SPIN-WAVE EXCITATIONS OF PARAMAGNETIC IMPURITIES IN SUPERCONDUCTORS

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The existence of spin-wave excitations of paramagnetic impurities in a superconductor in an external magnetic field due to the long-range exchange interactions is predicted. The damping has been calculated and possible manifestations of this collective excitations in ESR experiments are analysed.

1. In the present paper we discuss the possibility of the existence of weakly damped long-wavelength magnons in the system of paramagnetic impurities in superconductors. These collective modes are caused by a long-range indirect exchange interaction between the magnetic ions in a superconductor [1,2]:

$$J(r) = -J_0(v_0/4\pi\xi^2 r)\,\mathrm{e}^{-r/\xi}\,,$$

$$J_0 = \tfrac{1}{2}J_{\mathrm{sf}}^2\rho v_0(1-\chi^{\mathrm{s}}/\chi^{\mathrm{n}})\,, \qquad (1)$$

where χ^{s} and χ^{n} are the homogeneous susceptibilities of the electron gas in a superconducting and a normal metal, respectively, J_{sf} is the exchange integral of the interaction of the conduction electron with an impurity spin, ρ is the density of states at the Fermi level, v_0 is the volume of a unit cell, ξ is the coherence length of a "dirty" superconductor. The exchange potential (1), arising due to the coherence effects in the conduction electron system, is very small but it has a large interaction radius. The latter leads to the smallness of the exchange field fluctuations even in the paramagnetic phase, and the spectrum of the long-wavelength excitations ($q \lesssim \xi^{-1}$) of the localized moments in the external magnetic field is of a spin-wave character. The dispersion law of these excitations has the form

$$\omega_q = \omega_0 - I\xi^2 q^2 + \mathrm{i}\gamma_q\,, \qquad (2)$$

where ω_0 is the Zeeman frequency, $I = cJ_0\langle S^z\rangle$ is the width of a magnon band and c is the concentration of the magnetic ions.

2. It is convenient to calculate the magnon damping γ_q by the diagram method, developed in ref. [3]. In this method γ_q is expressed as a power series in the reciprocal numbers of the interacting spins $\alpha = N^{-1}$ (in our case $N \sim c\xi^3/v_0$). Taking the usual values $c \sim 10^{-2}$ and $\xi \sim 10^2$–10^3 Å, we obtain $\alpha \ll 1$ and the diagram series is well convergent. In the paramagnetic phase the terms of the first and second order in the parameter α are equal ($q \lesssim \xi^{-1}$):

$$\gamma_q^{1\mathrm{f}} = (7/12\pi)(Ib/\langle S^z\rangle^2)v_0\xi^2 q^5\,, \qquad (3)$$

$$\gamma_q^{2\mathrm{s}} = \frac{1}{96\pi^3}\,\frac{I}{\langle S^z\rangle^2}\,\frac{\mathrm{e}^{\beta\omega_0}}{(\mathrm{e}^{\beta\omega_0}-1)^2}\,\frac{v_0^2 q^2}{\xi^4}\,, \qquad \omega_0 > I,$$

$$= \frac{1}{32\pi^3}\,\frac{1}{I\langle S^z\rangle^2\beta^2}\,\ln^2(I/\omega_0)\,\frac{v_0^2 q^4}{\xi^2}\,, \qquad \omega_0 < I\,, \qquad (4)$$

where

$$b = \tfrac{1}{4}\mathrm{sh}^{-2}(\omega_0\beta/2) - (S+\tfrac{1}{2})^2\,\mathrm{sh}^{-2}[\omega_0\beta(S+\tfrac{1}{2})]\,,$$

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