INFLUENCE OF IMPURITIES ON THE EFFECT OF PRESSURE ON THALLIUM. II

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The effect of pressure P (up to 28 000 atm) on the superconducting transition temperature T_c was investigated for pure thallium and thallium containing mercury as an impurity. It was found that at high pressures (20 000—28 000 atm) the dependence of T_c on P for mercury-bearing thallium was similar to the analogous dependence for pure thallium ($dT_c/dP = -1.4 \times 10^{-5}$ deg/atm). At low pressures (up to ≈ 7000 atm), the dependence of T_c on P for pure thallium was different from that for thallium with the impurity (the sign of the effect changed at a certain concentration). It is suggested that this behavior of thallium and its alloys is related to the characteristic features of the pressure dependence of the density of states on the Fermi surface. It is possible that these features correspond to changes in the Fermi surface topology of thallium.

IN investigating the influence of impurities on the superconducting transition temperature T_c of thallium under pressure,[1] it was discovered that the effect of pressure was sensitive to the valence of the impurity atom and that even small concentrations of bismuth, antimony, and mercury impurities altered the pressure effect from positive to negative. On the assumption that pressure and an impurity of higher valence alter the Fermi energy ϵ_F in the same direction, while pressure and an impurity of lower valence alter this energy in opposite directions, we proposed a qualitative dependence of the quantity $\rho = V\partial N/\partial\epsilon$ on ϵ near the Fermi boundary energy ($\partial N/\partial\epsilon$ is the density of states on the Fermi surface, and V is the electron—phonon interaction constant).

To develop these propositions further, it was necessary to investigate the influence of pressure on the temperature T_c over a wider range of pressures, both for pure thallium and for thallium with mercury as an impurity. The results of such an investigation at pressures up to 28 000 atm are given in the present paper.

SAMPLES AND MEASUREMENT METHOD

In the present set of measurements, we used the same thallium—mercury alloys from which samples were prepared to measure the pressure effect in the earlier investigation.[1] Steps were taken to obtain the best possible homogenization of the alloy (thorough mixing in the liquid phase and prolonged annealing of the samples). The measurements were carried out on cylindrical samples of 2.5 mm diameter and 3—4 mm long. The width of the superconducting transition on the temperature scale for the Tl—Hg alloys was found to be similar to that for pure thallium, which indicated that the impurity distribution was highly uniform in our samples. The superconducting transition in the samples and in a tin manometer was recorded by an ac induction method.[2]

To establish pressures above 2000 atm, we used the method described in detail in[2,3]. A small modification was made in the present study: the pressure was transmitted from the piston made of the hard alloy VK-3 to the sample by means of a copper rod, 10 mm long, surrounded by a graphite lubricant and placed in the inner duct of the pressure booster. A similar rod was used earlier to reduce the influence of the magnetic field established by the residual magnetic moment of the piston.[4]

RESULTS OF MEASUREMENTS

We investigated samples of pure thallium having the residual resistance $R_{4.2°K}/R_{300°K} = 1 \times 10^{-4}$, and samples of Tl-Hg alloys having $R_{4.2°K}/R_{300°K} = 1.8 \times 10^{-2}$ (≈ 0.45 at.% Hg) and 3.6×10^{-2} (≈ 0.9 at.% Hg). The superconducting transition temperature was determined from the middle of the curve representing the temperature dependence of the

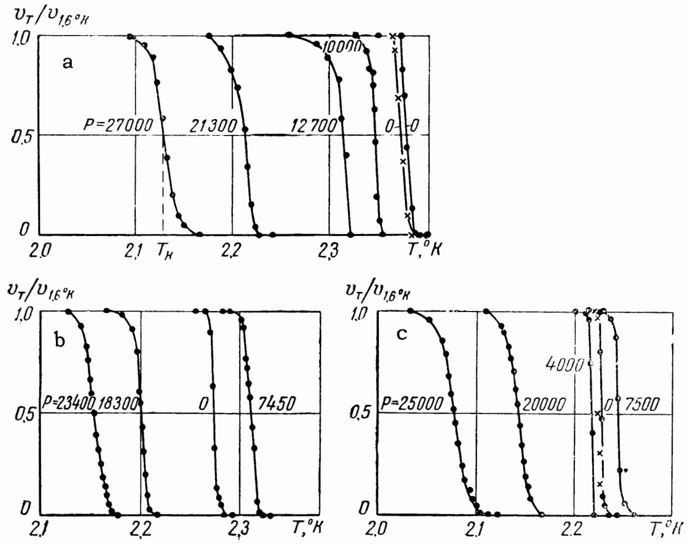

FIG. 1. Superconducting transition curves: a) Tl, b) Tl–Hg with $R_{4.2°K}/R_{300°K} = 1.7 \times 10^{-2}$; c) Tl–Hg with $R_{4.2°K}/R_{300°K} = 3.5 \times 10^{-2}$ at various pressures (atm); × – data at P = 0, obtained after repeated compression cycles.

