

gap of the alloys, however, uncertainty concerning the band structure of the alloys requires that this interpretation be viewed with caution.

The low-temperature Hall and resistivity measurements are indicative of alloy scattering. If these samples were available as high-purity single crystals, a conclusive argument could certainly be made. With such samples one could apply the type of analysis which has been employed here at 300°K, to a range of temperatures. At lower temperatures one would expect that the dips in the curves of A and x versus composition would be stronger. With such samples it might be possible to establish the temperature dependence of the alloy scattering and to determine the relative magnitudes of alloy and thermal scattering. With the samples presently available, it may be possible to make meas-

urements at somewhat higher temperatures, although not entering the intrinsic range, and to observe a gradual diminution in the effects of alloy scattering. The curves of A and x would not dip as strongly.

5. ACKNOWLEDGMENTS

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Effects of Stress on Superconducting Sn, In, Tl, and Al†

NILS L. MUENCH*

The Rice Institute, Houston, Texas

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Hydrostatic pressures of 0 to 100 atmos obtained with helium gas pressure, and of 1.9×10^3 atmos obtained by an ice expansion bomb technique are used to measure the pressure displacement of critical temperature T_c . The coefficient $(\partial T_c / \partial p)$ for Sn, In, Tl, and Al is -4.7 ± 0.2 , -4.0 ± 0.2 , $+0.6 \pm 0.3$, and -2.0 ± 0.2 in units of 10^{-5} °K/atmos, respectively. The temperature dependence of $R = (\partial H_c / \partial p)_T / (\partial H_c / \partial p)_{T_c}$ above 1°K is described by $R = 0.61 + 0.029T^2$ for Sn, and $R = 0.77 + 0.020T^2$ for In. This result is discussed in connection with the similarity principle, $H_0/T_c = \text{constant}$. From an analysis combining stress and isotope effects, it is seen that T_c , or H_c , is more sensitive to volume changes, holding zero-point lattice vibration amplitude fixed, than to zero-point amplitude changes, holding V fixed: $(\partial H_c / \partial \ln V)_T^2 = 5.5 \times (\partial H_c / \partial \ln q^2)_V$ for Sn. Zero-pressure critical field data are also presented for the subject metals.

I. INTRODUCTION

THE dependence of the superconducting critical temperature T_c on mechanical stress^{1,2} has received renewed interest since the discovery of the isotope effect and the introduction of the theories by Fröhlich³ and Bardeen.⁴ The critical temperature T_c decreases under pressure for most superconductors studied so far, but increases under pressure for Tl, NiBi₃, and RhBi₄.⁵ As Marcus⁶ first noted, the stress effect is not adequately explained as the result of a change in amplitude

of the zero-point lattice vibrations. The isotope effect ($M^x T_c = \text{constant}$, where M is the isotopic mass) is usually understood as the result of a change in lattice vibration amplitude. The exponent x is approximately $\frac{1}{2}$, but varies from metal to metal; this has been explained by deLaunay⁷ from a consideration of the vibration spectrum of a real lattice. Thus understanding of the isotope effect seems as satisfactory as can be expected in the absence of a good quantum theory of superconductivity. The understanding of stress effects is less satisfactory, and there is clearly a need for more quantitative data. We have studied the displacement of T_c in Sn, In, Tl, and Al using pressures of 0 to 100 atmos obtained with helium gas pressure, and a pressure of 1.9×10^3 atmos obtained by an ice expansion bomb technique.⁸ For Sn and In, the value of $(\partial H_c / \partial p)_T$ has been measured as a function of temperature, and it is found to remain finite as T tends to 0°K. The temperature dependence of $(\partial H_c / \partial p)_T$ for tin is shown

† This research was supported in part by the National Science Foundation.

* Magnolia Petroleum Fellow in Physics; now with Humble Oil Research Center, Houston, Texas.

¹ G. J. Sizoo and H. Kamerlingh Onnes, Leiden Comm. No. 180b (1925).

² C. F. Squire, *Progress in Low Temperature Physics*, edited by C. J. Gorter (Interscience Publishers, Inc., New York, 1955), Vol. I, p. 151.

