points 2 and 2' the situation is reversed; the heating leads to the result that these points approach the purely phonon part of the spectrum, with corresponding decrease in the susceptibility in view of the increase in the threshold. The inverse coupling in this case will be negative and the location of the maximum absorption will be stable. The experimentally observed behaviors of the absorption maximum—splitting and the dependence of the location of the split maxima on the amplitude of the high-frequency field (Fig. 4)—confirms these considerations.

Thus, the rather complicated properties observed in parallel pumping in $MnCO_3$ at a frequency near 1000 MHz are qualitatively described by the excitation of nuclear magnons and magnetoelastic waves with account of the phenomenon of overheating of the nuclear magnetic system of the sample.

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The role of drag effects in pure superconductors

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The effect of drag processes on the thermal conductivity of superconductors is investigated. It is shown that for normal metals and for superconductors in the region $\beta < 1$, the correction to the phonon distribution function is completely determined by drag effects. In the region $\beta > 1$, the solution is identical with that obtained by Gurevich and Krylov {Zh. Eksp. Teor. Fiz. 68, 1337 (1975) [Sov. Phys. JETP 41, 665 (1975)}. The influence of boundaries, impurities and defects is considered, and it is shown that drag effects are always a correction to the total thermal conductivity in the parameter Θ_D/ϵ_F.

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1. THE KINETIC EQUATION FOR EXCITATIONS

For relaxation processes in pure superconductors, the principal role is played by the electron-phonon interaction. In this case the exact solution of the problem requires the consideration of a system of kinetic equations for phonon and electron excitations. Account of drag processes corresponds to account of nonequilibrium corrections to the phonon distribution function in the kinetic equation for electron excitations, and of corrections to the electron distribution function in the equation for the phonons. The electron thermal conductivity $\varkappa_e$, which is connected with the scattering of the electrons by phonons without account of drag effects, was considered earlier by a number of authors.[1,2] The phonon thermal conductivity $\varkappa_{ph}$, which is connected with the scattering of phonons by electrons ($\varkappa_{ph\,e}$)for the case of dirty superconductors, when the phonon thermal conductivity can be comparable with the electron conductivity not only near $T=0$, was considered in Ref. 3. However, the account of drag effects in the case of pure superconductors can bring about a significant contribution to $\varkappa_e$ as $T\to 0$ and to $\varkappa_{ph}$ at $T\sim T_c$; in this case, however, the contribution of drag effects to the total thermal conductivity is small, because of the smallness of the ratio Θ_D/ε_F (or s/v_F). It can be shown that the Umklapp processes make a small contribution and can be disregarded.

In a recent work, Gurevich and Krylov[4] showed that account of nonequilibrium phonons begins to play a decisive role in the determination of the electron distribution function at sufficiently low temperatures, and the possibility of experimental testing of this fact is predicted. The analysis was carried out in an approximation in which the nonequilibrium contributions to the electron distribution function in the kinetic equation for phonons were not taken into account. However, the discarded terms are not small and are decisive in the case of normal metals and in a whole range of temperatures for superconductors. Moreover, it should be noted that the total momentum of the electrons and phonons should be conserved. Mathematically, this corresponds to the condition of solvability of the linearized set of equations—any solution of the conjugate homogeneous equation should be orthogonal to the free term. As a consequence of the self-conjugate character of the integral kernel in the given case, the free term should be orthogonal to the solutions of the homogeneous equation, which are equal to the energy and momentum.[5,6] The kinetic equation should be supplemented by the equation of continuity, which is independent for superfluid Fermk systems.[7,8] In pure superconductors, the stronger condition of electrical neutrality (the sum of the electron normal and superconducting currents is equal to zero) is imposed.

Upon consideration of the thermal conductivity, the set of kinetic equations takes the form[9]

$$-\frac{\partial f_0}{\partial \varepsilon}\nabla T\left(\frac{\partial \varepsilon}{\partial \mathbf{p}}\frac{\varepsilon}{T}-\mathbf{p}c\right)=\iint d\tau'\frac{d\mathbf{q}}{(2\pi)^3}|V|^2$$
$$\times\Big[\left(1+\frac{\xi\xi'-\Delta^2}{\varepsilon\varepsilon'}\right)f_0f_0'N_0e^{\varepsilon'/T}(\eta+\varphi-\varphi')\delta(p'-p-q)$$
$$+\left(1+\frac{\xi\xi'-\Delta^2}{\varepsilon\varepsilon'}\right)f_0f_0'N_0e^{\varepsilon/T}(\varphi-\varphi'-\eta)\delta(p-p'-q)$$
$$+\left(1-\frac{\xi\xi'-\Delta^2}{\varepsilon\varepsilon'}\right)f_0f_0'N_0e^{\omega/T}(\varphi+\varphi'-\eta)\delta(p+p'-q)\Big], \quad (1)$$

