Physics of Complex Systems (National Track)

Program for “Out of Equilibrium Physics” course

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Course description

Out of equilibrium physics is a fascinating and multi-disciplinary topic that finds applications in various contexts, where standard equilibrium approach cannot be applied.

The course is meant to provide an introduction to some general theoretical methods and techniques to approach out of equilibrium problems. A particular focus will be devoted to quantum systems, with examples and a hands-on approach to solve problems in condensed matter physics and to discuss their experimental realization.

Expected Learning Outcomes

After this course the student is expected to learn some general theoretical methods and techniques to approach problems of out of equilibrium physics. Furthermore, the student will be able to apply these methods to some problems of condensed matter physics, and to explicitly compute quantities that are experimentally measurable.

Pre-requirements

Quantum Mechanics and Equilibrium Statistical Mechanics

Course Topics

PART 1: Classical and semi-classical approaches

-The early approaches to out of equilibrium phenomena. The phenomenological Drude model for transport.
-Classical particle under a stochastic force. The Langevin Equation.
-Microscopic modelling of a system-bath coupling. The damping kernel and the bath spectral function.
-The Boltzmann equation, hypotheses, the collision integral, and properties.
-Toward the quantum world: Quantum ingredients in the Semi-Classical Boltzmann Equation
-The relaxation-time approximation.
-Linear response theory. Charge and heat transport. Onsager relations
-Applications to Condensed Matter: The Boltzmann Equation in a random potential; microscopic derivation of Ohm’s law, scattering processes of electrons in solids.

PART 2: Out of Equilibrium Quantum Systems

A) <u>General Aspects</u>

-Quantum effects in Nanoscience

-The density matrix. Pure and mixed states. The Liouville von-Neumann Equation. Example: a two-level system

-Quantum pictures: Schrödinger, Heisenberg, Interaction pictures, time-ordering and anti-time ordering of quantum operators

-Linear response theory. The Kubo formula

-The fluctuation-dissipation theorem. Kramers-Kronig relations

-Quantum systems coupled to a bath: The Caldeira-Leggett model

-Decoherence effects. The spin-boson model. The reduced density matrix.

-Phenomenological approach to dissipation and decoherence: the T1-T2 model, applications to a two-level system exposed to a time-dependent perturbation

[*if time is enough: The Keldysh-Schwinger formalism and non-equilibrium Green functions.*]

B) <u>The coherent limit</u>

-Introduction to quantum mesoscopic physics.

-Scattering matrix formalism, the Landauer-Büttiker formula for transport in mesoscopic systems.

-The quantum of resistance. Conductance quantization.

-Examples of quantum interference phenomena in nanosystems (electronic Fabry-Pérot interferometer; the Aharonov-Bohm effect; Weak localization).

Course Structure

The course consists in 34 Theory lectures (=51 hours) + 6 Exercise classes (=9 hours). Concerning the Exercise classes, a few days earlier the exercise texts will be handed out to the students, who are supposed to cooperate to find the solution. During the Exercise classes, students are asked to show how they approached the problem, in an interactive way with the teacher and their colleagues. Should the Exercise classes take place in online mode, the students are required to use a tablet or a display with an electronic pencil, or at least a physical whiteboard with a thick pencil.

Reading Material

R. Zwanzig, Nonequilibrium Statistical Mechanics (Oxford Univ Press)

L. E. Reichl, A modern course in Stitistical Physics (John Wiley & Sons)

J. Rammer, Quantum Field Theory of nonequilibrium states (Cambridge Univ. Press)

A. Kamenev, Field Theory of Nonequilibrium systems (Cambridge Univ. Press)
U. Weiss, Quantum Dissipative Systems (World Scientific)
Haug-Jauho, Quantum kinetics in Transport and optics of semiconductors (Springer)

Assessment and grading criteria
The exam consists in an oral test, with questions on 2-3 topics chosen from a list of topics. The list will be provided at the end of the course and covers the material discussed during the course. The first topic may be chosen by the student. The other topics are chosen by the teacher (it can also be one of the exercises proposed during the course). The knowledge of the out of equilibrium physics methods is tested by asking the student to illustrate the key concepts, to derive proofs of the main results, and to apply the techniques to some examples and applications discussed during the course.
-for online exam: the oral test will take place remotely, using the software provided by Politecnico di Torino. The students should use a tablet or a display with an electronic pencil, or at least a physical whiteboard with a thick pencil.
-for onsite exam: the oral test will take at the blackboard.