Field Re-entrant Superconductivity Induced by the Enhancement of Effective Mass in URhGe

Atsushi MIYAKE$^{1,2}$, Dai AOKI$^1$, and Jacques FLOQUET$^1$

$^1$INAC/SPSMS, CEA-Grenoble, 17 rue des Martyrs, 38054 Genoble, France
$^2$KYOKUGEN, Osaka University, Toyonaka, Osaka 560-8531, Japan

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High quality single crystals of a ferromagnetic superconductor URhGe were successfully grown. The electrical resistivity was measured for the field along b-axis in the orthorhombic crystal structure in order to study precisely its field re-entrant superconductivity which occurs in the vicinity of the field $H_R$, where the easy magnetization switches from c to b-axis. The field re-entrant superconductivity of URhGe is analyzed with special focus on its dependence with the value of residual resistivity $\rho_0$ and the coefficient $A$ of $T^2$ term of the resistivity. The experimental results are well explained by a crude model related with the field dependence of the effective mass $m^*$, where the corresponding critical temperature $T_{sc}(m^*)$ and the upper critical field $H_{c2}$ are strongly enhanced. Discussion is made on the interplay between magnetic and superconducting phase diagram as well as the link between $T_{sc}$ and $A$ in other heavy fermion superconductors.

KEYWORDS: Field re-entrant superconductivity, URhGe, Ferromagnetic superconductor, Effective mass

1. Introduction

Ferromagnetism and superconductivity had been thought to be mutually competitive phenomena, since the large internal field easily destroys the Cooper pair for conventional superconductivity. In 1970s, the superconductivity was found in 4f-localized ferromagnets, such as ErRh$_4$B$_4$ where the superconducting critical temperature $T_{sc}$ is larger than the Curie temperature $T_{Curie}$. Below $T_{Curie}$, the superconducting phase is expelled, thus the both phases are competing with each other. In these systems, two separated magnetic phase (localized 4f electrons and light itinerant electrons), the ferromagnetism is a robust quantity even for $T_{Curie} < T_{sc}$. The discovery of superconductivity in the 4f-itinerant ferromagnet UGe$_2$ under pressures was one of the breakthrough in the unconventional superconductivity. Contrary to ErRh$_4$B$_4$, $T_{sc}$ is lower than $T_{Curie}$ in UGe$_2$ and the superconductivity exists only in the ferromagnetic phase on the pressure-temperature phase diagram, where the superconductivity coexists with the ferromagnetism. The triplet superconductivity with equal spin pairing is, therefore, believed, because the large internal field will not prevent the formation of the Cooper pair.

Other examples for the coexistence of ferromagnetism and superconductivity are URF$^4$ and the recently found UCoGe$^5,6$ which crystallize in the orthorhombic structure with TiNiSi-type. In the case of URhGe, the ferromagnetic (FM) transition occurs at $T_{Curie} = 9.5\,K$ and its ordered moment is $M_0 = 0.4\,\mu_B$/U. The superconductivity (SC) was found to exist below $T_{sc} = 0.25\,K$ at ambient pressure. The upper critical fields $H_{c2}$ are larger than the Pauli limiting field, thus the spin-triplet state is most likely realized. Striking feature is the field re-entrant superconductivity (RSC).$^8,9$ With increasing the magnetic field along the b-axis in the orthorhombic structure, the moment starts to tilt from the easy magnetization c-axis to b-axis, and then the ordered ferromagnetic moment is completely aligned to the b-axis above a reorientation field $H_R = 12\,T$. The RSC is observed between $H_1 = 8$ and $H_2 = 12.7\,T$ and detected in wide range of the field angle around $H \parallel b$. Thus, this superconductivity is not due to the so-called Jaccarino-Peter effect,$^{10}$ which has been found in the Chevrel phase compound$^{11}$ and the organic superconductors, such as $\kappa$-(BETS)$_2$FeBr$_4$,$^{12}$ where the RSC is due to a compensation of the external field by the internal exchange field.