$$-\frac{\partial N_0}{\partial \omega}\nabla T\left(\frac{\partial \omega}{\partial \mathbf{q}}\frac{\omega}{T}-\mathbf{q}c\right)=\iint d\tau\, d\tau'|V|^2$$
$$\times\Big[\left(1+\frac{\xi\xi'-\Delta^2}{\varepsilon\varepsilon'}\right)f_0f_0'N_0e^{\varepsilon'/T}(\eta+\varphi-\varphi')\delta(p'-p-q)$$
$$+\frac{1}{2}\left(1-\frac{\xi\xi'-\Delta^2}{\varepsilon\varepsilon'}\right)f_0f_0'N_0e^{\omega/T}(\eta-\varphi-\varphi')\delta(p+p'-q)\Big]; \quad (2)$$

$$f=f_0-f_0(1-f_0)\varphi,\qquad N=N_0-N_0(1+N_0)\eta,$$
$$f_0=[e^{\varepsilon/T}+1]^{-1},\qquad N_0=[e^{\omega/T}-1]^{-1},$$
$$\varepsilon=(\xi^2+\Delta^2)^{1/2},\qquad \omega=sq,\qquad d\tau=2d\mathbf{p}/(2\pi)^3,$$
$$|V|^2=|V'|^2q,\qquad \delta(p-p'-q)=\delta(\varepsilon-\varepsilon'-\omega)\delta(\mathbf{p}-\mathbf{p}'-\mathbf{q}).$$

The constant c is determined from the condition of orthogonality of the left sides of (1) and (2) to the total momentum $(\mathbf{p}, \mathbf{q})$.

Using the following relations

$$S_e=-\int d\tau\,[f\ln f+(1-f)\ln(1-f)]=-\frac{1}{T}\int\xi^2\frac{\partial f}{\partial \varepsilon}d\tau, \quad (3)$$
$$3S_{ph}=4E_{ph}/T,\qquad \rho_{nph}=4E_{ph}/3s^2, \quad (4)$$
$$p\approx p_0(1+\xi/2\varepsilon_F), \quad (5)$$

we find the constant c:

$$c=S/\rho_n, \quad (6)$$

where $S=S_e+S_{ph}$ is the total entropy of the system, $\rho_n=\rho_{ne}+\rho_{nph}$ is the total normal density.

The expression (6) can also be obtained from the set of hydrodynamic equations of two-fluid hydrodynamics.[10] The velocity $\mathbf{v}_s$ is determined from the condition of electrical neutrality:

$$\rho_{es}\mathbf{v}_s+\int \mathbf{p}f\,d\tau=0,$$
$$\rho_{es}=\rho_e\pi T\Delta^2\sum_\omega\frac{1}{(\omega^2+\Delta^2)^{3/2}}, \quad (7)$$

$\omega=(2n+1)\pi T$, $\rho_e=mn$. In addition, the total momentum of the excitations should be conserved:

$$\int \mathbf{p}f\,d\tau+\int \mathbf{q}N\frac{d\mathbf{q}}{(2\pi)^3}=0. \quad (8)$$

The total heat flow is determined by the equation

$$\mathbf{Q}=\int\varepsilon\frac{\partial\varepsilon}{\partial\mathbf{p}}f\,d\tau+\int\omega\frac{\partial\omega}{\partial\mathbf{q}}N\frac{d\mathbf{q}}{(2\pi)^3}. \quad (9)$$

The distribution functions f and N are made up as usual of the solution of the homogeneous equation and the particular solution of the inhomogeneous equation.

