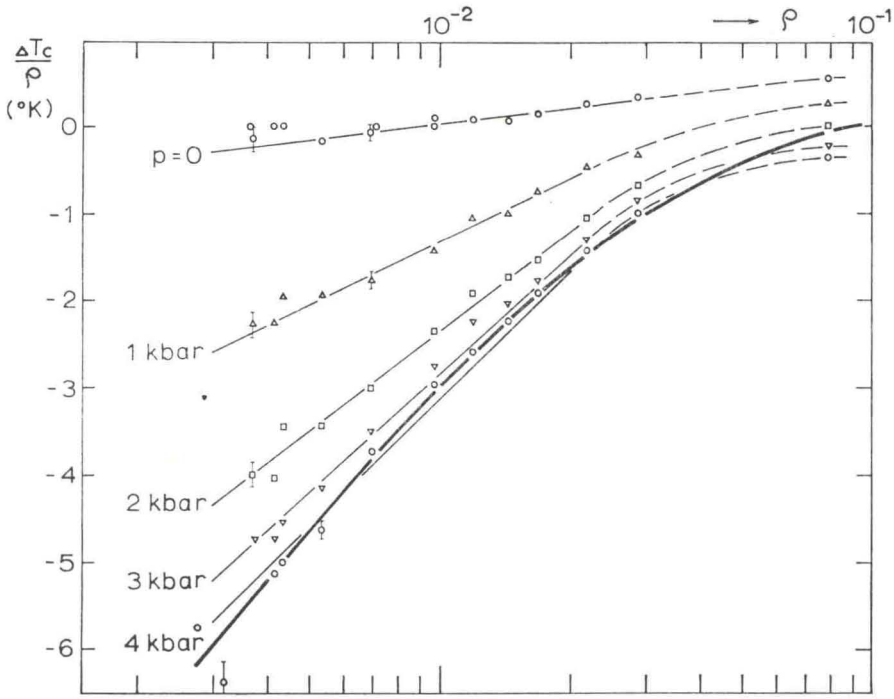

FIG. 4. $\Delta T_c/\rho$ versus ρ plot for various pressures up to 4 kbar. The slope of the linear parts of the curves are measures of the anisotropy parameter $\langle a^2 \rangle$. The data points at $\rho = 80 \times 10^{-3}$ were obtained by forcing the sample through a high-pressure phase transformation. Bars at several points indicate an uncertainty of determination of T_c of ± 0.5 mdeg. The heavy solid line represents the exact function $I_c'(\rho)$ of Markowitz and Kadanoff's theory for $p = 4$ kbar.

Markowitz and Kadanoff, as $\rho = R_{2.5°K}/R_{295°K}$, the reciprocal of the usual quantity.

Measurements of the changes of ρ produced by excursions of applied pressure to various values showed that detectable plastic deformation began to appear only above pressures of 4 kbar. Thus it was possible to use the same apparatus to produce plastic deformation by applying very high pressures and to obtain virtually hydrostatic stress by confining pressure to a low-pressure regime below 4 kbar.

For measurement of the resistance of the sample, it is connected to four platinum ribbons (cross section 0.1 mm$\times$0.02 mm) which serve as current and potential leads (see Fig. 1). That even during the application of high pressure, no appreciable geometrical deformation of the sample occurs was confirmed by the observation that the room-temperature value of the resistance of the sample changed less than 0.2% during repeated (10–15 times) application of pressure up to 32 kbar. The transition to superconductivity was observed by continuously recording the resistance of the sample during temperature changes. For the unstrained sample just above the critical temperature, measuring currents of 1 mA yielded voltages of the order of 0.2 μV. It was shown that currents smaller than 2 mA did not shift or broaden the transition noticeably. The width of the transition, taken between 10% and 90% of normal resistivity, varied between 8×10^{-3} and 12×10^{-3} °K for all pressures and degrees of deformation. These small widths were only obtained after carefully de-Gaussing the ferromagnetic Carboloy pressure piston. The temperature at which half of the normal resistance occurs was taken as the transition temperature T_c. Without changing the pressure or the defect concentration, the reproducibility of the measured T_c was better than 0.5×10^{-3} °K.

