OBSERVATION OF SUPERCONDUCTING CURRENT EXCITED IN A SUPERCONDUCTOR BY HEAT FLOW

N. V. Zavaritskii
Institute of Physics Problems, USSR Academy of Sciences
Submitted 12 January 1974
ZhETF Pis. Red. 19, No. 4, 205 – 208 (20 February 1974)

It has been observed experimentally that a temperature gradient produces flow of superconducting current in a circuit made up of superconductors. The dependence of the effect on the temperature and on the characteristics of the superconductor is investigated.

According to the theory of thermoelectric effects [1], a temperature gradient in a superconductor gives rise to a thermoelectric current of normal excitations $j_n = \alpha\sigma\nabla T$ (α is the differential thermoelectric power, σ is the conductivity of the sample). A current of superconducting electrons $j_s = -j_n$ is produced together with j_n. The presence of j_s, as noted in [2], leads to the appearance in the superconductor of an order-parameter phase difference $\Delta\phi = (2m/e\hbar)(\alpha\sigma/n_s)\Delta T$ (n_s is the density of the superconducting electrons). As is well known, $\oint\Delta\phi = 0$ around a circuit made up of superconductors. Therefore if two points of a superconductor, between which a phase difference $\Delta\phi$ exists, are joined by a superconducting circuit, then a magnetic flux $\Delta\Phi = (-\hbar/2e)\Delta\phi$ is produced in the closed circuit, or equivalently, a current $i_s = \Delta\Phi/L$ is produced (L is the inductance of the circuit). Since heat flow produces a change of phase along the circuit, it can obviously excite a superconducting current in the circuit. Of course, in this case $\Delta\phi$ is produced simultaneously in all the circuit sections in which there is a temperature gradient, and accordingly the sought effect is proportional to $[(\alpha\sigma/n_s)_1 - (\alpha\sigma/n_s)_2]\Delta T$ (the subscripts denote different sections of the circuit with inhomogeneous temperature). By proper choice of the circuit elements, however, it is easy to cause the heat flow to lead to a significant change of $\Delta\phi$ in only one part of the circuit. This condition is satisfied, for example, by a circuit made up of superconductors with different T_c. In the experiments undertaken to search for the effect described above we used mainly the pair tin ($T_c = 3.72$°K) and lead ($T_c = 7.2$°K).

The diagram of one of the experimental variants is shown in Fig. 1. The superconducting circuit contains two identical Sn-Pb junctions, the temperatures of which can be varied during the course of the experiments. All the remaining superconductor junctions are at constant liquid-helium temperature. The investigated junctions are made as follows. The sample is a tin cylinder of 4 mm diameter and 2.5 mm thickness. A lead wire passes inside the cylinder and makes contact with the tin in only the upper part of the sample. The thermometer is in a channel inside the lead. The heater is wound around the upper part of the sample. The thermometer and heater are electrically

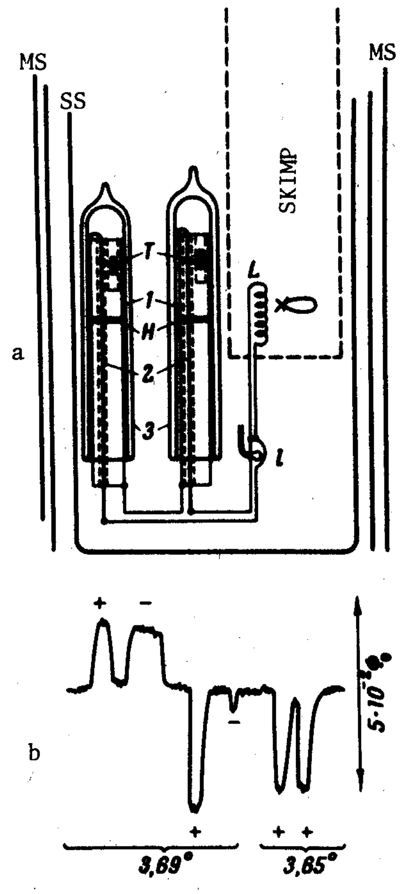

Fig. 1. a) Measurement setup: 1 — Sn sample, 2 — Pb sample, 3 — thermometers, H — heaters, L — coil for coupling with the superconducting interferometer SKIMP, ℓ — circuit and coil used to check on the sensitivity of the apparatus, 3 — inverted Dewar, SS — superconducting lead shield, MS — permalloy magnetic shields. b) Typical plot of the SKIMP apparatus as a function of the time; $T_1 = 3.51$°K and T_2 is marked under the curves. The deviations from zero in opposite directions correspond to temperature rises in two different Sn samples. The + or - sign denotes the direction of current flow through the heater; ϕ_0 is the quantum of magnetic flux (2×10^{-15} Wb).