relative change in a signal $v_T/v_{1.6°K}$ at the output of the electronic apparatus (Fig. 1a). Some superconducting transition curves of the investigated samples are shown in Fig. 1. The nature of these curves and the good reversibility of the results when the pressure was released indicated that the single-phase nature of the alloys was retained over the whole range of pressures.

Figure 2 shows the pressure dependence of the superconducting transition temperature T_c of the investigated samples. The change in T_c in the range of pressures up to 2000 atm, obtained for the same samples in the earlier investigation,[1] is in good agreement with the curves given here. The magnitude and position of a maximum on the $T_c(P)$ curve of thallium (curve II in Fig. 2) are in good agreement with the measurements carried out by Jennings and Swenson[5] in the pressure range up to 6000 atm and with the data of Bowen and Jones,[6] obtained at pressures up to 10 000 atm.

At pressures greater than 10 000 atm, a further reduction in T_c is observed but $\partial T_c/\partial P$ increases as the pressure is increased. In the pressure range from 20 000 to 28 000 atm, $\partial T_c/\partial P = -1.4 \times 10^{-4}$ deg/atm for thallium.

The observed increase in the derivative $\partial T_c/\partial P$ for the Tl–Hg alloy with $R_{4.2°K}/R_{300°K} = 1.8 \times 10^{-2}$[1] leads, as shown in Fig. 2, to an increase in the magnitude of the maximum on the $T_c(P)$ curve and to a shift (compared with pure thallium) into the region of higher pressures (curve II in Fig. 2). The maximum increase in T_c of this alloy amounts to 0.05°K at a pressure of about 5000 atm. At higher pressures, the nature of the change in T_c is analogous to the change in T_c of pure thallium.

An unexpected result was obtained in the investigation of the Tl–Hg alloy with $R_{4.2°K}/R_{300°K} = 3.6 \times 10^{-2}$ (curve III). After a small drop in T_c,[1] this temperature remained constant within the experimental error up to pressures of 6000 atm. At pressures above 7000 atm, the $T_c(P)$ dependence was similar to curves I and II in Fig. 2, although the value $\partial T_c/\partial P$ at pressures from 800 to 28 000 atm was somewhat lower than for pure thallium. In the pressure range from 5500 to 7500 atm, the value of T_c rose by 0.025°K.

DISCUSSION OF RESULTS

In the earlier investigation,[1] the anomalous change in T_c of thallium under the simultaneous influence of impurities and pressure was ascribed to a complex dependence of the quantity $\rho = V\partial N/\partial \epsilon$ on energy near ϵ_F. The following assumptions were made in the establishment of the qualitative nature of the behavior of the derivative $\partial \rho/\partial \epsilon$ near ϵ_F:

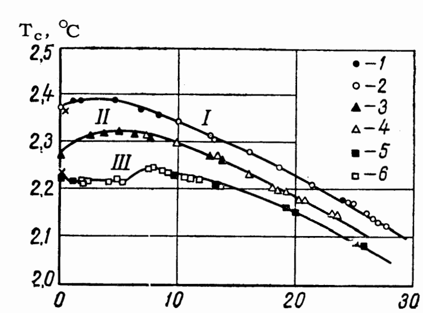

FIG. 2. Pressure dependence of the superconducting transition temperature for Tl (curve I) and for Tl–Hg alloys with values $R_{4.2°K}/R_{300°K} = 1.7 \times 10^{-2}$ (curve II) and 3.6×10^{-2} (curve III). Sample numbers are given in the figure; × – data obtained at the end of the investigation after the release of pressure.

a) thallium has two components in the pressure dependence of T_c: a linear component with a negative value of $\partial T_c/\partial P$, and a nonlinear component with a positive value of $\partial T_c/\partial P$;

b) an impurity affects mainly the nonlinear component.

