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NUCLEAR MAGNETIC RESONANCE IN DILUTE MAGNETIC ALLOYS AND SUPERCONDUCTORS

N.G.FAZLEEV, G.I.MIRONOV

Department of Physics, Kazan State University, Kazan 420008, USSR

The longitudinal and transverse spin-lattice relaxation rates for paramagnetic ion-nuclei in dilute Kondo systems are calculated. It is shown that observation of the Kondo anomalies in the NMR parameters is facilitated by either high temperatures ($kT \gg \omega_s$, the resonance frequency for localized moments) or low temperatures ($kT \ll \omega_s$). The longitudinal spin-lattice relaxation of paramagnetic ion-nuclei in "dirty" type II superconductors is investigated. The influence of the order parameter fluctuations on relaxation of paramagnetic ion-nuclei in type II superconductors is studied at temperatures slightly above the transition temperature T_c.

1. INTRODUCTION

Contrary to EPR of magnetic impurities, magnetic resonance of paramagnetic ion-nuclei in metals and type II superconductors is insensitive to electron bottleneck effect and thus gives direct information on fluctuations in the spin system of paramagnetic impurities. The aim of the present work is to study Kondo anomalies in relaxation of paramagnetic ion-nuclei in magnetic alloys and to investigate longitudinal spin-lattice relaxation of paramagnetic ion-nuclei in "dirty" type II superconductors.

2. KONDO ANOMALIES IN NMR

The properties of localized moments (LM), conduction electrons (CE) and nuclear spins in a metal in an external dc magnetic field H are described by the Hamiltonian (2)

$$H = H_o + H_{sI} + H_{es} , \qquad (1)$$

where H_o describes free motion of CE, LM and nuclear spins in the dc magnetic field; H_{es} determines the exchange interaction of CE with LM; H_{sI} is the Hamiltonian of the hyperfine interaction. For a two level system ($I=1/2$) the longitudinal and transverse nuclear relaxation rates can be expressed in the following form (3)

$$T_1^{-1}=(A_s^2/2g_s^2)\coth(\omega_N/2T)\,\mathrm{Im}\,\chi_s^{-+}(\omega_N), \qquad (2)$$

$$T_2^{-1}=(A_s^2/g_s^2)T\lim_{\omega\to 0}\{\mathrm{Im}\,\chi_s^{zz}(\omega)/\omega\} + T_1^{-1}/2 . \qquad (3)$$

The longitudinal $\chi_s^{zz}(\omega)$ and transverse $\chi_s^{-+}(\omega)$ spin susceptibilities of LM are determined by the temporal Fourier transformation of the retarted Green functions

$$G_s(t)=\theta(t)e^{-\varepsilon t}(M_s^\alpha(t),M_s^\beta)= \qquad (4)$$
$$=\int_{-\infty}^{\infty} d\omega (M_s^\alpha,M_s^\beta)_\omega e^{-i\omega t},$$

where $M_s^\alpha=g_s\sum_j S_j^\alpha$; $\alpha,\beta=z,z;-,+$; in the following form (3)

$$\chi_s^{\alpha\beta}(\omega)=\{(M_s^\alpha,M_s^\beta)+i\omega(M_s^\alpha,M_s^\beta)_\omega\}/2T . \qquad (5)$$

To calculate $G_s^{\alpha\beta}(t)$ we write a chain of equations, performing time differentiation and temporal Fourier transformation. We obtain

$$(\omega+i\varepsilon)(M_s^\alpha,M_s^\beta)_\omega= i(M_s^\alpha,M_s^\beta)+(\dot M_s^\alpha,M_s^\beta)_\omega \qquad (6)$$

Here $\dot M_s^\alpha=[M_s^\alpha,H_{es}]$. We introduce the mass operator $\Sigma_{se}^{\alpha\beta}(\omega)$ for $G_s^{\alpha\beta}(\omega)$ with the help of relation

$$\Sigma_{se}^{\alpha\beta}(\omega)(M_s^\alpha,M_s^\beta)_\omega = -i(\dot M_s^\alpha,M_s^\beta)_\omega \qquad (7)$$

and calculate it up to the third order in the exchange interaction. Finally we obtain for the longitudinal nuclear relaxation rate the expression ($\omega_N \ll \omega_s$, T)

$$T_1^{-1}=A_s^2T\chi_s\mathrm{Im}\Sigma_{se}^{-+}(\omega_N)/g_s^2\{[\omega_s'-\mathrm{Re}\Sigma_{se}^{-+}(\omega_N)]^2+$$
$$+[\mathrm{Im}\Sigma_{se}^{-+}(\omega_N)]^2\} , \qquad (8)$$

$$\mathrm{Re}\Sigma_{se}^{-+}(\omega_N)=2(\rho J)^2\omega_s\ln|D/y| ,$$

$$\mathrm{Im}\Sigma_{se}^{-+}(\omega_N)=\pi(\rho J)^2[\omega_s\mathrm{cth}(\omega_s/2T)+2T]\cdot$$
$$\cdot[1-4\rho J\ln|D/y|],$$

where $y=\max\{T,\omega_s\}$; $\omega_s'=\omega_s(1+\lambda\chi_e)$; $\chi_s(\chi_e)$ is the static susceptibility of LM (CE);