ICTP SUMMER COLLEGE 2009
"Nonequilibrium Physics from Classical to Quantum Low Dimensional Systems"

LECTURE COURSES

Lecturer: Prof. Yuval Gefen (Weizmann Institute)

Title: Noise and Nonequilibrium Phenomena in Nanostructures

Syllabus:

1. **Introduction**
   a. An overview of (classical) noise: Nyquist, shot, fluctuations, fluctuation-dissipation, Onsager relations.
   b. Quantum shot noise; scattering (Landauer-Buttiker) theory.
   c. A few experimental examples.
2. **“Classic” Approaches**
   a. Rate equations
   b. Boltzmann-Langevin approach.
3. **Zero- and One-Dimensional Systems Out of Equilibrium.**
   a. Quantum Dots under a finite bias.
   b. Luttinger liquids out of equilibrium
4. **Noise and Quantum Statistics**
   a. Hanbury-Brown and Twiss effect.
   b. Two-particle interferometry
   c. Fractional statistics
5. **Quantum Measurement and Noise**
   a. Weak measurement
   b. Weak value.

Lecturer: Prof. Norman O. Birge (Michigan State University)

Title: Nonequilibrium Experiments in Mesoscopic Systems.

Syllabus:

1. **Electron-electron interactions in metals and carbon nanotubes**
   a. The distribution function f(E) in nonequilibrium situations
   b. How to measure f(E) using tunneling spectroscopy
   c. Measurements of f(E) in metals, and the role of dilute magnetic impurities
   d. Measurements of f(E) in carbon nanotubes

2. **Measuring Full Counting Statistics with a Josephson junction**
   a. Introduction to Full Counting Statistics (FCS)
   b. The idea of Tobiska and Nazarov: using a current threshold detector
   c. The physics of the current-biased Josephson junction: the RCSJ model
   d. Practical implementation of a Josephson junction to measure FCS
   e. Measurements of the 3rd moment of current fluctuations in a tunnel junction

3. **Nonequilibrium experiments in S/N hybrid systems**
   a. Introduction to Andreev reflection and Andreev bound states in S/N/S systems
   b. The nonequilibrium "pi-junction" in diffusive S/N/S Josephson junctions
   c. Engineering the distribution function in S/N/S junctions
   d. Tentative: Causing superconductivity to collapse via a nonequilibrium f(E)

Lecturer: **Pasquale Calabrese (Universita' di Pisa)**

Title: Quantum quenches in extended systems

Syllabus:

1. **Introduction to Quantum Quenches**
   a. Path Integral formulation of the Quantum Quench
   b. Conformal Field Theory and Quantum Quenches in 1d
   c. Entanglement entropy after a quantum quench
   d. Physical interpretation: horizon effect and effective temperature

2. **Local and dishomogeneous quenches**

3. **First principle calculations: from Bethe ansatz to nonequilibrium dynamics**

Lecturer: **David Huse (Princeton University)**

Title: Entanglement and ergodicity or localization in quantum many-body systems at nonzero temperature.

References:

1. Anderson, P. W (1958). Physical Review 109, 1492.
2. "On the problem of many-body localization", D. M. Basko , I. L. Aleiner , B. L. Altshuler. , arXiv:cond-mat/0602510.
3. "Localization of interacting fermions at high temperature", Vadim Oganesyan, David A. Huse, Phys. Rev. B 75, 155111 (2007).

Lecturer: **Boris Altshuler (Columbia University)**

Title: Anderson localization and nonequilibrium effects in quantum transport

Lecturer: Anatoli Polkovnikov (Boston University)

Title: Quantum and classical dynamics in interacting Hamiltonian systems

1. **Non-adiabatic dynamics and thermodynamics in isolated out of equilibrium systems.**

   a- Basic facts from thermodynamics: energy, heat, work, first and second laws of thermodynamics, fundamental thermodynamic relation. Non-equilibrium work relations (Jarzyisky equality).
   b- Thermalization in isolated systems; eigenstate thermalization hypothesis
   c- Connection between quantum and thermodynamic adiabatic theorems.
   d- Heat, entropy and defects generation in driven gapless systems.
   e- Scaling of various thermodynamic quantities for fast and slow quenches near quantum critical points.
   f- Work distribution for sudden quenches and the Loschmidt echo.

