The difference between acoustoelectric and thermoelectric phenomena in superconductors

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The acoustoelectric effect in superconductors is discussed. It is compared with the acoustoelectric effect in normal conductors, as well as with the thermoelectric effect in superconductors. We come to the conclusion that, in contrast to the thermoelectric effect, the acoustoelectric effect can be observed in a monometallic superconducting loop. The necessary condition is an asymmetric distribution of the acoustical flux, which is schematically depicted. Different ways of enhancing the acoustoelectric effect are also discussed. It is pointed out that the enhancement of the effect may be achieved if an acoustical wave propagates in a part of a loop where a large number of magnetic flux quanta are trapped. Some possible masking effects (such as discussed by Pegrum and Guenault) which may prevent observation of acoustoelectric and thermoelectric effects are discussed. We discuss also the ways to diminish these masking effects and to extract the effects in question from the experimental data.

The purpose of the present paper is to discuss some special features of acoustoelectric effect in superconductors. This effect takes place if a traveling acoustical wave propagates in the bulk of a superconductor. It was first discussed by the authors in Refs. 1–3.

Later, in his paper[4] Falco also discussed the acoustoelectric effect in superconductors. He came to some important conclusions concerning the possibility of its experimental observation. At the same time we cannot agree with his statement that "in the geometry discussed by them (Gal'perin *et al.*[2,3]) there would be no effect." We shall discuss the difference between acoustoelectric and thermoelectric phenomena in superconductors in detail. We are going to demonstrate that while no thermoelectric effect can exist in a loop consisting of a homogeneous conductor, acoustoelectric phenomena can exist in such a loop provided it is acoustically nonhomogeneous, i.e., the acoustical flux propagates only along a part of the loop.

Our other purpose is to discuss some further aspects of the theory of acoustoelectric as well as thermoelectric phenomena in superconductors, in particular some possible ways of enhancing these effects.

Let us begin with the description of acoustoelectric and thermoelectric effects in normal conductors. Though these are well known, we think that a discussion of both phenomena in the normal state might help one to reach a better understanding of our point of view concerning superconductors.

In a normal metal a temperature gradient produces the well-known thermoelectric current

$$j^{(T)} = -\eta \nabla T. \tag{1}$$

In order to obtain the total current one should add to Eq. (1) the Ohmic term,

$$j = j^{(\sigma)} + j^{(T)} = \sigma E - \eta \nabla T, \tag{2}$$

σ being the conductivity. Thus, the thermoelectric voltage across an isolated normal sample equals

$$V^{(T)} = \int_{T_1}^{T_2} \alpha(T)\, dT. \tag{3}$$

Here, T_1 is the temperature of the cold end of the sample while T_2 is the temperature of the hot end;

$$\alpha = \eta/\sigma \tag{4}$$

is the Seebeck coefficient.

When studying thermoelectric phenomena one usually deals with a circuit consisting of two different conductors: I and II. The thermoelectric voltage across such a circuit is

$$V^{(T)} = \int_{T_1}^{T_2} (\alpha_{\mathrm{I}} - \alpha_{\mathrm{II}})\, dT = \int_{T_1}^{T_2} \left(\frac{\eta_{\mathrm{I}}}{\sigma_{\mathrm{I}}} - \frac{\eta_{\mathrm{II}}}{\sigma_{\mathrm{II}}} \right) dT, \tag{5}$$

while the total thermoelectric current in a closed circuit $J^{(T)}$ is

$$J^{(T)} = V^{(T)}/R, \tag{6}$$

where R is the total resistance of the circuit.

If the circuit is made of a homogeneous conductor then $\alpha_{\mathrm{I}} = \alpha_{\mathrm{II}}$, and $V^{(T)}$ as well as $J^{(T)}$, vanishes, in accordance with the well-known fact that it takes two different conductors to make a thermopair.

Another way to understand this physical picture is to use symmetry considerations. The thermoelectric current in a closed circuit creates a magnetic flux. The magnetic field which is a pseudovector is proportional to the temperature gradient which is a true vector. So one needs another vector nonparallel to the temperature gradient to construct a pseudovector as the vector product. In the case of two different conductors one can draw such a vector, say, from conductor I to conductor

II. In the case of one homogeneous conductor there is, in general, no way to draw such a vector; therefore, no thermoelectric effect can exist.

