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Magnetic-Field-Induced Superconductivity in $Eu_{0.8}Sn_{0.2}Mo_6S_{7-y}Se_y$*

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Synopsis

The electrical resistance of $Eu_{0.8}Sn_{0.2}Mo_6S_{7-y}Se_y$ $(0 \leq y \leq 0.7)$ was measured under the magnetic fields up to 230 kOe. The hysteresis of the resistance was observed in the field range where the superconductive-normal-superconductive transitions appear. Analysis of the hysteresis provides a direct evidence that the magnetic-field-induced superconductivity of these compounds is caused by the Jaccarino-Peter compensation mechanism.

I. Introduction

The research on the interplay between superconductivity and magnetism was proposed by Ginzburg.$^{1)}$ But in early stage, the influence of small amount of the magnetic impurity on the transition metal superconductors was investigated. In 1970s, the advanced progress in this subject was achieved by the synthesis of the ternary compounds: so-called magnetic superconductors, RMo_6S_8 and RRh_4B_4, where R represents rare-earth element. In these compounds, it was clarified that superconductivity was observed in spite of the existence of the magnetic moments, and then the interplay between the superconductivity and the magnetism was extensively studied.

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Maekawa and Tachiki predicted that superconductivity is induced by the application of the magnetic field in these magnetic superconductors.[3] They proposed two mechanisms: the compensation of the applied magnetic field by the exchange field due to the rare-earth magnetic moments (Jaccarino-Peter effect [4]) and the suppression of the fluctuation of magnetic moments by the applied magnetic field (the effect of the spin fluctuation). Following their prediction, Isino et al. of our group discovered that the electrical resistance disappear under the magnetic field near 70 kOe in $Eu_{0.8}Sn_{0.2}Mo_6S_7$.[5] They called the phenomena as the magnetic-field-induced superconductivity (MFIS). Later, Meul et al. confirmed that superconductivity induced by the magnetic field is destroyed by the application of higher magnetic field than 160 kOe.[6]

In this paper, we report the electrical resistance of $Eu_{0.8}Sn_{0.2}Mo_6S_{7-y}Se_y$ measured under the magnetic fields up to 230 kOe to investigate the mechanism of MFIS and discuss the direct evidence of the Jaccarino-Peter effect.

II. Experimental

The samples of $Eu_{0.8}Sn_{0.2}Mo_6S_{7-y}Se_y$ ($0 \leq y \leq 0.7$) were prepared as follows. Powders of EuS, SnS, Mo, S and Se were mixed, pressed into a pellet and sealed in an evacuated quartz tube. Then, it was heated for 36 hours at 1250 °C. X-ray analysis showed small amount of remanent Mo, but did not show any other impurity phase.

The electrical resistance was measured by DC four probe method above 0.5 K up to 230 kOe using ^{3}He refrigerator and a hybrid magnet. It was measured also by AC four probe method above 50 mK up to 120 kOe using a dilution refrigerator and a superconducting magnet.

III. Results and Discussion

In Fig. 1, the electrical resistance of the sample with $y = 0.2$ is shown as a function of the applied field. Solid lines indicate the results measured with current of 101 μA by the use of the ^{3}He refrigerator and the hybrid magnet. At 0.5 K, the electrical resistance appears at about 10 kOe, has a peak at about 25 kOe, then decreases with increasing magnetic field and increases again in higher fields than 160 kOe. In the field range from 120 to 160 kOe, the resistance becomes constant but remains finite. However, the current dependence of the resistance is remarkable in this field range. Triangles, squares and circles in Fig. 1 are the measuring points with the current of 19.9 μA by the use of the dilution refrigerator and the superconducting magnet. At 0.5 K, the resistance becomes zero at 120 kOe (triangles in the figure). From the investigation of the current dependence of resistance at 120 kOe, we found that the resistance appears