An enhancement of $H_{c2}$ related to the metamagnetic transition has been observed in the ferromagnetic superconductor UGe$_2$, as well.$^{13}$ When the magnetic field is applied along the easy-magnetization axis (a-axis) at a pressure of $P = 1.35\,GPa$, the ferromagnetic phase changes from FM1 (weakly polarized phase) to FM2 (strongly polarized phase) at $H_x$ with increasing field. The $H_{c2}$-$T$ phase diagram shows the step-like increase of $H_{c2}$ at $H_x$ and $H_{c2}(0)$ in FM2 is higher than that expected in FM1.

Here we report the careful studies on the field dependence of the inelastic $T^2$ term $A$ of the electrical resistivity $\rho$ by using the high quality single crystals in order to study the RSC of URhGe. The resistivity follows the quadratic temperature dependence, namely $\rho = \rho_0 + AT^2$ for all the measured field range. The RSC is well explained by the enhancement of the effective mass $m^*$.

2. Experimental

The single crystals of URhGe were grown by the Czochralski pulling method in the radio frequency furnace under purified Ar atmosphere gas with a stoichiometric ratio of the starting materials, U (Purity: 3N-99.9%), Rh (4N) and Ge (6N). The ingot was annealed at 1300°C under ultra high vacuum (UHV) for one day. The single crystal ingot was oriented by the Laue photo-
Results and Discussion

Figure 1 represents the field dependence of the resistivity $\rho$ for #1a, #1b and #2 at 72, 200 and 400 mK. For sample #1a with RRR = 40, the RSC was clearly observed between $H_1 = 10.7$ T and $H_2 = 14.2$ T at 72 mK, where $H_1$ and $H_2$ are defined as mid points of the drop of resistivity. At high temperature of 400 mK, the resistivity shows the peak at $H_{R} = 13.7$ T, corresponding to the reorientation of the moment. The crystal seems to misalign slightly from the field direction respect to the $a$-axis, because $H_1$, $H_2$ and $H_R$ are larger than those in the previous reports.\(^8,9\) The purer sample, i.e. higher value of RRR, shows the wider superconducting windows and the higher transition temperatures. It is interesting to note that for sample #2, only track of SC is suspected at low field, while rather deeper drop on the resistivity is observed in a very narrow field window. The same trend is observed in sample #1b, where the resistivity shows rather sharp drop due to the RSC, although the step-like behavior is observed near $H_{c2}$ for the low field SC. These observation indicates the strict condition for RSC. That suggests a strong increase of the coherence length in the RSC phase. On the other hand, the reorientation field $H_R$ is not sensitive to the sample quality. The insensitivity is also a FM property at zero field.\(^4\) It is noted that $H_1$ is more sensitive to the sample quality compared to $H_2$, indicating that the RSC strongly stick to $H_R$.

Figure 2 shows the superconducting phase diagram and reorientation field $H_R$. In sample #1a, the upper critical field $H_{c2}(0) = 2$ T is clearly larger than the Pauli limiting field $H_p = 0.46$ T estimated from $T_{c2}(0) = 0.25$ K, indicating that $H_{c2}$ is determined by the orbital limit depending on the effective mass. The RSC is observed between $H_1 = 10.7$ T and $H_2 = 14.2$ T at 72 mK for sample #1a. It is interesting that $T_{sc}(H)$ for RSC reaches a temperature of 330 mK at 13.3 T, which is larger than the value of $T_{sc}(0) = 250$ mK at zero field. This peculiar behavior is consistent with the analysis of $T_{sc}$ by the enhancement of effective mass $m^*$ in Fig. 6 as discussed later. At high temperatures, the reorientation field $H_R$ starts to decrease with increasing temperature. Finally, $H_R$ seems to be connected to the Curie temperature $T_{Curie} = 9.5$ K at zero field.

Figure 3 represents the variations of $H_{c2}$, $H_1$, $H_2$ and $H_R$ at 72 mK as a function of $\rho_0$, which is inversely proportional to the mean free path, i.e. $\rho_0 \propto 1/l$. For unconventional superconductivity like URhGe, the $T_{sc}$ must depend on the variation of the parameter $\xi/l$ between the superconducting coherence length $\xi$ and $l$ according to the Abrikosov-Gor’kov pair breaking mechanism.\(^14\) where $l$ must be larger than the coherence length $\xi$. The so-called clean limit condition must be satisfied. Such a dependence has been actually observed in previous studies on polycrystalline samples\(^15\) and single crystals.
The effective mass is no more the effective mass at zero field, but the mass \( m^{**} \) built by the \( H \) dressing of the quasiparticle.

