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Pressure Dependence of the Kondo Resistance Anomaly and the Pair Breaking Effect in La-Ce Alloys

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The pressure dependence of the pair breaking effect and of the resistance anomaly was measured in LaCe alloys. The results indicate that the maximum in the pressure dependent pair breaking effect is due to a monotonic shift of the Kondo temperature T_k with pressure from values $T_k \ll T_{c0}$ to $T_k \gg T_{c0}$, where T_{c0} is the superconducting transition temperature of pure lanthanum.

Introduction

Measurements of the superconducting transition temperature T_c of La-Ce alloys by Smith[1] have shown that the depression of T_c by paramagnetic impurities of concentration c is pressure dependent. Coqblin and Ratto[2] have explained this effect by assuming a pressure dependent enhancement of the exchange parameter $|J|$, defined by the Hamiltonian $H=-J\boldsymbol{S}\cdot\boldsymbol{\sigma}$ where $\boldsymbol{S}$ and $\boldsymbol{\sigma}$ are the spins of the localized impurity and the conduction electron, respectively. Referring to the theories of Zuckermann[3] and Müller-Hartmann and Zittartz[4], a relative maximum of $\Delta T_c/\Delta c$ has been predicted as a function of pressure[5]. According to these theories $\Delta T_c/\Delta c$ is a function of T_k/T_{c0} (T_k=Kondo Temperature, T_{c0}=superconducting transition temperature of the host metal), and the maximum of $\Delta T_c/\Delta c$ corresponds to a certain value of $T_k/T_{c0}=\vartheta$ which amounts to $\vartheta\simeq 2$ (Ref.[3]) or $\vartheta\simeq 12$ (Ref.[4]). For a Kondo alloy with $T_k \ll T_{c0}$ (at zero pressure) the depression of the transition tempera-

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2 Coqblin, B., Ratto, C. F.: Phys. Rev. Letters **21**, 1065 (1968).
3 Zuckermann, M. J.: Phys. Rev. **168**, 390 (1968).
4 Müller-Hartmann, E., Zittartz, J.: Z. Physik **234**, 58 (1970).
5 Umlauf, E.: In: Sommerschule für Supraleitung. Steibis 5.–10. Oct. 1969, ed. by Universität Köln.

ture $\Delta T_c(p)=T_{c0}(p)-T_c(p)$ is thus expected to have a maximum if the Kondo temperature is shifted monotonically to values $T_k \gg T_{c0}$ by application of pressure. The pressure p_m at the maximum should characterize the Kondo temperature $T_k(p_m)=\vartheta \cdot T_{c0}(p_m)$. Meanwhile Maple *et al.*[6,7] have found such a maximum of $\Delta T_c(p)$ in La-Ce. Their explanation, however, is based on the assumptions that, with gradual application of pressure, ΔT_c first increases as a consequence of an increase in $|J|$ and then decreases because the Ce ion undergoes a transition from a magnetic to nonmagnetic state. These authors already mention the possibility that such a transition may also be caused by the development of a quasi bound state as a consequence of an increase in the Kondo temperature; or that, alternatively, the decrease in ΔT_c may reflect the gradual onset of magnetic order at higher pressure. Although the present understanding of the Kondo effect is still semiquantitative at best, it offers a quite natural explanation of the observed $T_c(p)$ variation. We have thus compiled further experimental information on this problem by measuring the pressure dependence of both the superconducting transition temperature and the resistance anomaly. From the latter a considerable increase of the Kondo temperature with pressure can be deduced.

Experimental Results

First the depression $\Delta T_c(c)$ at zero pressure was measured for several alloys with different Ce concentrations c. The results for the dhcp and the fcc phase are 1.22±0.05 (K/at %) and 1.45±0.05 (K/at %), respectively. From these data the Kondo temperatures can be calculated from the relation

$$\frac{\Delta T_c}{\Delta c}=\frac{1}{8k_B N(0)}\,\frac{\pi^2(S+1/2)^2}{(\ln T_k/12\,T_{c0})^2+\pi^2(S+1/2)^2} \cdot\left[1+\frac{B\left[(\ln T_k/12\,T_{c0})/(S+1/2)\right]}{(S+1/2)^2}\right] \tag{1}$$

which is the main result of the theory of Ref.[4] where also a plot for the correction function B is given. Assuming $N(0)=2.4\ \text{eV}^{-1}$ (density of states)[8], $S=1/2$ (spin of the Ce ion), $T_{c0}=4.9$ K for dhcp La and $T_{c0}=6$ K for fcc La, we find $T_k=0.15$ and 0.20 K for the dhcp and the fcc phases, respectively.

It was also attempted to determine the Kondo temperature of a La 1% Ce alloy from resistance measurements down to 0.3 K. For the suppression of superconductivity a magnetic field of 8.5 kG is necessary

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7 Maple, M. B., Wittig, J., Kim, K. S.: Phys. Rev. Letters **23**, 1355 (1969).
8 Andres, K.: Phys. Rev. **168**, 708 (1968).