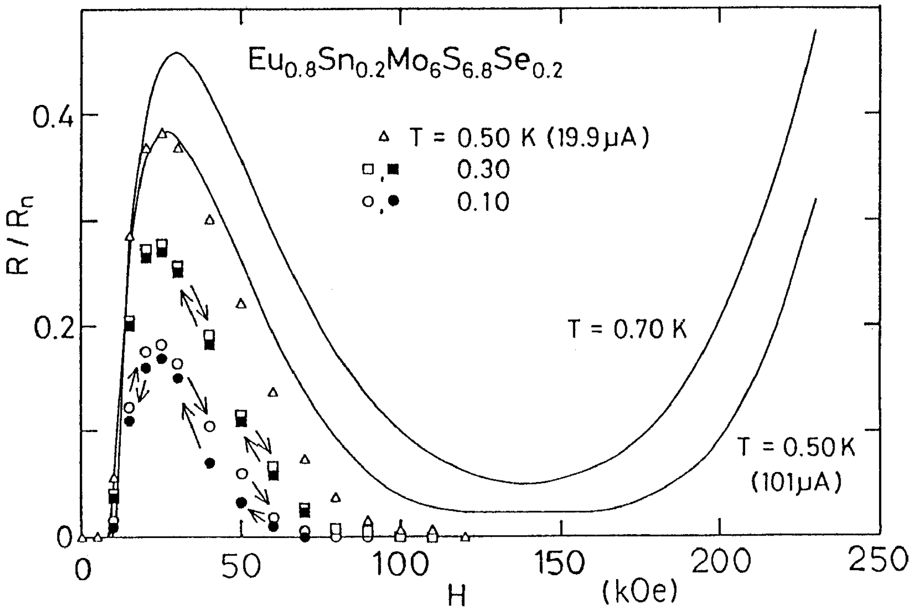

Fig. 1. Magnetic field dependence of electrical resistance normalized by the resistance just above T_c for $Eu_{0.8}Sn_{0.2}Mo_6S_{6.8}Se_{0.2}$.

above 30 μA. Although high noise level prohibits measurements with smaller current in the hybrid magnet, the electrical resistance is essentially zero between 120 and 160 kOe. Therefore in the sample with y =0.2, the superconductive-normal-superconductive-normal (S-N-S-N) transitions appear undoubtedly with increasing field below 0.5 K. Similar behavior of resistance was obtained in the sample with y =0.3, where the S-N-S-N transitions appeared below 0.1 K.

In both samples with y =0.2 and 0.3, the hysteresis of the resistance is observed in the field range below 120 kOe that S-N-S transitions appeared, where the resistance is smaller in decreasing field than in increasing one. In Fig. 1, open squares and open circles represent the resistance in increasing field and solid squares and solid circles represent the resistance in decreasing field.

One possible mechanism for the MFIS is the Jaccarino-Peter compensation effect.$^{4)}$ In the presence of the localized magnetic moments, the effective field H_J due to the exchange interaction acts on the conduction electron spins in addition to the applied field H_{ext}. Then, the superconductivity is mainly limited by the Pauli paramagnetic effect in the magnetic superconductors. If the exchange constant between the conduction electron spins and localized magnetic moments of the rare-earth ions is negative, H_J can compensate H_{ext}. Fig. 2 schematically illustrates how the Jaccarino-Peter compensation mechanism causes the S-N-

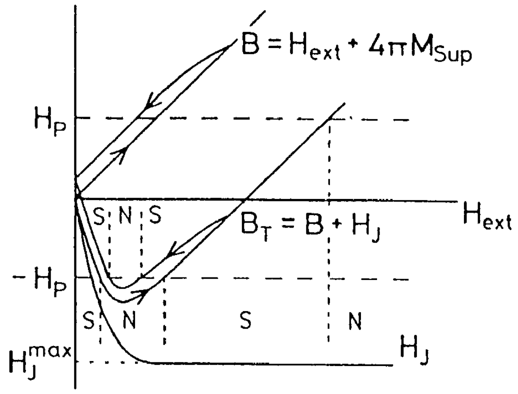

Fig. 2. Schematic diagram of applied field dependence of $B = H_{ext} + 4\pi M_{Sup}$ and $B_T = B + H_J$. H_P indicates Pauli paramagnetic field.