³ H. Fröhlich, *Phys. Rev.* **79**, 845 (1950).

⁴ J. Bardeen, *Phys. Rev.* **80**, 567 (1950).

⁵ Kan, Lazarev, and Sudovstov, *J. Exptl. Theoret. Phys. (U.S.S.R.)* **18**, 825 (1948); *Doklady Akad. Nauk. S.S.S.R.* **69**, 173 (1949).

⁶ P. M. Marcus, *Phys. Rev.* **91**, 216 (1953).

⁷ J. deLaunay, *Phys. Rev.* **93**, 661 (1954).

⁸ B. G. Lazarev and L. C. Kan, *J. Exptl. Theoret. Phys. (U.S.S.R.)* **14**, 439 (1944).

to be in agreement with the similarity principle $H_0/T_c = \text{constant}$, but for indium a marked departure from this principle is observed. Finally, an analysis combining stress and isotope data is presented that indicates that T_c , or H_c , is several times more sensitive to fractional changes in volume, holding lattice vibration amplitude fixed, than to fractional changes in vibration amplitude, holding volume fixed.

II. APPARATUS AND TECHNIQUE

The apparatus shown in Fig. 1 is the usual coaxial liquid helium-liquid nitrogen Dewar arrangement. A pressure cell containing a sample 12 cm long and 1 cm in diameter is immersed in the liquid helium. The superconducting transition is observed by means of a drop coil placed in the nitrogen bath and connected to a galvanometer. To obtain the data presented, the pressure and temperature of the specimen were held constant while a vertical magnetic field was increased in small increments. The drop coil was lowered after each change in H , and the resulting galvanometer deflection plotted *vs* magnetic field as in Fig. 2. The transitions for zero pressure and low pressures were about 1% of H_c in width as a consequence of the demagnetizing factor. The transitions at 1.9×10^3 atmos were also about 1 percent of H_c plus only a small constant broadening

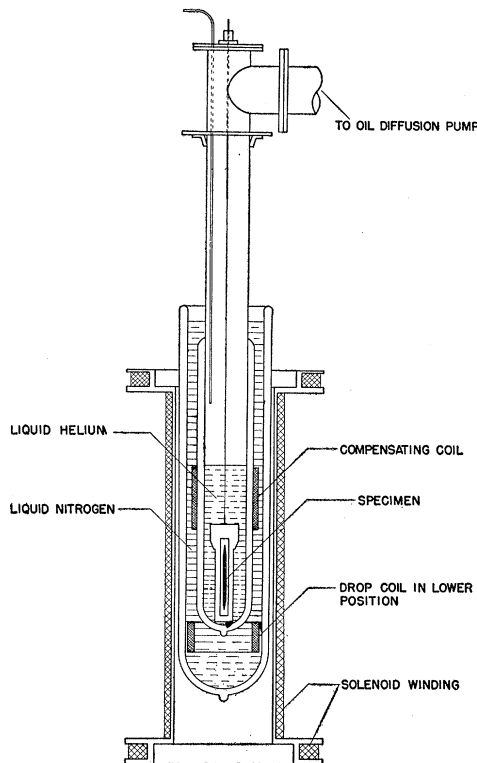


FIG. 1. Experimental apparatus. A radiation shield not shown was installed in the helium Dewar for temperatures in the region of 1°K.

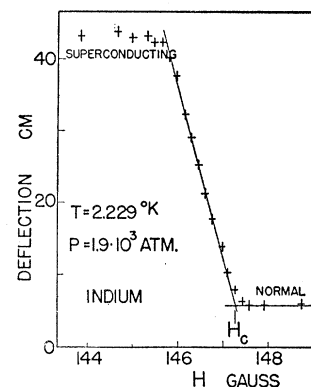


FIG. 2. Typical transition from the superconducting to the normal state at constant temperature and pressure. H_c is determined by extrapolation as shown.

which indicated that the ice pressure was uniform to about 4%.

