Summary

Superconductivity is a fascinating phenomenon. Over the last hundred years, researchers from all over the world have been working on superconducting materials. New superconductors are discovered on a daily basis, and superconductivity has found many applications. Nevertheless, we are still far away from understanding the mechanisms which drive superconductivity in several important classes of superconductors, like cuprates, pnictides and heavy-fermion compounds. In this thesis, we concentrate on three different unconventional superconductors.

UCoGe belongs to the family of superconducting ferromagnets. The physics of such systems is extremely rich. First of all, the coexistence of superconductivity and ferromagnetism within a single phase is quite unique. Only a few materials exhibit such a coexistence: UGe_2, URhGe and UCoGe. Secondly, these materials are strongly correlated electron systems with a heavy-fermion nature based on the uranium $5f$-electrons, which are responsible for both superconductivity and ferromagnetism. The combination of all mentioned properties makes UCoGe a unique laboratory tool to study ferromagnetic quantum criticality and the related effects, such as strong spin fluctuations and superconductivity in the vicinity of the quantum critical point.

Recently, a new class of unconventional superconductors received ample attention, topological superconductors, partly because it was theoretically predicted that they can host Majorana zero modes at the surface. Currently, two approaches to search for topological superconductors have been quite successful. First, doping of topological insulators may transform the material into a superconductor. Examples of such systems are $Sr_xBi_2Se_3$ and $Cu_xBi_2Se_3$. Recently, a surprising discovery was reported: the in-plane upper-critical field in these materials is strongly anisotropic. This finds an explanation in terms of nematic superconductivity, where the order parameter is a vector and can depend strongly on the direction of magnetic field. The second approach is based on the idea to search for topological superconductors

among materials which contain heavy elements. The presence of heavy elements, such as rare earth atoms, within the crystal, can create a band inversion in the electronic structure due to the strong spin-orbit coupling. Electronic structure calculations predicted a large number of compounds in which non-trivial topology may be realized. An example of such a system discussed in this thesis is HoPdBi, which is a member of the half-Heusler family with non-trivial topology.

An important part of this thesis project was devoted to the design and construction of a dilatometer with very high sensitivity that could be rotated in the magnetic field. Moreover, the dilatometer needed to be operated under extreme conditions, notably at milli-Kelvin temperatures and high magnetic fields. The design of the thermal expansion cell was chosen to satisfy the following criteria: a small size, a low cell effect, non-magnetic, and high resolution. For this a parallel-plate capacitance dilatometer was constructed. The resolution of the thermal expansion cell at low temperature is 0.03 Å. In order to conduct field-angle dependent measurements, a rotation mechanism was implemented. A piezo-electric rotator mounted onto a gear system was installed. The angular resolution of the device is 0.05°. A detailed description of the dilatometer, the rotation mechanism, the calibration of the system and other technical issues are presented in Chapter 3. In addition, the cryogenic equipment, other experimental techniques and the sample characterization are discussed in Chapter 3.

In the following two chapters, we focus on the superconducting and ferromagnetic properties of UCoGe. The phase diagram of this superconducting ferromagnet has been determined by dilatometry, a bulk sensitive probe. Measurements of the thermal expansion coefficient on a high-quality single crystal of UCoGe around the Curie point and the superconducting transition temperature in magnetic fields up to 12 T applied along the orthorhombic axes have been carried out. A precise orientation of the magnetic field with respect to the crystal axes was obtained by *in situ* rotation of the cell using the piezo-electric motor. The field variation of the superconducting and ferromagnetic transition temperatures was established. For small fields $B \parallel c$ the ferromagnetic transition becomes a cross-over and superconductivity is rapidly suppressed ($B_{c2} = 0.5$ T when $T \to 0$). For $B \parallel a, b$ the Curie point and superconductivity persist. With our bulk technique, we confirm the unusual S-shape of the upper-critical field for $B \parallel b$ and the enhancement of superconductivity above 6 T. At the same time, the Curie point shifts towards lower temperatures. This lends further support to theoretical proposals of spin-fluctuation mediated reinforcement of superconductivity for $B \parallel b$.

Next, an extensive magnetoresistance study on single crystals of UCoGe for a magnetic field directed along the c-axis is presented. We confirm a pronounced structure in the magnetoresistance, which takes place when the component of the field parallel to the c-axis reaches a value B^* = 9 T. Measurements of B^* as a function of pressure up to p = 1.5 GPa show a quadratic increase $B^*(p) = B^*(0) + bp^2$, where b = 3.0 T/GPa^2. The characteristic field B^* = 9 T is also observed in magnetostriction and magnetic torque measurements, albeit less prominent. The Fermi surface of UCoGe has been studied by quantum oscillations in the magnetoresistance. A pair of small Fermi surface pockets with a heavy effective mass was detected. Our results are in good agreement with recent magnetoresistance and thermopower measurements that revealed the presence of multiple Lifshitz transitions as a function of the applied magnetic field $B \parallel c$. This demonstrates the Fermi surface of UCoGe undergoes a dynamic reconstruction under large magnetic fields.

An important part of this thesis is dedicated to topological superconductors. The recent discovery of nematic superconductivity in $Sr_xBi_2Se_3$ provided the motivation to investigate this phenomenon under high pressures up to 2.2 GPa. Therefore, Chapter 6 focuses on a high-pressure study of $Sr_{0.15}Bi_2Se_3$ in order to investigate the unusual basal-plane anisotropy of the upper-critical field. The superconducting transition temperature is found to be rapidly depressed with a critical pressure of $\sim$ 3.5 GPa. $B_{c2}(T)$ has been determined for the B-field applied along two orthogonal crystal directions, a and a^*, in the basal plane. The pronounced two-fold basal-plane anisotropy $B_{c2}^{a}/B_{c2}^{a^*} = 3.2$ at $T = 0.3$ K is robust under pressure and attains a value of $\sim$ 5 at the highest pressure (2.2 GPa). The two-fold anisotropy of $B_{c2}(T)$ provides solid evidence for rotational symmetry breaking in the D_{3d} crystal structure. This puts stringent conditions on the superconducting order parameter, namely it should belong to a two-dimensional representation (E_u). Rotational symmetry breaking seems to be ubiquitous in the family of doped Bi_2Se_3-based superconductors. This offers an exciting opportunity to study nematic superconductivity with a two-component order parameter.

In Chapter 7, the transport, magnetic and thermal properties of the half-Heusler antiferromagnet HoPdBi are discussed. We discovered superconductivity at 1.9 K as evidenced by electrical resistivity and ac-susceptibility data. However, the transition to bulk superconductivity sets in at a lower temperature of 0.75 K. The Néel temperature T_N is 2.0 K as determined by thermal expansion and dc-magnetization measurements. The superconducting and magnetic phase diagram in the $B - T$ plane has been determined: superconductivity is confined to the antiferromagnetic phase. Electronic structure calculations show HoPdBi is a topological semimetal with a band inversion at the Γ-point. This is in-line with the semimetallic behaviour observed in the electrical resistivity and the low carrier concentration extracted from the Shubnikov-de Haas effect. HoPdBi belongs to the half-Heusler REPdBi series with a topological band structure and presents a new laboratory tool to study the interplay of antiferromagnetic order, superconductivity, and topological quantum states.