DS 37: Focus Session on 2D Materials: Ballistic Quantum Transport in Graphene (jointly with HL, MA, TT)

Ballistic electron waves yielded a plethora of insights already in 2D semiconducting heterostructures. Recent experimental techniques have paved the way to this regime also for graphene. The massless, relativistic, and chiral nature of its charge carriers enriches ballistic transport by qualitatively new physical phenomena, such as ambipolar states near pn-junctions, Klein tunneling, or a zeroth Landau level in a perpendicular magnetic field. This session will review the actual status.

Organisation: Wolfgang Häusler, Universität Augsburg; Reinhold Egger, Universität Düsseldorf; Klaus Richter, Universität Regensburg

Time: Thursday 9:30–13:00 Location: HSZ 03

Invited Talk DS 37.1 Thu 9:30 HSZ 03
Kondo Screening of a Vacancy Magnetic Moment in Graphene — •Eva Y. Andrei — Dept. of Physics, Rutgers University, Piscataway, NJ

Graphene in its pristine form has transformed our understanding of 2D electron systems leading to fundamental discoveries and to the promise of important applications. When the perfect honeycomb lattice of graphene is disrupted by single atom vacancies new phenomena emerge including the buildup of local charge and the appearance of a local moment. Using scanning tunneling microscopy to identify Kondo screening of the vacancy moment by its spectroscopic signature, we demonstrate that the local magnetic moment can be controlled either by doping or through the local curvature. This allows to detect and map the quantum phase transition separating magnetic from non-magnetic states in this pseudogap system.

Invited Talk DS 37.2 Thu 10:00 HSZ 03
Higher-Than-Ballistic Conduction in Viscous Electron Fluids — •Leonid Levitov — Physics Department, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA02139

This talk will argue that in viscous electron flows interactions facilitate transport, allowing conductance to exceed the fundamental Sharvin-Landauer quantum-ballistic limit. The effect is particularly striking for the flow through a viscous point contact, a constriction exhibiting the quantum-mechanical ballistic transport at zero temperature but governed by electron hydrodynamics at elevated temperatures. The crossover between the ballistic and viscous regimes occurs when the mean free path for e-e collisions becomes comparable to the constriction width. Further, we will discuss the negative nonlocal response, a signature effect of viscous transport. This response exhibits an interesting nonmonotonic behavior vs. temperature at the viscous-to-ballistic transition. The response is negative but small in the highly viscous regime at elevated temperatures. The value grows as the temperature is lowered and the system becomes less viscous, reaching the most negative values in the crossover region where the mean free path is comparable to the distance between contacts. Subsequently, it reverses sign at even lower temperatures, becoming positive as the system enters the ballistic regime. This peculiar behavior provides a clear signature of the ballistic-to-viscous transition and enables a direct measurement of the electron-electron collision mean free path.

Invited Talk DS 37.3 Thu 10:30 HSZ 03
Electron Optics in Ballistic Graphene — •Ming-Hao Liu — Department of Physics, National Cheng Kung University

Electrons in clean graphene are known to behave like "charged photons" due to its celebrated energy dispersion linear in momentum, providing an ideal platform for exploring electron optics. Despite the discovery of graphene in 2004, devices of ultraclean samples with micron-scale mean free paths became accessible only recently. Reliable quantum transport simulations in the ballistic limit for understanding and predicting high-quality transport experiments have therefore become increasingly demanded nowadays. In this talk, an overview of our recent progress on simulating a variety of ballistic graphene transport experiments will be given, such as Fabry-Pérot interference, snake states, and gate-defined electron waveguides [1]. Keys to such quantum transport simulations will be briefly introduced [2]. Ongoing works possibly including *pnp* junctions in the presence of 2D Moiré superlattice and Weiss oscillation due to 1D periodic gating will be mentioned at the end of the talk.

[1] P. Rickhaus *et al.*, Nat. Communs. **4**, 2342 (2013); M. Drienovsky *et al.*, Phys. Rev. B **89**, 115421 (2014); A. Varlet *et al.*, Phys. Rev. Lett. **113**, 116601 (2014); P. Rickhaus *et al.*, Nat. Communs. **6**, 6470 (2015); P. Rickhaus *et al.*, Nano Lett. **15**, 5819 (2015).
[2] M.-H. Liu *et al.*, Phys. Rev. Lett. **114**, 036601 (2015).

15 min. break.

Invited Talk DS 37.4 Thu 11:15 HSZ 03
Ballistic Transport in Mesoscopic Graphene Devices — •Christoph Stampfer — JARA-FIT and 2nd Institute of Physics, RWTH Aachen University, 52074 Aachen, Germany — Peter Grünberg Institute (PGI-9), Forschungszentrum Jülich, 52425 Jülich, Germany

The recent technological advances in encapsulating graphene by hexagonal boron nitride forming artificial van-der-Waals heterostructures allows the fabrication of graphene devices with high electronic quality. Outstanding charge carrier mobilities and mean free paths with more than 10 micrometer are now accessible making this material stack interesting for studying ballistic transport. By further structuring the graphene-hBN based heterostructures mesoscopic devices can be fabricated on which phase coherent ballistic quantum transport can be studied.