Let us turn to the acoustoelectric effect in normal conductors. As was pointed out by Parmenter in Ref. 5, if a traveling acoustical wave propagates along a conductor an acoustoelectric current $j^{(a)}$ appears. Usually it is proportional to the ultrasonic energy flux density S. If the sound propagates along of a direction of sufficiently high symmetry then the vectors S and $j^{(a)}$ are parallel. For the sake of simplicity we shall consider only this case which describes the usual experimental situation. To obtain the total current density one should add to $j^{(a)}$ the Ohmic term,

$$j = j^{(a)} + \sigma E. \tag{7}$$

The acoustoelectric voltage across an isolated normal sample equals

$$V^{(a)} = -\frac{1}{\sigma}\int_0^L j^{(a)}(x)\,dx\,, \tag{8}$$

where one should integrate along the whole length L of the sample. Here we have taken into account the fact that the acoustoelectric current $j^{(a)}$ is usually coordinate-dependent because sound is absorbed in a conductor and therefore the sound intensity S depends on the coordinate x along the sample.

The total acoustoelectric current in a closed circuit is

$$J^{(a)} = V^{(a)}/R, \tag{9}$$

where R is the total resistance of the circuit.

We see that while it is necessary to use a bimetallic sample to observe the thermoelectric effect, the acoustoelectric effect can exist in a homogeneous monometallic sample because the distribution of an acoustical flux itself can create the necessary inhomogeneity. In other words, the pseudovector of the magnetic field in the last case may be proportional to the vector product of two vectors, one of them being the acoustical-energy-flux-density $\vec{S}$ while the other one characterizes the symmetry of the acoustical-flux distribution. The acoustoelectric effect vanishes only in the special case where both the sample and the distribution of acoustical flux are symmetric. Both situations are schematically illustrated in Fig. 1.

We think that the simplest experimental arrangement for observing the acoustoelectric effect is of the sort depicted in Fig. 1. In part I of the closed circuit a traveling acoustical wave propagates, while in part II there is no acoustical flux. The acoustoelectric effect can manifest itself by the magnetic field created by a circular current. Both parts of the circuit may be made of the same metal, as well as of different metals. However, it is better to use the same metal for this purpose because usually sound absorption is accompanied by the formation of a temperature gradient. Therefore, in the case of a bimetallic loop the acoustoelectric effect may be masked by the thermoelectric one, whereas there is no masking thermoelectric effect in a monometallic loop.

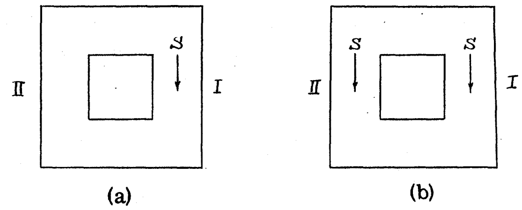

FIG. 1. Schematic picture of the acoustoelectric effect. All parts of the circuit are made of the same material: (a) The acoustical wave propagates only in part I. The observation of the acoustoelectric effect is possible. (b) the acoustical flux S is symmetrically distributed among parts I and II. There is no acoustoelectric effect, in accordance with the conclusion of Falco.

Now let us turn to the immediate purpose of our paper, i.e., the discussion of the acoustoelectric effect in superconductors. At finite temperatures there are normal excitations in superconductors which behave essentially in the same manner as electrons in normal conductors. In particular, they are dragged by a traveling acoustical wave and, as a result, a normal acoustoelectric current appears. We shall use the same notation $\vec{j}^{(a)}$ for the density of this current. As in a normal metal, it is proportional to the acoustical-energy-flux-density $\vec{S}$. (The exact expression for $\vec{j}^{(a)}$ in terms of $\vec{S}$ will be given below.)

