

Increase of the Anisotropy of the Energy Gap in Superconducting Thallium under Pressure*

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A study has been made of the dependence of the superconducting transition temperature of thallium on the density of lattice defects due to plastic deformation, as a function of hydrostatic pressures up to 4 kbar. The change in critical temperature with resistivity ratio is found to be pressure-dependent. It can be accounted for by a theory of gap anisotropy given by Markowitz and Kadanoff and yields a strongly pressure-dependent anisotropy parameter $\lambda(a^2)$ which varies from 0.0008 at zero pressure to 0.007 at $p=4$ kbar. Only a little change in the "valence" effect with pressure is observed. The well-known anomalous enhancement of the transition temperature of thallium at pressures up to 2 kbar can be explained quantitatively by this increase of the gap anisotropy under pressure.

INTRODUCTION

IN this paper we will try to explain an irregularity of an effect which itself has not yet been explained satisfactorily. This situation occurs in the pressure dependence of the superconducting transition temperature T_c of thallium. In contradiction to the behavior of the majority of superconductors, in which the transition temperatures decrease nearly linearly with pressure¹—an effect which itself is not understood at present²—the transition temperature of thallium increases by about 0.01°K at lower pressures up to 2 kbar, passes through a maximum, and then decreases.³ It is this enhancement which we will try to explain.

In the last year several papers have presented new data on this subject.⁴⁻⁷ By studying the influence of dilute alloying of bismuth, antimony, and particularly mercury on the pressure dependence of T_c of thallium, these authors concluded that the $T_c(p)$ behavior of thallium can be expressed as the sum of a regular, linearly decreasing term and a nonlinear term for which changes in the topology of the Fermi surface are responsible. In an earlier paper⁸ we suggested that the

observed disappearance of the enhancement of T_c upon introduction of lattice defects supported the assumption that this effect is due to smoothing out of a pressure-dependent anisotropy of the energy gap as the electronic mean free path is reduced. In the present paper we offer a detailed investigation. The data are now precise and reproducible enough to be susceptible to a treatment in terms of the special theory of Markowitz and Kadanoff,⁹ and in fact confirm our earlier conclusion.

EXPERIMENTAL TECHNIQUES AND DATA ANALYSIS

We have studied the effects of lattice imperfections, as measured by the resistivity ratio, on the pressure-

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¹ See review articles: M. Levy and T. L. Olsen, in *Physics of High Pressures*, edited by A. van Itterbeek (North-Holland Publishing Company, Amsterdam, 1965); N. B. Brandt and N. I. Ginzburg, *Usp. Fiz. Nauk* **85**, 485 (1965) [English transl.: *Soviet Phys.—Usp.* **8**, 202 (1965)].

² James W. Garland, Jr., *Phys. Rev. Letters* **11**, 114 (1963).

³ L. D. Jennings and C. A. Swenson, *Phys. Rev.* **112**, 31 (1958).

⁴ B. G. Lazarev, L. S. Lazareva, V. I. Makarov, and T. A. Ignat'eva, *Zh. Eksperim. i Teor. Fiz.* **48**, 1065 (1965) [English transl.: *Soviet Phys.—JETP* **21**, 711 (1965)].

⁵ V. I. Makarov and V. G. Bar'yakhtar, *Zh. Eksperim. i Teor. Fiz.* **48**, 1717 (1965) [English transl.: *Soviet Phys.—JETP* **21**, 1151 (1965)].

⁶ N. B. Brandt, N. I. Ginzburg, T. A. Ignat'eva, B. G. Lazarev, and V. I. Makarov, *Zh. Eksperim. i Teor. Fiz.* **49**, 85 (1965) [English transl.: *Soviet Phys.—JETP* **22**, 61 (1966)].

⁷ B. G. Lazarev, L. S. Lazareva, T. A. Ignat'eva, and V. I. Makarov, *Dokl. Akad. Nauk SSSR* **165**, 74 (1965) [English transl.: *Soviet Phys.—Doklady* **10**, 620 (1966)].

⁸ W. Gey, *Solid State Commun.* **4**, 403 (1966).

⁹ D. Markowitz and L. P. Kadanoff, *Phys. Rev.* **131**, 563 (1963)

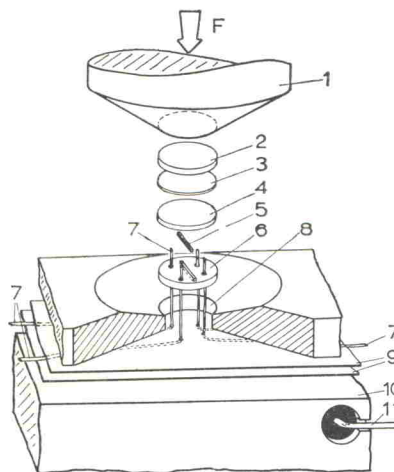


FIG. 1. Exploded view of the pressure cell showing mounting of the sample. 1. Carboloy truncated-cone piston. 2. Hardened tool-steel piston, 0.5 mm thick, 3.0-mm o.d. 3. Nickel gasket, 0.13 mm thick. 4. Steatite disk 0.20 mm thick, 3.0-mm o.d. 5. Specimen, 2.5×0.04×0.04 mm. 6. Steatite disk, 0.25 mm thick with groove for specimen and four holes for platinum ribbons. 7. Platinum ribbons, cross section 0.1×0.02 mm: The ends that stick out though part 6 are just bent down over the sample.. 8. Pressure cylinder, height 0.75 mm, o.d. 3.0 mm. 9. Cigarette-paper insulating sheets. 10. Countersupport. 11. Thermoresistor.