It is well known that the calculation of \( T_{sc}(m^*) \) is a difficult task which requires the solution of the Eliashberg equation. However, we will show that the RSC in URhGe seems to be well explained by a crude model where \( T_{sc} \) is related to the field variation of the effective mass \( m^*_H \). The simplicity of URhGe comes from its non-proximity to the ferromagnetic instability; the pressure \((P)\) increases \( T_{Curie} \), and decreases \( T_{sc} \) as well as the \( A \) coefficient. \( P \) and \( H \) scans show that URhGe corresponds to the simple case where the variation of the \( A \) coefficient (basically \( m^* \)) and \( T_{sc} \) are coupled, that is, the enhancement of \( A \) leads to an enhancement of \( T_{sc} \).

The chosen expression of \( T_{sc}^{0}(m^*_H) \) is

\[
T_{sc}^{0}(m^*_H) = T_0 \exp \left( -\frac{m_H}{gm^{**}} \right),
\]

where the effective mass \( m^*_H \) is described by the band mass \( m_B \) plus an extra mass \( m^{**} \) directly related to the source of SC pairing, namely,

\[
m^*_H = m_B + m^{**}.
\]

Assuming \( g = 1 \) for simplicity,

\[
T_{sc}(m^*_H) = T_0 \exp \left[ -\left( \frac{m_H}{m^{**}} + 1 \right) \right]
\]

The expression is based on the McMillan-like formula,\(^{19}\) for FM superconductors, it was theoretically proposed far from FM instability.\(^{20–22}\) Taking the logarithmic derivative of eq. (3), it is interesting to remark that Grüneisen
parameter for $T_{sc}$ will be linked to the Grüneisen parameter of the effective temperature $T_B \sim 1/m_B$ and $T^{**} \sim 1/m^{**}$ as,

$$\Omega_{T_{sc}} = \frac{1}{\lambda} (\Omega_{T_B} - \Omega_{T^{**}}),$$

(4)

where Grüneisen parameter is defined as $\Omega_T = -d(\log T)/d(\log V)$, and $\lambda = m^{**}/m_B$. If the main phenomena is due to the volume dependence of $T_B$, that is, the systems are mainly dependent on the $\Omega_{T_B}$, $T_{sc}$ and $T_B$ will go to the same direction. In other word, $T_{sc}$ will increase when the band mass $m_B$ decreases. Basically it is the main argument that considering different strongly correlated electron system from heavy fermion systems to high $T_{sc}$ oxides, $T_{sc}$ scales the inverse of the specific heat coefficient $\gamma$;\textsuperscript{23, 24} basically SC can appear only below the Fermi temperature which is related to $\gamma^{-1}$. If the main phenomena is the volume dependence of $T^{**}$, which is observed in uranium heavy fermion compounds like UPt$_3$, URu$_2$Si$_2$ and UBe$_{13}$, the Grüneisen parameter of the SC and normal phases have opposite sign.\textsuperscript{25} The same trend is observed in URhGe.

Assuming the relation $A \sim (m^*)^2$, and that the upper critical field $H_{c2}(H)_{T \rightarrow 0}$ is governed by the orbital limit for this triplet superconductor, $H_{c2}(H)_{T \rightarrow 0}$ is given by the equation,

$$H_{c2}(H)_{T \rightarrow 0} \sim [m^*(H)/T_{sc}^0(m_{H}^*)]^2,$$

(5)

one can estimate $T_{sc}^0(m_{H}^*)$ and $H_{c2}(H)$ for a given value of $A_c \sim (m_B)^2$. Figure 6 represents the predicted $H$ dependence of $T_{sc}^0(m_{H}^*)$ and $H_{c2}(m_{H}^*)$ as a function of $H$ for sample #1a, where $A_c = 1.1 \mu\Omega \text{cm/K}^2$ is chosen, corresponding to the hypothesis of a field independent band mass $m_B$. Following our suggestions,\textsuperscript{26} similar calculations were made,\textsuperscript{27} however, no measurements were carried out for the field dependence of $T^{2}$-law in the resistivity. As shown in the inset of Fig.5, the quadratic temperature dependence of the resistivity were observed at high fields.