In an isolated sample the presence of a normal current is offset by a supercurrent

$$\vec{j}^{(s)} = \beta N_s \nabla\chi, \tag{10}$$

where χ is the phase of the order parameter, β is a constant which in the effective-mass approximation equals $e\hbar/2m$ (where e is the electron charge), while $N_s(T)$ is the so-called superconducting electron concentration. The last quantity equals the total electron concentration N_0 in the limit $T \to 0$. On the other hand, if $T_c - T \ll T_c$ (where T_c is the critical temperature of the superconductor) we have

$$N_s(T) = 2N_0(T_c - T)/T_c. \tag{11}$$

The sum $\vec{j}^{(a)} + \vec{j}^{(s)}$ being zero, one may conclude that the traveling acoustical wave (as well as any other sort of perturbation that produces a stationary voltage across a sample of a normal conductor) creates a stationary phase difference in a superconductor. To calculate the phase difference one should replace σ by βN_s in the expression for the voltage. For the acoustoelectric phase difference $\delta\chi^{(a)}$ one has

$$\delta\chi^{(a)} = -\frac{1}{\beta N_s(T)}\int_0^L j^{(a)}(x)\,dx\,. \tag{12}$$

We think that the simplest experimental arrangement for observing the acoustoelectric effect in superconductors is a monometallic loop, as schematically depicted in Fig. 1. The measured quantity may be the magnetic flux through the loop. In order to calculate this quantity, it is necessary to use the gauge-covariant generalization of Eq. (10):

$$\vec{j}^{(s)} = 2\beta N_s \vec{p}_s/\hbar\;;\vec{p}_s = \tfrac{1}{2}\hbar[\nabla\chi - (2e/\hbar c)\vec{A}], \tag{13}$$

where $\vec{A}$ is the vector potential.

Since the total current density in the bulk of a superconductor is zero, one can write

$$\nabla\chi = (2e/c\hbar)\vec{A} - (1/\beta N_s)\vec{j}^{(a)}. \tag{14}$$

In order to determine the total magnetic flux through the loop,

$$\varphi = \int \mathrm{curl}\vec{A}\,dS = \oint \vec{A}\,d\vec{r}, \tag{15}$$

one may integrate Eq. (14) along the closed path within the bulk of the superconducting loop where the total current vanishes. Inasmuch as

$$\int \nabla\chi\,d\vec{r} = 2\pi n\,, \tag{16}$$

n being an integer, we get the following expression for the total magnetic flux through the loop:

$$\varphi = \phi_0(n + \delta\chi^{(a)}/2\pi), \tag{17}$$

where $\phi_0 = \pi\hbar c/e$ is the magnetic-flux quantum.

It might be worthwhile to point out here that there are other ways to observe the acoustoelectric effect in superconductors. For instance, one may use the Zimmerman and Silver interferometer, the Mercereau interferometer, or some more complicated scheme consisting of superconductors and weak links. We wish, however, to emphasize that the acoustoelectric characteristics of the superconductor enter any formula describing the operation of such a device through the angle $\delta\chi^{(a)}$ (or through the algebraic sum of the angles for a series of superconductors). All the rest is determined by the electrodynamics of the superconductors and weak links themselves. For example, the critical current of the Mercereau interferometer is

$$2J_c \cos\tfrac{1}{2}\delta\chi^{(a)}, \tag{18}$$

if we suppose for simplicity that the critical currents of both weak links of the interferometer are equal to each other and denote them by J_c (the corresponding formula for $\delta\chi^{(a)}$ was derived by the authors in Refs. 2 and 3). In the case of the Zimmerman and Silver interferometer with one weak link we get the following equation connecting the magnetic flux φ through the loop with the magnetic flux created by the external magnetic field ϕ_e:

$$\varphi + (LJ_c/c)\sin(2\pi\varphi/\varphi_0 + \delta\chi^{(a)}) = \phi_e, \tag{19}$$

where L is the inductance of the interferometer.

We see from these formulas, as well as from the physical picture described above, that even if all the parts of these systems, except the weak links, are made of the same material, it is still possible to observe the acoustoelectric effect in such a system (in contrast to the opinion expressed by Falco in Ref. 4) provided the system itself is acoustically asymmetric.