2. SOLUTION OF THE KINETIC EQUATIONS

The solution of equations (1) is sought in the form (cf. Ref. 4)

$$\varphi=\left[\varphi_1(T)-\varphi_2(\varepsilon,T)+\frac{\xi}{|\xi|}\varphi_3(\varepsilon,T)\right]\cos(\mathbf{p},\nabla T), \quad (10)$$
$$\eta=\eta(\omega)\cos(\mathbf{q},\nabla T). \quad (11)$$

The constant φ, has the relative order $(T/\Theta_D)^2\varphi_1\sim\varphi_2$, as a consequence of the cancellation of Landau and Pomeranchuk.[11,9] However, since a solution of the momentum type

$$\varphi=\text{const}\,p\cos(\mathbf{p},\nabla T),\qquad \eta=\text{const}\,q\cos(\mathbf{q},\nabla T),$$

i.e.,

$$\varphi_1=\varphi_1^{(0)},\qquad \varphi_3=|\xi|m\varphi_1^{(0)}/p_0^2,\qquad \eta(\omega)=q\varphi_1^{(0)}/p_0, \quad (12)$$

is a solution of the homogeneous equation, the constant φ_1 can always be eliminated by the transformation

$$\varphi_3=|\xi|m\varphi_1/p_0^2+\tilde\varphi_3,\qquad \eta(\omega)=q\varphi_1/p_0+\tilde\eta(\omega).$$

This can be established by a direct test if we take Eq. (6) into account.

We shall consider temperature ranges for which

$$\beta\left(\frac{T}{\Theta_D}\right)^2\ll 1,\qquad \beta=\left(\frac{T}{\Theta_D}\right)^2\frac{\varepsilon_F}{\Theta_D}e^{\Delta/T}. \quad (13)$$

Under these conditions, we can disregard the constant c of (6) in Eq. (2) (but this is not the case in (1)). In the lowest approximation, under the condition $T\ll\Theta_D$, it suffices to consider only the equations for φ_3 and η. By virtue of the vector character of the solution $(\varphi_2, \varphi_3, \eta)$, it is important to keep track of the relative order of the terms in the kernel of the integral.

After averaging over the angles,[14] we get

$$-\frac{\partial f_0}{\partial\varepsilon}\frac{\xi}{T}\frac{p_0}{m}=\iint d\tau'\frac{dq}{(2\pi)^3}|V'|^2q\Big\{\Big[\frac{\xi}{|\xi|}\left(1-\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\varphi_3$$
$$-\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi'}{|\xi'|}\varphi_3'-\left(1-\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\frac{\xi m}{p_0q}\eta+\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi' m}{p_0q}\eta\Big]$$
$$\times f_0f_0'N_0e^{\varepsilon'/T}\delta(p'-p-q)+\Big[\frac{\xi}{|\xi|}\left(1-\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\varphi_3$$
$$-\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi'}{|\xi'|}\varphi_3'-\left(1-\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\frac{\xi m}{p_0q}\eta+\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi' m}{p_0q}\eta\Big]\times$$

$$\times f_0 f_0' N_0 e^{\varepsilon/T}\delta(p-p'-q)+\left[\frac{\xi}{|\xi|}\left(1+\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\varphi_3\right.$$

$$\left.+\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi'}{|\xi'|}\varphi_3'-\left(1+\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\frac{\xi m}{p_0 q}\eta-\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi' m}{p_0 q}\eta\right] f_0 f_0' N_0 e^{\omega/T}\delta(p+p'-q)\Big\}, \quad (14)$$

$$-\frac{\partial N_0}{\partial\omega}\frac{s\omega}{T}=\iint d\tau\, d\tau' |V'|^2 q\left\{\left[\left(1-\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\eta\right.\right.$$

$$+\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi}{|\xi|}\frac{\xi' m}{p_0 q}\varphi_3+\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi'}{|\xi'|}\frac{\xi m}{p_0 q}\varphi_3'-\frac{\xi}{|\xi|}\frac{\xi m}{p_0 q}\left(1-\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\varphi_3$$

$$\left.-\frac{\xi'}{|\xi'|}\frac{\xi' m}{p_0 q}\left(1-\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\varphi_3'\right] f_0 f_0' N_0 e^{\varepsilon'/T}\delta(p'-p-q)$$

$$+\frac{1}{2}\left[\left(1+\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\eta-\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi}{|\xi|}\frac{\xi' m}{p_0 q}\varphi_3-\frac{\xi\xi'}{\varepsilon\varepsilon'}\frac{\xi'}{|\xi'|}\frac{\xi m}{p_0 q}\varphi_3'\right.$$

$$\left.-\frac{\xi'}{|\xi'|}\frac{\xi' m}{p_0 q}\left(1+\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\varphi_3'-\frac{\xi}{|\xi|}\frac{\xi m}{p_0 q}\left(1+\frac{\Delta^2}{\varepsilon\varepsilon'}\right)\varphi_3\right]$$

