Non-fermi liquid behaviour in uranium-based heavy-fermion compounds

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1. Introduction

1.1. Scope

"Condensed matter physics has been surprisingly fertile in giving rise to new and unexpected phenomena, associated very often with new ground states of the electronic system. Many of them lurk at the fringes of interest until they are received into the Church of Physics by baptism with a name, and the latest such addition is provided by what are now called *heavy-fermion* materials". This sentence, written by B.R. Coles [1] more than a decade ago in the introduction of a review paper on heavy-fermion compounds, can now be used in the introduction of this thesis by simply replacing the term *heavy-fermion* by *non-Fermi liquid*.

Landau's Fermi liquid theory has been outstandingly successful in describing the low-temperature properties of normal and heavy-fermion metals. However, in the past decade an increasing number of heavy-fermion systems has been reported to show strong deviations from Fermi liquid behaviour at low temperatures. This so called non-Fermi liquid (NFL) behaviour is generally believed to represent a new type of ground state of metals, thus challenging both theorists and experimentalists to properly describe this new behaviour [2]. This represents the main motivation for the work described here.

Different mechanisms leading to NFL behaviour have been proposed. Some of these mechanisms are based on the physics of quantum phase transitions, while others are based on local Fermi liquid descriptions. NFL materials can normally be grouped into one of these two classes of mechanisms. Up to now, a theoretical model which yields an universal description of NFL behaviour is not available. Crystallographic disorder, which is present in most NFL materials, is expected to play an important role in modelling certain types of NFL behaviour, however its precise influence is far from being understood. The lack of a full theoretical understanding of NFL behaviour asks for careful and detailed studies of the low-temperature properties of heavy-fermion compounds exhibiting NFL behaviour.

In the course of this thesis work, several systems exhibiting NFL behaviour were studied. Among them, U_2Pt_2In appeared to be the most interesting system and a detailed study of its electronic, thermal and magnetic properties was carried out. Although U_2Pt_2In is a "difficult" material from the metallurgical point of view, it is the first stoichiometric uranium-based compound discovered to exhibit NFL behaviour at ambient pressure. U_2Pt_2In is a promising compound to study NFL behaviour because: i) it is a stoichiometric compound, thus the physics might not be dominated by disorder; ii) the observation of NFL behaviour at ambient pressure, enables the use of a wide range of experimental techniques. These points, together with the availability of samples in a single-crystalline form, yield the motivation to study U_2Pt_2In extensively.

Hopefully, this thesis will serve as a reference work to NFL behaviour in heavy-fermion compounds. No definite answer as to the origin of the observed NFL behaviour is given. Actually, considering the state of the art of NFL physics, no definite answer *can* be given at present. The experimental results presented here are discussed in terms of possible mechanisms, yielding strong indications for collective (as in quantum criticality) or single-ion (as in local Fermi liquid descriptions) phenomena.

1.2. Outline

Throughout this thesis, the discussion of the results runs in parallel with the presentation and analysis of the experimental data. A general discussion of the physical properties and/or a summary of the results is given at the end of each chapter.

A brief introduction to heavy-fermion compounds and Fermi liquid theory, as well as an overview of the relevant models that predict NFL properties is given in Chapter 2. In this chapter, a short overview of materials exhibiting NFL behaviour is given as well.

A description of the experimental techniques used throughout this work can be found in Chapter 3. As most of these experimental techniques and set-ups have been described extensively elsewhere, the presentation is kept relatively short. However, the high-pressure technique, used in Chapters 6 and 7, and the muon spin relaxation and rotation (μSR) technique, used in Chapters 5 and 7, are described in more detail.

In Chapter 4, an introduction to the U_2T_2X family of compounds is given and a Doniach phase diagram is constructed for the families with X=In and Sn. In the case of U_2Pt_2In, measurements of the magnetization, resistivity, magnetoresistance, specific heat, specific heat in field and thermal expansion are presented, analysed and discussed. The data presented in this chapter undoubtedly establish the NFL character of U_2Pt_2In.

Zero-, longitudinal- and transverse-field μSR spectra taken on U_2Pt_2In are discussed in Chapter 5. These experiments served to confirm the absence of static magnetic order in U_2Pt_2In. In the NFL regime, pronounced magnetic fluctuations are found.

Chapter 6 deals with resistivity measurements on U_2Pt_2In under hydrostatic pressure, as well as with Th-doping studies. Results of the recovery of a Fermi liquid state in U_2Pt_2In under pressure and the possible emergence of magnetic ordering in Th-doped U_2Pt_2In are presented. For comparison, the suppression under pressure of magnetism in U_2Pd_2In was studied. A discussion in terms of the Doniach phase diagram is given. In addition, magnetization measurements are presented for several compounds of the U_2T_2X family in order to investigate their location in the Doniach diagram.

Besides the U_2T_2X family, several other uranium intermetallic systems exhibiting NFL behaviour were studied. Namely, $U_3Ni_3Sn_4$ was studied by means of specific heat, resistivity (under pressure) and μSR experiments, $U(Pt_{1-x}Pd_x)_3$ by means of μSR experiments and $URh_{1/3}Ni_{2/3}Al$ by means of resistivity measurements. The results are presented in Chapter 7 in a collection of published (or submitted for publication) articles.

Some concluding remarks are made in Chapter 8.

Several abbreviations are introduced in this thesis. A list is presented in Table 1.1.

Table 1.1 - List of abbreviations used in this work.

AF	AntiFerromagnetism	QCP	Quantum Critical Point
CW	Curie-Weiss	QKE	Quadrupolar Kondo Effect
EPMA	Electron Probe MicroAnalysis	RE	Rare Earth
FC	Field Cooled	RKKY	Rudermann-Kittel-Kasuya-Yosida
FL	Fermi Liquid	RT	Room Temperature
FM	FerroMagnetism	SBF	Symmetry Breaking Field
GPS	General Purpose Spectrometer	SC	SuperConductivity
HF	Heavy Fermion	SCR	Self-Consistent Renormalization
HTSC	High-Temperature SuperConductivity	SDW	Spin Density Wave
INS	Inelastic Neutron Scattering	SEM	Secondary Electron Microscopy
LDA	Local Density Approximation	SG	Spin Glass
LF	Longitudinal Field	SMAF	Small-Moment AntiFerromagnetism
LMAF	Large-Moment AntiFerromagnetism	SQUID	Superconducting QUantum Interference Device
LTF	Low Temperature Facility	TCKE	Two-Channel Kondo Effect
MCW	Modified Curie-Weiss	TEM	Transmission Electron Microscopy
MORE	Muons On REquest	TF	Transverse Field
MR	MagnetoResistance	XRD	X-Ray Diffraction
NFL	Non-Fermi Liquid	ZF	Zero Field
NMR	Nuclear Magnetic Resonance	ZFC	Zero Field Cooled
OFHC	Oxygen-Free High Conductivity	μ-s.s.	Muon Stopping Site
PSI	Paul Scherrer Institute	μSR	Muon Spin Relaxation or Rotation

References

1. B.R. Coles, Contemp. Phys. 28 (1987) 143.
2. Proc. ITP Conference on Non-Fermi Liquid Behaviour in Metals, Santa Barbara, 1996, in J. Phys.: Condens. Matter 8 (1996) 9675 ff.