Theory of superconducting alloys with rare-earth impurities

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It is shown that the scattering of electrons by impurity nuclei plays an important role in the destruction of superconducting correlations in alloys with rare-earth impurities in the singlet ground state. The results of the experiments are explained.[1,2]

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The effect of paramagnetic impurities on the transition of metals to the superconducting state is attributable to nonconservation of electron spin in the exchange scattering by localized magnetic moments of impurities, which gives rise to a finite lifetime of the Cooper pairs.[3] It was recently observed[1,2] in the measurement of tunneling of Al-AlO$_x$-LaPr junctions that the tunnel density of states of the LaPr alloy cannot be described by the Abrikosov-Gor'kov (AG) theory.[3] This is associated with the fact that the Pr^{3+} ions in a crystal field of a La matrix have a singlet ground state. Since the average spin S of an ion in the ground state is equal to zero, the classical-spin approximation of the AG theory[3] gives an infinite time τ_s for the spin path of electrons. A mechanism, which gives a finite τ_s for a nonmagnetic ground state of an impurity, was proposed by Fulde and Peschel.[4] It occurs in an inelastic scattering of electrons in the overlying levels of an impurity ion in a crystal field. However, the scattering of electrons by excited states of ions gives a characteristic frequency dependence of the tunnel density of states, which has not been confirmed by the results of a detailed investigation of Al-AlO$_x$-LaPr junctions.[2]

In this communication we propose a mechanism for destruction of superconducting correlations, which is associated with the scattering of conduction electrons by nuclear spins of impurities, and we explain the data of the experiments in terms of this mechanism.[1,2]

A hyperfine interaction $\mathcal{H}_{sI}$ between the electron moment S and the nuclear moment I of an impurity ion (in the simple, isotropic case $\mathcal{H}_{sI} = ASI$) and the *s-f* exchange $\mathcal{H}_{sf} = KS\sigma$ give rise to an effective interaction of conduction electrons with the ion nuclei:

$$\mathcal{H}_{\sigma I} = K \sum_i L_\parallel \sigma_z I_z^i + K \sum_i L_\perp (\sigma_- I_+^i + \sigma_+ I_-^i)$$

$$L_\parallel = 2A \sum_k \frac{|<0|S_z|k>|^2}{E^\circ - E_k}, \quad L_\perp = A \sum_k \frac{|<0|S_-|k>|^2 + |<0|S_+|k>|^2}{E_0 - E_k}. \tag{1}$$

The electron scattering, which is determined by the interaction (1), is elastic and allowance for the time τ_s of the electron spin path is in complete analogy with the AG method for magnetic impurities. For the interval δ between the ground (nonmagnetic) level and the first excited level of an ion, the time τ_s is determined by the expression

$$\frac{1}{\tau_s} = K^2 n \frac{m p_0}{2\pi^2} I(I+1)\left(\frac{A}{\delta}\right)^2, \tag{2}$$

where n is the impurity concentration.

The experimental dependence of tunneling σ on the voltage V at the Al-AlO$_x$-LaPr (10% Pr) junction, which is given in Refs. 1 and 2, corresponds to $(\tau_s \Delta)^{-1} = 8 \times 10^{-5}$, according to our calculations. Assuming that $K \approx 0.1$ eV and $I = 5/2$, we obtain $A/\delta = 7.5 \times 10^{-3}$. Since the hyperfine interaction constant for the LaPr alloys is $A \approx 0.1$ cm^{-1},[5] we obtain a value of the order of 15 K for the level splitting δ. This value is in good agreement with the experimental data obtained from the measurement of susceptibility.

The inelastic scattering of electrons by virtually excited states of ions[4] also occurs. It is effective, however, only in the neighborhood of the critical temperature T_c (under the experimental conditions[2] $T_c = 3$ K), where it plays a major role in the observed decrease of T_c as the amount of impurities increases. The time τ_s corresponding to it depends exponentially on the parameter δ/T, and, as the temperature drops (the experiment[2] was performed at $T = 1.2$ K), it greatly exceeds the spin relaxation time determined by the expression (2).

Thus, the results of the measurements of $\sigma(V)$ (Refs. 1 and 2) are described fairly well by the "nuclear" mechanism for destruction of superconducting correlations analyzed in our investigation. The data of Refs. 1 and 2 are apparently the first experimental evidence of the considerable influence of the nuclear spin system on the superconducting characteristics of rare-earth alloys.

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