Summary

Superconductivity has played a prominent part in condensed matter physics for more than 100 years, but the understanding of this intriguing phenomenon still remains a theoretical challenge. Almost all current theoretical interpretations consider the key element making up the superconducting condensates to be the very formation of Cooper pairs derived from the microscopic Bardeen-Cooper-Schrieffer (BCS) theory in 1957. In this context, superconductors can be classified as conventional (BCS) or unconventional based on the symmetry of the Cooper pairs. Notably, the discovery of superconductivity in the ferromagnet UGe_2 in 2000 came as a big surprise because according to the BCS formalism, ferromagnetic order impedes the formation of Cooper pairs in spin-singlet states. Subsequently, only few other superconducting ferromagnets have been discovered: URhGe (2001), UIr (2004) and UCoGe (2007). To explain the coexistence of superconductivity and ferromagnetism on the microscopic scale, the most sophisticated theoretical treatment is to employ models of spin fluctuations near the quantum critical point. Here spin fluctuations mediate superconductivity, rather than phonons. However, what exactly the superconducting pairing mechanism is in the superconducting ferromagnets is still under debate.

Another highly interesting research field that has come to the fore in recent years is that of materials called topological superconductors, because these could host Majorana zero modes, which themselves offer a route to applications in topological quantum computation. Investigation and understanding of the intrinsic properties of topological superconductivity are therefore not only crucial for the realization of novel states of quantum matter but could also pave the way to potential device applications. This PhD work is an experimental study of unconventional superconductivity in the superconducting ferromagnet UCoGe and two candidate topological superconductors $Cu_xBi_2Se_3$ and YPtBi. The main techniques applied have been transport, magnetic and μSR measurements, and these have been carried out so as to shed further light on the intricate superconducting pairing mechanism in these novel materials.

In Chapter 2, a short description of the experimental techniques used throughout this dissertation is presented. The equipment for measuring at low temperatures and strong magnetic fields is introduced. We have also discussed the calibration of the RuO_2 thermometer in high magnetic field, as well as of the high-pressure cell. A brief discussion of the μSR technique employed at the Paul Scherrer Institute is also presented.

Chapter 3 is aimed at a concise theoretical overview of the related research themes presented throughout this project. We provide a general picture and link to the experimental work presented in later chapters. An overview of superconductivity, quantum criticality and quantum phase transitions is given in a close connection to the novel class of quantum matter: the superconducting ferromagnet. This is followed by a description of the intriguing properties of the latest member in the family, UCoGe. The chapter continues with a brief overview of the recent discovery and on the robust properties of topological insulators and topological superconductors. Next, we discuss superconductivity in a magnetic field. In particular, 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 studied in much detail in Chapters 4 and 5 on $Cu_xBi_2Se_3$ and YPtBi, respectively.

By means of magnetic and transport measurements carried out on the candidate topological superconductor $Cu_xBi_2Se_3$, we have investigated in Chapter 4 the response of superconductivity in this system to a magnetic field and high pressures up to 2.3 GPa. Upon increasing the pressure, superconductivity is smoothly depressed and vanishes at $p_c \sim 6.3$ GPa. At the same time, the metallic behaviour is gradually lost. These features are explained by a simple model for a low electron carrier density superconductor. The analysis of the upper critical field shows that the $B_{c2}(T)$ data collapse onto a universal curve, which clearly differs from the standard curve of a weak coupling, orbital limited, spin-singlet superconductor. Although an anisotropic spin-singlet state cannot be ruled out completely, the absence of Pauli limiting and the similarity of $B_{c2}(T)$ to a polar-state function point to spin-triplet superconductor. Our observations are in line with theoretical proposals that $Cu_xBi_2Se_3$ is a promising candidate for the realization of a topological superconductor.

Transport, magnetic and μSR measurements on one of the few candidates for topological superconductivity in the Half Heusler family, YPtBi, are presented in Chapter 5. AC-susceptibility and DC-magnetization data provide unambiguous proof for bulk superconductivity. An upper bound of the spontaneous field possibly associated with odd-parity superconductivity is obtained from the zero-field Kubo-Toyabe relaxation rate extracted from the μSR data. The temperature dependence of the upper critical field, $B_{c2}(T)$, deduced from electrical resistivity measurements at ambient pressure and pressure up to 2.3 GPa, signals a superconducting state at odds with the expectation of the standard BCS scenario. Most importantly, the $B_{c2}(T)$ data point to the presence of an odd-parity Cooper pairing component in the superconducting order parameter, in agreement with theoretical predictions for noncentrosymmetric and topological superconductors.

Finally, in Chapter 6, we present an extensive magnetoresistance study conducted on single-crystalline samples of the ferromagnetic superconductor UCoGe for a magnetic field directed in the bc- and ac-planes of the orthorhombic unit cell. We pinpoint a pronounced structure in the magnetoresistance, which takes place when the component of the magnetic field along the c-axis reaches a value $B^* = 8.5$ T. Angle dependent measurements reveal that this field-induced phenomenon has uniaxial anisotropy. Magnetoresistance measurements under pressure show a roughly linear and rapid increase of B^* with pressure, with a dB^*/dp of 3.2 T/GPa. The uniaxial nature of B^* and its large pressure variation are consistent with the interpretation that the change in the magnetoresistance regime at B^* is related to an unusual polarizability of the U and Co moments. Upper critical field measurements corroborate the extraordinary S-shaped $B_{c2}(T)$-curve for a field along the b-axis of the orthorhombic unit cell. Although these and other studies have helped pin down the properties of UCoGe further, in order to finally unravel the intriguing properties of UCoGe, notably with respect to the close connection between field-induced phenomena such as a quantum critical point or Lifshitz transition and superconductivity, a continuous research effort is required to probe the strongly anisotropic thermal, magnetic and transport properties in this important superconductor.