Experimental investigation of potential topological and p-wave superconductors

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Chapter 1 Introduction

1.1 General introduction

Superconductivity discovered by the Dutch physicist Heike Kamerlingh Onnes in Leiden in 1911 has provided one of the most fascinating research fields [1]. Not only is it a very special state of matter compared to the well-known states, conducting, semiconducting and insulating, but also the understanding of this novel ground state in some materials systems appears to be a great theoretical challenge. As regards its understanding, the microscopic theory which explains superconductivity in most materials was proposed by Bardeen, Cooper and Schrieffer (BCS) in 1957, and is based on the attractive rather than repulsive effective interaction between two electrons with anti-parallel spins of a Cooper pair via lattice vibrations [2]. However, more and more materials have been discovered which cannot be explained by BCS theory, the so-called unconventional superconductors (SCs). Unconventional superconductivity has been found in numerous systems over the last forty years, *e.g.* the prime example ^{3}He [3,4], later on heavy fermion compounds (see for instance [5–13]), cuprates [14,15] and iron pnictides [16,17].

Frequently, superconductivity emerges in the paramagnetic phase of a metal as a consequence of phonon-mediated pairing. Therefore, the coexistence of ferromagnetism and superconductivity in the same material, which is a so-called ferromagnetic superconductor (FMSC), has become a mesmerizing research field. The first example discovered in 2000 is UGe_2 [10]. Later, three other uranium-based FMSCs were found: URhGe [11], UIr [18] and UCoGe [19]. The emergence of this robust class of superconducting compounds requires novel theoretical insights rather than the standard BCS formalism. Theoretical predictions of *p*-wave SC in itinerant ferromagnets [20] were made long before the first FMSC was experimentally realized. In these first models, the exchange of longitudinal spin fluctuations near the ferromagnetic quantum critical point (FM QCP) was proposed as the pairing mechanism for triplet Cooper pairs. However, this simple model lacks an explanation for the non-zero superconducting transition temperature T_c at the QCP in UCoGe. Later on, more sophisticated theoretical models based on spin fluctuation approaches have appeared [21–24]. In these models, superconductivity and ferromagnetism coexist on the microscopic scale. Superconductivity is closely related to a magnetic instability near the FM QCP, and the same electrons are responsible for band ferromagnetism and superconductivity [25].

In addition, theoretical predictions followed by the experimental realization have very recently led to a completely new research field: topological insulators (TIs) [26,27]. These novel materials have a close connection to the quantum Hall effect (QHE), one of the central discoveries in the field of condensed matter physics in the 1980s. In the QHE, electrons that are confined to two dimensions and are subjected to a strong magnetic field, exhibit a special, topological, type of order. A few years ago, it was realized that topological order can emerge quite generally in specific two and three dimensional materials. These materials are now called TIs [26,27]. Not only do TIs possess intriguing properties, which require novel insights and physics, but also these new materials have sparked wide research interest, because they offer new playgrounds for the realization of novel states of quantum matter [28,29]. In 3D TIs the bulk is insulating, but the 2D surface states - protected by a nontrivial Z_2 topology - are conducting. Most interestingly, the concept of TIs can also be applied to superconductors (SCs), due to the direct analogy between topological band theory and superconductivity: the Bogoliubov-de Gennes Hamiltonian for the quasiparticles of a SC has a close similarity to the Hamiltonian of a band insulator, where the SC gap corresponds to the gap of the band insulator [30,31]. Consequently, this analogy leads to another novel concept in condensed matter physics which is the so-called topological superconductor (TSC). Topological superconductivity can be adopted as a state that consists of a full superconducting gap in the bulk, but is topological and protected by symmetries at the boundaries of the system. The remarkable point is that the topological surface states can presumably harbor Majorana states. A Majorana zero mode is a particle that is identical to its own antiparticle. Majorana zero mode states are expected to be a key element for future topological quantum computation schemes. Experimentally, the most well known candidate for TSC is superfluid ^{3}He (phase B) [32–34] described by the topological invariant $\mathbb{Z}$. Yet another promising test case for 2D chiral superconductivity is the triplet superconductor Sr_2RuO_4 [35], but experimental evidence remains under debate, for instance, as regards the existence of the gapless surface states [29]. Other promising candidate topological superconductors can be found among the doped 3D TI $Cu_xBi_2Se_3$ (chapter 4) [36,37], the half-Heusler platinum bismuthide families with 111 stoichiometry LaPtBi, YPtBi (Chapter 5) and LuPtBi [38–43], the doped semiconductor $Sn_{1-x}In_xTe$ [44] and the recent new comer ErPdBi [45].

