TT 80: Graphene

Time: Thursday 9:30–13:00 Location: H 3005

TT 80.1 Thu 9:30 H 3005

Transport in systems with nodal degeneracy — •Andreas Sinner and Klaus Ziegler — Institut für Physik, Theorie II Universität Augsburg Universitätsstr. 1 D-86159, Augsburg, Germany

We study the DC conductivity of a weakly disordered 2D electron gas with two bands and spectral nodes, employing the field theoretical version of the Kubo-Greenwood conductivity formula. Disorder scattering is treated within the standard perturbation theory by summing up ladder and maximally crossed diagrams. The emergent gapless (diffusion) modes determine the behavior of the conductivity on large scales. We find a finite conductivity with an intermediate logarithmic finite-size scaling towards smaller conductivities but do not obtain the logarithmic divergence of the weak-localization approach. Our results agree with the experimentally observed logarithmic scaling of the conductivity in graphene with the formation of a plateau near the universal conductivity. We extend our analysis by including effects of anisotropy on hexagonal lattices.

[1] A. Sinner, K. Ziegler, Phys. Rev. B 90, 174207 (2014).
[2] A. Sinner, K. Ziegler, J. Phys. Condens. Matter. 28, 305701 (2016).
[3] A. Sinner, K. Ziegler, Europhys. Lett. 119, 27001 (2017).

TT 80.2 Thu 9:45 H 3005

Echoes of zitterbewegung in graphene — •Phillipp Reck[1], Cosimo Gorini[1], Arseni Goussev[2], Viktor Krueckl[1], and Klaus Richter[1] — [1]Institut für Theoretische Physik, Universität Regensburg, Germany — [2]Department of Mathematics, Physics and Electrical Engineering, Northumbria University, Newcastle Upon Tyne, UK

In the last decade, Zitterbewegung (ZB) – the trembling motion of (effectively) relativistic particles – has attracted the attention also in the solid state community [1], e.g. in graphene [2]. The advantage of solid state systems is the lower energy difference of particle- and antiparticle-like states that defines the frequency of the ZB, which is the reason for a supposedly easier experimental detection.

However, the ZB of a wave packet decays over time because of the separation of the two sub-wave packets in the two bands and the according loss of interference. On the other hand, Quantum Time Mirrors in graphene have been recently proposed to invert the motion of wave packets [3]. Here, we discuss the application of the Quantum Time Mirrors on the sub-wave packets after the ZB has decayed, which is supposed to make the separated sub-wave packets interfere again and accordingly, to create an echo of the ZB.

[1] J. Schliemann, D.Loss, R. M. Westervelt, Phys. Rev. Lett. **94**, 206801 (2005)
[2] W.Zawadzki and T.M. Rusin , J. Phys.: Condensed Matter **23**, 143201 (2011)
[3] P. Reck, C. Gorini, A. Goussev, V. Krueckl, M. Fink, K. Richter, Phys. Rev. B **95**, 165421 (2017)

TT 80.3 Thu 10:00 H 3005

Tunable quantum random walks in graphene — •Vanessa Junk, Phillipp Reck, Cosimo Gorini, and Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, Germany

One of the many fascinating aspects connected to quantum computing are quantum random walks [1] which can be used to speed up classical algorithms.

We show that such a quantum walk can be physically implemented in graphene by extending a recently proposed Quantum Time Mirror [2]. The pulse used in Ref. [2] for the time reversal can be tuned such that an initial wave-packet is split into two parts moving in opposed directions. By adjusting the pulse length, the amplitudes of the two resulting packets can be chosen arbitrarily. Hence, applying such a pulse is equivalent to the coin toss in descrete time quantum walks [3] with the advantage of having additional degrees of freedom in the “coin”. Moreover, the system we are dealing with is continuous in space. This allows for arbitrary timing of the pulses which leads to further variety in the probability distribution of the wave-packet in space.

In this talk we will discuss the described system and show the influence of the coin parameters on the resulting quantum walk of charge carriers in graphene.