Let us discuss now the difference between acoustoelectric and thermoelectric phenomena in superconductors. As early as 1944 Ginzburg[6] suggested that in the presence of a temperature gradient, there appears in a superconductor a normal current of the form given by Eq. (1). The microscopic calculation of the transport coefficient η for the case of impurity scattering of the normal excitations in a superconductor was made in Refs. 7, 8. It was also pointed out by Ginzburg[6] that the total current in the bulk of a homogeneous isotropic superconductor vanishes because the normal current is offset by a supercurrent, and that this makes impossible the direct observation of the thermoelectric effect in a simple connected isotropic homogeneous superconductor. He considered also in his paper simple connected anisotropic or nonhomogeneous superconductors as systems where it is possible to observe thermoelectric phenomena by measuring the magnetic field produced by a temperature gradient.

In our opinion, the best way to observe thermoelectric phenomena in superconductors, in particular to measure the thermoelectric coefficient η of an isotropic homogeneous superconductor, is to make it part of a bimetallic superconducting loop that may also contain weak links. We shall formulate the following quantitative results concerning thermoelectric phenomena in isotropic superconductors in terms of the phase difference $\delta\chi^{(T)}$ across an isolated sample where a temperature gradient is maintained. According to the rule formulated above one can obtain the expression for the phase difference by replacing σ by βN_s in Eqs. (3) and (4):

$$\delta\chi^{(T)} = \frac{1}{\beta}\int_{T_1}^{T_2} \frac{\eta(T)}{N_s(T)}\,dT\,. \tag{20}$$

For a small temperature difference $\Delta T = T_2 - T_1$

this equation gives

$$\delta\chi^{(T)} = [\eta(T)/\beta N_s(T)]\Delta T. \tag{21}$$

We derived Eq. (21) in Ref. 1 whereas Eq. (20) was obtained by the authors in Ref. 8. In the same paper we have analyzed the general temperature dependence of $\delta\chi^{(T)}$ given by Eq. (20) in the immediate vicinity of the critical temperature T_c:

$$\delta\chi^{(T)} = T_c\eta(T_c)/2\beta N_0 \ln[(T_c - T_1)/(T_c - T_2)]. \tag{22}$$

In a thermopair made of two different superconductors the thermoelectric effect is determined by the difference

$$\delta\chi^{(T)} = \delta\chi_{I}^{(T)} - \delta\chi_{II}^{(T)} = \int_{T_1}^{T_2} dT\left(\frac{1}{\beta_I}\,\frac{\eta_I(T)}{N_{sI}(T)} - \frac{1}{\beta_{II}}\,\frac{\eta_{II}(T)}{N_{sII}(T)}\right), \tag{23}$$

which vanishes for identical conductors. This phase difference can manifest itself in the same various ways as the acoustoelectric phase difference discussed above [see Eqs. (17)–(19)].

One should note that there is some essential difference between Eq. (5) for normal conductors and Eq. (23) for superconductors. Roughly speaking, the numerators in all these formulas are proportional to the normal electron mean free path l. The denominators in Eq. (5) are also proportional to l thus making the l dependence of the whole expression (5) not too significant. At the same time, the denominators in Eq. (23) are independent of l. It means that $\delta\chi^{(T)}$ is proportional to l. Thus one may conclude that the phase difference $\delta\chi^{(T)}$ can be appreciable only for pure superconductors. If, for instance, conductor I is pure while conductor II contains many impurities, it is only the first conductor that makes an essential contribution to Eq. (23). This makes it possible to measure the thermoelectric contribution of a single pure superconductor in spite of the fact that, in principle, the thermoelectric effect in superconductors, as well as in normal conductors, is a differential one.

Now we can formulate the principal difference between acoustoelectric and thermoelectric phenomena in superconductors as we see it: While it is impossible to create a temperature difference in one part of a closed circuit and to maintain a constant temperature in another which is in thermal contact with the first one, it is definitely possible to excite an acoustical flux in one part of a closed circuit while the rest of it remains acoustically free. This is why one can observe the acoustoelectric effect in a closed circuit made of a superconducting material, and we think this experimental arrangement is the best because in this case the acoustoelectric effect cannot in principle be masked by the thermoelectric one (such masking was discussed above for normal conductors and by Falco for superconductors). Possible complications of this simplest experimental situation will be discussed below.