In this dissertation, we present the results of an extensive experimental study on some of these exemplary (candidate) unconventional superconductors: $Cu_xBi_2Se_3$, YPtBi and UCoGe. We employ magnetic and transport measurements as well as the muon spin relaxation (μSR) technique to further unravel the superconducting nature of these novel materials.

1.2 Outline of the thesis

This dissertation consists of six chapters. The content of Chapters 2-6 is laid out as follows.

Chapter 2

This chapter summarizes a number of experimental techniques that have been used throughout this work in the Van der Waals-Zeeman Institute (WZI). Transport measurements were performed using several cryogenic aparatuses: a Maglab Exa, a ^{3}He refrigerator referred to as the Heliox and a dilution refrigerator referred to as the Kelvinox in the following. All three instruments are made by Oxfords Instruments. High pressure measurements at pressures up to 2.5 GPa have carried out using a hybrid piston-cylinder pressure cell. Additionally, the μSR technique used for experiments carried out at the Paul Scherrer Institute (PSI) is briefly discussed in this chapter.

Chapter 3

The theoretical aspects of the research topics presented in this thesis are given in this chapter. The aim is to provide a general picture and links to the experimental work presented later on. We introduce a brief overview of superconductivity, quantum criticality and quantum phase transitions. The recent discovery of FMSC as a novel class of unconventional SCs is discussed; in particular, we focus on the intriguing properties of the latest member of the family, UCoGe. Furthermore, a concise discussion is presented of the recent discovery as well as of the intriguing properties of topological insulators and possible topological superconductors. Subsequently, we discuss superconductivity in a magnetic field. Particularly, we consider the temperature variation of the upper critical field for both conventional BCS *s*-wave and unconventional superconductors. The analysis of the upper critical field is further investigated in details in Chapters 4 and 5 to unravel the superconducting nature of the studied materials.

Chapter 4

Transport measurements were made at both ambient and high pressure on the doped second generation 3D TI $Cu_xBi_2Se_3$. It is demonstrated that the temperature variation of the upper critical field $B_{c2}(T)$ strongly deviates from the spin-singlet Cooper pair state in the conventional BCS formalism. The data rather point to an unconventional polar *p*-wave superconducting phase. Our study strongly supports theoretical proposals that this material is a prime candidate for TSC.

Chapter 5

One of the 111 compounds in the Half Heusler family, YPtBi, is studied by means of transport, magnetic measurements and μSR. AC-susceptibility and DC-magnetization data show unambiguous proof for bulk superconductivity. The zero-field Kubo-Toyabe relaxation rate extracted from µSR data allows the determination of an upper bound for the spontaneous field associated with odd-parity superconducting pairing. Transport measurements under pressure are used to establish the temperature dependence of the upper critical field, $B_{c2}(T)$, which tells us the superconducting state is at variance with the expectation of simple *s*-wave spin-singlet pairing. The $B_{c2}(T)$ data are consistent with the presence of an odd-parity Cooper pairing component in the superconducting order parameter, in agreement with theoretical predictions for noncentrosymmetric and topological superconductors.

Chapter 6

We present a magnetotransport study on the ferromagnetic superconductor UCoGe. The data, taken on high quality single crystalline samples, identify a significant structure near $B^* = 8.5$ T when the applied magnetic field is parallel to the spontaneous moment. We show that this feature has a uniaxial anisotropy. Moreover, it is very pronounced for transverse measurement geometry and rather weak for longitudinal geometry. The uniaxial nature of the B^* feature and its large enhancement under pressure provide strong indications that it is closely related to an unusual polarizability of the U and Co moments. Transport measurements around the superconducting transition in fixed magnetic fields with $B \parallel b$ corroborate that our samples exhibit an extraordinary S-shaped B_{c2}-curve when properly oriented in the magnetic field. This field reinforced SC appears to be connected to critical spin fluctuations associated with a field-induced quantum critical point.

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