Surprisingly, the predicted $H_{c2}$ is in good agreement with the results of experiments, as shown in Fig. 6(b). $T_{sc}$ at $H_R$ is enhanced by a factor of 1.7, which is larger than the estimated value from the field variation of $\rho_0/\sqrt{A}$, as discussed above. Here we note that the $T_{sc}^0(m^*(H))$ strongly depends on the chosen value of $A_c$, namely $m_B$. When $m_B$ increases, the evaluated $T_{sc}^0(m^*(H))$ increases as well.

URhGe is a good example where the RSC due to the
spin reorientation can be described by a field enhancement of the correlation, namely enhancement of $m^*$. The spin reorientation mechanism leads to escape from the rigidity of Ising spin dynamics. The fluctuation between $c$ and $b$-axis component of the magnetization in the large field range may lead to a large field window of the mass enhancement, which is in agreement with the large field region of RSC. According to the recent neutron scattering analysis, a perfect scaling occurs for $M^\parallel b$. The sublattice magnetization for $c$-axis, $M_c$, starts to decrease from 8 T and becomes zero at $H_R = 11.5$ T with increasing field. On the other hand, the sublattice magnetization for $b$-axis, $M_b$, linearly increases from zero, and becomes $M_b = M_c$ at 10.5 T. Finally, $M_b$ is fully polarized at $H_R = 11.5$ T. It means that the fluctuation between $M_b$ and $M_c$ starts to develop from 8 T. Simply thinking, when $M_b = M_c$ is realized, the magnetic fluctuation may become maximum, implying the large enhancement of the effective mass. This may correspond to a maximum value of $A$ at a field, which is slightly lower than $H_R$ defined as a peak of $\rho_0$, as shown in Fig. 2. A fit of the resistivity $\rho$ by a $T^2$ law lead to find another weak maxima of $A$ for sample #1a and #1b. Its origin is left to the future study. It may be caused by the intrinsic effect due to a $H$ crossover between collision and quantum criticality regime or the small misalignment inside the crystal.

On the other hand, for the other FM superconductor UGe$_2$, the field change of SC properties corresponds to a drastic switch in the description of the ferromagnetism: from perfectly polarized FM2 to imperfectly polarized FM1 according to the recent neutron scattering analysis. For UGe$_2$, the Ising character is preserved at the switch from FM1 to FM2 at $H_F$, furthermore this switch is associated with a drop of $m^*$. The key phenomena for SC does not appear in the proximity to the ferromagnetic-paramagnetic (FM-PM) instability but in the instability at $P_c$, where the system may switch from FM2 to FM1. The pressure dependence of $T_{sc}$ cannot be related to the pressure increase of $\gamma$ term from FM2 to FM1, via an increase of $m^*$ and application of the eq. (3). Obviously, the main phenomena is either a change in the Fermi surface topology as discussed in ref. 31 or another origin of pairing as proposed in the charge density wave scenario. At least in the frame of our model, $T_{sc}$ must change on both side of $P_c$. It is more complicated than the case of URhGe. The drastic change of Fermi surfaces in UGe$_2$ were reported between $P < P_c$ and $P > P_c$, but the experimental results between $P_c$ and $P$ are still unclear.

It is interesting to compare URhGe with CeRu$_2$Si$_2$, a heavy fermion compound highly studied for its metamagnetic transition at $H_M$ where a sharp crossover occurs between a low field paramagnetic phase (PM) and a high field polarized paramagnetic (PPM) phase at $H_M = 7.7$ T. Figure 7 shows the relative field variation of $A_H/A_H^\parallel$, in reduced scale of $H/H^*$, where $H^*$ corresponds to $H_R$ and $H_M$ for URhGe and CeRu$_2$Si$_2$, respectively. A perfect scaling occurs for $H/H^* > 1$, here both cases are governed by Ising ferromagnetic spin dynamics. Below $H/H^* < 1$, the systems are quite different. However, enhancement of $A(H^*)$ are rather similar, $A(H^*)/A(0) = 1.4$ and 2 for URhGe and CeRu$_2$Si$_2$, respectively.