The solenoid used to produce the vertical field H was calibrated by using a ballistic galvanometer and coil in conjunction with a long thin solenoid. The long solenoid was wound in a single layer in machined grooves so that the magnetic field could be calculated accurately from geometry. Solenoid current was supplied by a generator and electronic regulation system giving a 30-minute stability of 2 parts in 10^4 . Current was measured with a potentiometer and standard resistance. The earth's field was compensated by Helmholtz coils.

The temperatures above 2°K were controlled through automatic regulation of the vapor pressure. At 3.6°K, the regulation was $\pm 0.00015^\circ\text{K}$ over 30 minute periods. To obtain temperatures between 2°K and 1.3°K the pumping orifice was set and the system was allowed to come to equilibrium with the pumps. To obtain temperatures between 1.3°K and 0.9°K the power input to the MB-200 oil diffusion pump was fixed and the system was allowed to come to equilibrium. In this last temperature range, a spiral radiation shield installed in the helium Dewar reduced the helium boil-off rate by a factor of 3. Vapor pressures were measured with a mercury manometer or McLeod gauge, depending upon pressure. The chief difficulty in temperature control occurs in the He I region where large thermal gradients usually exist in the He bath. Since these gradients can easily introduce an uncertainty of 0.01°K, whereas an accuracy of 0.0002°K is required, considerable attention was devoted to this matter. Originally carbon resistance thermometers with a sensitivity of 0.0001°K were used, but for reasons not understood, the stability of the resistors or measuring circuit over periods of 15 hours was only 0.001°K. Therefore, to obtain most of the data, 10^{-2} watt was supplied to a 500-ohm wire wound resistor placed in the bottom of the bath. This seems to be sufficient power input to insure that the liquid helium is boiling in the vicinity of the specimen. The specimen temperature then was obtained by adding the hydrostatic head pressure of the helium to the measured vapor pressure before referring to the 1949 vapor

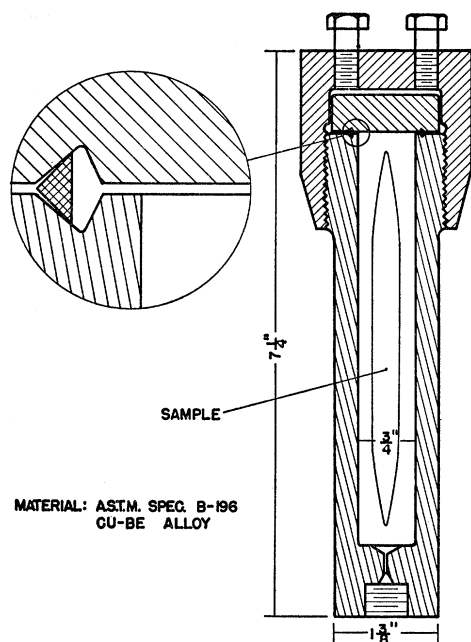


FIG. 3. Nonmagnetic pressure cell for 2×10^3 atmos. This cell is used with the ice technique (1.9×10^3 atmos) and also with helium-transmitted pressures (100 atmos). The seal is made with a triangular cross section metal ring.

pressure tables. To determine the helium level, a number of 160-ohm carbon resistors were strung vertically in the Dewar; a ohmmeter provided sufficient accuracy to determine whether a resistor was immersed in the liquid He.

Two methods were used for applying hydrostatic pressure to the specimen. Pressures of less than 100 atmos were obtained by applying helium gas pressure to a cell containing the specimen. This pressure is limited by the solidification pressure⁹ of helium. A pressure of 1.9×10^3 atmos was obtained by freezing water in a constant volume cell (Fig. 3) containing the specimen. From the density of ice I and water, and the thermal expansion and compressibility of the ice, specimen, and cell, one may estimate that a pressure of 3000 atmos would thus be generated. However, a polymorphic phase transition occurs in ice at 2200 atmos.¹⁰ Since this transition is found to proceed rapidly at, say, 240°K, the maximum pressure obtained is fixed by the ice I-ice III equilibrium. If the cell is cooled from 240°K to 78°K in a few hours, the ice I-III and the ice III-II transitions are frozen-in. Then the pressure at 78°K or 4°K is just that of the I-III equilibrium reduced by differential thermal contraction of the ice, specimen, and cell. Lazarev and Kan⁸ first used this technique and have studied the matter in detail. We have not repeated their studies of the pressure produced by the ice. Instead we have con-

⁹ W. H. Keesom, *Helium* (Elsevier Publishing Company, Amsterdam, 1942).

