Magnetoimpurity waves in metals

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Electromagnetic waves of a new class are predicted in conductors having magnetic-impurity electron states. The dispersion relation and the damping of these waves are calculated.

Impurities in a metal play a twofold role.[1,2] On the one hand, by limiting the mean free path of the conduction electrons they serve as a source of damping of electromagnetic waves which are propagating through a sample.[3] On the other, impurity atoms can radically change the electron energy spectrum, giving rise to local and quasilocal states.[2] These states can in turn give rise to new branches in the spectrum of collective excitations of the metal.

A magnetic field promotes a localization of electrons in the field of an attractive impurity potential. Magnetoimpurity states (local[4,5] and quasilocal[6,7]) arise even when a localization would be impossible in the absence of a magnetic field.

Magnetoimpurity electron states cause a resonant absorption of electromagnetic waves in a metal. The resonant frequencies, which are related to transitions between

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magnetoimpurity levels and Landau levels, are $\omega_s = \Delta + s\Omega$, where Δ is the binding energy of the electron, Ω is the cyclotron frequency, and $s = 0,1,...$ is the index of the resonance. The resonances are accompanied by new branches in the spectrum of electromagnetic excitations of the metal.[3,8] On one side of a resonant frequency the dissipative part of the conductivity, associated with an absorption of waves, is large. On the other side, the nondissipative part is large in comparison with the dissipative part. This circumstance is the reason for the existence of weakly damped waves.

In this letter we wish to predict a new class of weakly damped electromagnetic waves, which are related to resonant transitions between magnetoimpurity levels and Landau levels. We will see that the localization of electrons at magnetoimpurity levels weakens the dissipative processes and thereby gives the metal some transmission bands adjacent to the resonant frequencies. We call these waves "magnetoimpurity waves."

A resonance occurs at the frequency $\omega_0 = \Delta$ only if the Fermi boundary lies between the Landau level and the quasilocal level split off from it. In the opposite case, low-frequency resonant transitions are forbidden by the Pauli principle. This resonance makes the propagation of helical magnetoimpurity waves possible.

If the wave vector q of an electromagnetic wave is oriented along the magnetic field, and if the wavelength is large in comparison with the Larmor radius, the spectrum $\omega(q)$ and the damping of a helical wave can be found from the dispersion relation

$$c^2 q^2 / \omega_p^2 = \alpha_0 \left(\frac{\omega_0}{\omega_0 - \omega - i\Gamma} \right)^{1/2} \mp \omega / \Omega + i\nu\omega / \Omega^2, \quad (1)$$

where $\alpha_0 \sim n_i \epsilon_F \omega_0 / n_e \Omega^2$ is an effective oscillator strength of the resonant transition (n_e and n_i are the densities of electrons and impurity atoms, and ϵ_F is the Fermi energy), Γ is the half-width of the quasilocal level nearest the Fermi boundary, ν is the collision rate set by the potential scattering of electrons, ω_p is the plasma frequency, and c is the velocity of light. The $\mp$ signs refer to helical waves of opposite circular polarizations. The first term on the right side of (1) results from the resonant scattering of electrons by impurity atoms in a magnetic field; the second and third terms are in the standard form.[3]

When magnetoimpurity states are taken into account, the propagation of a helicon with a left-hand polarization (an antihelicon) becomes possible; this case corresponds to the minus sign in (1). In a pure electron conductor, this wave does not propagate.[3] Figure 1 shows dispersion curves for an antihelicon for various values of the parameter $\xi = \alpha_0 \Omega / 2\omega_0$. The damping rate for this wave is

$$\gamma(\omega) = \frac{|h'|}{2^{1/2} h''} \left\{ \left[1 + 4 \frac{h''^2}{h'^4} \left(\xi \frac{\Gamma}{\Omega} \left(\frac{\omega_0}{\omega_0 - \omega} \right)^{3/2} + \frac{\nu\omega}{\Omega^2} \right)^2 \right]^{1/2} - 1 \right\}^{1/2}, \quad (2)$$

where

$$h(\omega) = \alpha_0 \left(\frac{\omega_0}{\omega_0 - \omega} \right)^{1/2} - \frac{\omega}{\Omega},$$

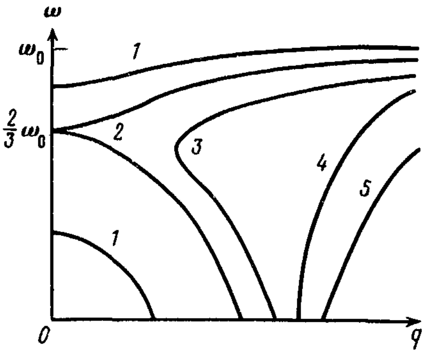

FIG. 1. Dispersion diagram of an antihelicon. $1-\xi<3^{-3/2}$; $2-\xi=3^{-3/2}$; $3-3^{-3/2}<\xi<1$; $4-\xi=1$; $5-\xi>1$.

and the prime means the derivative with respect to ω.

At $\omega>\Omega$ there is a series of high-frequency, linearly polarized magnetoimpurity waves. Their dispersion relation is

$$\omega_s(q) = \omega_s\left[1-\frac{\alpha_s^2}{\left(1+\dfrac{c^2q^2}{\omega_p^2}\right)^2}\right], \tag{3}$$

where $\alpha_s<1$ are the corresponding oscillator strengths, and $s=1,2,\ldots$ is the wave index. In particular, we have $\alpha_1 \sim n_i/n_e\,(\Omega/\Delta)^{1/2}$. The damping rate of these waves is

$$\gamma_s(q) = \frac{2\nu\alpha_s^2}{\left(1+\dfrac{c^2q^2}{\omega_p^2}\right)^3}+\Gamma . \tag{4}$$

It can be seen from (3) and (4) that the maximum value of the damping rate $\gamma_s(0)=2\nu\alpha_s^2+\Gamma$ is small in comparison with ω_s if ν and Γ are sufficiently small. We can thus say that the metal acquires transmission bands adjacent to the resonant frequencies. The width of band s is $\delta\omega_s=\omega_s\alpha_s^2$; with increasing s, this width falls off as s^{-2}.

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