The Superconducting Transition Temperature for La$_{1-x}$Gd$_x$

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The deviation of the superconducting transition temperature from the Abrikosov-Gorkov behavior in the case of La$_{1-x}$Gd$_x$ is explained considering the presence of short range spin-glass at low temperature. The theoretical results show good agreement with the experimental data.

1. INTRODUCTION

During the last decade, the dependence of the superconducting transition temperature on paramagnetic impurities has received considerable attention. However, the dependence of the superconducting transition temperature on the concentration of paramagnetic impurities in alloys like La$_{1-x}$Gd$_x$ (Ref. 1) or La$_{3-x}$Gd$_x$In (Ref. 2) is not wholly explained, and a very different dependence is found than is expected for paramagnetic alloys.

Many attempts have been made to explain this unusual behavior, considering the coexistence between superconductivity and ferromagnetism, antiferromagnetism, or the polarization effect of the electrons at the Fermi surface caused by the magnetic order. Following Ref. 3, where this anomalous behavior is held to be the effect of short-range magnetic forces between the spins of the solute atoms (see also Ref. 1), we analyze the coexistence between superconductivity and short-range magnetic order, which is supposed to be the spin-glass state. We make use of Ref. 8 to treat the influence of a short-range spin-glass on superconductivity, and we write the Hamiltonian as

$$\mathcal{H} = - \sum_{i \neq j} E_{ij} S_i S_j$$  \hspace{1cm} (1)
The exchange interaction is considered as

$$E(r) = a \frac{\cos 2p_0 r}{r^3} e^{-r/\xi}$$

where $a$ is a constant,

$$a = \frac{m p_0 (\frac{I}{c})^2}{4\pi^3}$$

$r$ is the interspin distance, $p_0$ is the Fermi momentum, $m$ is the electron mass, $I$ is the electron-spin exchange interaction energy, $c$ is the atomic density of the host metal, and $\xi$ is the coherence length for electrons in the superconducting state. Another characteristic of the system is the average near-neighbor interspin distance:

$$r_0 = \int_0^\infty rP(r) \, dr = \Gamma(\frac{4}{3}) \left( \frac{4\pi}{3} n_m \right)^{-1/3}$$

where $P(r)$ represents the probability that the neighbor of the spin at the origin is at a distance $r$ from the origin. If we denote by $n_m$ the volume concentration of the magnetic impurities, then the short-range condition $\xi \ll r$ becomes

$$\xi n_m^{1/3} \ll 1$$

We describe the short-range spin-glass on the basis of the Abrikosov-Moukhin model, according to which the spin-glass state comes into being at the "freezing temperature" as a consequence of the formation of an infinite cluster. Using (2), we find that the molecular field created by the near-neighbor spin is

$$H(r) = A \frac{\cos 2p_0 r}{r^3} e^{-r/\xi}$$

with $A = Sa$, and because of the short-range interaction, only the spins that interact with the molecular field (6) are important. The interaction energy $SH(r)$ has to be of the order of the thermal energy $k_B T$. From this consideration we can define the characteristic distance between spins as

$$SH(r_c) = k_B T$$

which is important in the definition of different temperature regions.

2. THE RELAXATION TIME

The dependence of the superconducting transition temperature on the concentration of paramagnetic impurities has been treated by Abrikosov