

PHY632: Transport in Mesoscopic Systems

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Course Description: Recent advances in quantum materials, topological insulators, and low-dimensional conductors have revived interest in mesoscopic transport. This course builds conceptual and computational foundations for understanding transport in graphene, Weyl semimetals, and hydrodynamic electron systems. The aim is to develop a unified understanding of charge and spin transport across Ohmic, ballistic, and hydrodynamic regimes. Additionally, we will explore how band geometry, through Berry curvature, quantum metric, and orbital moments, drives novel electronic responses.

Prerequisites: Basic knowledge of quantum mechanics (at the level of PHY431 or equivalent) and an introductory understanding of condensed matter physics.

Tentative List of Topics: The following sequence provides a thematic overview. Selected advanced topics may be emphasized depending on class interest and time.

1. **Introduction:** Basic length, time, and energy scales in mesoscopic conductors; quantum versus classical regimes.
2. **Classical Transport:** Drude model, diffusion equation, Einstein relation, and classical size effects.
3. **Quantum Diffusive Transport:** Phase coherence, weak localization, and universal conductance fluctuations.
4. **Ballistic and Hydrodynamic Regimes:** Landauer picture of conduction, quantized conductance, electron-electron interactions, viscous flow, Gurzhi effect, and crossovers between ballistic, hydrodynamic, and Ohmic regimes.
5. **Ballistic Transport Formalism:** Landauer-Büttiker approach, scattering matrix, and non-equilibrium Green's function (NEGF) formalism.
6. **Band-geometry induced transport:** Boltzmann transport framework, role of Berry curvature, quantum metric, and orbital moments in nonlinear and anomalous transport phenomena; Hall, Nernst, and spin responses in topological and low-symmetry materials.
7. **Quantum Hall Physics:** Landau levels, edge states, and the integer and fractional quantum Hall effects.
8. **Coulomb Blockade and Quantum Dots:** Charging effects and single-electron transport in confined systems.
9. **Mesoscopic Superconductivity (Selected Topics):** Josephson effect, Andreev reflection, and proximity-induced superconductivity.

Reference Books:

1. Y. Imry, *Introduction to Mesoscopic Physics* (Oxford University Press).
2. S. Datta, *Electronic Transport in Mesoscopic Systems* (Cambridge University Press).
3. C. W. J. Beenakker and H. van Houten, *Quantum Transport in Semiconductor Nanostructures*, in *Solid State Physics*, Vol. 44.
4. Yuri M. Galperin, *Quantum Transport* (available online lecture notes).
5. A. Lucas and K. C. Fong, *Hydrodynamics of electrons in graphene and beyond*, J. Phys.: Condens. Matter 30, 053001 (2018).
6. D. Xiao, M.-C. Chang, and Q. Niu, *Berry Phase Effects on Electronic Properties*, Rev. Mod. Phys. 82, 1959 (2010).

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