N. V. Zavaritskiĭ. Thermoelectric Phenomena in Superconductors. The presence of a temperature gradient in a metal results in the appearance of a thermoelectric voltage. This voltage appears because the heat flux is accompanied by a thermoelectric current. The result is a redistribution of charges over the sample and the appearance of a voltage whose magnitude is such that the current in the specimen stops flowing.

The thermoelectric voltage vanishes when the metal goes over to the superconducting state. Ginzburg[1] drew attention to the fact that the thermoelectric current due to normal excitations in a superconductor remains unchanged, at least near the transition temperature, but that charge transfer offsets the superconductive current of Cooper pairs. The result in a superconductor with a temperature gradient is circulation of the normal-excitation thermoelectric current $j_n = -\alpha\sigma\nabla T$ (α is the coefficient of the differential thermal emf and σ is the conductivity of the metal) and circulation of the superconductive current $j_s \equiv -j_n$.

A superconductor is a system whose quantum properties are manifested on the macroscopic scale. The state of the superconducting Cooper pairs is described by assigning a wave function $\Psi = \Psi(r)e^{i\varphi}$. The density n_s of the superconducting pairs is defined as $|\Psi|^2$, and the superconducting current is proportional to the phase gradient: $j_s = (e\hbar n_s/2m)\nabla\varphi$. The presence of a temperature current in a superconductor must obviously be accompanied by a phase change along the sample[2] $\Delta\varphi = (2m/e\hbar)(\alpha\sigma/n_s)\Delta T$. Clearly, thermoelectric phenomena can be observed only in a closed circuit composed of superconductors with different characteristics.

One of the phenomena associated with the presence of a temperature gradient in a circuit composed of superconductors consists in the appearance of a magnetic flux in the thermoelectric loop. We know that the magnetic flux in the superconductive loop is $\Phi = n\Phi_0$, where $\Phi = 2.07 \times 10^{-7}$ Oe/cm^2 is the quantum of the magnetic flux in the superconductor and n is an integer. Temperature gradients lead to the appearance of an additional nonquantized thermoelectric magnetic flux[3-5]

$$\Delta\Phi = \frac{2m}{eh}\Phi_0 \oint\limits_L \frac{\alpha\sigma}{n_s}\nabla T \quad (1)$$

or, if the temperature change takes place on part of the loop,

$$\Delta\Phi = \frac{2m}{eh}\Phi_0 \left[\left(\frac{\alpha\sigma}{n_s}\right)_1 - \left(\frac{\alpha\sigma}{n_s}\right)_2\right]\Delta T; \quad (2)$$

the subscripts denote the segments of the loop along which the temperature change occurs.

This thermoelectric magnetic flux is small and amounts under optimum conditions to a fraction of Φ_0, but it can be observed in experiment by using a highly sensitive superconductive quantum magnetic fluxmeter for the measurements[6].

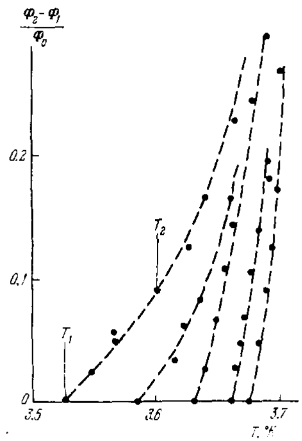

FIG. 1. Variation of magnetic moment in a thermoelectric superconducting loop for various temperature distributions. T_1 is the temperature of the cold junctions of the loop and T_2 is the temperature of the heated junction. T_2 varies along each curve.

