Thermal conductivity of the antiferromagnetic organic superconductor κ-(BETS)$_2$FeBr$_4$ in the low-field and field-induced superconducting states

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Abstract

The thermal conductivity of the antiferromagnetic organic superconductor κ-(BETS)$_2$FeBr$_4$ was measured in oriented magnetic field. Both the antiferromagnetic state with $T_N = 2.3$ K and the superconducting state with T_c= 1.1 K are shown to be of bulk nature. In the parallel fields above 10 T the thermal conductivity shows an anomaly, being consistent with the formation of a reentrant superconducting state due to a Jaccarino-Peter effect.

Key words: Organic superconductors, antiferromagnetic superconductors, Jaccarino-Peter effect

In organic salts of general formula (BETS)$_2MX_4$ [1], with BETS standing for donor molecule bis-(ethylenedithiolo)tetraselenfulvalene, M for trivalent metal ion and X for a halogen, the band structure is predominantly formed by HOMO of BETS molecules, packed in an alternating layered structure with tetrahedral anion. The compounds are strongly anisotropic, with the electron density concentrated on molecular layer. The atoms in the anion layer are interacting weakly with donor molecules. When M is magnetic ion, like Fe^{+3}, the interaction between the magnetic moment and conduction electron produces a number of interesting phenomena.

In the λ-polymorph of (BETS)$_2$FeCl$_4$ an insulating state is formed on antiferromagnetic (AF) ordering of magnetic moments of Fe^{+3} ions. When the order is suppressed by a magnetic field H [2], the metallic state is restored and, in H parallel to the conducting plane, a field-induced superconductivity (SC) is observed [3] due to Jaccarino-Peter effect [4]. The range of SC domain is in good agreement with the critical fields of a non-magnetic analogue λ-(BETS)$_2$GaCl$_4$ [5].

In the κ-polymorph of (BETS)$_2$FeCl$_4$ and in its analogue, κ-(BETS)$_2$FeBr$_4$, the AF ordering does not destroy the metallic state [6], and the salt undergoes SC transition at low temperatures. The bulk character of the AF state was supported by the observation of anomaly in the specific heat at T_N. However no anomaly was observed at T_c [6]. The possibility of SC reentrance in this salt in parallel H was discussed by Cepas *et al.* [7]. Based on an evaluation of internal magnetic field from the Shubnikov-de Haas measurements [8] the reentrance of SC was predicted in the range from 9 to 13 T. The resistive anomaly in this range was indeed observed by Fujiwara *et al.* [9] below 0.6 K.

We report study of thermal conductivity (κ) of κ-(BETS)$_2$FeBr$_4$ in parallel H, giving the first evidence of bulk character of superconductivity in this compound. An anomaly in the field dependence of κ, consistent with formation of SC state, is observed in the

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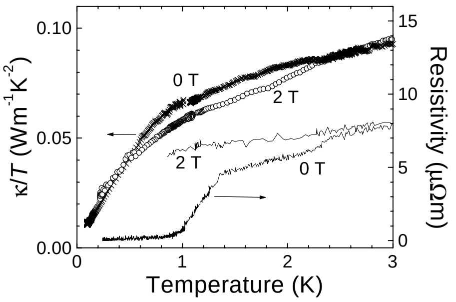

Fig. 1. Temperature dependence of thermal conductivity a of resistivity in H=0 and 2 T.

same H range where the formation of reentrant S state was indicated. This shows that the reentrant s perconductivity is a universal property of this fam of compounds.

Measurements of thermal conductivity in orient magnetic field up to 17 T were performed by t standard one-heater-two-thermometers technique a miniature rotatable vacuum cell [10], with deta described elsewhere [11].

In Fig. 1 we show the temperature dependence the thermal conductivity together with that of the r sistivity in a range below 3 K. A clear anomaly is se in both data at antiferromagnetic (AF) transition te perature T_N. This shows that the magnetic momen of Fe^{+3} ions are not completely isolated from the co duction band formed by orbitals of BETS molecules and there is a notable p-d interaction. The change the electronic contribution at T_N, estimated from r sistivity measurements via the Wiedemann-Franz law, is not large enough to account for variation of the measured κ. This indicates that AF ordering influences not only the electronic system, but also the lattice heat conduction κ^g, changing the phonon mean free path. Of note that the superconducting transition does not give a sharp anomaly in $\kappa(T)$ at T_c. The difference in κ between the normal and SC states develops gradually, which does not allow us to use the thermal conductivity measurements for determination of the upper critical fields of this salt in the range of validity of Ginzburg-Landau theory close to T_c. However, at low temperatures the magnitude of the difference between the normal and superconducting states accounts for 30 to 70 % of thermal conductivity in the normal state. This clearly shows that the main SC state is bulk in nature.

In Fig. 2 we show field dependence of thermal conductivity together with the field dependence of resistivity, measured at 0.2 K in magnetic field along the c-axis in the conducting ac-plane. On the field increase the thermal conductivity increases rapidly to H_{c2}, showing weak anomaly at the field of metamagnetic transition (6T), stays constant and then shows slight decrease in

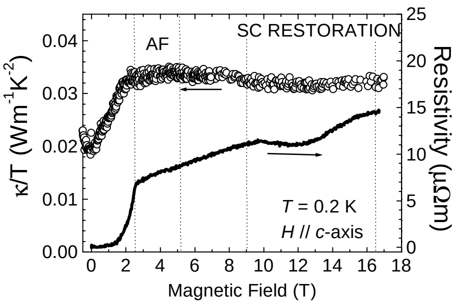

Fig. 2. Field dependence of thermal conductivity and of resistivity at 0.2 K. Vertical lines show positions of phase transformations between SC, AF, polarized AF and reentrant SC phases.

the same field range where the resistive anomaly was observed. In normal metals the decrease of resistance should give an *increase* of κ. As it can be seen from Fig. 2, opposite is the case, as expected for a superconducting state. Since the SC condensate does not carry heat, in the SC state the decrease of resistivity is accompanied by a decrease of κ, caused by a decrease of the density of normal electrons. This observation strongly supports superconducting origin of the anomaly.

In conclusion, the superconducting state of κ-$(BETS)_2FeBr_4$ is of bulk nature. This result indicates the intrinsic coexistence of antiferromagnetism and superconductivity in the salt. The anomaly in resistance measurements, observed recently in high-field region in the parallel field and assigned to reentrant superconducting transition [9], gives a decrease of κ, supporting its superconducting interpretation.

Acknowledgements

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