Mass Enhancement and Reentrant Ground State under Magnetic Field in Heavy Fermion Superconductors

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Abstract.

Three different cases of magnetic field induced reentrant ground states in heavy fermion systems URhGe, UGe$_2$ and CeRhIn$_5$, recently studied in Grenoble, are discussed. URhGe is a ferromagnetic superconductor with the reentrance of superconductivity under magnetic field ($H$) which is associated to a spin reorientation. In the ferromagnetic superconductor UGe$_2$ an enhancement of the superconducting upper critical field $H_{c2}$ appears at its metamagnetic transition between two ferromagnetic phases. CeRhIn$_5$ is a superconductor under high pressure and reentrance of antiferromagnetism is induced by magnetic field. We analyze the links between the $H$ enhancement of the different contributions to the effective mass and the field reentrant phase.

The unconventional superconductivity (SC) of heavy fermion compounds often occurs close to quantum singularities driven by magnetic or valence instabilities. Here we will present three cases of field reentrant phenomena linked to the interplay between field changes of their magnetic and superconducting properties.

URhGe is a very nice example of ferromagnetic (FM) superconductor; i.e. (i) its critical superconducting transition temperature $T_{sc} \sim 0.27$ K is far below its Curie temperature $T_{Curie} \sim 9.5$ K [1]. (ii) Applying pressure drives the system deeper in the FM domain as shown in Fig. 1(a) [2, 3]. Thus, one escapes from a FM quantum singularity where $T_{sc} \sim T_{Curie}$. (iii) At $T_{Curie}$, the Fermi surface is well formed and thus the Fermi liquid regime is also well established (the resistivity shows a nice $AT^2$ dependence). (iv) Furthermore, the rather weak magnetic anisotropy leads to the remarked phenomena that the sublattice magnetization $M_0$ changes its alignment from the initial easy $c$-axis to the $b$-axis at a field $H_R \sim 12$ T applied along one of the hard axis (the $b$-axis) without any drastic change of $M_0 \sim 0.4\,\mu_B$ [4]. The surprising result is that the reentrant superconductivity (RSC) is observed for $H \parallel b$-axis in a rather large $H$ window around $H_R$ [4]. By a careful study of the resistivity under pressure and magnetic field, we have recently demonstrated that the SC properties can be well understood via a McMillan type formula, $T_{sc} = T_0 \exp(-m^*/m^{**})$, where the effective mass $m^*$ is the sum of a renormalized band mass $m_B$ and of a correlated mass $m^{**}$ which is the source of the SC pairing [5]. A strong enhancement of $m^{**}(H)$ is observed in the vicinity of $H_R$, while $m_B$ appears as field and also pressure invariant. The upper critical fields at $T = 0$ K of the low field SC and RSC phase...
in this equal spin pairing triplet SC is estimated by the orbital limit according to the relation \(H_{c2}(m^*(H), T \rightarrow 0 \text{ K}) \sim [m^*(H)T_{sc}(m^*(H))]^2\). Under pressure, \(m^*(H = 0)\) decreases thus \(T_{sc}(m^*(H = 0))\) and also \(H_{c2}(m^*(H = 0), T \rightarrow 0 \text{ K})\) [3]. The RSC is strongly affected by the concomitant decrease of \(T_{sc}(m^*(H_R))\) and of \(H_{c2}(m^*(H_R), T \rightarrow 0 \text{ K})\). As predicted by our simple model, the RSC collapses at a pressure \(P_{RSC} \sim 1.5 \text{ GPa}\), where \(H_{c2} = H_R\), far lower than the pressure \(P_{sc}\) where the low field SC will disappear (Fig. 1(b)). The low field SC seems to disappear only near 4 GPa, i.e. \(m^*(0)\) will collapse (see [3]).

![Figure 1](image)

**Figure 1.** (a) \((P, T)\) phase diagram of URhGe at \(H = 0 \text{ T}\). (b) Pressure dependence of \(T_{sc}\) at \(H = 0 \text{ T}\) (circle) and \(H_R\) (square).

In UGe\(_2\), the SC dome is not linked to the proximity of the FM quantum singularity where FM will disappear but to the first order singularity at \(P_x \sim 1.3 \text{ GPa}\) where the system switches from a low pressure high sublattice magnetization FM2 phase \((M_0 = 1.5 \mu_B)\) to a high pressure low sublattice magnetization FM1 phase \((M_0 = 1 \mu_B)\). As shown in Fig.2(a), the new features are revealed that i) the first order line \((T_x, P_x)\) between FM1 and FM2 terminates at a critical end point \((T_{cr} = 15 \text{ K}, P_{cr} = 1 \text{ GPa})\) and ii) SC appears just above \(P_{cr}\) and only in the FM phase. The crossover from FM1 to FM2 due to a continuous mixing of the both phases below \(P_{cr}\) was drawn from the broadening of the temperature dependence of the thermal expansion and the resistivity. At ambient pressure, this definition corresponds to the upper limit of 10% of emerging FM2 content in FM1 and the lower limit to 10% remaining FM1 phase in FM2 as determined by combined specific heat and thermal expansion measurements [6]. At a pressure \(P_x + \epsilon \sim 1.35 \text{ GPa}\) applying a magnetic field along the easy axis leads to switch from the initial FM1 to the FM2 state via a metamagnetic transition; the consequence for SC shown in Fig.2(b) is that the system reenters in the SC+FM2 phase, which has at a given pressure quite different characteristic values of \(T_{sc}\) and \(H_{c2}\) than SC+FM1 phase [7]. Up to now the SC boundary close to \(P_x\) has not been determined precisely. New experiments are necessary to clarify if through \(P_x\) only a change in the magnitude of \(m_B\) and \(m^*\) is responsible for the change in the superconducting properties or if not a modification of the SC order parameter itself appears. In contrast to URhGe, as \(M_0\) is not preserved a drastic change of the Fermi surface occurs [8]. The concomitant variation of \(m_B\) and of \(m^*\) are marked by the fact above \(P_x\) that its Sommerfeld coefficient is almost pressure invariant while \(T_{sc}(P)\) in the FM1 phase changes drastically [9]. This simultaneous \((P, H)\) variation of \(m_B\) and \(m^*\) was predicted in the theoretical model of Ref. [10] with a double peaked structure in the density of states.

