NMR IN STRONGLY CORRELATED MATERIALS

Electron-electron interactions are at the origin of many exotic electronic properties of materials which have emerged from recent experimental observations. The main important phenomena discovered are related with electronic magnetic properties, which have been quite accessible to Nuclear Magnetic Resonance techniques. Those specifically permit to distinguish the orbitals or electronic bands responsible for the magnetism, the metallic properties and superconductivity...and to reveal the physical properties which are distinct from expectations in an independent electron scheme. The description of some selected experimental cases permits us to underline the importance of the technique and to reveal altogether to the reader a wide range of novel phenomena specific to correlated electron physics.

Introduction

In non interacting electronic systems, one considers energy levels with spin degenracy and fills them with two electrons par level, without any consideration of *U*, the local coulomb repulsion on atomic orbitals. But as soon as one considers a solid which displays magnetic properties the latter has to be considered, as *U* is responsible for atomic and solid state magnetism. An introduction to these aspects has been given in a previous Scholarpedia article on the electronic properties of "Strongly Correlated Electron Systems", which will be quoted as **SCES**throughout this article.

If one starts with a completely free electron gas, the first incidence of weak correlations can be expressed in a Fermi liquid approach, that is the electronic states at the Fermi level are not single particle states but rather quasiparticle states in which the electron is dressed by an electronic cloud which involves the electronic correlations. Those quasiparticles are populated in a same way as free electron cases, except that the population jump at the Fermi level is smaller than unity. Correspondingly these quasiparticles have effective masses m_* which differ from the electron mass. This is seen for instance in the specific heat and the Pauli susceptibility.

With increasing electron correlations one reaches situations where electron states are in an intermediate regime between independent extended electronic states and local states. Those intermediate electronic states are at the basis of the correlated electron physics which gives exotic properties to the materials and various competing low *T* states which are far from being understood at this time.

Here we shall take advantage of a series of NMR experimental investigations done on correlated electron systems, to introduce various specific effects which have been highlighted in such systems. The principal useful NMR parameters and technical details have been introduced in a previous Scholarpedia article "NMR studies of electronic properties of solids" that we shall quote as **NMREPS** from now on. The good knowledge of the NMR characteristics in solids for which non interacting electron theories apply quite well, naturally permitted in the initial experiments to detect the unexpected modifications of electronic properties which occur in the presence of strong electronic correlations. This appears as an advantage of the NMR technique, with respect to most recent experimental probes which have been developed specifically to study strongly correlated electron systems.

This article will be organised as follows. We shall recall first in **section 2** the relatively simple case of the NMR studies on the magnetic properties of 3*d* impurities in metallic *sp* systems, which has been highlighted as the **Kondo effect**. This has been the earliest correlated electron physics case which has been understood. It has opened the way to the study of **Heavy Fermions**and **Kondo lattices** which will be touched in **section 3**.

The **High** T_c **cuprates** is of course the family of compounds which has attracted a large interest on correlated electron physics especially in the low doping part of the phase diagram where NMR experiments have permitted to reveal the occurrence of a **pseudogap** as is detailed in **section 4**. The original properties induced by electron interactions in 1D systems, that is**Luttinger liquids** will be briefly mentioned then in **section 5**. We detail in **section 6** the original behavior of **impurities** in correlated electron systems, spin chains, cuprates, which have been important to reveal some of the physical properties which were difficult to probe by distinct approaches. This altogether has induced large efforts to clarify the incidence of disorder on the properties of correlated electron systems. The study of **exotic superconductivities** and the capability of NMR to give some hints on the SC order parameter symmetry is illustrated in**section 7**. An important tendency towards **charge ordering** situations has been proposed to dominate the electronic properties of correlated electron systems. We shall illustrate in **section 8**, in the particular case of Na cobaltates, that NMR ideally permits to unravel such situations in great detail. Of course purely magnetic insulating states are essential cases of correlated electron physics. Those imply a large variety of magnetic states, from ordered spin lattices to disordered spin glasses and **spin liquid** states which are highlighted when frustration effects occur in an ordered lattice. Some of the specific information which can be brought by NMR experiments on such magnetic states are discussed in **section 9**. Finally we illustrate in **section 10** how NMR techniques permitted to study recently the insulator to metal transition induced by pressure in undoped half filled systems, that is the actual **Mott transition**. This has been made possible by the recent discovery of quasi 2D organic and 3D alkali fulleride compounds, which display quasi ideal 2D or 3D Mott transitions. Let us point out that throughout this article we restrict ourselves to a presentation of some robust experimental evidences on these correlated electron systems. We avoid as much as possible entering into the theoretical debates which are natural in a vivid research area and are not solved so far.