Upper critical field and field-induced superconductivity in layered superconductors with antiferromagnetic subsystems

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Abstract

The phase diagrams on the temperature and magnetic field plane are examined in layered superconductors with antiferromagnetic subsystems in parallel magnetic fields. The field-induced superconductivity (FISC) occurs for strong Kondo coupling $J_{\rm K} \gg zJ$ by the Jaccarino-Peter mechansim, where J denotes the antiferromagnetic coupling constant of the subsystem. The experimental phase diagram of λ-(BETS)$_2$FeCl$_4$ is semi-quantitatively reproduced by taking into account the Fulde-Ferrell-Larkin-Ovchinnikov state with an order-parameter mixing effect. On the other hand, for weak Kondo coupling, an enhancement of the upper critical field occurs instead of the FISC. In particular, for $J_{\rm K} \sim zJ \gg \Delta_0$, the system is practically free from the paramagnetic pair-breaking effect, and very large areas of the superconductivity are obtained in the phase diagram.

Key words: upper critical field; organic superconductor; generalized Kondo lattice model; field induced superconductivity

1. Introduction

Interplay between magnetism and superconductivity is a subject of current interest in connection with a number of organic and oxide superconductors. For example, a λ-(BETS)$_2$FeCl$_4$ compound exhibits an interesting phase diagram with a field-induced superconductivity (FISC). The magnetic anions FeCl$_4$ are considered to play an essential role in the FISC by the Jaccarino-Peter (JP) mechanism [1,2]. On the other hand, hybrid ruthenate and cuprate compounds such as RuSr$_2$GdCu$_2$O$_8$ have the antiferromagnetic (AF) ruthenate layers (with weak ferromagnetic moments due to a canted spin structure) and the superconducting (SC) cuprate layers.

Motivated by the discoveries of such compounds, we examine layered superconductors with AF subsystems. In this paper, we assume that the subsystems consist of localized spins with AF exchange interactions J between them. The Kondo exchange interactions $J_{\rm K}$ exist between the localized spins and the conductive electrons which are responsible for the superconductivity. The exchange interactions J may include indirect interactions via the conduction electron band in addition to the direct interactions.

2. Compensation effect and phase diagrams

For weak magnetic fields, a canted spin structure occurs in the localized spin subsystem, while for sufficiently strong magnetic fields, the spin moments are saturated. We apply the magnetic field H parallel to the conductive layers. At zero temperature $T = 0$, the cant angle θ satisfies $\cos\theta = \mu_e H/zJS$ for $|\mu_e H| \le zJS$ within a mean field theory, while $\theta = 0$ for $|\mu_e H| \ge zJS$. Here, μ_e is the electron magnetic moment. We assume that the AF transition temperature is much larger than the SC transition temperature $T_{\rm c}$ for simplicity, so that the temperature dependence of θ is negligible.

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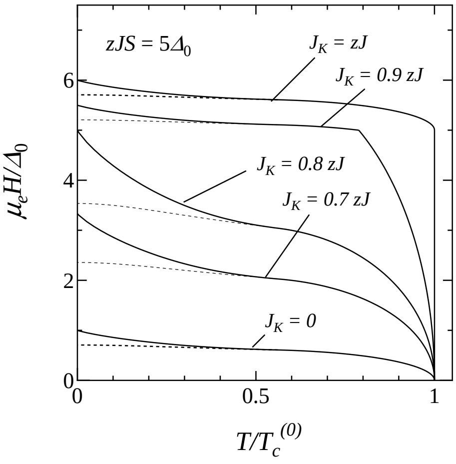

Fig. 1. The phase diagrams for $J_{\rm K} \leq zJ$. The solid and dotted curves show the upper critical fields when the FFLO state is taken into account and ignored, respectively. $T_{\rm c}^{(0)}$ is the zero field transition temperature.