[1] Y. Aharonov, L. Davidovich, and N. Zagury, Phys. Rev. A **48**, 1687-1690 (1993)
[2] P. Reck, C. Gorini, A. Goussev, V. Krueckl, M. Fink, K. Richter, Phys. Rev. B **95**, 165421 (2017)
[3] J. Kempe, Contemporary Physics **44**, 307-327 (2003)

TT 80.4 Thu 10:15 H 3005

Quantum interference assisted spin-filtering in graphene nanoflakes — •Angelo Valli[1,2], Adriano Amaricci[1,2], Valentina Brosco[1,2], and Massimo Capone[1,2] — [1]Scuola Superiore di Studi Avanzati (SISSA), Trieste, Italy — [2]Democritos National Simulation Center, CNR-IOM, Trieste, Italy

We present a theoretical investigation of the transport properties through magnetic zigzag graphene nanoflakes. In the ballistic regime, we identify transmission antiresonances as clear fingerprints of destructive quantum interference (QI), analogous to those observed in molecular junctions. The QI antiresonances are remarkably robust and can be rationalized in terms of symmetries. In the presence of short-range magnetic ordering, the interplay of QI and magnetism results in spin-resolved QI features and in a nearly-perfect QI-assisted spin-filtering effect. We also devise a protocol to achieve electrostatic control over the efficiency of the spin filter. Such a device benefits of the extraordinary conduction properties of graphene, and operates without any external magnetic field, paving the path toward QI-assisted spintronics.

TT 80.5 Thu 10:30 H 3005

Valleytronics in elastically defomed graphene — •Nikodem Szpak[1], Thomas Stegmann[2], and Ralf Schützhold[1] — [1]Faculty of Physics, University of Duisburg-Essen, Germany — [2]Instituto de Ciencias Fisicas, Universidad Nacional Autonoma de Mexico, Cuernavaca, Mexico

Electrons in graphene obey at low energies the 2D-Dirac equation with two psuedospin (valley) degrees of freedom. Manipulation of the valley polarization of the electronic current has potential applications in nanoelectronics, known as valleytronics. We discuss systems based on elastically deformed graphene in which the Dirac equation couples to effective curvature and pseudo-magnetic field introduced by strain. We introduce the basic theory and special approximations developed to enable an efficient design of intended valleytronic systems. We present results of numerical simulations of the current flow and compare different models. Finally, we present particular systems for efficient manipulation of the valley polarization which, among others, can act as ultrasensitive nanosensors.

TT 80.6 Thu 10:45 H 3005

Hybrid Monte Carlo simulations the electronic Lifshitz transition in monolayer graphene — •Michael Körner[1], Dominik Smith[1], Pavel Buividovich[2], Maksim Ulybyshev[2], and Lorenz von Smekal[1] — [1]Institut für theoretische Physik, Justus Liebig Universität Gießen, 35392 Gießen, Germany — [2]Institut für theoretische Physik, Universität Regensburg, 93053 Regensburg, Germany

We report on Hybrid-Monte-Carlo simulations at finite spin density of the pi-band electrons in monolayer graphene with realistic interelectron interactions. Unlike simulations at finite charge-carrier density, these are not affected by a fermion-sign problem. We nevertheless observe effects that are quite similar to observations in angle resolved photoemission spectroscopy experiments on charge doped graphene, such as an interaction-induced warping of the Fermi contours or a reduction of the bandwidth. Furthermore, we find evidence that the neckdisrupting Lifshitz transition, which occurs when the Fermi level traverses the van Hove singularity (VHS), might become a true quantum phase transition due to interactions. This is in-line with an instability of the VHS towards the formation of electronic ordered phases, which has been predicted by a variety of different theoretical approaches.

TT 80.7 Thu 11:00 H 3005

Lifshitz transition and thermoelectric properties of bilayer graphene — Dominik Suszalski, Grzegorz Rut, and •Adam Rycerz — Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland

This is a numerical study of thermoelectric properies of ballistic bilayer graphene in the presence of trigonal warping term in the effective Hamiltonian. We find, in mesoscopic samples of the length exceeding 10 micrometers at sub-Kelvin temperatures, that both the Seebeck co-

efficient and the Lorentz number show anomalies (the additional maximum and minimum, respectively) when the electrochemical potential is close to the Lifshitz energy, which can be attributed to the presence of the van Hove singularity in a bulk density of states. At higher temperatures the anomalies vanish, but measurable quantities characterizing remaining maximum of the Seebeck coefficient still unveil the presence of massless Dirac fermions. Behavior of the thermoelectric figure of merit (ZT) is also discussed.