S-N transitions with increasing field. The net magnetic induction B_T is given by the equation: $B_T = H_{ext} + 4\pi M_{Sup} + 4\pi M_{Eu} + H_J$, where M_{Sup} and M_{Eu} are the magnetization due to superconductivity and that due to Eu moments, respectively. In low field region where the absolute value of the net magnetic induction B_T is smaller than Pauli paramagnetic field H_P, the resistance is zero. As the applied field increases, the absolute value of H_J increases. When B_T reaches $-H_P$, the superconductivity is destroyed. After H_J saturates with the further increase of the applied field, the reduction of the absolute value of B_T brings the superconductivity. When B_T exceeds H_P in higher field, the superconductivity is destroyed again.

Considering the Jaccarino-Peter effect, the observed hysteresis is understood as follows. In this mechanism, the direction of the net field acting on conduction electron spins is opposite to that of applied field in the field range of S-N-S transitions, as indicated in Fig. 2. Especially in inhomogeneous systems, $4\pi M_{Sup}$ has hysteresis and $H_{ext} + 4\pi M_{Sup}$ is larger in decreasing field than in increasing one. In usual case that the direction of B_T is the same as that of H_{ext}, the hysteresis of $4\pi M_{Sup}$ makes the resistance larger as the field decreases than as the field increases. When the direction of B_T is opposite to that of H_{ext} in lower fields on the contrary to the usual case, hysteresis of $4\pi M_{Sup}$ makes B_T smaller in decreasing field than in increasing one, as shown schematically in Fig. 2. As a result, the resistance is smaller as the field decreases than as the field increases. This analysis explains the observed hysteresis of resistance. Therefore, our experimental results on the hysteresis confirm directly that the MFIS of these samples is caused by the Jaccarino-Peter compensation mechanism for the first time. It is to be noticed that $4\pi M_{Eu}$ and H_J should have negligible hysteresis when Eu moments nearly saturate in the field above 10 kOe at low temperature. Below 10 kOe and above 0.5 K, the hysteresis of the resistance does not appear because the Eu moments do not yet saturate and H_J increases rapidly with increasing field at the S-N transition, thus masking out the hysteresis of $4\pi M_{Sup}$. The hysteresis around the field of 50 kOe where the Eu moments saturate, is larger than the hysteresis around 10 kOe where the Eu moments do not yet saturate completely.

Fig. 3 shows the temperature dependence of the upper critical field determined as the field where the extrapolated resistance intersects the zero resistance line. In Fig. 3, solid lines indicate the calculation by the multiple pair-breaking theory by Fischer,$^{7)}$ which takes into account the Jaccarino-Peter effect in the formalism of the Werthamer-Helfand-Hohenberg (WHH) theory. Among four parameters, the values of T_c obtained in our measurements are used. Three other parameters are obtained by the fitting: Maki parameter $\alpha = 5.3$, the saturated value of the exchange field, $H_J^{max} = -400$ kOe and the spin-orbit scattering parameters λ_{so} are given in the figure. The calculation reproduces our observed H_{c_2} as reported by Meul et al.$^{6)}$ It seems to be well established that the main origin for the MFIS in these compounds is the Jaccarino-Peter effect.

In addition to the resistance measurements, the specific heat of the samples with y =0 and 0.2 was measured under the magnetic field up to 60 kOe.$^{8)}$ Because the observed specific heat had the Schottky contribution due to Eu magnetic moments in addition to the electronic contributions, it was proved that Eu ions in these compounds are not Eu^{3+} but divalent Eu^{2+} ions which have magnetic moments and can contribute to the mechanism for the MFIS. The Schottky specific heat due to Eu^{2+} ions ($J = 7/2$) calculated on the basis of the crystal field Hamiltonian having a uniaxial parameter $B_2^0 = -0.09$ K reproduced roughly our experimental results. In zero field, this crystal field Hamiltonian gives the overall splitting of crystal field levels of 3.2 K and the level separation of 1.6 K between the lowest doublet and the first excited one.

