Symposium Hydrodynamic Electronics: Transport in ultra-pure Quantum Systems (SYHE)

jointly organized by
the Low Temperature Division (TT),
the Magnetism Division (MA), and
the Dynamics and Statistical Physics Division (DY)

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The fluid flow of liquids is governed by the laws of hydrodynamics. Nonlocal transport behavior and turbulence are among the hallmarks of hydrodynamic flow. Recently, major experimental and theoretical progress has been made in identifying and investigating quantum materials with hydrodynamic flow of electrons. Examples are ultraclean graphene, Weyl semimetals, and delafossites, where momentum- conserving collisions dominate over all other scattering processes. Hydrodynamic transport coefficients, such as the electron viscosity or energy diffusivities, reveal key information about the strength of interactions and the nature of thermalization in a quantum many-body system. These issues are of relevance in systems as diverse as cold atomic gases, the quark gluon plasma, and the above electronic materials. The phenomena to be discussed include non-local transport, hydrodynamic magneto-transport, super-ballistic current flow, flow vorticity in graphene, extreme thermal conductivities, coupled energy-charge solitons, and electron-phonon fluids. New theoretical concepts include nonlinear flow responses, quantum-critical transport, bounds on transport coefficients, and applications of string theoretical methods to capture the physics of hydrodynamic electronics. The aim of this symposium is to bring together the leading experimental and theoretical experts, and thus to directly address some of the most pressing controversies in this field.

Overview of Invited Talks and Sessions

(Lecture hall H1)

Invited Talks

SYHE 1.1	Wed	9:30–10:00	H1	**Hydrodynamic theory of dissipative magnetophonons** — •Sean Hartnoll
SYHE 1.2	Wed	10:00–10:30	H1	**Unconventional transport in mesostructures of ultra-pure delafossite metals** — •Andrew Mackenzie
SYHE 1.3	Wed	10:30–11:00	H1	**Topological Materials with liquid electrons** — •Claudia Felser, Johannes Gooth
SYHE 1.4	Wed	11:15–11:45	H1	**Hydrodynamic approach to electronic transport** — •Boris Narozhny
SYHE 1.5	Wed	11:45–12:15	H1	**Electron hydrodynamics in graphene: introduction and status** — •Denis Bandurin

Sessions

SYHE 1.1–1.5	Wed	9:30–12:15	H1	**Hydrodynamic electronics: Transport in ultra-pure quantum systems**

SYHE 1: Hydrodynamic electronics: Transport in ultra-pure quantum systems

Time: Wednesday 9:30–12:15 Location: H1

Invited Talk SYHE 1.1 Wed 9:30 H1
Hydrodynamic theory of dissipative magnetophonons — •Sean Hartnoll — Stanford University, USA

Magnetophonons are collective modes that arise in clean electronic systems with spontaneously broken translational symmetry (for example, a Wigner crystal), in the presence of a strong magnetic field. The non-dissipative dynamics of magnetophonons with dispersion $w \sim k^2$ is well understood. I will describe a new and elegant hydrodynamic description of the dissipative dynamics of magnetophonons. The formulae obtained will be seen to give an excellent description of the temperature dependence of the magnetophonon, observed over a decade ago across the melting point of the Wigner crystal state in GaAs. The bigger picture here will be that electronic systems can host hydrodynamic physics much richer than that of the viscous flow of conventional fluids.

Invited Talk SYHE 1.2 Wed 10:00 H1
Unconventional transport in mesostructures of ultra-pure delafossite metals — •Andrew Mackenzie — Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

I will discuss experiments from my group and collaborators in which we prepare meso-structures from the delafossite metals and study magneto-transport. These experiments reveal direct evidence for mean free paths of tens of microns, and allow the study of directional ballistics and crossovers between the ohmic, ballistic and hydrodynamic regimes.

Invited Talk SYHE 1.3 Wed 10:30 H1
Topological Materials with liquid electrons — •Claudia Felser and Johannes Gooth — Max Planck Institute Chemical Physics of Solids

Topology a mathematical concept became recently a hot topic in condensed matter physics and materials science and the identification via elementary band representation is easy [1,2]. One important criteria for the identification of topological material is the band inversion and the crystal symmetry. In my talk I focus on Weyl semimetals. Binary phoshides are the ideal material class for a systematic study of Weyl physics. Weyl points, a new class of topological phases was also predicted in NbP, NbAs. TaP, MoP and WP2 [3-6]. In NbP micro-wires we have observed the chiral anomaly but NbP has served also as a model system for astrophysics: realizing the gravitational anomaly in NbP with a ultrahigh mobility [3,4] and the hydrodynamic flow of electrons in WP2 [5]. MoP and WP2 show exceptional properties such as high conductivity higher than copper [5,6], high mobilities and a high magneto-resistance effect. [1] Bradlyn et al., Nature 547 298, (2017) [2] Vergniory, et al., preprint arXiv:1808.01163 [3] Shekhar, et al., Nat. Phys. 11, 645 (2015) [4] Gooth et al., Nature 547, 324 (2017) [5] Gooth et al., Nat. Com. 9, 4093 (2018) [6] Kumar, et al., Nat. Com. 8, 1642 (2017)

15 min. break

Invited Talk SYHE 1.4 Wed 11:15 H1
Hydrodynamic approach to electronic transport — •Boris Narozhny — Karlsruhe Institute of Technology, Karlsruhe, Germany

The last few years have seen an explosion of interest in hydrodynamic effects in interacting electron systems in ultra-pure materials. One such material, graphene, is not only an excellent platform for the experimental realization of the hydrodynamic flow of electrons, but also allows for a controlled derivation of the hydrodynamic equations on the basis of kinetic theory. The resulting hydrodynamic theory of electronic transport in graphene yields quantitative predictions for experimentally relevant quantities, e.g. viscosity, electrical conductivity, etc. In this talk I will review recent theoretical advances in the field, compare the hydrodynamic theory of charge carriers in graphene with relativistic hydrodynamics and recent experiments, and discuss applications of hydrodynamic approach to novel materials beyond graphene.

Invited Talk SYHE 1.5 Wed 11:45 H1
Electron hydrodynamics in graphene: introduction and status — •Denis Bandurin — Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Transport in systems with many particles experiencing frequent collisions has been studied for more than two centuries and is accurately described by the theory of hydrodynamics. It has been argued theoretically for a long time that the collective behaviour of charge carriers in solids can also be treated by the hydrodynamic approach. However, despite numerous attempts, very little evidence of hydrodynamic electron transport has been found.

Graphene encapsulated between hexagonal boron nitride offers an ideal platform to study electron hydrodynamics as it hosts an ultra-clean electronic system with electron-electron collisions being the dominant scattering source at elevated temperatures. In the first part of my talk, we will discuss why it was challenging to detect electron hydrodynamics before and how it manifests itself in graphene. It will be shown that electrons in graphene can behave as a viscous fluid forming vortices of applied electron current. In the second part, we will talk about the behaviour of electron fluids in the presence of magnetic field where I will report the experimental measurements of the odd (Hall) viscosity. This dissipationless transport coefficient has been widely discussed in the theoretical literature on fluid mechanics, yet, until now, any experimental evidence has been lacking. Finally, we will discuss how electron hydrodynamics can help in the development of resonant THz detectors where I will report some recent progress in this direction.