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Spin dynamic properties of the Kondo system

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The Kondo effect in the dynamics of localized moments (LM) in metallic hosts is studied in the whole temperature range, taking into account the electron bottleneck effect. Calculations of the total dynamic response of the Kondo system are performed within the approximation that the magnetic moment of the impurity is not quenched by conduction electrons (CE). Electron spin resonance (ESR) parameters are studied for different conditions of the dynamic coupling between LM and CE. Experimental ESR studies of the Kondo system Au:Yb are discussed.

The theory of paramagnetic resonance in metals with magnetic impurities is rather well developed for the cases: a) when the exchange interaction between LM and CE is smaller than the electron lattice coupling (Korringa relaxation of LM, Overhauser relaxation of CE); b) when the exchange interaction is sufficiently strong compared to the electron–lattice coupling and there is the electron bottleneck in a system. In the latter case the Kondo effect can manifest itself in ESR parameters. Attempts to investigate the Kondo effect by ESR methods without adequate development of the theory led to unphysical results: values of Kondo temperature determined from impurity g-factor shift and from spin relaxation rate of LM differ by four orders of magnitude [1]. The aim of the present work is the microscopic study of the influence of the Kondo effect on the ESR parameters in magnetic alloys taking into account the electron bottleneck effect.

The properties of LM and CE in an external dc $\boldsymbol{h}_0$ and a weak ac $\boldsymbol{h}(t)$ magnetic fields, are described by the Hamiltonian [2]

$$H(t) = H_0(t) + H_{es} + H_{eL}. \qquad (1)$$

Here, $H_0(t)$ is the Hamiltonian of LM and CE in the external magnetic fields; H_{es} and H_{eL} determine the interaction of CE with magnetic and nonmagnetic impurities, respectively.

To evaluate total response of a system the Bethe–Salpeter equations for the vertex parts of the dynamic transverse susceptibilities of LM and CE, $\chi_s(\omega)$ and $\chi_e(\omega)$ respectively, are constructed to the third order terms in the interaction constants. All terms in the equations are expressed through the "dressed" single particle Green's functions, calculated to the same order in the interactions. For high ($kT \gg \omega_s$, ω, the resonant and external frequencies) and low ($kT \ll \omega_s$, ω) temperatures the integral vertex equations are reduced to the coupled system of equations [3]

$$\begin{aligned} a_s(\omega)\chi_s(\omega) + b_e(\omega)\chi_e(\omega) &= c_s(\omega), \\ b_s(\omega)\chi_s(\omega) + b_e(\omega)\chi_e(\omega) &= c_e(\omega). \end{aligned} \qquad (2)$$

The parameters $a_i(\omega)$, $b_i(\omega)$, $c_i(\omega)$ ($i =$ s, e) are defined by the expressions:

$$a_i(\omega) = \omega_i' - \omega - \Theta_i \Sigma_{ij}(\omega) - \Sigma_{iL}(\omega),$$

$$b_i(\omega) = \lambda\chi_j\left[\Sigma_{jL}(\omega) - \omega_j\right] + g_i\Theta_i\Sigma_{ij}(\omega)/g_j,$$

$$c_i(\omega) = \chi_i\left[\omega_i' - \Sigma_{ij}(\omega) - \Sigma_{iL}(\omega)\right] + g_i\chi_j\Sigma_{ji}(\omega)/g_j,$$

where [3] $\omega_i' = \omega_i(1 + \lambda\chi_j)$, $\Theta_i = 1 + \lambda\chi_i g_j/g_i$, $\lambda = 2J/g_s g_e$, Im $\Sigma_{eL}(\omega) =$ Im $\Sigma_{eL} = (2/3)\pi\rho|V_{so}|^2 C' \int d\Omega \sin \Theta + Dq^2$, $D = v_F^2\tau_P/3$, $\tau_P^{-1} = 2\pi\rho C|V|^2$, Re $\Sigma_{eL}(\omega) = 0$, $g_s(g_e)$ is the g-factor of LM (CE), $\chi_s(\chi_e)$ the static susceptibility for LM (CF), J the exchange interaction constant, C_m, C and C' the concentrations of LM and of nonmagnetic impurities with Coulomb and the spin–orbit potentials V and V_{so}, respectively; $2D$ is the bandwidth; ρ the density of states of CE on the Fermi surface. The imaginary parts of $\Sigma_{ij}(\omega)$ ($ij =$ se, es, eL) determine the transverse spin relaxation rates of LM and CE due to the exchange interaction and CE spin–orbit scattering by nonmagnetic impurities, while the real parts correspond to the shifts in resonant frequencies of LM and CE. The next higher-order corrections in the exchange interaction in the Bethe–Salpeter equations for the vertex parts of LM and CE only redefine $\Sigma_{ij}(\omega)$, leaving the form of the equations unchanged [4]. Using the method of the dynamical renormalization groups [5], we get the following expressions for the kinetic coefficients

$$\text{Im } \Sigma_{se}(\omega_s) = \begin{cases} \pi kT \ln^{-2}(T/T_K), & kT \gg \omega_s, \\ \pi\omega_s \ln^{-2}|\omega_s/kT|/4, & kT \ll \omega_s, \end{cases} \qquad (3)$$

$$\text{Im } \Sigma_{es}(\omega_s) = \begin{cases} \pi C_m/2\rho \ln^2(T/T_K), & kT \gg \omega_s, \\ \pi C_m/4\rho \ln^2|\omega_s/kT_K|, & kT \ll \omega_s, \end{cases} \qquad (4)$$