¹⁰ P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **47**, 441 (1912).

cluded from the width of superconducting transitions in small fields that a reproducible pressure homogeneous to 4% is obtained. We have used the superconducting transition in tin and indium to determine the pressure produced by the ice bomb. That is, we determine $(\partial T_c / \partial p)$ using helium gas pressure, and then we observe that ΔT_c produced by the ice bomb. Using the fact that $(\partial T_c / \partial p)$ is pressure independent for low pressures,¹¹ we find that the pressure necessary to produce the observed ΔT_c is 1.9×10^3 atmos for both Sn and In, in fair agreement with Lazarev and Kan and with the pressure expected from the reduced ice I-III equilibrium. For our studies on Al and Tl we have assumed that the ice pressure is again 1.9×10^3 atmos. This assumption is reasonable since the ice bomb pressure is determined primarily by the I-III equilibrium, and since this pressure is found to be the same for Sn and In.

The sources and purities of the specimen metals are as follows: Sn, Vulcan Detinning Company, 99.998%; In, Indium Corporation of America, 99.97%; Tl, Johnson-Mathey Company, Ltd., 99.98%; Al, supplied courtesy of the Aluminum Corporation of America, 99.99%. The Al was received in the form of a cold worked rod and was machined to ellipsoidal shape and annealed at 650°F for 24 hours. The Sn and Tl were cast in a vacuum in a Pyrex tube and cooled slowly from the bottom. The In was drawn from a molten bath of In maintained at the melting temperature. All samples were 12 cm long by 1 cm in diameter, shaped to be approximately ellipsoidal.

III. EXPERIMENTAL RESULTS

Figure 4 gives typical low-pressure data for Sn at fixed temperature. Similar data are obtained for In. H_c is measured as a function of pressure with temperature fixed. To obtain the data points, the pressure is cycled a number of times at each temperature, and several values of H_c are determined each cycle. No cold work effect¹² was observed. Although the vapor pressure is fixed, the bath level, and thus specimen temperature,

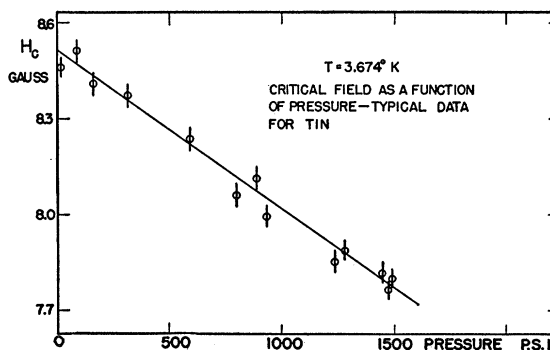


FIG. 4. Typical critical field data for tin at constant temperature.

¹¹ P. F. Chester and G. O. Jones, *Phil. Mag.* **44**, 1281 (1953).

¹² M. Garbor and D. E. Mapother, *Phys. Rev.* **94**, 1065 (1954).