$$\times f_0 f_0' N_0 e^{\omega/T}\delta(p+p'-q)\Big\}. \quad (15)$$

Account of the discarded terms corresponds to an expansion of the kernel in the parameters $(\Theta_D/\varepsilon_F)^2$, (T/Θ_D), $(T/\Theta_D)^2 T/\varepsilon_F$ and higher order. It follows from (4) and (15) that the ratio of the correction from the disequilibrium of the electron distribution function in (15) to the free term is of the order of β^{-1}. In order to establish this, it is sufficient to multiply Eq. (14) by $\xi m/p_0^2$ and integrate over p; we then multiply (15) by q/p_0 and integrate over q. Upon addition, the terms containing φ_3 cancel out.

Thus, in the case of pure superconductors, the drag effects for $\varkappa_{ph}$ are large for $\beta \ll 1$, i.e., in the case $T \lesssim T_c$, and for $\varkappa_e$ (see below) in the region

$$(\Theta_D/\varepsilon_F)^2\beta \gg 1, \quad (16)$$

i.e., as $T \to 0$. In the region $\beta \ll 1$, the phonon distribution function follows the electron distribution adiabatically. This behavior is a direct consequences of the fact that $\tau_{ph\,e} \ll \tau_{e\,ph}$ under these conditions. In the region $\beta \gg 1$, we can neglect the effect of the electrons on the phonon distribution function ($\tau_{ph\,e} \gg \tau_{e\,ph}$) and thus the approximation of the work of Gurevich and Krylov is achieved. [4] By virtue of the additivity of the corrections to the distribution function in the total thermal conductivity $\varkappa = \varkappa^{(0)} + \tilde{\varkappa}$, we can separate the corrections $\tilde{\varkappa}$ connected with the drag. We then get from (9), (14), (15),

$$\varkappa_e^{(0)} \sim \frac{p_0^4 s^3}{m^2 T^2}\frac{e^{-\Delta/T}}{|V'|^2}, \quad (17)$$

$$\tilde{\varkappa}_e \sim \frac{p_0 s^2}{m}\frac{1}{|V'|^2}, \quad (18)$$

$$\varkappa_{ph}^{(0)} \sim \frac{T^2}{m^2 s}\frac{e^{\Delta/T}}{|V'|^2}, \quad (19)$$

$$\tilde{\varkappa}_{ph} \sim \frac{p_0 s^2}{m}\frac{1}{|V'|^2}. \quad (20)$$

As is seen from (17)–(20), the drag effects always give a small correction to the total thermal conductivity, to the extent that s/v_F (or Θ_D/ε_F) is small. A more detailed study of (14) is given in the next section. In (17)–(20), we limited ourselves to an order-of-magnitude estimate, since those parts which determine the contribution to the total thermal conductivity had already been calculated. [3,4,9] The corrections to $\varkappa$, connected with the solution of the homogeneous equation (12) and the conditions (7) and (8), make a small contribution under the condition (13).

To conclude this section, we consider the effect of scattering at the boundaries, which plays a role also for pure superconductors, and the scattering from impurities and defects in the lattice. Account of these processes leads to the appearance on the right hand sides of (1) and (2) of the terms $\delta f/\tau_e^{(0)}$ and $\delta N/\tau_{ph}^{(0)}$ (for scattering of phonons at the boundaries $\tau_{ph}^{(0)} \sim d/s$, where d is the size of the sample).

We shall not consider the solution in general form, and confine ourselves only to the consideration of the two most interesting cases.

In the region

$$\tau_{phe} \ll \tau_e^{(0)} \ll \tau_{eph} \quad (21)$$

the corrections to the electron distribution function are determined by the scattering from the boundaries (impurities), and the phonon distribution function follows the electron distribution adiabatically, independently of the relation between $\tau_{ph\,e}$ and $\tau_{ph\,e}^{(0)}$. Under the conditions (21), the total thermal conductivity is determined by the electron part, the explicit form of which is given in Ref. 9.

