Anisotropic Superconductivity in Magnetic Field Induced Superconductors λ-(BETS)$_2$Fe$_x$Ga$_{1-x}$Cl$_4$

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Abstract

Resistance measurements in λ-(BETS)$_2$Fe$_x$Ga$_{1-x}$Cl$_4$ (x=0.45) have been performed to investigate the field induced superconductivity. In magnetic fields parallel to the conduction layers (c-axis), the superconducting (S) phase is induced between 5 T and 24 T at 1.6 K. However, when the field is tilted from the c-axis to the b*-axis (normal to the conduction layers), the S phase disappears at around 6 degrees. This strong anisotropic behavior shows that the orbital effect plays a significant role in the destructive mechanism of the superconductivity. The orbital critical field normal to the conduction layers is estimated to be 1.5 T at 1.6 K.

Key words: organic superconductor;anisotropy ; λ-(BETS)$_2$Fe$_x$Ga$_{1-x}$Cl$_4$

For conventional superconductors, Cooper pairs are destabilized under magnetic fields by both the Zeeman and orbital effects. However, it was recently found that a magnetic two dimensional (2D) organic conductor λ-(BETS)$_2$FeCl$_4$, where BETS is bis(ethylenedithio)tetraselenafulvalene, shows a superconducting phase only under high magnetic fields [1,2]. At zero magnetic field, λ-(BETS)$_2$FeCl$_4$ shows a metal-insulator transition around 8 K, which is associated to the antiferromagnetic order of the Fe^{+3} spins (S=5/2) [3,4]. The antiferromagnetic insulating (AFI) phase is removed by the application of a field of the order of 10 T which stabilizes a paramagnetic metallic (PM) phase due to the gain of Zeeman energy of Fe^{+3} moments. Below 1 K, and when a magnetic field is applied parallel to the conduction layers, superconductivity (S) is induced above 17 T and then destroyed above 42 T [1,2]. This field-induced S phase does not appear for fields applied perpendicularly to the 2D conducting layers. In contrast, the iso-structural nonmagnetic salt λ-(BETS)$_2$GaCl$_4$, which has a similar Fermi surface[5], remains metallic and shows a superconducting transition at T_c~6 K. The superconductivity is destroyed under a magnetic field of 13 T (3 T) parallel (perpendicular) to the conduction layers [6].

In order to investigate the anisotropic field induced superconductivity, we have performed the resistance measurements in λ-(BETS)$_2$Fe$_x$Ga$_{1-x}$Cl$_4$ (x=0.45).

Figure 1 shows $T-H$ phase diagram for $H \parallel c$. We have the field induced S phase above 5 T. The maximum T_c is ~3 K at ~14 T.

The possibility of Jaccarino and Peter(J-P) effect [7] has been proposed as the mechanism responsible for the field induced S phase in λ-(BETS)$_2$FeCl$_4$ [1,2]. In

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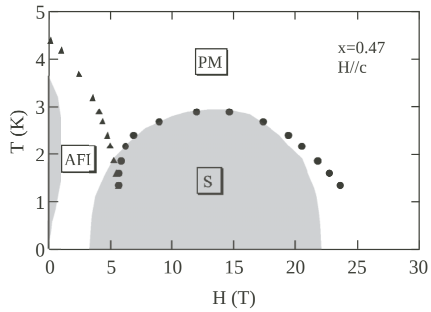

Fig. 1. $T-H$ phase diagram in λ-$(BETS)_2Fe_xGa_{1-x}Cl_4$ (x=0.45) The shaded areas show the calculated S phases based on Fisher's theory.

