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Ferromagnetic superconductors

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ABSTRACT

The co-existence of superconductivity and ferromagnetism is of potential interest for spintronics and high magnetic field applications as well as a fascinating fundamental state of matter. The recent focus of research is on a family of ferromagnetic superconductors that are superconducting well below their Curie temperature, the first example of which was discovered in 2000. Although there is a 'standard' theoretical model for how magnetic pairing might bring about such a state, why it has only been seen in a few materials that at first sight appear to be very closely related has yet to be fully explained. This review covers the current state of knowledge of the magnetic and superconducting properties of these materials with emphasis on how they conform and differ from the behaviour expected from the 'standard' model and from each other.

Contents

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1. Introduction

The search for ferromagnetic superconductors dates from before the 1960s. Early attempts were made by alloying solid solutions that contained superconductors and ferromagnets as end members, such a (Ce–Gd) Ru_2 [1]. The failure to find any co-existence of the two phenomena, supported the conclusion that conventional singlet superconductivity is incompatible with the strong exchange fields that align spins in a ferromagnet and the two orders are in competition. In the following decades, by choosing the Curie temperature T_C to be much lower than the superconducting transition temperature T_s the competition was brought to a balance and a type of co-existence induced. This was extensively explored in Chevrel phase and borocarbide compounds [2–5]. Even in this case the resulting state was found to be non-uniform; both the superconductivity and magnetism are modulated such that their order-parameters oscillate out of phase to reduce their spatial overlap. A theoretical mechanism for the modulation based on a how the superconducting gap affects the susceptibility was given by Anderson and Suhl [6]. A different explanation based on a Ginzburg–Landau theory purporting closer agreement with experiment was later developed by Blount and Varma [7]. In these materials the magnetic order is clearly associated with local moments, while the conduction electrons carry superconductivity.

A few experimental cases of homogeneous bulk uniform co-existence did emerge from these studies, although extremely fragile. In one case, found in $AuIn_2$, the nuclear moments order ferromagnetically but are so weakly coupled with the electrons that the superconductivity survives [8]. In a second, a fragile metastable co-existence of homogenous ferromagnetism with superconductivity in the Chevrel phase $HoMo_6S_8$ was demonstrated [9]. The conclusion from these studies is that although it is possible to have conventional singlet superconductivity in ferromagnets, such states are limited to cases where the ferromagnetism is weak with $T_C < T_s$. The Pauli-limited critical field for superconductivity also has to be larger than the exchange field.

Pairing electrons in a triplet configuration to avoid the Pauli limit appears to offer the only possibility to obtain superconductivity with $T_C > T_s$. The anti-symmetry of fermions under exchange then requires that the order parameter has odd parity. This in turn requires that the pairing interaction has a strong q-dependence on the scale of the Fermi-wavevector. Phonon mediated interactions are inherently short range (their range is set by Thomas Fermi screening) and appear incapable of providing an interaction of the correct form under most circumstances. Magnetic interactions provide an alternative to phonons [10,11], analogous to the pairing mechanism for atoms realised in superfluid ^{3}He [12]. Close to a ferromagnetic quantum critical point where ferromagnetism is suppressed, low energy long wavelength magnetic excitations are expected to be prevalent and have an appropriate wavelength dependence. This motivated searches for magnetically mediated superconductivity in a number of weak or incipient itinerant ferromagnets.

The search for a superconducting analogue to the superfluidity in ^{3}He resulted in the discovery of superconductivity deep in the ferromagnetic state in UGe_2 [13], the first uniform ferromagnetic superconductor with $T_C > T_s$. This was followed by the observation of superconductivity in URhGe [14] and in an isostructural isoelectronic material UCoGe [15], although the latter only just satisfies $T_C > T_s$. To date these are the only fully established examples of ferromagnetic superconductors with $T_C > T_s$.

Before restricting our discussion to the above three materials, we briefly mention three other materials where co-existence of bulk ferromagnetism and superconductivity with $T_C > T_s$ has been claimed. (i) The itinerant ferromagnet $ZrZn_2$ with $T_C \sim 28$ K created some excitement in 2001 when superconductivity was reported in high-quality crystals. However superconductivity was later shown to be limited to a layer at the sample surface that had been modified by spark-erosion [16]. (ii) For compounds with formula in the range Y_4Co_3–Y_9Co_7 superconductivity and very weak ferromagnetism with $T_C > T_s$ was reported as long ago as 1980. These compounds have a complex structure with a partially occupied Co site (hence the composition range) located in 1D channels [17]. The evidence for superconductivity is clear cut, but the case for bulk homogeneous ferromagnetism is less clear. It is suggested that the ferromagnetism is sensitive to the precise Co positions in the channels [18] and experimentally it is absent in better ordered samples [19]. Most work has been done on polycrystals with the exception of structural studies made on very small single crystals. The available evidence points to the superconductivity being conventional. (iii) UIr was discovered to be superconducting in a narrow pressure range with $T_s = 0.14$ K [20] just below the pressure at which ferromagnetism is suppressed. There are a succession of magnetic transitions with pressure and the phase supporting superconductivity (called "FM3") is possibly only present at low temperature in experiments with a non-hydrostatic pressure medium [21]. The low temperature moment has not been measured at the same pressure as superconductivity is observed, but at lower pressure in FM3 it is very small ($< 0.05\mu_B$) [22]. The upper critical field for superconductivity H_{c2} is < 30 mT and the highest superconducting fraction reported is <20% [22]. The bulk coexistence of ferromagnetism and superconductivity is therefore not fully established. However, non-fermi-liquid power laws for the temperature dependence of the resistivity suggest that quantum criticality may be relevant to the pairing mechanism and the fact that the superconductivity is found close to a transition between competing magnetic states resembles UGe_2. Unlike UGe_2, URhGe and UCoGe the structure of UIr does not have inversion symmetry. In the following we focus on only UGe_2, URhGe and UCoGe where the evidence for bulk co-existence in the best quality samples is clear.

It is surprising that so few ferromagnetic superconductors are known, now 15 years after the discovery of superconductivity in UGe_2. Although UGe_2, URhGe and UCoGe have some obvious points in common, they are also distinct from each other in important ways. Each is also amenable to different experimental probes. This review begins with a general review of the common traits of the three materials before discussing each in turn. The main theme of the review is the identification of the mechanism and special circumstances required to achieve superconductivity in ferromagnets. Other recent reviews include [23–26]. This review is of experimental work and only limited reference is made to theory.

2. Overview of UGe_2, URhGe and UCoGe

2.1. Magnetic properties

All the above ferromagnetic superconductors have an orthorhombic structure. Several of their normal state, magnetic and superconducting properties are listed in Table 1. They all contain uranium and are 'heavy-fermions' with moderately high effective mass. The enhanced effective mass in the ferromagnetic state is noteworthy, since the Kondo mechanism usually invoked as the origin of an enhanced mass might be expected to be suppressed by the exchange field below T_C. Understanding how a heavy mass survives could be key to identifying the pairing mechanism, although there is only limited theoretical work on this [36–38]. The large effective mass is important for achieving a low fermi-velocity and coherence length $\xi \sim \hbar v_f/(k_B T_c)$. The coherence length has to