DS 9: Transport: Graphene and Carbon Nanostructures (jointly with HL/MA/TT)

Time: Monday 15:00–18:15 Location: HSZ 204

DS 9.1 Mon 15:00 HSZ 204

Creating and steering highly directional electron beams in graphene — Ming-Hao Liu[1,2], •Cosimo Gorini[1], and Klaus Richter[1] — [1]Institut für Theoretische Physik, Universität Regensburg, Regensburg, Germany — [2]Department of Physics, National Cheng Kung University, Tainan, Taiwan

We put forward a concept to create highly collimated, non-dispersive electron beams in pseudo-relativistic Dirac materials such as graphene or topological insulator surfaces [1]. Combining negative refraction and Klein collimation at a parabolic *pn* junction, the proposed lens generates beams, as narrow as a few Fermi wave lengths, that stay focused over scales of several microns and can be steered by a magnetic field without losing collimation. We demonstrate the lens capabilities by applying it to two paradigmatic settings of graphene electron optics: We propose a setup for observing high-resolution angle-dependent Klein tunneling, and, exploiting the intimate quantum-to-classical correspondence of these focused electron waves, we consider high-fidelity transverse magnetic focusing accompanied by simulations for current mapping through scanning gate microscopy. Our proposal opens up new perspectives for next-generation graphene electron optics experiments.

[1] M.-H. Liu, C. Gorini, K. Richter, arXiv:1608.01730.

DS 9.2 Mon 15:15 HSZ 204

Graphene *p-n* junction in a magnetic field as a valley switch — •Tibor Sekera, Rakesh P. Tiwari, and Christoph Bruder — Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

Low-energy excitations in graphene exhibit relativistic properties due to the linear dispersion relation close to the Dirac points in the first Brillouin zone. Two of the cones located at opposite corners of the first Brillouin zone can be chosen as inequivalent, representing a new *valley* degree of freedom, in addition to the charge and spin of an electron. Using the valley degree of freedom to encode information aroused significant interest, both theoretically and experimentally, and gave rise to the field of *valleytronics*.

We study a graphene *p-n* junction in an out-of-plane magnetic field as a platform to generate and controllably manipulate the valley polarization of electrons. We show that by tuning the external potential giving rise to the *p-n* junction we can switch the current from one valley polarization to the other. We also consider the effect of different types of edge terminations and present a setup, where we can partition an incoming valley-unpolarized current into two branches of valley-polarized currents. The branching ratio can be chosen by changing the location of the *p-n* junction.

DS 9.3 Mon 15:30 HSZ 204

Probing electronic wave functions in a nanotube quantum dot via conductance in a magnetic field — Magdalena Marganska[1], Alois Dirnaichner[1,2], Daniel R. Schmid[2], Peter L. Stiller[2], Christoph Strunk[2], Milena Grifoni[1], and •Andreas K. Hüttel[2] — [1]Institute for Theoretical Physics, Universität Regensburg, Regensburg, Germany — [2]Institute for Experimental and Applied Physics, Universität Regensburg, Regensburg, Germany

The tunneling of electrons through a contact between two systems depends on the overlap of their electronic wave functions. In quantum dots the overlap is often tuned via the height of tunneling barriers. Conversely, in carbon nanotubes the unique combination of cylindrical topology and honeycomb atomic lattice allows for a manipulation of the longitudinal component of the electronic wave function via a parallel magnetic field. The amplitude of the wave function at the point of contact with the leads is directly reflected in the coupling strength. Experimentally, we detect the changes in the electronic wave function through the evolution of conductance resonances corresponding to single particle quantum states with magnetic field. The magnitude of the magnetic field in our experiment, up to 17 T, allows us to confirm our prediction of the very different behaviour of the two valley states. The K' valley states experience a strengthening of the tunnel coupling at low magnetic field, followed by subsequent decoupling. In contrast, the K valley states decouple from the leads monotonically, and coupling becomes unmeasurably small already for moderate magnetic fields.

DS 9.4 Mon 15:45 HSZ 204

Electron-electron interaction correction to tunneling in graphene-graphene nanojunctions — •Matthias Popp, Ferdinand Kisslinger, and Heiko B. Weber — Lehrstuhl für Angewandte Physik, FAU Erlangen-Nürnberg (FAU), Erlangen, Germany.

In weakly disordered conductors, electron-electron interaction is expected to provide a zero-bias anomaly in tunneling characteristics [1]. This purely electronic effect is seemingly suppressed in scanning tunneling spectroscopy experiments on graphene due to momentum mismatch, which requires phonon assisted tunneling. [2,3]. In order to overcome this limitation, we fabricate in-plane graphene-graphene nanojunctions by an electro burning process using epitaxial graphene on SiC as starting material. In some junctions with an overall conductance of about e^2/h we indeed observed a zero-bias anomaly at low temperatures which follows the logarithmic scaling characteristics predicted by *Altshuler* and *Aronov*. These experiments offer the opportunity to study the nonlocal aspects of electron tunneling via manipulation of the environment.