These two examples of FM-SC corresponds to the case where \(T_{sc} \ll T_{Curie}\). With the recent case of UCoGe having \(T_{Curie} \sim 3 \text{ K}\) and \(T_{sc} \sim 0.6 \text{ K}\) [11], the hope is to get new coexisting states
when $T_{\text{Curie}}$ and $T_{\text{sc}}$ will cross under pressure as the possibility of a cascade from paramagnetic, superconducting and mixed SC+FM states [12].

![Figure 2.](image)

As a guide line for the antiferromagnetic case, it is interesting to look to careful studies realized under $(P, H)$ on CeRhIn$_5$ [13, 15, 16]. As shown in Fig.3(a), antiferromagnetism (AF) and SC are robust at low and high pressure, respectively. A coexisting SC+AF phase at zero field occurs only between $P \sim 1.7$ GPa and $P^*_c \sim 2$ GPa, where $T_N$ and $T_{\text{sc}}$ merge into one point [16]. The simple idea is a competition or interplay between an AF pseudogap $\Delta_{\text{AF}}$ and the SC gap $\Delta_{\text{sc}}$ assuming that both the AF and the SC phase will have the same $(1/2, 1/2, 1/2)$ hot spot in the coexisting domain which seems to be shown by recent NQR results [17, 18]. As shown in Fig. 3(b), between $P^*_c < P < P_c \sim 2.5$ GPa the new event is the field reentrance of AF under magnetic field and the associated creation of vortices [15, 16], $T_N(H)$ can exceed $T_{\text{sc}}(H)$ as the critical magnetic field $H_M \sim 40$ T at $T \rightarrow 0$ K is much larger than the value of the upper critical field $H_{c2}(0) \sim 10$ T, so far $T_N$ does not collapse, i.e. $P$ is lower than $P_c$. As indicated in Fig.3(b), the reentrant AF will collapse at $P_c$ close to $H_{c2}(0)$. Up to now, attempts to fit the upper critical field curves $H_{c2}(T)$ via the orbital and Pauli contribution plus additional possibility of strong coupling constant ($\lambda = m^*/m_B - 1$) have failed [16]; as discussed previously on FM-SC, for SC of CeRhIn$_5$ there is clearly the necessity to incorporate the $H$ dependence of $m^*$ which is not only pressure dependent. Furthermore in the coexisting AF+SC phases, the presence of one phase will react on the properties of the other.

A simple picture is that AF will reenter under magnetic field in the SC phase when $\Delta_{\text{sc}}(H)$ is lowered in magnetic field down a critical value $\Delta_c$ where itinerant AF can occur. The related superconductor CeCoIn$_5$ is a particularly striking case as, in absence of SC, CeCoIn$_5$ at $P = 0$ may be just above $P^*_c$, and $H_M$ must be lower than $H_{c2}(0)$. When the SC occurs, at low field firstly AF is repealed as the superconducting gap is too strong. However, increasing $H$ will decrease $\Delta_{\text{sc}}(H)$ down to $\Delta_c$ (see J. Panarin et al to be published) and then AF will be restored. AF will appear glued to $H_{c2}$ as a pseudogap like AF structure induced by SC will only collapse at $H_{c2}(0)$. Thus the fancy effect in CeCoIn$_5$ is that the recovery of a superconducting
Figure 3. (a) $(P,T)$ phase diagram of CeRhIn$_5$ at $H = 0$ T from ac calorimetry (circles) and from recent NQR experiments (square) [14, 17, 18]. (b) $(T,H)$ phase diagram at a pressure close to $P_c$ of $P = 2.4$ GPa. Arrows indicate the evolution under pressure

pseudogap under fields allows to stabilize AF at a field value far above $H_M$ (for CeRhIn$_5$ almost up to $P_c$, $H_M$ remains higher than $H_{c2}(0)$, the collapse of AF coincides with the collapse of the AF+SC domain to $H_{c2}(0)$ at $P_c$).

A further interesting effect in CeCoIn$_5$ is the strong pressure dependence of the strong coupling parameter $\lambda$ as it will play a key role in the enhancement of $\Delta_{SC}/k_B T_{SC}$. Taking into account the $P$ dependence of the strong coupling correlation, with this picture we arrive to the conclusion that increasing the pressure and thus decreasing the strength of $\lambda$, the AF phase will expand in a larger $H(P)/H_{c2}(P)$ domain than in zero pressure in good agreement with the experiment (see [16]).

The comparison of the three cases where reentrant phenomena exists show clearly the importance to take into account the $P$ and also $H$ dependence of the effective mass. For FM-SC of URhGe the simplicity is that only the field dependence of the correlated mass $m^{**}$ must be considered; in UGe$_2$ the $P$ and $H$ variation affect both contributions of the effective mass. With the case of CeRhIn$_5$ and CeCoIn$_5$, the interplay between an AF pseudogap and the SC gap appears the appealing key parameter. Next interesting example to reveal the relation between magnetism and SC is a careful study of the FM superconductor UCoGe in the critical regime near 1 GPa where $T_{SC} = T_{Curie}$ [19].

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