Thermo-emf and the critical temperature of the superconducting transition of thallium and rhenium accompanying a topological transition

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Thermo-emf in rhenium and thallium produced as a result of a pressure-induced topological transition exhibits large anomalies (on the order of a measurable quantity) which uniquely correspond to a nonlinear variation of the critical superconducting transition temperature T_c. The intrinsic lifetime of quasiparticles (charge carriers) has a considerable effect on the magnitude of the thermo-emf anomaly.

Topological transitions in an electron system were predicted theoretically by Lifshitz[1] and observed experimentally in several metals under hydrostatic compression[2–4] and under an elastic uniaxial deformation.[5,6] These transitions are also accompanied by thermo-emf anomalies[7] α manifested as extrema in the dependence of α on the parameter which determines the Fermi energy. These particular features of the thermo-emf were studied in 2D systems by varying the surface-charge density,[8] under an elastic uniaxial deformation of metals,[9,10] and in the $Li_{1-x}Mg_x$ alloys.[11]

In the present letter we report a study of pure thallium and rhenium and also thallium with a mercury impurity, in which the transitions where previously detected from the T_c anomalies upon a hydrostatic compression.[2–4]

The thallium samples with $RRR \sim 6000$ and with a small mercury impurity ($\lesssim 1.0\%$) were prepared the same way as in Ref. 2, by pressing the material through a 4-mm-diam hole and then annealing it for 50 h at 100 °C. The RRR of rhenium single crystals 2×2 mm in cross section, with the (0001) and ⊥(0001) axes directed along the sample was in the range from 500 to 22 000.

To measure the thermo-emf under a pressure of up to 13 kbar, we used a high-pressure chamber[12] with an 8-mm channel diameter. The temperature gradient along the samples (~ 0.02 K) and the average temperature T (up to 7 K) of the samples were measured with a 3LZh-superconductor thermocouple, whose characteristics were constant[13] up to 12 kbar. The potential difference was determined through a compensation with a SKIMP as the null indicator (the sensitivity is 10^{-14}–10^{-15} V). The temperature dependence of the sample's thermo-emf and its critical temperature T_c were measured at the given pressure. The pressure was determined from the manganin and superconducting pressure gauges to within 200 bar. The agreement between $\alpha(T)$ measured in a vacuum and $\alpha(T)$ measured in a high-pressure chamber at $P \sim 0$ kbar was a test of the validity of the measurement results.

The measurement results of the thermo-emf of thallium and rhenium are shown as a plot fo $a = \alpha/T$ versus T^2 in Fig. 1 which is generally used in the analysis of the

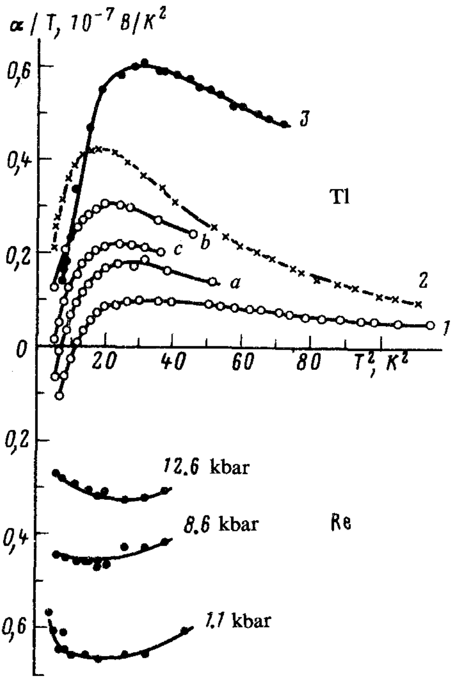

FIG. 1. Thermo-emf of thallium (top) and rhenium at various pressures: 1—Tl + 1% Hg, $P = 0$ kbar; *a*—3.5 kbar, *b*—5.6 kbar, *c*—8.1 kbar; 2—Tl + 0.45% Hg, $P = 0$ kbar; 3—pure Tl, $P = 0$ kbar.

thermo-emf. The peak on the $\alpha(T^2)$ curves at $T^2 \sim 20 (T \sim 4.5$ K) is attributed, as in Ref. 14, to the transfer processes in the phonon system. The most intriguing result of those we obtained is the nonmonotonic dependence of the thermo-emf of the Tl + 1% Hg sample on the pressure. As the pressure is increased from 0 to 6 kbar, we observe a significant increase (up to a factor of three) in the thermo-emf. As the pressure is further increased to 12 kbar, the thermo-emf decreases almost to the original value. This behavior correlates well1) with the particular features of $(\partial T_c/\partial P)(P)$ (Fig. 2). The thermo-emf anomaly we have observed is asymmetric with respect to the maximum, a characteristic feature of the topological transitions.[1,2] The pressure at which the transition occurs, which is determined from these results, is $P_c \sim 5$ kbar for this sample. There is also a correlation between the $T_c(P)$ and $\alpha(P)$ curves for rhenium (Fig. 2). It turned out in this case, however, that $P_c \sim 10$–12 kbar for the samples studied by us. This value is greater than that reported previously[4]: $P_c \sim 8$ kbar, so that we can detect a change in the values only in the region $P \lesssim P_c$.

The features on the $\alpha(P)$ curves for rhenium and Tl + 1% Hg are smeared with respect to pressure, presumably because of the considerable scattering of electrons by the impurities.