[1] Altshuler, B. L. and Aronov, A. G., *Electron-Electron Interaction in Disordered Conductors*, 1985
[2] Brar, V. W. et al., Applied Physics Letters, 2007, 91, 122102
[3] Zhang, Y. et al., Nature Physics, 2008, 4, 627-630

DS 9.5 Mon 16:00 HSZ 204

Electroluminescence of Graphene Nanojunctions — •Christian Ott, Konrad Ullmann, and Heiko B. Weber — Lehrstuhl für Angewandte Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstr. 7/A3, D-91058 Erlangen, Germany

We report on electroluminescence (EL) detected at graphene nanojunctions, the latter being formed by electroburning of epitaxial graphene ribbons on silicon carbide [1]. The EL shows a broad spectrum with emphasis on the near infrared regime. Its intensity scales with applied current and is temperature independent down to liquid helium temperatures. Surprisingly, we find a weak voltage dependence. The spectrum is similar to blackbody radiation with apparent temperatures well above the damage threshold of graphene and the silicon carbide substrate. A similar phenomenon has already been observed in single atom point contacts [2] and island metal films [3]. There a model was proposed based on hot electron luminescence which goes along with a large mismatch between electron gas temperature and lattice temperature due to a reduced electron-phonon interaction in nanoscopic structures. A critical discussion of the underlying mechanism is provided.

[1] Ullmann et al, Nano Letters 15, 5 (2015)
[2] Downes et al., Applied Physics Letters 81, 7 (2002)
[3] Fedorovich et al., Physics Reports 328 (2000)

DS 9.6 Mon 16:15 HSZ 204

Reversible Photochemical Control of Doping Levels in Supported Graphene — •Marie-Luise Braatz[1,2], Nils Richter[1,2], Hai I. Wang[1], Axel Binder[3], Mischa Bonn[4], and Mathias Kläui[1,2] — [1]Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany — [2]Graduate School of Excellence Materials Science in Mainz (MAINZ), 55128 Mainz, Germany — [3]BASF SE, 67056 Ludwigshafen, Germany — [4]Max Planck Institute for Polymer Research, 55128 Mainz, Germany

The type and density of carriers in graphene are important parameters to control its properties. Based on Terahertz (THz)-spectroscopy and electrical characterization of Nitrogen-doped graphene, we show that the doping level can be optically tuned between the p-type and intrinsic n-type regime [1]. This is achieved photochemically by controlling the dynamical equilibrium between the oxygen adsorption and desorption process via UV laser pulse irradiation treatment [2]. This approach is reversible, easy to use and contact free. This simple method can be used to write doping structures with spatial control by a focused laser beam, not requiring sophisticated nanostructuring to generate doping for instance by gate electrodes that need to be defined at the time of device fabrication.

[1] H. I. Wang, M.-L. Braatz et al., submitted (2016)
[2] S. M. Hornett et al., Phys Rev B 90 (2014)

15 min. break.

DS 9.7 Mon 16:45 HSZ 204

Time evolution of Floquet states in graphene — •Matteo Puviani[1], Francesco Lenzini[1], and Franca Manghi[1,2] — [1]Dipartimento FIM, Università di Modena e Reggio Emilia — [2]CNR - Institute of NanoSciences - S3, Modena

When a time-periodic field is applied to electrons in a lattice the Bloch theorem can be applied twice, both in space and in time, to describe the photon-dressed quasiparticles which are formed. This is the essence of Floquet theory, which has recently attracted a large renewed interest for its ability to describe topological phases in driven quantum systems. The discovery that circularly polarized light may induce nontrivial topological behavior in materials which would be standard in static condition has opened the way to the realization of the so-called Floquet Topological Insulators. In these systems, the topological phases may be engineered and manipulated by tunable controls such as polarization, periodicity and amplitude of the external perturbation.

In the presence of a continuous time-periodic driving, electrons are in a non-equilibrium steady state characterized by a time-periodic dependence of the wave function, and therefore of the expectation values of any observable. In this talk we will consider the prototypical case of graphene that, under the influence of circularly polarized light, exhibits in its Floquet band structure the distinctive features of a topological insulator, namely a gap in 2D and linear dispersive edge states in 1D (graphene nanoribbon). In particular, we will discuss how these characteristics affect the time behavior of some relevant observables such as energy, charge and current density.

DS 9.8 Mon 17:00 HSZ 204

Quantum chaos and out-of-time order correlation functions in graphene — •Markus Klug, Mathias Scheurer, and Jörg Schmalian — Institute for Theoretical Condensed Matter Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Deutschland

Out-of-time order correlation functions of type $C = \langle A(t)B(0)A(t)B(0)\rangle_\beta$ are believed to be a reasonable measure of quantum chaos which manifests in an exponential growth of C with a certain Lyapunov exponent determined by the microscopic model under considerations. Recently, it was conjectured hat this Lyapunov exponent is be bounded by $\lambda \leq 2\pi k_B T/\hbar$ [1].

In this work we investigate the out-of-time order correlation functions in graphene subject to the long range Coulomb interaction. To this end we develop a formalism to capture the relevant effects which determines the dominant time dependence of C. We demonstrate that the critical Dirac fluid graphene is a good candidate for saturating the bound mentioned above.