Pressures up to 2000 atm, used in the earlier work,[1] made it possible to observe changes only in the initial part of the dependence on ΔT_c on P. The results given in Fig. 2 allow us to judge the influence of an impurity on the two components of the pressure effect at the same time. It is evident from curves I-III in Fig. 2 that the very weak influence of the mercury impurity on the slope of the $T_c(P)$ curves at high pressures (where the linear component of the dependence of T_c on P is dominant) and the qualitative change in the nature of the curves at low pressures (where the nonlinear component is dominant) confirm these assumptions.

If we assume that the linear component is the same for pure thallium and for thallium with impurities, we can isolate the nonlinear component, which is the difference between the experimental curve and the straight line with $\partial T_c/\partial P = -1.4 \times 10^{-5}$ deg/atm. Figure 3 shows the pressure dependence of the change in the superconducting transition temperature of thallium and its alloys (curves I—III). Curves a in Fig. 3 represent the linear components ($\partial T_c/\partial P = -1.4 \times 10^{-5}$ deg/atm), while curves b_1, b_2, b_3 represent the nonlinear components of curves I, II, III, respectively, obtained by the method mentioned above. It is evident from Fig. 3 that when the impurity concentration is increased, the nonlinear component increases. For pure thallium and for thallium with ≈ 0.45 at.% mercury impurity, the nonlinear component appears immediately at low pressures, while for thallium samples with ≈ 0.9 at.% mercury impurity, the nonlinear component begins to appear only from a pressure of about 500 atm (curve b_3, Fig. 3). The pressures applied to the Tl—Hg alloys are insufficient to reach complete saturation of the nonlinear component, in contrast to pure thallium, which does exhibit such saturation. In the saturation region, the ratio of ΔT_c to T_c for the nonlinear component is ≈ 0.1.

Thus, the nonlinear component is important in the pressure effect in thallium at pressures of $\lesssim 30\,000$ atm. The dependence $\partial T_c/\partial P$ (or $\partial \rho/\partial \epsilon$) for the nonlinear component of the pressure effect in pure thallium and its alloys is represented by dashed curves in Fig. 3.

Curve b_3 in Fig. 3 confirms the qualitative nature of the behavior of the derivative $\partial \rho/\partial \epsilon$ near ϵ_F proposed in the earlier investigation.[1] Since

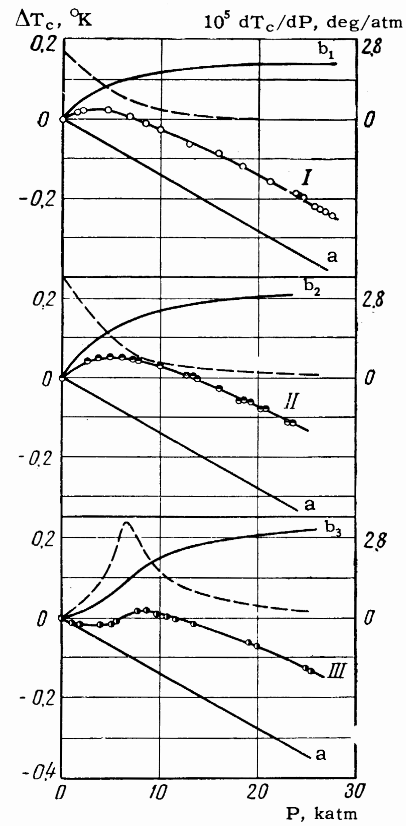

FIG. 3. Pressure dependence of the change in the superconducting transition temperature of thallium and its alloys: I) pure Tl; II) Tl–Hg ($\approx$ 0.45 at.% Hg); III) Tl–Hg ($\approx$ 0.9 at.% Hg). Curves: a — linear components; b_1, b_2, b_3 — nonlinear components; dashed curves represent $\partial T/\partial P$ for the nonlinear components.

$\rho = V\partial N/\partial \epsilon$, this curve obviously represents the characteristic features of the dependence of $\partial N/\partial \epsilon$ on P. According to I. M. Lifshitz,[7] such behavior of the density of states at the Fermi surface boundary may possibly represent an electron transition, i.e., a change in the topology of the Fermi surface of thallium. It is interesting that in thallium containing ≈ 0.9 at.% of mercury this feature is observed at a pressure of ≈ 7000 atm. As the impurity concentration decreases, the maximum shifts toward even lower pressures, and for pure thallium it would occur at negative pressures of the order of a few thousand atmospheres. It is possible that a simultaneous investigation of the influence of impurities and pressure on other superconductors may show similar effects.

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