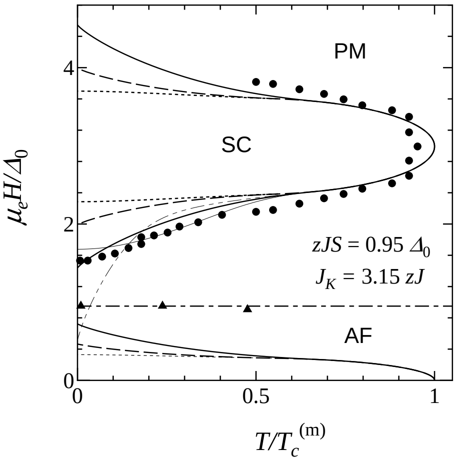

Fig. 2. The phase diagram for $J_{\rm K} \gg zJ$. The solid, dashed, and dot-dashed curves show the SC transition temperatures for $T_{\rm c}^{(p)}/T_{\rm c}^{(\rm m)} = 0.01$ and 0, and the AF phase boundary, respectively. Here, $T_{\rm c}^{(\rm m)}$ and $T_{\rm c}^{(p)}$ are the maximum of $T_{\rm c}$ and the p-wave transition temperature, respectively. The dotted curve is the SC transition curve when the FFLO state is ignored. The closed circles and triangles show the experimental data of SC and AF transition points in λ-(BETS)$_2$FeCl$_4$ [8]. We have assumed that $T_{\rm c}^{(\rm m)} = 4.2$ K in plotting the experimental data. The thin solid and thin two-dot-dashed curves exhibit the transition temperatures of the $d_{x^2-y^2}$-wave FFLO states with $\varphi_{\bf q} = \pi/4$ and 0, respectively, where $\varphi_{\bf q}$ denotes the angle between $\bf q$ and x axis, and $T_{\rm c}^{(p)}/T_{\rm c}^{(\rm m)} = 0.1$ assumed.

When $J_{\rm K} > 0$, the Zeeman energy of the conductive electrons is partly cancelled by $J_{\rm K} S \cos\theta$ due to a compensation effect like that by the JP mechanism. In the present mechanism, however, the compensation energy is proportional to H due to the canted spin structure in contrast to the original JP mechanism. As a result, the superconductivity occurs when $|H| < H_{\rm c}(T) \equiv H_{\rm c}^{(0)}(T)/|1 - J_{\rm K}/zJ|$ for $|\mu_e H| \leq zJS$, where $H_{\rm c}^{(0)}(T)$ is the upper critical field in the absence of the compensation effect. On the other hand, for $|\mu_e H| \geq zJS$, the superconductivity occurs when $J_{\rm K}S/|\mu_e| - H_{\rm c}^{(0)}(T) < |H| < J_{\rm K}S/|\mu_e| + H_{\rm c}^{(0)}(T)$. The ground state phase diagram was shown in our previous paper [3]. Here, we examine the phase diagrams at finite temperatures.

Figure 1 shows the results for $zJS = 5\Delta_0$, where Δ_0 is the zero field BCS gap. When $J_{\rm K} \sim zJ$, extraordinarily large areas of the superconductivity are found instead of the reentrant transition to the FISC. On the other hand, Fig. 2 shows the result for $zJS = 0.95\Delta_0$ and $J_{\rm K} = 3.15zJ$. The experimental phase diagram of λ-(BETS)$_2$FeCl$_4$ [4,5] is reproduced quantitatively. In addition to the present compensation mechanism, the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state with order parameter mixing effect plays an essential role in this reproduction [6,7]. The low-field SC phase in Fig. 2 is suppressed when the system is insulating at half-filling for $|\mu_e H| < zJS$ in accordance with the experimental result.

3. Conclusion

The layered superconductors with the AF subsystems could be free from the paramagnetic pair-breaking effect up to an extraordinarily high magnetic field when $J_{\rm K} \sim zJ \gg \Delta_0$. On the other hand, when $J_{\rm K}S \gg zJS \sim \Delta_0$, the FISC occurs due to the JP mechanism. In particular, the experimental phase diagram of λ-(BETS)$_2$FeCl$_4$ is semi-quantitatively explained by a combination of the JP mechanism and the FFLO state.

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