RELAXATION OF PARAMAGNETIC-IMPURITY NUCLEI IN METALS

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Recent investigations of the properties of simple metals containing small additions of transition elements have shown that when the temperature is lowered below a certain characteristic value T_c, formation of bound state of the impurity electron spins with the conduction electrons is observed [1]. This is a sui generis manifestation of the dynamic character of the exchange interaction of the localized d-spins with s-electrons [2], which can be written in the form

$$\mathcal{H}_{sd} = I v_0 (\psi^+ s \psi) S .$$

The occurrence of the bound states changes the spectrum of the fluctuations of the impurity electron spin, and this should be reflected in the character of the relaxation of the nuclear spin of the impurity atom.

To calculate the rate of relaxation of the spins of the paramagnetic impurity nuclei, we can confine ourselves to a consideration of the effective interaction

$$\mathcal{H}_{Id} = A\mathbf{I}\mathbf{S} = A\mathbf{I}\langle \mathbf{S}\rangle + A\mathbf{I}\delta\mathbf{S},$$

where I is the spin of the impurity nucleus and S is the spin of the impurity electron shell. This interaction ensures thermal contact of the nuclear spins of the impurity atoms with the "lattice" via the s-d exchange.

The probability of spin flip of the impurity nucleus ($m \to m'$ transition) is given by

$$W_N(m \to m') = A^2 (m\,|I^i|\,m')(m'\,|I^j|\,m) S^{ij}(\omega_{mm'}) ,$$

where

$$S^{ij}(\omega) = \int_{-\infty}^{+\infty} \langle S^i S^j(t) \rangle e^{i\omega t} dt.$$

In the usual situation (when there are no bound state) the width of the spectral distribution $S^{-+}(\omega)$ is determined by the quantity $1/\tau \simeq (\ell\rho_1)^2 T$, where ρ_1 is the state density of the conduction electrons at the Fermi level (τ - spin-lattice relaxation time of the electron spin of the paramagnetic atom in the metal). In this case

$$S^{-+}(\omega) \simeq 2\pi \langle S^- S^+ \rangle \frac{1}{\pi} \frac{1/\tau}{(\omega - \omega_0)^2 + (1/\tau)^2} ,$$

where ω_0 is the Larmor frequency.

Inasmuch as the frequency of the nuclear transition $\omega_{mm'} \ll \omega_0$, we get

$$W_N \simeq A^2 \frac{\tau}{1 + (\omega_0 \tau)^2} , \qquad (1)$$

and if $\omega_0 \sim T$ we have $\omega_0 \tau \gg 1$, and then

$$W_N \simeq A^2 (\ell\rho_1)^2 T / \omega_0^2 . \qquad (2)$$

Let us see now how this estimate changes in the case when the aforementioned bound state is produced ($T < T_c$). Using the Abrikosov procedure and applying it formally to the problem with $S = 1/2$, we can easily show that

$$S^{-+}(\omega) = 2\pi Q^{-1}\int_{-\infty}^{+\infty} g_{1/2}(\omega' + \omega) g_{-1/2}(\omega') f(\omega')[1 - f(\omega' + \omega)] d\omega', \qquad (3)$$

where $f(\omega) = (e^{\omega/T} + 1)^{-1}$, and the spectral density of the fermion pseudoparticles is

$$g_{\pm 1/2}(\omega) = \frac{1}{\pi} \frac{\Delta}{(\omega \pm \omega_{0}/2)^2 + \Delta^2}, \; \omega_0 << \Delta.$$

Here Δ denotes the binding energy of the electron-impurity pair, and the factor Q^{-1} in (3) "cancels" the presence of unphysical impurity states. It is easy to verify that in the case below $Q = 1/2$.

Inasmuch as $\omega_{mm'} << (\omega_0, T, \Delta)$, we find that when $(\omega_0, T) << \Delta$ the probability of reorientation of the nuclear spin of the impurity atom is

$$W_N \simeq A^2 T/\Delta^2. \qquad (4)$$

This differs appreciably from expression (2), for now W_N is practically independent of the external magnetic field. It is easy to understand the cause of the change occurring in the character of the dependence of the rate of nuclear relaxation on ω_0. Upon formation of bound states, the width of the spectrum of the impurity electron-spin fluctuations is determined by the binding energy $\Delta >> 1/\tau$, and when $\omega_0 \simeq T << T_c$ the earlier strong-field condition ($\omega_0\tau >> 1$) changes into the weak-field condition ($\omega_0/\Delta << 1$). This suppresses the dependence of the nuclear relaxation rate on ω_0.

When the temperature is gradually increased ($T \to T_c$) the rate of relaxation of the spins of the impurity nuclei increases and can greatly exceed the value given by formula (2) in the region $\Delta(T) \simeq \omega_0$. When the temperature goes through T_c and increases further, the impurity relaxation rate should gradually increase to its "normal" value given by (1). The region $T \gtrsim T_c$ deserves a special investigation (which is beyond the scope of the calculation scheme employed above).

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FIELD STATISTICS IN PARAMETRIC LUMINESCENCE

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A large number of recent theoretical and experimental papers are devoted to the process of parametric luminescence (PL) - the scattering of intense monochromatic light (pump) by a crystal with quadratic polarizability (see [1], where other references are cited). In the