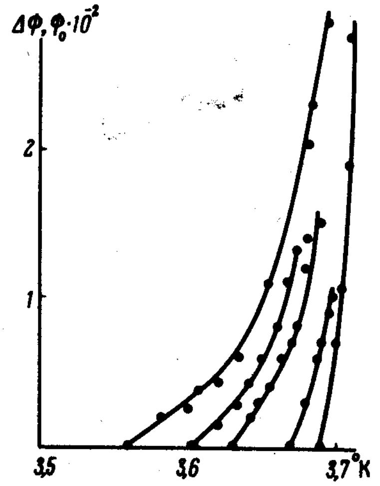

Fig. 2

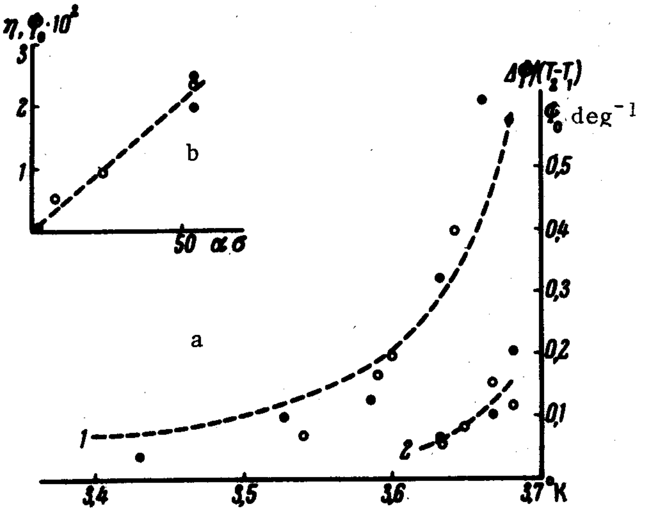

Fig. 3

Fig. 2. Variation $\Delta\Phi$ of the flux in the SKIMP circuit with the junction temperature T .

Fig. 3. a) Plot of $\Delta\Phi/(T_2 - T_1)$ vs. the temperature T_1. The symbols are explained in the text. b) Dependence of the investigated effect on the characteristics of the tin samples. A circle with a point represents a pair experiment. Circle — Sn($\alpha\sigma$ = 54) and Sn($\alpha\sigma$ = 2) pair.

insulated from the sample. The greater part of the sample is insulated from the surrounding liquid helium by a small inverted Dewar. The superconducting current is measured by including in the circuit the coupling coil L of the SKIMP superconducting interferometer [3]. The inductance is $L \simeq 150$ cm (1.5×10^{-7} H), and the coupling coefficient of the magnetic fluxes of the coil and of the interferometer is ~ 0.1.

During the experiment, the temperature T_1 of the helium bath was kept constant and the changes of the SKIMP readings were measured as functions of the hot-junction temperature T_2. It is seen from the curves of Fig. 1b that a change in the direction of the heat flow causes a reversal in the sign of the investigated effect. The currents through the heater were periodically reversed during the experiment to eliminate the parasitic magnetic field of the heaters. The main measurements were made at $T_1 \lesssim 3.68$°K.

Using plots similar to Fig. 1b we could determine the variation $\Delta\phi$ of the flux in SKIMP, or, equivalently, the superconducting current in the sample, as a function of the temperature of the hot junction T_2. If the temperature difference between the hot and cold junctions is $T_2 - T_1 \ll T_c - T_1$, then $\Delta\Phi$ is proportional to $T_2 - T_1$ (see Fig. 2).

Figure 3 shows a comparison of the initial slope of the $\Delta\Phi(T_2)$ curve. We see that the quantity $\Delta\Phi(T_2 - T_1)^{-1}$ decreases with decreasing T_1, in first approximation, in inverse proportion to $T_c - T_1$. This dependence is shown dashed in Fig. 3. We recall that in a superconductor near T_c we have $n_s \propto T_c - T$. Figure 3a shows results obtained by investigating several samples, viz., the results of two independent measurements of one of the samples (1), and the data obtained in the experiment with a pair of junctions (2). It is seen from the presented data that the effect is reproducible for each of the samples. This allows us to set the magnitude of the effect in correspondence with the characteristics of the lead.

In all the investigated samples, we measured in the interval 4.2 - 3.73°K the values of σ in ohm^{-1} cm^{-1} and of α in V/deg. It is convenient to describe the magnitude of the investigated effect by the quantity $\eta = \Delta\Phi(T_c - T_1)/(T_2 - T_1)$, which varies very little with temperature. It follows from the foregoing estimates that η should vary in direct proportion to $\alpha\sigma$. The obtained experimental data (Fig. 3b) do not contradict this relation.

The investigated effect can obviously be observed in an Sn-Sn pair if α and σ of the samples in contact are different. Additional experiments have confirmed this possibility. Thus the results obtained for the pair Sn (ασ = 54) and Sn (ασ = 2) were identical with the data obtained for the Sn (ασ = 54) - Pb pair (see Fig. 3b).

All the results agree well both with the foregoing estimates and with the detailed theory of the investigated phenomenon, developed independently by Yu. Gal'perin, V. Gurevich, and V. Kozub [4]. A detailed comparison of the results of the experiment with the calculations will be presented in the future.

The author is grateful to P. L. Kapitza for support, and to A. F. Andreev and V. L. Gurevich for discussions, and to N. A. Nikitin for technical collaboration.

[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. Zavaritskii and A. N. Vetchinkin, "The SKIMP Installation," Prib. Tekh. Eksp. No. 6, (1973).
[4] Yu. M. Gal'perin, V. A. Gurevich, and V. I. Kozub, Zh. Eksp. Teor. Fiz. 66, No. 4 (1974) [Sov. Phys.-JETP 39, No. 4 (1974)].