[1] J. Maldacena, S.H. Shenker and D. J. Stanford, High Energ. Phys. (2016) 2016: 106.

DS 9.9 Mon 17:15 HSZ 204

Interaction induced Dirac fermions from quadratic band touching in bilayer graphene — •Thomas C. Lang[1], Sumiran Pujari[2], Ganpathy Murthy[2], and Ribhu K. Kaul[2] — [1]Institute for Theoretical Physics, University of Innsbruck, Austria — [2]Department of Physics & Astronomy, University of Kentucky, Lexington, KY

We revisit the effect of local interactions on the quadratic band touching (QBT) of Bernal stacked bilayer graphene models using renormalization group (RG) arguments and quantum Monte Carlo simulations of the Hubbard model. We present an RG argument which predicts, contrary to previous studies, that weak interactions do not flow to strong coupling even if the free dispersion has a QBT. Instead they generate a linear term in the dispersion, which causes the interactions to flow back to weak coupling. Consistent with this RG scenario, in unbiased quantum Monte Carlo simulations of the Hubbard model we find compelling evidence that antiferromagnetism turns on at a finite U/t, despite the $U = 0$ hopping problem having a QBT. The onset of antiferromagnetism takes place at a continuous transition which is consistent with $z = 1$ as expected for Gross-Neveu criticality. We conclude that generically in models of bilayer graphene, even if the free dispersion has a QBT, small local interactions generate a Dirac phase with no symmetry breaking and there is a finite-coupling phase transition out of this phase to a symmetry-broken state.

DS 9.10 Mon 17:30 HSZ 204

Dynamical charge and pseudospin currents in graphene and possible Cooper pair formation — •Klaus Morawetz — Münster University of Applied Sciences, Stegerwaldstrasse 39, 48565 Steinfurt, Germany — International Institute of Physics (IIP) Av. Odilon Gomes de Lima 1722, 59078-400 Natal, Brazil — Max-Planck-Institute for the Physics of Complex Systems, 01187 Dresden, Germany

With the quantum kinetic equations for systems with SU(2) structure, regularization-free density and pseudospin currents are calculated in graphene realized as the infinite mass-limit of electrons with quadratic dispersion and a proper spin-orbit coupling. The intraband and interband conductivities are discussed with respect to magnetic fields and magnetic domain puddles. The optical conductivity agrees well with the experimental values using screened impurity scattering and an effective Zeeman field. The universal value of Hall conductivity is shown to be modified due to this Zeeman field. The pseudospin current reveals an anomaly since a quasiparticle part appears though it vanishes for particle currents. The density and pseudospin response functions to an external electric field are calculated and the dielectric function is discussed with respect to collective excitations. A frequency and wave-vector range is identified where the dielectric function changes sign and the repulsive Coulomb potential becomes effectively attractive allowing for Cooper pairing.

[1] Phys. Rev. **B 94** (2016) 165415

DS 9.11 Mon 17:45 HSZ 204

Interplay between the long-range Coulomb interaction and edge-state magnetism in zigzag graphene nanoribbons — •Marcin Raczkowski and Fakher Assaad — Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

Quasi-one-dimensional graphene nanoribbons terminated by zigzag edges host partially flat bands at the Fermi energy. Theoretical studies of the Hubbard model with the effective on-site interaction only predict spontaneously induced spin polarizations at the zigzag edges and the associated finite dispersion of the low-energy band. Here, we revisit the stability and dynamical signatures of spin-polarized edge states by performing projective quantum Monte Carlo simulations of a more realistic model with long-range Coulomb interactions. On the one hand, increasing the relative strength of nonlocal interactions with respect to the on-site repulsion reduces noticeably the spin correlation length along the zigzag edge; nevertheless the tendency towards the extended spin polarization along the edges remains dominant over the competing short-range charge correlations. On the other hand, growing charge fluctuations are responsible for the emergence of incoherent low-energy excitations in the dynamical charge structure factor. In addition, we resolve a systematic shift of the dominant low-energy peak in single-particle spectral function on the edge towards higher frequencies that we attribute to quasiparticle scattering from charge excitations.

DS 9.12 Mon 18:00 HSZ 204

Quantum phase transition in effective spin ladders derived from graphene nanoribbons — •Cornelie Koop and Stefan Wessel — Institut für Theoretische Festkörperphysik, RWTH Aachen University

Zigzag edges of graphene nanoribbons host localized edge states, which show a ferromagnetic coupling along each edge and an antiferromagnetic one to the opposite edge. Using an effective model that treats the edge-bulk interaction as a perturbation to the edge-edge interaction, we can drastically reduce the numerical effort needed for this system, and we eventually find a rather general spin ladder model.

We examine this model at low, but finite temperatures by means of Monte-Carlo techniques using the stochastic series expansion method. Susceptibilities and correlation functions can be investigated. We find a quantum-phase transition (QPT), as a function of the antiferromagnetic inter-leg coupling strength, between a weak-coupling phase with long-range ferromagnetic order along each leg, which does not have a spin excitation gap, and a disordered, gapped singlet-phase. The location and estimates for the critical exponents are assessed by numerical methods and compared to known results from renormalization group calculations.