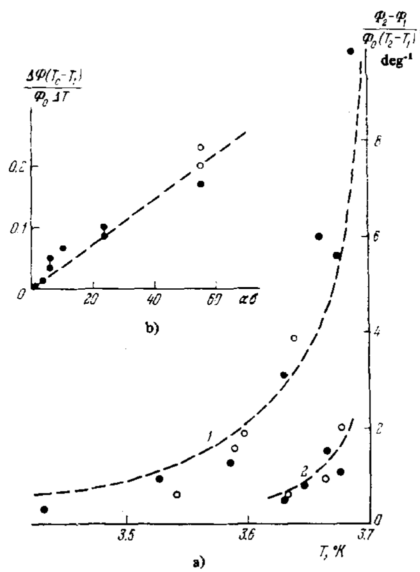

FIG. 2. (a) Variation of initial slope of $\Delta\Phi/\Phi_0\Delta T$ curves for two samples (1 and 2) $\Delta\Phi = \Phi_2 - \Phi_1$, $\Delta T = T_2 - T_1$; the open and dark circles correspond to different series of measurements, and the dashed curves to the theory; b) thermoelectric magnetic moment $\Delta\Phi\,(T_C - T_1)/\Delta T$ as a function of the characteristics of tin in the normal state (dark circles represent a tin-lead thermocouple, in paired experiments, when connected; the open circles represent the tin ($\alpha\sigma = 56$) - tin ($\alpha\sigma = 2$) thermocouple).

In an experiment of[3], the magnetic flux $\Delta\Phi = \Phi(T_2) - \Phi(T_1)$ that arises when a heater is switched on to produce a temperature gradient was measured in a circuit consisting of tin and lead. It was observed that $\Delta\Phi$ is directly proportional to ΔT at small temperature gradients (Fig. 1). The ratio $\Delta\Phi/\Delta T$ varies with temperature, decreasing with deviation from T_C. This variation of $(\Delta\Phi/\Delta T)(T_1)$ (Fig. 2a) agrees well with the theoretical conclusions and is due basically to the temperature dependence of n_S, $n_S = (N_0/2) \times (T_C - T)/T_C$, near T_C. The magnitude of the thermoelectric magnetic flux depends on the characteristics of tin in the normal state, vanishing, as is seen from Fig. 2b, for samples with small values of $\alpha\sigma$. This is because the contribution of the lead to the total thermoelectric magnetic flux is a small one, owing to its high critical temperature $T_{C\,Pb} = 7.2°K$.

Further experiments showed that a thermoelectric magnetic flux can also be excited in a circuit consisting of tin alone by using samples with different values of $\alpha\sigma$. It was found with the aid of such circuits that the sign of the flux is determined by the difference $(\alpha\sigma)_1 - (\alpha\sigma)_2$ and does not depend on $(\alpha_1 - \alpha_2)$. When several thermocouples were connected in series, the thermoelectric flux in the superconductors was additive.

A thermomagnetic flux can also arise in a bulky superconductor sample[1]. We see from (1) that this requires the presence of a nonzero circulation of the normal-excitation thermoelectric current. It was on bulky samples that the first experimental attempts were made to observe thermoelectric phenomena in superconductors[7]. The appearance of a magnetic field in the presence of a heat flux was observed in the experiments of[7,8], but these experiments can still be interpreted in different ways.

The occurrence of thermoelectric phenomena in superconductors is yet another manifestation of the quantum nature of superconductivity. Study of these phenomena will probably yield additional information on relaxation processes in which normal excitations of the superconductor participate. Nor can we exclude the possibility that these effects may prove useful in various superconductor interference devices.

1. V. L. Ginzburg, Zh. Eksp. Teor. Fiz. 14, 177 (1944).
2. Yu. M. Gal'perin, V. L. Gurevich, and V. I. Kozub, ZhETF Pis. Red. 17, 687 (1973) [JETP Lett. 17, 476 (1973)].
3. N. V. Zavaritskiĭ, ibid. 19, 205 (1974) [19, 126 (1974)].
4. Yu. M. Gal'perin, V. L. Gurevich, and V. I. Kozub. Zh. Eksp. Teor. Fiz. 66, 1387 (1974) [Sov. Phys.-JETP 39, 680 (1974)].
5. J. C. Jarland and D. Y. Van Harlangton, Phys. Lett. A47, 423 (1974).
6. N. V. Zavaritskiĭ and A. N. Vetchinkin, Prib. Tekhn. Éksperim. No. 1, 247 (1974).
7. N. V. Zavaritskiĭ, ZhETF Pis. Red. 16, 99 (1972) [JETP Lett. 16, 67 (1972)]; Zh. Eksp. Teor. Fiz. 72, 1969 (1974) [sic!]
8. P. M. Selzer and W. M. Fairbank, Phys. Lett. A48, 279 (1974).