel'ev[1], •Wolfgang Häusler[2], and Peter Hänggi[2] — [1]Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom — [2]Institut für Physik Universität Augsburg, D-86135 Augsburg, Germany

We derive the exact time evolution according to the Dirac-Weyl equation, describing a mono-layer of graphene, in the presence of a scalar potential $U(x,t)$ of arbitrary spatial and temporal dependence at normal incidence, $p_y = 0$. This solution shows that the Klein paradox (the absence of backscattering) persists even for arbitrary temporal modulations of the barrier. Moreover, we identify an unusual oscillating current j_y running along the barrier, despite of the vanishing momentum in y-direction. This current exhibits resemblence to the Josephson current in superconductors, including the occurance of Shapiro steps and its sine-like dependence on the phase difference of wave functions.
[1] S.E. Savel'ev, W. Häusler, and P. Hänggi, ArXiv: 1107.4983 .