The authors have obtained the following expression for the acoustoelectric-current density in an isotropic superconductor:

$$\vec{j}^{(a)} = (\sigma\Gamma_s\vec{S}/eN_0 w)F(\Delta/T), \tag{24}$$

where σ is the residual conductivity of the metal in the normal state, Γ_s is the sound-absorption coefficient of the superconductor calculated in Ref. 2, w is the sound velocity, and

$$F(x) = \frac{1}{4}\,(e^x + 1)\int_0^\infty \frac{(x+y)\,dy}{y^{1/2}(2x+y)^{1/2}}\;\frac{1}{\cosh^2[\frac{1}{2}(x+y)]} \tag{25}$$

is the function introduced by the authors in Refs. 2, 3 and plotted by Falco in Ref. 4.

Falco in his paper[4] analyzes in detail the conditions necessary for the observation of the acoustoelectric effect in a bimetallic superconducting circuit and concludes that the observation is possible in a narrow temperature interval near T_c. According to our opinion, which we hope to have substantiated in the present paper, all his estimates remain valid for a monometallic superconducting loop where an acoustical flux is distributed asymmetrically (of course with the exception of his stipulation concerning the thermoelectric contribution to the phase difference).

Let us now turn to some other aspects of acoustoelectric and thermoelectric phenomena in superconductors. The estimates of the acoustoelectric effect by Falco[4] are valid only for the simplest case discussed above. One often meets with more complicated cases where these estimates should be modified. Now we are going to discuss some aspects of this modification by means of a comparison of thermoelectric and acoustoelectric phenomena in superconductors. An interesting possibility exists of enhancing thermoelectric and acoustoelectric effects.

As was shown by Aronov,[9] in the presence of a persistent current $j^{(s)}$ a temperature gradient generates, in addition to the usual thermoelectric current $j^{(T)}$ discussed in detail above, an extra current $j^{(A)}$. This current is also proportional to ∇T, its vectorial structure being determined by the product $\vec{p}_s(\vec{p}_s \cdot \nabla T)$. The origin of such a current is closely connected with the additional term $\vec{p}_s \cdot \vec{v}$ in the expression for the excitation energy $\tilde{\epsilon}$,

$$\tilde{\epsilon} = \epsilon(\vec{p}) + \vec{p}_s \cdot \vec{v}$$

in the presence of a supercurrent. Here, $\vec{v}$ is the normal electron velocity while $\epsilon(\vec{p})$ is the excitation energy in the absence of a supercurrent.

Due to this term, a nonequilibrium part of the quasiparticle distribution function appears which is of first order in ∇T and at the same time a function of the total energy $\tilde{\epsilon}(\vec{p})$. Therefore it relaxes owing only to inelastic scattering by phonons. It is this part of the nonequilibrium distribution function that is responsible for the current $j^{(A)}$. This is why the current $j^{(A)}$ is proportional to the relaxation time τ_{ph} while the current $j^{(T)}$ is proportional to τ_i, τ_i^{-1} being the impurity scattering rate. Since experiments are usually performed at sufficiently low temperatures where $\tau_{\text{ph}} \gg \tau_i$ the current $j^{(A)}$ may be larger than $j^{(T)}$ provided p_s is large enough (although still much smaller than its critical value). Thus, this effect of combined nature may enhance the total thermoelectric phase difference in superconductors.

Aronov in Ref. 9 has considered the case of a sample that has the form of a cylinder with extremely thin walls (their thickness being much less than the penetration depth λ). An effect of the same nature in a more realistic situation where the loop is made of a thick superconductor (as compared to the penetration depth) has been considered in detail by one of the authors[10] (V.I.K). He has come to the conclusion that in this case an additional current density of the same physical nature and of practically the same order of magnitude as the Aronov current density $j^{(A)}$ calculated in Ref. 9 is localized near the surface of the sample. In spite of this, one can obtain the correct order of magnitude of the contribution to the magnetic flux in the cavity of the loop assuming a homogeneous current-density distribution in the sample with the current density equal to the surface current density and applying the standard procedure described above for the current $j^{(T)}$.