15 min. break.

TT 80.8 Thu 11:30 H 3005

Suppression of high magnetic-field-induced electronic transitions in graphite micro flakes — •J. Barzola Quiquia[1], C. Precker[1], M. Stiller[1], M. Zoraghi[1,3], T. Förster[2], Th. Herrmannsdörfer[2], and P. Esquinazi[1] — [1]Felix-Bloch Institute for Solid State Physics, University of Leipzig, 04103 Leipzig, Germany — [2]Forschungszentrum Dresden-Rossendorf, PF 510119, D-01314 Dresden, Germany — [3]MPI for Human Cognitive and Brain Sciences, 04103 Leipzig, Germany

We report a detailed study of the magnetoresistance (MR) in bulk and microflakes of highly oriented pyrolytic graphite samples. Measurements have been done at different temperatures with stationary (7 T) and pulsed magnetic fields to 62 T applied parallel to the c-axis. We found that at low temperature, the MR increases rapidly from 0 to ≈ 20 T, and then it saturates at fields to ≈ 50 T. At higher fields the MR decreases. At temperatures $T \geq 50$ K, the MR increases rapidly from 0 to ≈ 20 T, at higher fields it increases further but with a smaller slope. In thick samples we found also the well-known sudden jumps in the MR in a restricted field region that were interpreted in the past as field-induced electronic phase transitions in graphite associated with a charge density wave. In the case of the thin graphite flakes the jumps in the MR nearly vanish. Our present results indicate that the field-induced electronic transitions observed in bulk graphite are not intrinsic but originate at the two-dimensional (2D) metallic system formed at the interfaces between the different stacking orders or twisted graphite crystalline regions only.

TT 80.9 Thu 11:45 H 3005

Extreme magneto resistance in Ar$^+$ ion radiated graphene — •Paul Linsmaier[1], Lorenz Weiss[1], Tobias Weinberger[1], Ferdinand Kisslinger[2], Heiko B. Weber[2], and Christoph Strunk[1] — [1]Inst. f. Exp. and Appl. Physics, University of Regensburg — [2]Fac. of Physics, F.-A. University Erlangen-Nürnberg

We report on magnetotransport measurements of epitaxial graphene on SIC [1], bombarded with Ar$^+$ ions. For different strength of disorder, $\rho_\square(300\mathrm{K}) = 15 - 30\mathrm{k}\Omega$, an Arrhenius temperature dependence of the resistance is found at low temperatures and zero magnetic field. In perpendicular magnetic field, we see a drastic change in the conductivity from Arrhenius ($B = 0$T) to Efros-Shklovskii ($B_\perp = 12$T) Coulomb-gap-like behavior, with an extreme negative magnetoresistance (NMR) of $\rho(B_\perp)/\rho(0) < 0.01$ at $B = 12$T and 300mK. This might indicate a gap, resulting from magnetic interactions in graphene. In parallel magnetic field, we find a much smaller magnetoresistance with a sign change from a NMR at low temperatures to a positive magnetoresistance with increasing temperature and magnetic field.

[1] K. V. Emtsev et al., Nat. Mat. 8, 203 - 207 (2009).

TT 80.10 Thu 12:00 H 3005

Mechanisms of magnetoconductance oscillations in graphene pn junctions — •Ming-Hao Liu[1] and Klaus Richter[2] — [1]Department of Physics, National Cheng Kung University, Tainan 70101, Taiwan — [2]Institute for Theoretical Physics, University of Regensburg, D-93040 Regensburg, Germany

Two-terminal conductance of a graphene pn junction may oscillate with various dependencies, such as carrier density, magnetic field, or even the position of the pn junction. In this talk, various mechanisms giving rise to the oscillation are discussed, focusing on the recent two experiments supported by our quantum transport simulations, one at intermediate magnetic fields [1] and the other at high magnetic fields [2]. The former corresponds to a regime with high filling factors and shows an unusual even-odd effect of the Landau levels, with the underlying mechanism not completely clear. The latter corresponds to a regime with low/lowest filling factors, showing first experimental evidence of valley-isospin-dependent conductance oscillation [3].

