Fermi-liquid electromagnetic modes in layered conductors

Valentin G.Peschansky [a,1], Olga V.Kirichenko [a], Dmitry I.Stepanenko [b]

[a] *B.I.Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of the Ukraine, Kharkov, Ukraine*

[b] *V.N.Karazin Kharkov National University, Kharkov, Ukraine*

Abstract

We have analysed propagation of electromagnetic waves in a Fermi liquid of charge carriers in Q2D layered conductors. It is shown that high-frequency collective modes, which are absent in a gas of charge carriers, can be observed even at low intensity of the Fermi-liquid interaction. The spectrum and amplitude of low-frequency weakly damping waves in a vicinity of the electron phase transition followed by the formation of diamagnetic domains, have been obtained.

Key words: layered conductors; Fermi liquid; electromagnetic waves

Allowance for the Fermi-liquid correlation of conduction electrons results in appearance of high-frequency collective modes which are absent in a gas of charge carriers. By studying these waves one can make a detailed investigation of correlation effects in the electron subsystem of a conducting medium. In metals the experimental observation of Fermi-liquid waves is complicated by the fact that their frequency ω is close to the plasma frequency ω_p, which is extremely high. The specifics of the Q2D electron energy spectrum of layered conductors gives rise to peculiar Fermi-liquid modes, which are more easy to study experimentally.

We consider the propagation of the waves in a layered conductor when the wave vector k as well as an external magnetic field are directed along the normal to the layers (z axis). In a layered conductor the dependence of the charge carriers energy ε upon their momentum $\mathbf{p}$ can be represented in the form

$$\varepsilon(\mathbf{p}) = \sum_{n=0}^{\infty} \varepsilon_n(p_x, p_y) \cos \frac{anp_z}{\hbar}. \quad (1)$$

Here a is the distance between layers, $\hbar$ is the Planck constant. The factors $\varepsilon_n(p_x, p_y)$ fall off rapidly with increasing n, so that the maximum value of $\varepsilon_1(p_x, p_y)$ at the Fermi surface ($\varepsilon(\mathbf{p}) = \varepsilon_F$) is equal to $\eta\varepsilon_F$, where the quasi-two-dimensionality parameter η is supposed to be much less than unity.

The Fermi-liquid interaction between electrons is described by means of the Landau correlation function, which depends weakly on p_z as well as the energy of conduction electrons in a layered conductor.

Joint solution of the set of Maxwell equations and kinetic equation for the electron distribution function in the linear approximation in the electric field, makes it possible to obtain the dispersion equation

$$k^2c^2 = \omega^2\{1 + \frac{\omega_p^2}{-\omega\sqrt{(\tilde{\omega} \mp \Omega)^2 - (\eta k v_F)^2} + \omega^2\lambda}\} \quad (2)$$

which determines the spectrum of collective electromagnetic modes. Here $\tilde{\omega} = \omega + i/\tau$, Ω is the cyclotron frequency of conduction electrons, τ is their free path time, v_F is the characteristic value of the Fermi velocity in the layers-plane, c is the velocity of light, λ is the parameter of the Fermi-liquid interaction, the dispersion law of electrons is supposed to be isotropic in the layers-plane.

If the following condition is satisfied

[1] Corresponding author. Present address: B.I.Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of the Ukraine, 47 Lenin ave, Kharkov, 61103, Ukraine E-mail:vpeschansky@ilt.kharkov.ua

$$(\omega \mp \Omega)^2 - (\lambda\omega)^2 < (\eta k v_F)^2 < (\omega \mp \Omega)^2, \qquad (3)$$

then at frequencies below the plasma frequency and in the collisionless limit ($\tau \to \infty$) there exist real solutions for k of the equation (1), which are absent at $\lambda = 0$. They describe cyclotron modes arising from the correlation effects in the conductor. The dispersion law for these excitations has the form

$$\omega^{\pm} = [1 - (\lambda - \omega_p^2/k^2c^2)^2]^{-1}\{\pm\Omega + \qquad (4)$$

$$+\sqrt{(\eta k v_F)^2 - [(\eta k v_F)^2 - \Omega^2](\lambda - \omega_p^2/k^2c^2)^2}\},$$

$$\Omega < \eta k v_F, \ 0 < \lambda < 1.$$

The Fermi-liquid collective modes exist for $k > k_{min} = \omega_p/c\sqrt{\lambda}$, and so $\omega_{min} = (\omega_0/\sqrt{\lambda}) \pm \Omega$, where $\omega_0 = \omega_p \eta v_F/c$. There are windows of transparency of the layered conductor for two high-frequency electromagnetic waves with different polarization. The presence of two waves with the frequencies $\omega^{\pm}$ is due to the fact that the magnetic field lifts the degeneracy of the spectrum of the electromagnetic field oscillations.

