Chapter 1
Introduction to the Volume

Roberta Citro and Ferdinando Mancini

Abstract A brief introduction on the content of the Volume with a summary of the main topics for each Chapter is reported. The Volume covers the physics of correlated systems out of equilibrium from a theoretical, numerical and computational point of view. It also contains training sessions, which could be beneficial to researchers approaching the field of nonequilibrium many-body systems. The readers will strongly benefit from the different overviews.

1.1 Introduction

In the last decade, novel pathways to explore correlated materials have been devised, ranging from hetero- and nano-structuring to the possibility to detect measurements of the real-time evolution of samples brought out of equilibrium by an external stimulus. The latter is what happens in pump-and-probe spectroscopies [1], where a laser excites the system in a non-thermal excited state, and different spectroscopies (optical, photoemission) are performed at different delays to monitor the evolution of the system and its relaxation to equilibrium. These approaches have been used to explore a variety of properties of strongly correlated materials with a particular focus on high-temperature superconductors, addressing, the electron-boson coupling [2–4], the condensate dynamics [5], the phonon response [6, 7], the quasiparticle dynamics [8, 9], the high-energy dynamics of the pseudogap and of the Mott gap [10–12]. Last,

R. Citro (✉) · F. Mancini
IIASS, International Institute for Advanced Scientific Studies "E.R. Caianiello",
Vietri sul Mare, SA, Italy
e-mail: citro@sa.infn.it

F. Mancini
e-mail: mancini@sa.infn.it

R. Citro · F. Mancini
Dipartimento di Fisica "E.R. Caianiello",
Università degli Studi di Salerno, I-84084 Fisciano, SA, Italy

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but not least, we mention experiments where excitation of lattice degrees of freedom can induce remarkable non-equilibrium phenomena [13–15].

On the other hand, various protocols can be used to study the non-equilibrium dynamics in cold-atoms systems [16, 17]. The main difference between actual solids and cold-atom systems is that the latter can reasonably be described as closed quantum systems, while in the former the electronic fluid is coupled with the environment and it can therefore dissipate the energy accumulated during the excitation process.

The fast developments of these experimental techniques have triggered the development of theoretical methods to study correlated fermions out of equilibrium. However, since the solution of the problem of many interacting electrons is notoriously a very hard problem, we can not hope to obtain exact solutions for the time-dependent properties except for very small systems which allow for an exact diagonalization of the Hamiltonian matrix. This Volume intends to introduce the readers to some of the approaches which have been introduced to study correlated systems, extended out of equilibrium. Among them one can quote the more analytical approaches based on non-equilibrium Green's function formalism and the mean-field type of approaches. Among the most successful, one can mention the Density-Matrix Renormalization Group (DMRG) [18] and the Dynamical Mean-Field Theory (DMFT) [19]. The DMRG works particularly well in one spatial dimension, a situation which can certainly be simulated with ultracold atoms while the DMFT, which becomes exact in the limit of infinite coordination, has been shown to reasonably describe the properties of three-dimensional systems.

Chapter 1 focuses on some "mean-field" approaches who share some conceptual similarities with DMFT and they can in fact be seen as simplified versions of DMFT. Among these, are discussed methods based on slave particles (slave bosons [20–22], slave rotors [23], slave spins [24]) and the methods based on the Gutzwiller wave approximation, which is equivalent to saddle point of the slave-boson approach. In particular, the focus will be on the Gutzwiller method, which has been applied to several non-equilibrium problems in the last few years. In order to better assess the quality of the Gutzwiller solution, the Chapter also addresses the comparison with DMFT results for the same problems. Thus a brief introduction on DMFT is also present, mainly to convince the reader that the Gutzwiller approximation can be viewed as a simplified version of the more accurate DMFT.

Chapter 2 starts from the description of the real-time Greens functions, which provide a rigorous framework to interpret electronic structure out of equilibrium. Afterwards the Keldysh formalism and its relation to the description of non-equilibrium states in terms of kinetic equations is introduced. Finally the non-equilibrium DMFT theory and some of its applications are largely discussed. The focus will be on photo-induced states in Mott insulators, which provides a paradigm example for a non-equilibrium system where well-defined quasiparticles are not established.

The goal of Chap. 3 is to illustrate connections between two widely used, but often separately adopted approaches to deal with quantum systems out of equilibrium, namely quantum master equations and nonequilibrium Green's functions. In particular, the paradigmatic case of the Anderson impurity model out of equilibrium is described and its description from one approach to the other is discussed.

At the end of the chapter, is shown how the best of the master equations versus the Green's function approach can be combined to obtain a highly accurate solution of this model, which resolves the nonequilibrium Kondo physics down to temperatures well below the Kondo scale.

As a training session, this Chapter is largely devoted to an introduction to the Lindblad quantum master equation based on standard treatments, as well as methods to solve this equation.

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