In the region

$$(1+\tau_{eph}/\tau_e^{(0)})^{-1}\beta \gg 1 \quad (22)$$

we can neglect the effect of the nonequilibrium state of the electrons in the phonon kinetic equation. Under the condition (22), the correction to the phonon distribution function has the form

$$\eta(\omega)=\frac{\eta^{(0)}(\omega)}{1+\alpha(\omega)},$$

$$\alpha(\omega) \sim \frac{(m^2 T|V'|^2 e^{-\Delta/T})^{-1}}{\tau_{ph}^{(0)}} = \frac{\tau_{phe}}{\tau_{ph}^{(0)}}, \quad (23)$$

where $\eta^{(0)}(\omega)$ is the correction to the distribution function without account of the effect of the boundaries (impurities).

Substituting the correction (23) in the equations (1) and (14), we obtain the result that the boundaries and impurities simultaneously suppress not only the phonon thermal conductivity but also the drag effects[1)]:

$$\varkappa_{ph} \sim \frac{\varkappa_{ph}^{(0)}}{1+\alpha}, \quad \tilde{\varkappa}_e \sim \frac{\tilde{\varkappa}_e^{(0)}}{1+\alpha}.$$

In the region of very low temperatures, $\varkappa_{ph} \propto T^3$ because of scattering from the boundaries.

3. ELECTRON KINETIC EQUATION

We consider Eq. (14) without account of the phonon correction to η (by virtue of the linearity of the equation, we can seek the corrections connected with η independently). We carry out the integration over q in (14) and in place of the function φ_3 we introduce the function

$$\tilde{\varphi}=\frac{T^4}{v_F^2 s^3}\frac{|V'|^2}{2\pi^2}\varphi_3.$$

Moreover, we denote $y=\varepsilon/T$, $b=\Delta/T$. We then obtain the following equation for the function $\tilde{\varphi}(y, b)$:

$$f_0 f_0 e^y y=\tilde{\varphi}(y,b)\left(\int_b^\infty \tilde{K}(y,y')dy'-\int_b^\infty \tilde{K}(y,-y')dy'\right)$$

$$+\int_b^\infty K(y,-y')\tilde{\varphi}(y',b)dy'-\int_b^\infty K(y,y')\tilde{\varphi}(y',b)dy'; \quad (24)$$

$$\tilde{K}(y,y')=\left(1-\frac{b^2}{yy'}\right)\frac{yy'}{(y^2-b^2)^{1/2}(y'^2-b^2)^{1/2}}K(y,y'),$$

$$K(y,y')=\frac{f_0 f_0' e^y e^{y'}(y'-y)^2}{|e^{y'}-e^y|}.$$

By virtue of the evenness of K and $\tilde{K}$ upon change of sign of both arguments

$$K(y,\ y')=K(-y,\ -y'),\quad \tilde{K}(y,\ y')=\tilde{K}(-y,\ -y')$$

it follows from (24) that $\tilde{\varphi}$ is an even function of y.

As $y\to b$ we have

$$\tilde{\varphi}(y,\ b)\to(y^2-b^2)^{1/2},$$

and at $y\gg b$

$$\tilde{\varphi}(y,\ b)\propto 1/y^2.$$

Since the region $y\lesssim b$ is important, we can take as the first approximation

$$\tilde{\varphi}=f_0 f_0 e^y y\Big/\left\{\int_b^\infty \tilde{K}(y,y')dy'-\int_b^\infty \tilde{K}(y,-y')dy'\right\}, \quad (25)$$

and seek additional corrections by iteration. The iteration parameter is of the order of $\sim\frac{1}{3}$. We can confine ourselves to the solution of Gurevich and Krylov[4] with the same order of accuracy.

For superconductors with weak coupling, the condition $\beta\sim 1$ begins to be satisfied at $T\lesssim 0.5\ T_c$, and in the case of strong coupling at somewhat higher temperatures. Although, as a consequence of the smallness of the ratio s/v_F (or Θ_D/ε_F), the corrections to the thermal conductivity from the drag effects turn out to be small, their study is of interest for at least two reasons. First, because of the complexity of the general system of equations, consideration is usually restricted to such physical situations in which the drag effects can be neglected. However, a correct estimate of the drag effects is necessary for the elucidation of the character of the approximations in the intermediate case. Second, it is possible that experimental techniques will allow us to separate the contributions from different processes to the thermal conductivity and to observe directly the corrections connected with the drag.[12] The study of other characteristics of the metal than the thermal conductivity is also of interest.

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[1)]Since the suppression of $\tilde{\varkappa}_{ph}$ by the boundaries takes place more slowly, this term can turn out to be substantial.

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