On the other hand, the current density $j^{(A)}$ can sometimes be much larger than $j^{(T)}$. Detailed analysis[10] gives the following order-of-magnitude estimate for the additional magnetic flux $\varphi^{(A)}$ generated by the current $j^{(A)}$:

$$\frac{\varphi^{(A)}}{\varphi_0 \Delta T} \simeq 100 \left(\frac{I^{(s)}}{\varphi_0 c}\right)^{3/2} \tau_{\text{ph}} \frac{\Delta^2}{T p_F} \frac{N_0 - N_s}{N_s} \lambda^{3/2} \xi^{1/2} . \tag{26}$$

Here, ΔT is the temperature difference which, for simplicity, we consider to be much smaller than $T_c - T$, ξ is the coherence length, $I^{(s)}$ is the surface current density (equal to the current density $j_0^{(s)}$ integrated along the normal to the surface of the sample); $j_0^{(s)}$ is the supercurrent density in the absence of temperature gradient (it is determined by the shape of the sample and the distribution of the magnetic field near its surface). This estimate is valid in the case where the semiclassical approach to the description of quasiparticles localized near the surface is valid. This approach holds for type-II superconductors provided v_s is large enough (see Ref. 11).

One may also expect a similar contribution to the acoustoelectric phase difference in the presence of a supercurrent.[12] The vectorial structure of such an additional acoustoelectric current $\vec{j}'^{(a)}$ is determined by the factor $\vec{p}_s(\vec{p}_s \cdot \vec{S})$; in a thick superconductor it is also localized near the surface. The estimate of its order of magnitude can be obtained in the same manner as for the thermoelectric current $j^{(A)}$. One can give the estimate for the ratio of this current density to the usual acoustoelectric one,

$$\frac{j'^{(a)}}{j^{(a)}} \simeq \frac{\tau_{\text{ph}}}{\tau_i} \left(\frac{p_F v_s}{T}\right)^{3/2} \left(\frac{\Delta}{T}\right)^{1/2} , \tag{27}$$

which is valid with the same assumptions as in Eq. (26) provided the sound wavelength is larger than the penetration depth and the excitation mean free path.

Inasmuch as $\tau_{\text{ph}} \gg \tau_i$ the ratio (27) may exceed unity even if v_s is much smaller than its critical value. As in the case of the thermoelectric effect, it can be shown that the order of magnitude of the magnetic flux in the cavity created by the current $j'^{(a)}$ in addition to the usual one, $\varphi^{(a)}$[Eqs. (12) and (17)], is described by Eq. (27) in spite of the surface nature of the current $j'^{(a)}$.

Now we wish to point out that for the thermoelectric phenomena discussed above there is some masking effect that may prevent their observation, whereas for the acoustoelectric phenomena one can, at least in principle, exclude a masking effect of this sort. In thermoelectric experiments in the presence of a persistent current thermoelectric effects are masked by the simple redistribution of the magnetic flux between the surface layer and the cavity of the sample due to the dependence of the penetration length on T. This effect was understood and experimentally observed by Pegrum and Guenault in Ref. 13. It should be emphasized that this effect should be taken into account in all the thermoelectric experiments (not only concerning the effect suggested by Aronov) provided in such experiments there is a trapped magnetic flux. Therefore the problem arises of extracting the real thermoelectric effects from the experimental data which contain a large contribution from the redistribution effect. One of the authors (V.I.K.), who studied this problem in detail,[10] has shown that the last effect can be diminished in a thermoelectric loop with a large value of the ratio of the circuit characteristic dimension (D) to the wire diameter (d). If supercurrents induced near the external and internal surfaces of such a circuit have opposite direction, the total supercurrent being small, this masking effect can decrease by a factor of d/D. It is this situation that occurs when supercurrents are induced by an external field which does not change after cooling the circuit below T_c.

Thus, our estimate of the possibility of observing unmasked thermoelectric effects is somewhat more optimistic than that of Pegrum and Guenault.[14] Therefore, we believe that Zavaritsky in Ref. 15 observed the real thermoelectric flux [Eqs. (17) and (23)].[16] We think this because of the reversibility of the effect with ∇T (which he checked) and the linear dependence of the effect on the mean free path of electrons (purity of samples), which coincides with our formulas (21) and (22). The masking effect discussed above cannot give such a dependence on l.

