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UPPER CRITICAL FIELDS IN RARE EARTH COMPOUNDS

S. Maekawa, M. Tachiki and H. Kurita

The Research Institute for Iron, Steel and Other Metals, Tohoku University, Sendai, 980 Japan

Abstract. The upper critical fields $H_{c2}$ in the rare earth superconductors are obtained in the dirty limit as functions of the intra- and interatomic exchange interactions and the concentration of the magnetic ions, by taking account of the spin fluctuations in a magnetic field as well as the spin-orbit scattering. It is proposed that in certain compounds superconducting state may appear only in a magnetic field.

In the superconducting compounds RERh$_4$B$_4$ and RE$_3$Mo$_6$X$_8$ with RE being rare earth ions and X being S or Se, the magnetic ions form primitive lattices /1,2/. Furthermore, the magnetic ions may be substituted by nonmagnetic ions such as La$^{3+}$ and Sn$^{3+}$. Therefore, these compounds are quite suitable for studying the interplay of superconductivity and magnetism. It is surprising that some of the compounds such as Sn$_{1.2(1-c)}$Eu Mo$_6$S$_8$ /3/ are ultra-high-field superconductors in spite of the existence of highly concentrated magnetic ions : $H_{c2}$ of this compound is higher than 300 kgauss. Particularly interesting is the Eu-concentration, $H_{c2}$ at absolute zero rather increases although the superconducting transition temperature $T_c$ decreases. Furthermore, the temperature dependence of $H_{c2}$ of the compound with the considerable amount of Eu ions is quite different from that of the usual superconductors/4,5/. The objective of this paper is to obtain $T_c$ and $H_{c2}$ as functions of the intra- and interatomic exchange interactions and the concentration of the spins.

The spin fluctuations inside a Cooper pair scatter the electrons inelastically and weaken the BCS coupling. It is because the spin fluctuations prefer the spin-triplet state rather than the spin-singlet state in a Cooper pair/6/. In a magnetic field, the local spins polarize uniformly. The vector potential acting on the orbital motion of conduction electrons is related to the magnetic induction $\mathbf{B}$ rather than the magnetic field $\mathbf{H}$. The polarization of the local spins in the magnetic field also causes the spin splitting of the conduction bands ; the electron-spin exchange interaction $\Omega$, which may have either sign, is of the order of one meV in the compounds as obtained in reference/6/. The spin fluctuations which suppress the effective BCS interaction decrease in the field, and thus the effective interaction increases with increasing the magnetic field. In calculating $T_c$ and $H_{c2}$, we restrict ourselves within the weak coupling limit for both the electron-phonon and electron-spin interactions and apply the Gorkov formalism. Since the spin fluctuations are of long range, the order parameter is non-local in space. The size of a Cooper pair in space is of the order of the coherence length $\xi_0^{-1}$, $\xi_0$ being the Fermi velocity. On the other hand, the force range of spin-spin interaction is of the order of the nearest neighbor distance between spins. Therefore, the correlation length of spins is also of the order of the distance unless the temperature is extremely near the magnetic transition temperatures $T_M$ in the paramagnetic phases/7/. Because of the smallness of the correlation length of spins compared with the size of a Cooper pair, we may replace the non-local order parameter by the local one after summing up the spin fluctuations inside a Cooper pair. Once we have written the Gorkov equation by using the local order parameter, we may calculate $H_{c2}$ in the standard way/4,5/. Then, we find the equation for determining $H_{c2}$ for the isotropic superconductors in the dirty limit.
where $T^*$ and $T$ are the relaxation times of conduction electron due to non-spin flip and spin-orbit scatterings, respectively, and the condition $T^* < T$ was assumed. The quantity $<S_z>$ is the polarization of a local spin induced by the field and $c$ is the concentration of the spins. $X(q)$ and $-X(q)$ are the differential susceptibilities with wave number $q$ in the field which is applied parallel to the $z$-direction. The other notations in equations (1)–(4) are the standard ones /4,5/

$$\psi(\frac{1}{2}+\alpha \pm)\psi(\frac{1}{2}) = 0 \quad (1)$$

$$b_s = (3\tau_{so})^{-1}$$

$$I_s = -\mu_B c + c <S_z> \quad (2)$$

$$\rho_\pm = (2\pi\tau)^{-1}[s_\pm/x_s^s - T^*]$$

$$T_{co}(H) = 1.14\omega_D \exp[-1/\beta_{eff} N(O)] \quad (3)$$

$$\beta_{eff} = s_{BCS} x = \frac{1}{2} \int_1^{\infty} d(\cos \theta) \left[ e^{2k_F \sin \frac{\theta}{2}} + X^+ \right]$$

$$\tau_{so} = 1.14\omega_D \exp[-1/\beta_{BCS}] \quad (4)$$

where $\tau_{so}$ and $T^*$ are the relaxation times of conduction electron due to non-spin flip and spin-orbit scatterings, respectively, and the condition $T^* < T$ was assumed. The quantity $<S_z>$ is the polarization of a local spin induced by the field and $c$ is the concentration of the spins. $X(q)$ and $-X(q)$ are the differential susceptibilities with wave number $q$ in the field which is applied parallel to the $z$-direction. The other notations in equations (1)–(4) are the standard ones /4,5/

The equation (1) is different from the usual one because the quantities $T_{co}(H), I_s$, and $B$ are functions of $H$. Among them, $T_{co}(H)$ is a function of the spin fluctuations. The spin fluctuations suppress $T_c$ at zero field. However, when the Zeeman energy of the local spins becomes large enough compared with the exchange energy, the local spins are forced to align due to the field and the spin fluctuations almost disappear. In this case, the effect of the local spins may be expressed only by $I_s$ and $B$. Therefore, in ultra-high-field superconductors the maximum value of $H_{c2}$ may not be influenced by the spin fluctuations although the fluctuations suppress $T_c$. This fact suggests a possibility of the onset of superconductivity in the field in the compounds in which the electron-electron interaction due to the spin fluctuations overcompensates the BCS interaction in no magnetic field.

We take a simple cubic lattice for local spins with the nearest neighbor exchange interaction $J$. Extending the effective Hamiltonian method of spin statistics developed by Oguchi et al. /8/, we calculate the spin susceptibilities in equation (4) in the field. Leaving the detailed calculation in a separate paper, we show the theoretical result of $H_{c2}$ for various values of $c$ in figure 1. In this calculation, the parameters $T_{co} = 1.14\omega_D \exp[-1/\beta_{BCS}]$ and $\alpha = \mu_B^2 T_{co}^2 \tau_{so} N(O)$, $J$, $S$, $\lambda_{so} = (3\pi^2 \tau_{so})^{-1}$ and $I$ are respectively taken as 12.5 K, 6.34 x 10^{-1} kgauss^{-1}, 0.3, -3.05 x 10^{-2}, 7/2, 4.25, and -1.55 meV. The Néel temperature $T_N$ in no magnetic field decreases from 1.3 K at $c = 1$ with decreasing $c$, and for $c < 0.8$ $T_c$ does not exist because of the statistical effect. As seen in figure 1, the theoretical result reproduces the characteristics of $H_{c2}$ observed by Fischer et al. /3/ in Sn_{1.2}(1-c)Eu_{0.25}Mo_6.35S_8.

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