In Fig. 2 we show the observed pressure dependence of T_c with the resistivity ratio ρ as parameter. As already mentioned, the curve for the unstrained sample with $\rho = 1.2 \times 10^{-3}$ agrees very well with Jennings and Swenson's data, thus indicating that our pressure is hydrostatic. Upon gradually raising the number of imperfections by cold-working, the enhancement in T_c disappears and the pressure dependence of transition temperature becomes linear with a negative slope $dT_c/dp = -1.50 \times 10^{-5}$ °K/bar when a comparatively high resistivity ratio $\rho = 80 \times 10^{-3}$ is reached. Actually this highest ρ value was not obtained in the described manner but by forcing the sample through a phase transformation at 37 kbar and subsequently removing the pressure at 2°K, which results in the reappearance of the low-pressure phase with an obviously much more heavily distorted lattice.[8]

In Fig. 3, the data are replotted with the pressure as parameter. The characteristic depression of T_c and the curvature of the T_c–p plot suggest that an anisotropy of the energy gap is smoothed out as the electronic mean free path is reduced by imperfections. The theoretical foundation of this concept has been given by Markowitz and Kadanoff[9] and successfully applied to various experimental results. In order to evaluate the governing parameters, we follow the standard treatment and show log ρ vs $\Delta T_c/\rho$ in Fig. 4, where the data plot nearly linearly for $\rho < 0.03$ and the slopes of the straight

lines are a direct measure of the anisotropy parameter $\langle a^2\rangle$ of Markowitz and Kadanoff. We immediately notice that $\langle a^2\rangle$ is pressure-dependent, rising monotonically from a small value at zero pressure to a value larger by a factor of 8 at 4 kbar. Data for a different sample (consisting of a smaller number of crystallites) show the same increase of $\langle a^2\rangle$ under pressure. Numerical values for the anisotropy parameter can be obtained by use of Eq. (50) of Ref. 9. This requires the knowledge of a characteristic number in the theory which is proportional to ρ:

$$\chi=\lambda\hbar[\bar{v}_f/(bkT_c)]\rho.$$

$\bar{v}_F$ is the average value of the Fermi velocity, $b=\rho l$ is the constant which relates the resistivity ratio to the electronic mean free path l at the measuring temperature, and λ is a constant which depends on scattering anisotropy and is unity for isotropic impurity scattering. Since in our case the scattering centers are mainly dislocations, λ may differ from unity. We account for this by keeping λ explicitly in the anisotropy parameter as $\lambda\langle a^2\rangle$. The values of $\bar{v}_F$ and b are properties of the host which are unfortunately not known experimentally for thallium. We therefore relate the unknown quantities to those which can be estimated. By setting $b=l_{2.5°K}\times(\sigma_{295°K}/\sigma_{2.5°K})$ and using the expression for the conductivity

$$\sigma=(Ne^2/m^*)\tau,$$

we obtain

$$\frac{\chi}{\rho\lambda}=\frac{\hbar Ne^2}{\sigma_{295°K}m^*kT_c}$$

where $\sigma_{295°K}=5.52\times10^4\,\Omega^{-1}\,\mathrm{cm}^{-1}$ is the conductivity at 295°K.[13] The unknowns are here the effective number of electrons per unit volume, N, and the effective electron mass m^*. Soven[14] suggests that the Fermi surface of thallium is fairly close to that obtained from a free-electron model for a trivalent hexagonal close-packed metal. By way of trial, we therefore set $m^*=m_0$, and choose for the effective number of electrons per atom $n=3$; we obtain