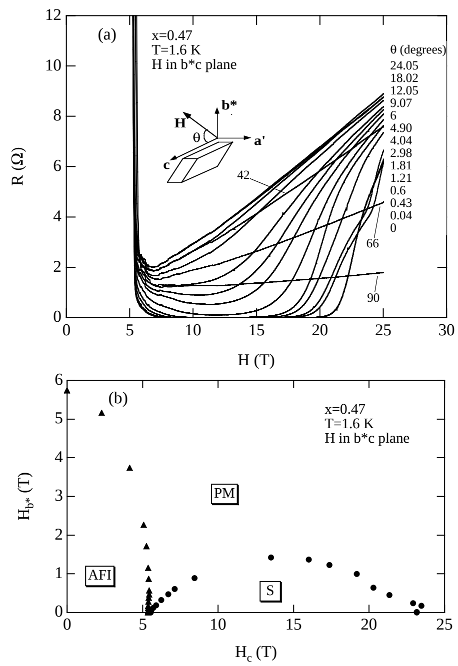

Fig. 2. (a) Field dependence of resistance in λ-$(BETS)_2Fe_xGa_{1-x}Cl_4$ (x=0.45) at various field angles. Inset: Schematic picture of the single crystal and the definition of the field angle θ. (b) H_{b^*}-H_c phase diagram at 1.6 K.

the PM phase of λ-$(BETS)_2FeCl_4$, the localized Fe moments are aligned along the external field (H). In the presence of a strong negative exchange interaction J between the Fe $3d$ and the conduction electrons spins, the conduction electron spins experience a strong internal magnetic field (H_J) created by the Fe moments, whose direction is antiparallel to H. Therefore, the resulting field experienced by the conduction electron spins approach zero when $H \approx H_J$ [8]. Under these conditions the Zeeman effect, one of two destructive mechanisms against superconductivity, is completely absent. As long as H is parallel to the conducion layers, the orbital effect, which is the other of two destructive mechanisms against superconductivity, is virtually suppressed. Therefore, superconductivity can be induced by high parallel fields H in the order of $\sim H_J$. After the initial idea of the compensation mechanism proposed by Jaccarino and Peter, Fisher developed a full description of a high field superconducting state in the case of 2D system with fields aligned along the conduction layers [8]. The shaded areas in Fig.1 show the calculated S phases with four parameters, T_c=3.6 K, λ_{so}=6, H^*_{c2}=28 T, and H^*_J= 15 T, where λ_{so}, H^*_{c2}, and H^*_J are the spin-orbit scattering parameter, the orbital critical field for T=0 in the absence of magnetic impurities, and the saturated value of the internal field by the Fe moments, respectively. The agreement with the experimental results seems satisfactory. The Fisher's theory predicts that S phase is also present in the low field region. However, the AFI phase is more stabilized at such low fields so that it can not be detected experimentally.

The resistance was measured at various field angles for T=1.6 K [Fig. 2 (a)]. As the field is tilted from the c axis, the S phase is suppressed although the AFI-PM transition field does not show significant change. From the data, we obtain the H_{b^*}- H_c phase diagram [Fig. 2 (b)]. The AFI phase is destabilized by 5.5 T, irrespective of the field direction. However, we note that the S phase is completely suppressed by the field H_{b^*}=1.5 T, where θ=6°. Since H^*_J= 15 T, H_J along the b^* axis is estimated to be 1.6 T. This fact shows that H along the b^* axis is almost compensated with H_J for θ=6°, i.e. the Zeeman effect is suppresed by accident. Therefore, we can conclude that the orbital critical field H^*_{c2} along the b^* axis is 1.5 T at 1.6 K. This is the first direct estimation of the orbital critical field in superconductors. The value of H^*_{c2} is much smaller than H_{c2} along the b^* axis 2.6 T at 1.6 K for λ-$(BETS)_2GaCl_4$ [6], which is determined by both the Zeeman and orbital effects. The small value of H^*_{c2} for λ-$(BETS)_2Fe_xGa_{1-x}Cl_4$ (x=0.45) is probably due to the fact that T_c and H_{c2} for organic salts generally depend significantly on sample quality and on stress upon cooling.

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