Evidence for this conclusion comes from the fact that the $\alpha(P)$ curve for the Tl + 0.2% Hg sample decreases more sharply as $P \to P_c$ (estimates based on this sample show that $P_c \sim -1$ kbar). At $P > P_c$ the thermo-emf anomaly varies as $\Delta\alpha \sim (P - P_c)^{-1/2}$ (the insert in Fig. 2) in a first approximation, a typical feature in topological transitions.

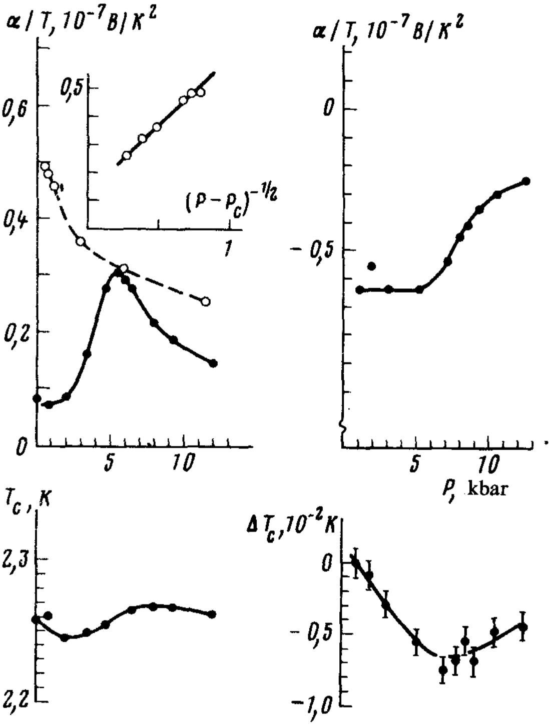

FIG. 2. Variation of the thermo-emf (at $T^2 = 20$) and critical temperature T_c of thallium (left) and rhenium (right). ●—Tl + 1% Hg; ○—Tl + 0.2% Hg.

The mean free path l of an electron, which is determined by the scattering by the impurities at the topological transition point,[2)] is[7]

$$l(p, \epsilon) = l_0(p, \epsilon) + \delta\nu(\epsilon) l_1(p, \epsilon), \tag{1}$$

where ϵ is the electron energy, and p is the electron momentum. The functions l_0 and l_1 depend smoothly on p and ϵ. $\delta\nu$ is an irregular part of the electron-state density which is associated with a change in the topology of the surface $\epsilon(p) = \epsilon$.

Following Ref. 15, we see that the thermo-emf anomaly, which is attributable to the second term in (1), is described by the equation

$$\delta(\alpha\sigma) = -\frac{2e}{T} I_0(\mu) \int_{-\infty}^{+\infty} (\epsilon - \mu)\, \delta\nu(\epsilon) \frac{\partial f_0}{\partial \epsilon}\, d\epsilon, \tag{2}$$

where f_0 is the Fermi distribution function, e is the electron charge, μ is the chemical potential, and σ is the electrical conductivity of the metal.

The function $I_0(\mu)$ for a crystal of cubic symmetry is

$$I_0(\mu) = \frac{1}{3(2\pi\hbar)^3} \int_{\epsilon(p)=\mu} \frac{dS_p}{|v_p|} (\mathbf{v}_p; l_1(p; \mu)),$$

where dS_p is the area element of a constant-energy surface, and $\epsilon(p) = \epsilon\ v_p = \partial\epsilon/\partial\mathbf{p}$ is the electron velocity.

If $\delta\alpha/\alpha_0 \gg \delta\sigma/\sigma_0$ (which is usually the case), the quantity $\delta\alpha$ is proportional to the anomalous part of the electronic component of the thermal expansion coefficient $\delta\beta$; i.e.,

$$\delta\alpha = c\delta\beta. \tag{3}$$

The numerical factor c can easily be found by comparing Eq. (2) with Eq. (3) of Ref. 16.

We see that expressions (2) and (3) are valid even when the finite lifetime of quasiparticles, τ_p, is taken into account. This lifetime is governed by the interaction of electrons with impurities for an arbitrary relationship between the quantities

$$\mu - \epsilon_c,\ T \text{ and } \Gamma, \text{ and } \mu >> T,\ \Gamma \qquad (\Gamma = \hbar/\tau_p).$$

For a topological transition corresponding to the formation of a new part of the Fermi surface, we have in this case

$$\delta\nu(\epsilon) \sim [\sqrt{(\epsilon-\epsilon_c)^2 + \Gamma(P_c)^2} + (\epsilon-\epsilon_c)]^{1/2}, \tag{4}$$

where ϵ_c is the critical energy.

A blurring of the features in Fig. 2 shows that a comparison of theory with experiment should be based on the use of Eq. (2) with the help of (4) [see Eq. (3) in Sec. 2 of Ref. 16].

After such a comparison, we can estimate the parameters characterizing a topological transition. In Tl + 1% Hg we have

$$\Gamma^2(P_c) \sim 1\ \mathrm{K}^2;\ P_c \cong 4.6\ \text{kbar}.$$

From the sign of $\delta\alpha > 0$ we conclude that the metals we have studied form new regions of the Fermi surface under hydrostatic compression.

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[1)] The results of the calculation of the dependence $T_c(P)$ for Tl and Re are consistent with those obtained previously.[2,4]

[2)] A change in the phonon drag due to a topological transition was ignored in this study.

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