As pointed out by Maekawa and Tachiki,$^{3)}$ another possible mechanism for MFIS is the effect of the spin fluctuation. The spin fluctuation has a destructive effect on the superconductivity, which is suppressed by the application of the magnetic field. Although the value of the level separation obtained by the analysis of the Schottky specific heat is smaller than that of other rare-earth ions, it is reasonably large in comparison with the antiferromagnetic transition temperature $T_N = 0.3$ K. The value of T_N is inferred from the minimum of $H_{c_2}(T)$ in the low field region indicated in the inset of Fig. 3. This anisotropy of Eu moments may considerably suppress the spin fluctuation prior to the application of the magnetic field. We suggest that the main reason which makes the effect of the spin fluctuation less important is the non-negligible anisotropy of Eu moments.

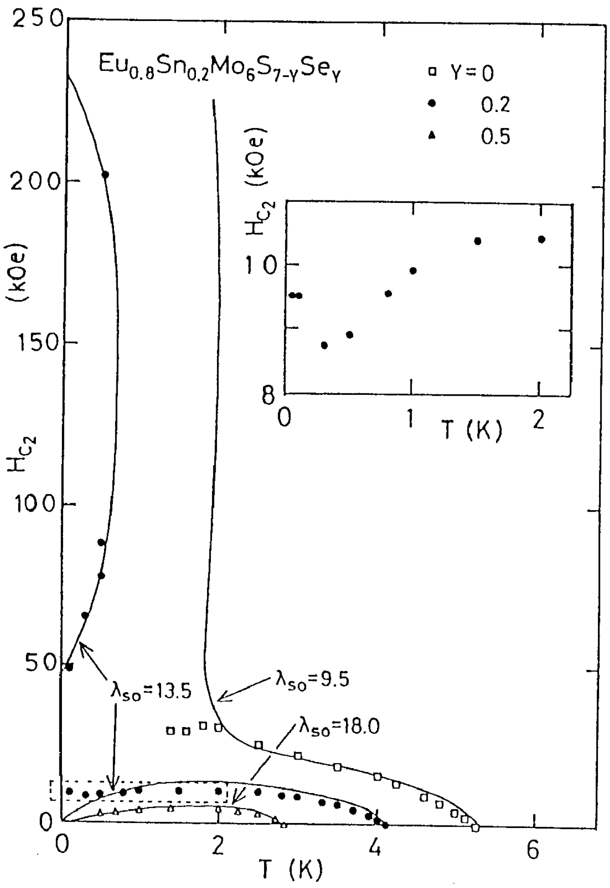

Fig. 3. Temperature dependence of the upper critical field for $Eu_{0.8}Sn_{0.2}Mo_6S_{7-y}Se_y$ ($y = 0, 0.2, 0.5$). Solid lines indicate the calculated H_{c_2} by the multiple pair-breaking theory based on the Jaccarino-Peter effect. The spin-orbit scattering parameters are represented in the figure and other parameters are given in the text.

Inset shows the low field region of H_{c_2} of the sample with $y = 0.2$.

IV. Summary

The electrical resistance of $Eu_{0.8}Sn_{0.2}Mo_6S_{7-y}Se_y$ was measured under the magnetic fields up to 230 kOe to investigate the mechanism of MFIS in this system. Our experimental results on the hysteresis of the resistance proved that the direction of the net field acting on the conduction electron spins is opposite to that of the applied field. From this fact, it was confirmed directly that the mechanism of the MFIS in this compounds originates from the Jaccarino-Peter effect. In addition, the temperature dependence of the upper critical field was consistently explained by the Jaccarino-Peter mechanism.

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