induced shift of the superconducting transition temperature of thallium. A pressure device which is similar to that described earlier¹⁰ was used for generation of suitable hydrostatic pressure up to 4 kbar. The polycrystalline sample¹¹ is embedded in a groove in a soft steatite disk and covered by another steatite disk, both of which provide the pressure medium (Fig. 1) and are surrounded by a short pressure cylinder. This type of mounting of the sample is essential to obtain hydrostatic pressure. That the strain is fairly hydrostatic in the low-pressure region can be checked in various ways: If the pressure were partly uniaxial, then an analogous experiment with well-known superconductors would yield smaller values for dT_c/dp than are known from the literature.³ Indeed, dT_c/dp is found to be reduced 4–6% when tin and indium samples with a thickness-to-width ratio of 10 are simply squeezed between two steatite disks. However, a sample with nearly square cross section, placed in an appropriate groove in the lower disk, yields good agreement of the measured data with those of Jennings and Swenson.¹² A second proof

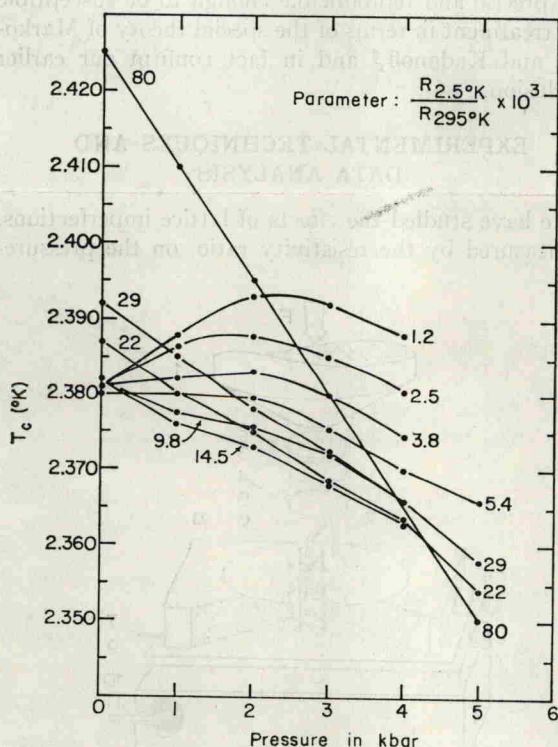


FIG. 2. Pressure dependence of the superconducting transition temperature of thallium with various resistivity ratios ($R_{2.5^\circ\text{K}}/R_{295^\circ\text{K}} \times 10^3$) as a parameter, showing the disappearance of the pressure-induced maximum in T_c upon increasing resistivity ratio.

¹⁰ W. Buckel and W. Gey, *Z. Physik* **176**, 336 (1963). Brief descriptions of the device in English are given in the review articles of Ref. 1.

¹¹ Asarco thallium of 99.999+% purity.

¹² Although the agreement in the low-pressure region is excellent, our described calibration shows slight deviations from that of Jennings and Swenson near 10 kbar; our T_c - p dependence for both Sn and In is more nearly linear.

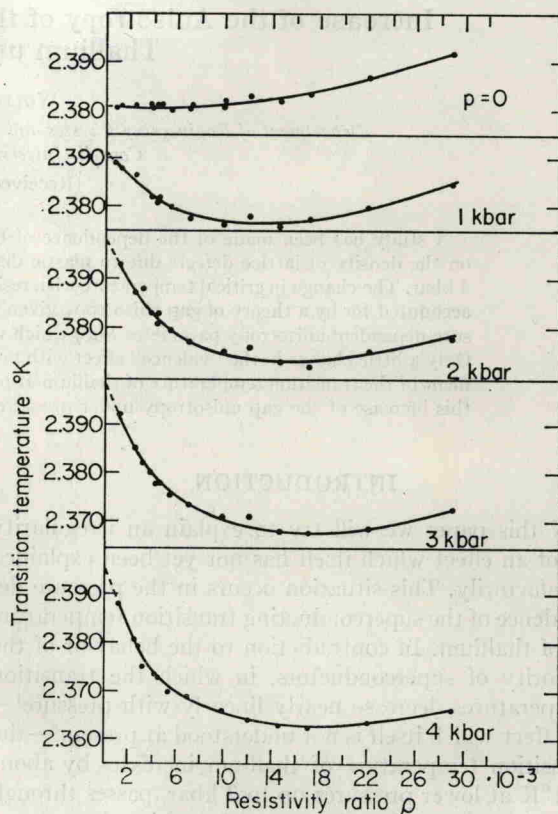


FIG. 3. Data of Fig. 2 replotted. Transition temperature of thallium as a function of resistivity ratio with pressure as a parameter, showing the drop in T_c characteristic for mean-free-path effects on gap anisotropy. Dashed lines: extrapolation to $\rho=0$.

that the pressure so obtained is fairly hydrostatic is seen in the agreement of our data on the undeformed pure Tl sample itself with those of Jennings and Swenson, who undoubtedly had highly hydrostatic conditions.

Lattice defects have been generated by repeated application of much higher pressures (up to 32 kbar) in the same apparatus at 2.5°K and subsequent removal of pressure at the same temperature. Pure hydrostatic pressure applied to a single crystal would yield no lattice imperfections. However, our samples are polycrystalline. Therefore, upon compression, shear at grain boundaries may occur in the elastically anisotropic hexagonal material—presumably in large part by the migration of dislocations from the boundaries into the bulk. Some support for this model is given by the observation that a sample which consisted of about 20 crystallites (sample 1) was much easier to load with imperfections than a sample with only 4–5 crystallites (sample 2). This grain growth was obtained by annealing the sample for 24 h just below the transformation temperature from the hcp to a bcc structure (at 234°C). As a measure of the degree of internal deformation, in accordance with common practice we use the residual resistivity ratio, which, however, we define, following