Below $H_M$, microscopic phenomena are now well clarified in CeRu$_2$Si$_2$. Antiferromagnetic (AF) correlation dominates below $H_M$ and collapses just at $H_M$, where the FM fluctuation becomes soft in a narrow field window centered at $H_M$. As discussed in ref. 38, an interesting situation would occur, if CeRu$_2$Si$_2$ were SC at $H = 0$ with $H_{c2}^* > H_M$. Assuming the switch with the fluctuation from AF to FM, the singlet pairing may be replaced by the triplet pairing. Unfortunately, the Ising character of the AF spin dynamics presumably prevents the establishment of SC.

Thus the simplicity of URhGe is that the FM mechanism is preserved; furthermore as $T_{Curie} > T_{sc}$, the $P$ and $H$ dependence of an unique parameter $m^*$ appears sufficient to describe the SC properties. Up to now for AF heavy fermion systems, only $H$ reentrance of AF in the SC state of CeRhIn$_5$ has been reported; it corresponds to hierarchy between the bare parameters ($T_N$: Néel temperature, $T_{sc}$, $H_c$: critical magnetic field of the AF–PM boundary and $H_{c2}$): $T_{sc} > T_N$ and $H_c > H_{c2}(0)$; AF survives the normal phase up to $H_c$.

An interesting case will be that $H_e$ is lower than $H_{c2}$, when $T_{sc} > T_N$. That may happen for CeCoIn$_5$ as no AF is detected above $H_{c2}(0)$, however, a new low temperature-high field superconducting phase is observed. In the framework of a magnetic scenario, one can imagine that the persistence of a SC gap inhibits the transition to PM phase which requires the collapse of the AF pseudogap; due to the interplay with SC, AF may be stucked to $H_{c2}(0)$. Up to now, the main trend is to neglect the possible magnetic origin, and to consider that the new phase of CeCoIn$_5$ is the evidence of the so-called FFLO state predicted four decades ago with a extra modulation of the order parameter along $H$. But still no definitive conclusion emerges from the experiments.

4. Conclusion

The reorientation of the moment from $c$ to $b$-axis for $H \parallel b$ is characterized by an invariance of $H_R$ on sample purity. While the RSC seems to strongly depend as its low field SC on the sample purity, indicating the unconventional nature for both RSC and low field SC. The $T^2$ Fermi liquid law of the resistivity is obeyed for all the field range, the amplitude of the $A$ coefficient has an enhancement at $H_R$ which is interpreted as an enhancement of the effective mass $m^*$. The enhancement of $m^*$ appears to concern mainly the effective mass contribution $m^{**}$ added by the magnetic correlation on the band mass $m_R$. The increase of $m^{**}$ in the vicinity of $H_R$ leads to a strong increase of the superconducting transition temperature $T_{sc}$ and of the upper critical field $H_{c2} \sim (m^{**})^2$. Surprisingly, a crude model assuming McMillan-type formula for $T_{sc}$ gives a good description of the experimental results. It is interesting to mention that the enhancement of the fluctuation is quite non symmetrical with respect to $H_R$. The feedback on SC is the
asymmetry of RSC boundary by reference to $H_R$. This property is clearly demonstrated in Fig. 7 by the comparison with CeRu$_2$Si$_2$. The difference of re-entrant phenomena between in URhGe and in UGe$_2$ has been discussed. The particularity of UGe$_2$ is to involve SC pairing between quite different FM phases (fully polarized and partially polarized). The main phenomena appear to be the change in Fermi surface topology. At least for both cases, only FM is considered. For the re-entrant phenomena on appearance of a new low temperature and high field phase as observed in so-called Ce115 compounds, the antiferromagnetic fluctuations are dominant at $H = 0$. However, a field sweep will reveal the interplay between AF, PM, PPM and SC phase. CeRhIn$_5$ appears a simple case where the field re-entrance of AF collapses rapidly under pressure. CeCoIn$_5$ is a more intriguing example, where AF may be stuck to $H_{c2}(0)$ over a rather large $P$ window; as indicated an alternative explanation is the formation of a FFLO state.

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