Here, I will present low-temperature magneto-transport measurements on both (i) graphene quantum point contacts and (ii) high mobility graphene rings encapsulated in hexagonal boron nitride. Our experiments allow to extract information on quantized conductance, renormalized Fermi velocities close to the charge neutrality point as well as the co-existence of weak localization, Aharonov-Bohm oscillations and universal conductance fluctuations in graphene rings.

Invited Talk DS 37.5 Thu 11:45 HSZ 03
Interaction-Induced Conductance from Zero Modes in a Magnetic Graphene Waveguide — •Alex Zazunov — Heinrich-Heine-Universität Düsseldorf

We consider a waveguide formed in a clean graphene monolayer by a spatially inhomogeneous magnetic field. The single-particle dispersion relation for this waveguide exhibits a zero-energy Landau-like flat band, while finite-energy bands have dispersion and correspond, in particular, to snake orbits. For zero-mode states, all matrix elements of the current operator vanish, and a finite conductance can only be caused by virtual transitions to finite-energy bands. We show that Coulomb interactions generate such processes. In stark contrast to finite-energy bands, the conductance is not quantized and shows a characteristic dependence on the zero-mode filling. Transport experiments thereby offer a novel and highly sensitive probe of electron-electron interactions in clean graphene samples.

DS 37.6 Thu 12:15 HSZ 03
Ballistic thermophoresis on graphene — •Emanuele Panizon[1], Roberto Guerra[1,2], and Erio Tosatti[1,2,3] — [1]SISSA, Trieste, Italy — [2]CNR-IOM Democritos, Trieste, Italy — [3]ICTP, Trieste, Italy

The textbook thermophoretic force acting on a diffusing body in a fluid is proportional to the local temperature gradient. This is not the case for a diffusing physisorbed body on a submicron sized 2D suspended layer. A Non-Equilibrium Molecular Dynamics study of a test nanosystem - a gold nanocluster adsorbed on a single graphene sheet of length L clamped between two temperatures ΔT apart - reveals a phoretic force that is parallel to, but essentially independent of, the gradient magnitude $\Delta T/L$ up to a substantial L of $150nm$.

This is argued to represent ballistic thermophoresis, where the force is provided by the flux of massively excited flexural phonons, whose flow is in turn known to be ballistic and distance-independent up to relatively long scattering lengths before the eventual onset of the more standard diffusive regime. The surprising thrust and real momentum provided by the flexural modes are analysed and understood in terms of the large mass non/uniformity involved with these modes. The ensuing surf-riding of adsorbates on the vibrating 2D hard sheet, and the resulting gradient independent thermophoretic force, are not unlikely to possess practical applications.

DS 37.7 Thu 12:30 HSZ 03

Quantum time mirrors in two-band systems with and without broken time-reversal symmetry — •Phillipp Reck[1], Cosimo Gorini[1], Arseni Goussev[2], Viktor Krueckl[1], Mathias Fink[3], and Klaus Richter[1] — [1]Institut für Theoretische Physik, Universität Regensburg — [2]Department of Mathematics, Physics and Electrical Engineering, Northumbria University, Newcastle Upon Tyne, UK — [3]Institut Langevin, ESPCI, CNRS, PSL Research University, Paris

Both metaphysical and practical considerations intrigued generations of scientists to devise and implement time-inversion protocols – in particular the Hahn echo [1], different forms of "time mirrors" for classical waves (see e.g. [2]), and recently an instantaneous time mirror for water waves [3]. With our proposal for an instantaneous Quantum Time Mirror [4], we showed the possibility to extend the family of time reversal protocols to *continuous quantum* systems, more precisely to wave packets in Dirac-cone systems, by changing the propagation direction with a short, time-dependent pulse.

In this talk, we discuss the effect on the Quantum Time Mirror of both, a static, out-of-plane magnetic field, which breaks time-reversal symmetry, and band structures other than the Dirac cone, e.g. the valence and conduction bands in direct gap semi-conductors.

[1] E. L. Hahn, Spin echoes. Phys. Rev.. 80, 580 (1950)
[2]M. Fink, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 39, 555, (1992)
[3]V. Bacot, et al., Nat. Phys. 12, 972–977 (2016)
[4]P. Reck, et al., arXiv:1603.07503 (2016)

DS 37.8 Thu 12:45 HSZ 03

Current flow paths in deformed graphene and carbon nanotubes — Erik Kleinherbers, •Nikodem Szpak, and Ralf Schützhold — Faculty of Physics, University of Duisburg-Essen, Germany

Due to imminent applications in nanoelectronics it is of high interest to understand the precise conductance properties of deformed graphene and bent carbon nanotubes. Since low-energy electronic excitations behave like massless Dirac fermions the current flow can be approximated semiclassically and used as a guide in the design of conducting nanoelectronic elements and nanosenors. Taking into account the curvature effects as well as an emerging inhomogeneous pseudo-magnetic field we calculate the current flow paths theoretically and compare them with numerical simulations of the full electronic transport.