The penetration depth of the Fermi-liquid waves into the conductor can be determined by measuring the surface impedance, which relates the field at the surface of the sample with the value of the total current. The real component of the impedance, which determines the electromagnetic wave absorption, attains a maximum in the range of wave frequencies where the Fermi-liquid modes are excited.

At low temperature the oscillatory component of magnetic susceptibility $\chi \equiv \chi_{zz}$ of a conductor placed in a quantizing magnetic field, may attain a value of the order of unity. This is the case when allowance for magnetism of medium presents a self-consistent problem even in conductors, in which magnetic order is absent. When $\chi > 1/4\pi$, the homogeneous state of a conductor is unstable and a specimen is divided into domains having different values of magnetic induction $\mathbf{B}$ [1].

When the inequality $\kappa^2 \equiv |1 - 4\pi\chi(\mathbf{B}_0| << 1$ is satisfied, the stationary solution of the Maxwell equations

$$B(y) = B_0 + B_1(y),$$

$$B_1(y) = b_0 \ \frac{\mu}{\sqrt{1+\mu^2}} sn\{\frac{y}{\delta\sqrt{1+\mu^2}}, \mu\} \qquad (5)$$

describes periodic domain structure with the period $Y = 4\delta\sqrt{1+\mu^2}\ K(\mu)$ and the domain wall thickness $\delta = \sqrt{4\pi} r_0/k$. Here $\mathbf{B_0} = (0, 0, B_0)$ is an uniform component of the magnetic induction $\mathbf{B}$, $b_0 = \kappa B_0(\hbar\Omega/\varepsilon_F)$, $r_0 = v_F/\Omega$, $K(\mu) = \int_0^1 dt[(1-t^2)(1-\mu^2 t^2)]^{-1/2} \equiv K$ is a total elliptic integral of the first kind. The modulus of the elliptic Jacobi's function sn defines the period Y and can be found from the condition for the total thermodynamics potential to be at its minimum as a function of Y with account of surface energy at the domain boundaries.

Represent the magnetic induction in the form

$$\mathbf{B}(y, z, t) = \mathbf{B}_1(y) + \tilde{\mathbf{B}}(y, z, t)$$

where $\tilde{\mathbf{B}}(y, z, t) = \mathbf{b}(y) \exp(-i\omega t + ikz)$ is the small alternating field and $\mathbf{B}_1 = (0, 0, B)$. Using Maxwell equations and material equations we obtain the following equation for the component $\tilde{B}(y, z, t)$:

$$\{i\omega + A(F\frac{\partial^2}{\partial y^2} - k^2)\}\{i\omega\tilde{B}_z + A(\frac{\partial^2 \tilde{H}_z}{\partial y^2} - k^2\tilde{B}_z)\} -$$

$$-C^2k^2\{\frac{\partial^2 \tilde{H}_z}{\partial y^2} - k^2\tilde{B}_z\} = 0. \qquad (6)$$

Here

$$\tilde{H}_z = (1 - 4\pi\chi(k,\omega))\tilde{B}_z +$$

$$+12\pi\beta\alpha(k,\omega)B_1^2(y)\tilde{B}_z - 4\pi\gamma(k,\omega)r_0^2\frac{\partial^2\tilde{B}_z}{\partial y^2},$$

$$A = c^2\sigma_{xx}/4\pi D, \ C = -c^2\sigma_{yx}/4\pi D,$$

$$D = \sigma_{xx}\sigma_{yy} - \sigma_{xy}\sigma_{yx}, \ F = D/\sigma_{xx}\sigma_{zz},$$

$\sigma_{ij} \equiv \sigma_{ij}(k,\omega)$ are the components of the electrical conductivity tensor, $\beta = (\varepsilon_F/\hbar\omega B_0)^2$, the coefficients α, γ are of the order of unity.

The dispersion equation for the wave propagating along the magnetic field has the form

$$(-i\omega + Ak^2)^2 + C^2k^4 = 0 \qquad (7)$$

Without account of the quantum corrections to the conductivity tensor this equation coincides with the equation (2) and the spectrum of the wave is determined by the formula (4).

In the most important case when the dimensions of the domains are great in comparison with the domain wall thickness δ (i.e. $K(\mu) >> 1$, $(1-\mu^2) << 1$), the elliptical function $sn(\zeta, 1)$ in the interval $2\sqrt{1+\mu^2}K\delta \leq y \leq 2\sqrt{1+\mu^2}K\delta$ can be replaced by $\tanh(\zeta)$. Then, one can represent the amplitude of the field $b_z(y)$ in the form of a functional expansion with coefficients expressed by means of simple recurrent relations. The component $\tilde{B}_z(y, t)$ differs essentially from zero in the region of the domain wall only, i.e. in the vicinity of the points $y_n = 2nK\delta\sqrt{1+\mu^2}$ where n is a whole number.

References

[1] J.Condon, Phys.Rev.**145** (1966) 526.