In acoustoelectric experiments there is at least in principle the possibility of keeping the temperature constant. Therefore, there is the possibility of eliminating not only the thermoelectric effect, mentioned by Falco,[4] but more important, the redistribution effect. We believe this fact to be of special importance in the case of the supercurrent-induced acoustoelectric effect discussed above.

From this point of view we believe that it is interesting to study acoustoelectric effects due to surface waves. Indeed, one can obtain an intense surface wave without considerable heating of the sample, so there is no masking effect even in the presence of a trapped magnetic flux. The acoustoelectric current, produced by the surface wave (and the superconducting counterflow as well), has an eddy component. Therefore, a magnetic flux is produced in the surface layer. Let us consider a closed loop made of bulk superconductors and enclosing the region of location of the surface wave. The total magnetic flux through the circuit (the flux through the contour in the bulk of the superconductors) is fixed. So a nonquantized additional magnetic flux is produced in the cavity of the loop which compensates the surface-layer flux due to the surface acoustoelectric current. It can be shown that the estimate of this flux is given by Eqs. (12) and (17) where $j^{(a)}$ is the value of the acoustoelectric normal current density at the surface. This estimate is valid if the sound wavelength is larger than (or of the order of) the penetration depth of the magnetic field. We want to emphasize that this picture is in fact similar to the one of super-current-induced acoustoelectric and thermoelectric phenomena in bulk samples discussed above. Indeed, the corresponding current densities $j^{(A)}$ and $j'^{(a)}$ have eddy components which produce the surface magnetic flux.

A detailed analysis of acoustoelectric phenomena concerning surface waves (both in the presence and in the absence of a supercurrent) will be published elsewhere.

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[1]Yu. M. Gal'perin, V. L. Gurevich, and V. I. Kozub, Pis'ma Zh. Eksp. Teor. Fiz. 17, 687 (1973), [JETP Lett. 17, 476 (1973)].

[2]Yu. M. Gal'perin, V. L. Gurevich, and V. I. Kozub, Zh. Eksp. Teor. Fiz. 65, 1045 (1973), [Sov. Phys. JETP 38, 517 (1974)].

[3]Yu. M. Gal'perin, V. L. Gurevich, and V. I. Kozub, Fiz. Tverd. Tela 16, 1151 (1974), [Sov. Phys. Solid State 16, 738 (1974)].

[4]C. M. Falco, Phys. Rev. B 14, 3853 (1976).

[5]R. H. Parmenter, Phys. Rev. 89, 990 (1953).

[6]V. L. Ginzburg, Zh. Eksp. Teor. Fiz. 14, 177 (1944).

[7]M. J. Stephen, Phys. Rev. 139, A197, (1965).

[8]Yu. M. Gal'perin, V. L. Gurevich, and V. I. Kozub, Zh. Eksp. Teor. Fiz. 66, 1387 (1974) [Sov. Phys. JETP 39, 680 (1974)].

[9]A. G. Aronov, Zh. Eksp. Teor. Fiz. 67, 178 (1974) [Sov. Phys. JETP 40, 90 (1975)].

[10]V. I. Kozub, Zh. Eksp. Teor. Fiz. 74, 344 (1978).

[11]M. Ya. Azbel', Zh. Eksp. Teor. Fiz. 59, 295 (1970) [Sov. Phys. JETP 30, 163 (1970)].

[12]This idea was suggested by A. G. Aronov.

[13]C. M. Pegrum and A. M. Guenault, Phys. Lett. A 59, 393 (1976).

[14]These estimates also enable us to believe that the effect connected with $j^{(A)}$ [Eq.(26)], based on the presence of a trapped flux, can be separated from the redistribution effect (taking especially into account their different dependence on the sign of ∇T and v_s).

[15]N. V. Zavaritsky, Pis'ma Zh. Eksp. Teor. Fiz. 19, 205 (1974) [JETP Lett. 19, 126 (1974)].

[16]In his work Zavaritsky used a geometry in which the magnetic flux is thermoelectrically generated in a loop made of two different superconductors. Such a geometry was theoretically considered by the authors (Ref. 8) and by Garland and Van Harlingen: J. C. Garland and D. J. Van Harlingen. Phys. Lett. A 47, 423 (1974).