$$\chi/\rho\lambda=1700.$$

Compared with the experimental data on tin and indium,[9] this number seems high. A check of it would be desirable. Thus, before presenting numerical values for the anisotropy parameter under pressure—the quantity we are most interested in—, we separate the accompanying effects that are independent of anisotropy. From analogous experiments done with doped superconductors we know that these effects, which are sometimes lumped into the term "valence effect," are linear in impurity concentration, at least for lower concentrations. It is this feature, of course, which permits the separation of anisotropy and "valence effect."[15] We shall see later that there is evidence that the linearity of the "valence effect" holds also for our lattice imperfections up to a resistivity ratio $\rho\sim30\times10^{-3}$. We are, therefore, justified in separating out the linear term, which we call $(\partial T_c/\partial\rho)_p$ as a function of pressure. It turns out that $(\partial T_c/\partial\rho)_p$ is rather sensitive to the choice of the quantity $\chi/\rho\lambda$, and we will use this to check the validity of our calculated number. In Fig. 5 the pressure dependence of $(\partial T_c/\partial\rho)_p$ is plotted for several values of $\chi/\rho\lambda$ near our calculated value 1700. Physically, we would expect $(\partial T_c/\partial\rho)_p$ not to change markedly with pressure: $(\partial T_c/\partial\rho)_p$ probably depends mainly on such parameters as ω_D, $N(0)$, and V, all of which determine the transition temperature in the BCS theory. Since pressures up to 4 kbar change T_c only about 3% at most, we can consider the pressure dependence of any combination of the above parameters to be negligible and are led to the assumption that $(\partial T_c/\partial\rho)_p$ is almost pressure-independent. Figure 5

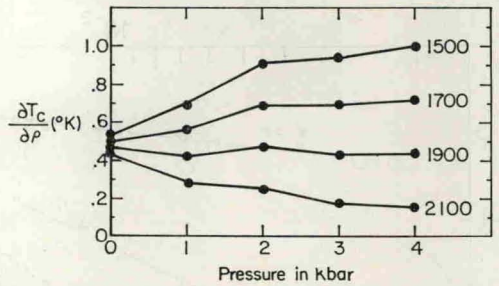

FIG. 5. Pressure dependence of the "valence effect" $\partial T_c/\partial\rho$ as obtained from the experimental data for different values of $\chi/\rho\lambda$.

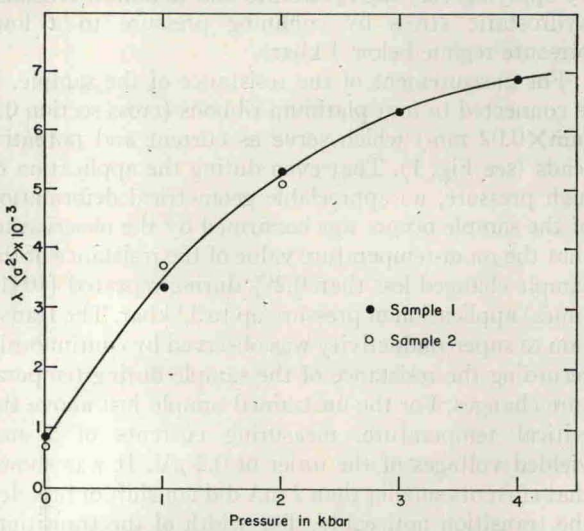

FIG. 6. Pressure dependence of the anisotropy parameter $\lambda\langle a^2\rangle$ in thallium as evaluated from the experimental data. The nonlinear rise of this quantity provides an explanation of the anomalous pressure-induced increase of T_c.

[13] *Landolt-Börnstein Zahlenwerte und Funktionen* (Springer-Verlag, Berlin, 1959), 6th ed., Chap. II/6, p. 1.

[14] P. Soven, Phys. Rev. **137**, A1706 (1965); **137**, A1717 (1965).

[15] Although actually no valence differences are involved in our case, we follow Markowitz and Kadanoff in adopting the term "valence effect," meaning all effects linear in ρ.