2. **Quantum dynamics in Hamiltonian systems near classical limit. Theory and applications to cold atom systems**

   a- Classical versus quantum description of dynamics. Determinism and uncertainty. Statistical nature of quantum mechanics
   b- Path integral description of quantum dynamics and the classical limit. Duality of corpuscular and wave classical limits. Superfluid-insulator transition as an example of this duality.
   c- Time evolution of the Wigner function. Moyal brackets and Liouville equation for the density matrix in the Wigner form. Classical trajectories as characteristics of the Liouville equation near the classical limit. Truncated Wigner approximation.
   d- Path integral derivation of the truncated Wigner approximation. Quantum corrections. Complete representation of quantum dynamics through classical trajectories.
   e-Examples.

3. **Stability and decay of superfluid motion in isolated systems.**

   a-Landau criterion for superfluidity and Landau critical velocity.
   b-Phase slips and LAMH theory of the decay of superconducting current in quasi one dimensional superconductors. Role of Galilean invariance.
   c- Superfluid currents in optical lattices (arrays of Josephson

junction). Current decay due to thermal and quantum phase slips. Role of dimensionality.

d- Non-equilibrium superfluid-insulator transition in a moving system of interacting bosons in an optical lattice.

e- Experimental examples.

f - Open questions.

Lecturer: Jorge Kurchan (Paris)

Title: Metastability, slow dynamics and large deviations.

1. Stochastic equations and probability evolution.
2. Spectral properties of the generator: an approach to metastability
3. Dynamical phase transitions and slow dynamics

Lecturer: Claudio Chamon (Boston University)

Title: Quantum Mechanics and Glasses.

1) Mapping between classical dynamics and quantum imaginary time evolution

a) From classical to quantum: writing stochastic models in terms of Hamiltonians

b) From quantum to classical: Hamiltonians which are sums of projectors in terms of classical dynamics

c) Examples: Quantum dimer models

d) Frobenius type problems vs. sign problems

e) Example of a sign problem: string nets and quantum loops

2) Mapping between classical dynamics and quantum imaginary time evolution

a) Equilibration of classical systems from the perspective of the mapped quantum models

b) How to construct examples of quantum glasses from classical glasses

c) examples of spin systems

3) Case studies: the superglass and a topologically ordered glass

a) Bosonic superglasses: a theory

b) Bosonic superglasses: review of experimental data

c) An example of a topologically ordered strong glass: wide vs. high tunneling barriers

Lecturer: David Weiss (Penn. State.)

Title: Dynamics of cold atomic gases .

1. Atomic gases in reduced dimensions
2. Non-equilibrium experiments with atomic gases

Lecturer: Ulrich Schollwock (Penn. State.)

Title: Numerical simulations of out-of-equilibrium physics.

In this lecture series, I want to discuss time-dependent DMRG as amethod to simulate the time-evolution of strogly correlated quantum systems in one dimension. I will first briefly explain the conceptual foundations of the method and discuss its limitations that stem from the evolution of quantum mechanical entanglement far from equilibrium. We will also discuss how this method can be extended to finite temperature dynamics and Lindbladian dynamics.

In the second part of my lectures, I will relate these discussions to actual physical problems of current interest. Those will be taken mainly from the field of ultracold atom physics, relating to the simulation of many-body relaxation and to the simulation of antiferromagnets pushed out of equilibrium. In a more traditional vein, I will also relate to close-to-equilibrium quantities such as linear-response quantities, because in this case we now often know how to overcome in practice the limits in reachable times for numerical simulations. If time permits, I will also discuss out-of-equilibrium in the adiabatic (slow parameter change) limit.

1) Methods

I.1. Density-matrix renormalization group: a variational method on matrix product states
I.2. DMRG and its link to quantum mechanical entanglement
I.3. Time-dependent DMRG: Trotter- and Krylov-based approaches
I.4. Evolution of quantum entanglement and limitations of simulations
I.5. Going to finite temperature

2) Applications

II.1. Relaxation in closed quantum systems: an experimentally accessible toy model in cold atoms

II.2. Relaxation in antiferromagnetic structures of cold atoms
II.3. General calculation of high-precision structure factors at finite temperature
(II.4. Adiabatic state evolution out-of-equilibrium)