[1] H. Overweg et al., Nano Lett. **17**, 2852 (2017)
[2] C. Handschin et al., Nano Lett. **17**, 5389 (2017)
[3] J. Tworzydło et al., Phys. Rev. B **76**, 035411 (2007)

TT 80.11 Thu 12:15 H 3005

Husimi Projections in Graphene: Measuring Klein Tunneling — •George Datseris, Theo Geisel, and Ragnar Fleischmann — Max Planck Institute for Dynamics and Self-Organization, Goettingen, Germany

One of the most intriguing electronic properties of graphene is the occurrence of Klein Tunneling: ballistic conduction electrons are expected to show full transmission on normal incidence on almost arbitrary potential barriers. On oblique incidence the transmission decays rapidly, leading to a collimation effect at the barrier. Recently graphene experiments have reached the ballistic regime and measurements confirmed collimated transmission, but measuring the characteristic transmission versus the angle of incidence $T(\theta)$ directly seems to be still out of reach. One reason for this is that it is hard to define an angle of incidence (and even hard to measure) in both experiments and tight-binding calculations.

In order to analyse $T(\theta)$ in a tight-binding quantum transport model we modify and employ the Husimi projection. We combine this approach with a Landauer-Büttiker type description of e.g. a graphene pn-junction. This allows us to observe $T(\theta)$ in a controlled but experimentally relevant model. In the absence of a magnetic field our results almost perfectly match the semi-classically derived formulas for transmission found in the literature. In the presence of a magnetic field, however, our results show strong differences from the semi-classical predictions.

TT 80.12 Thu 12:30 H 3005

Logarithmic Low-Bias Anomalies in the Differential Conductance of Graphene Structures — •Matthias Popp, Ferdinand Kisslinger, and Heiko B. Weber — Friedrich-Alexander-Universität Erlangen-Nürnberg Lehrstuhl für Angewandte Physik Staudtstraße 7 91058 Erlangen

We measured the voltage-dependent differential conductance of graphene-graphene tunneling junctions at low temperatures in order to probe electron-electron interaction corrections on the density of states (DOS). As predicted by Altshuler and Aronov [1] a logarithmic voltage dependence was observed [2]. Tunneling junctions provide a sharp voltage drop, therefore their differential conductance is a good measure for the DOS. To our surprise we also found logarithmic voltage dependencies in the differential conductance of graphene stripes where no sharp voltage drop is present. We explain this with a model involving voltage dependent heating of electrons in combination with electron-electron interaction as well as weak localization corrections to conductivity, both of which exhibit a logarithmic temperature dependence. We give an overview how to differentiate between these effects which all manifest themselves in logarithmic low-bias anomalies in differential conductance.

[1] B. Altshuler, A. Aronov, *Electron-Electron Interactions in Disordered Systems*, North Holland (1985)
[2] F. Kisslinger, et al., Annalen der Physik 1700048 (2017)

TT 80.13 Thu 12:45 H 3005

Interplay between the moiré superlattice and a npn-junction in a graphene-hBN heterostructure — •Rainer Kraft[1], Pranauv Balaji Selvasundaram[1,2], Ralph Krupke[1,2], Klaus Richter[3], Ming-Hao Liu[3,4], and Romain Danneau[1] — [1]Institute of Nanotechnology, Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Department of Materials and Earth Sciences, Technical University Darmstadt, Darmstadt, Germany — [3]Institute for Theoretical Physics, University of Regensburg, Regensburg, Germany — [4]Department of Physics, National Cheng Kung University, Tainan, Taiwan

Here, we present measurements on a device based on a graphene/hexagonal boron nitride van der Waals heterostructure with a moiré superlattice. The superlattice structure modulates the electronic band structure featuring interesting physics, such as new moiré minibands for Dirac electrons in graphene. With the combination of overall back-gate and local top-gate forming a npn-junction we are able to probe the effect of the superlattice by measuring complex sets of Fabry-Pérot interferences of confined charge carriers in several cavities as functions of bias or magnetic field. The decoding of the resulting interference patterns gives insight into the effects of the moiré superlattice on the band structure and as well on the nature of the cloned Dirac fermions.