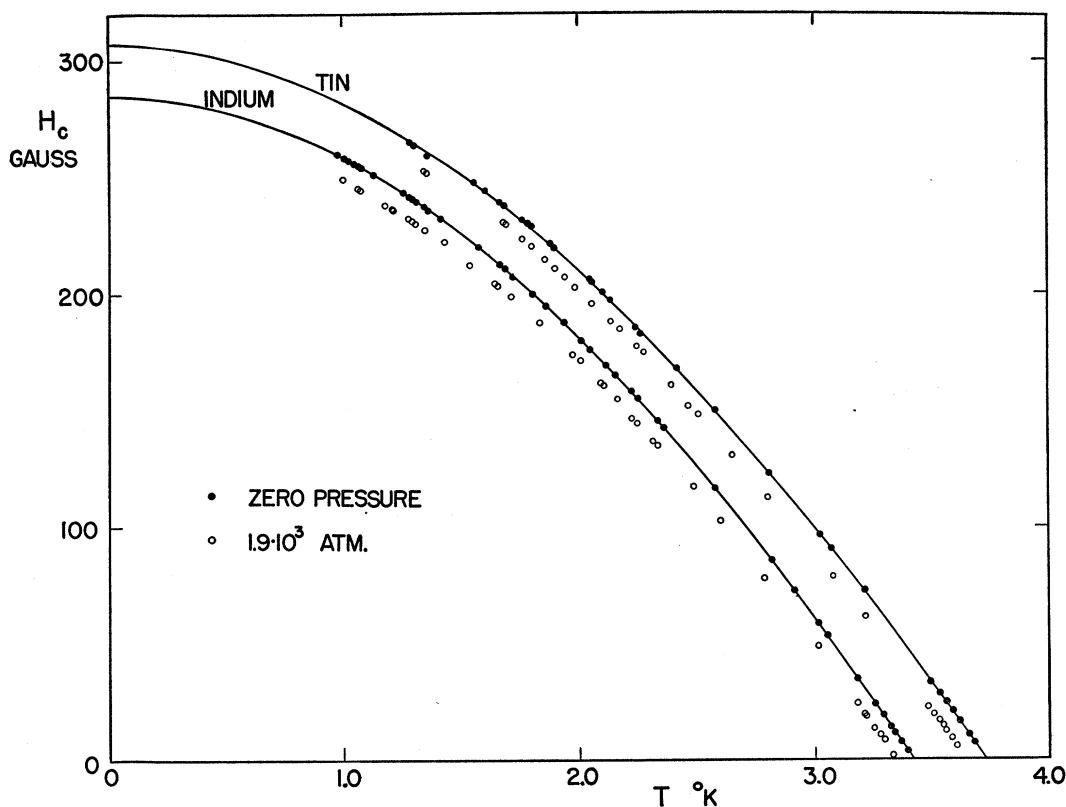


FIG. 5. Critical field data for Sn and In at constant pressure. Zero pressure and 1.9×10^3 atmos are shown.

change with time. Thus a small correction must be applied to the observed values of H_c so that they refer to a common temperature. This is done through knowledge of $(\partial H_c / \partial T)_p$.

The slope of the line through the data of Fig. 4 gives the value of $(\partial H_c / \partial p)_T$ at that temperature. A number of such determinations are made for Sn and for In at temperatures near T_c . The weighted average of these determinations for each metal is given in Table I. $(\partial T_c / \partial p)$ was obtained from $(\partial H_c / \partial p)_T$ through a knowledge of $(\partial H_c / \partial T)_p$. The data for Al and Tl were obtained by determining the critical field curves for both zero pressure and 1.9×10^3 atmos in the vicinity of T_c . The values of T_c were then obtained by extrapolation. The difference in the zero pressure and high pressure T_c was divided by 1.9×10^3 atmos to obtain the values given in Table I. Also included in Table I is a summary of existing determinations of $(\partial T_c / \partial p)$ for these metals.^{1,5,11-13} Measurements of simple tension^{1,14} are not included because Grenier¹⁵ has shown that stress effects in Sn are highly anisotropic, and thus the pressure coefficient cannot be obtained from tension measurements without a knowledge of crystal orientation.

¹³ M. D. Fiske, Phys. Rev. **94**, 495 (1954).

¹⁴ Grenier, Spöndlin, and Squire, Physica **19**, 833 (1953).

¹⁵ C. Grenier, Compt. rend. **238**, 2300 (1954).

The temperature dependence of $(\partial H_c / \partial p)_T$ was determined for Sn and In from the data shown in Fig. 5, which gives the zero pressure and high pressure critical field curves. The temperature dependence is given by specifying the ratio of $\Delta H_c(T)$ to $\Delta H_c(T_c)$, where $\Delta H_c(T)$ is the change in critical field at constant temperature. These data are given in Figs. 6 and 7. The points given were obtained by subtracting each high pressure point from the zero pressure curve adjusted for a best local fit with the zero pressure points. Since Chester and Jones¹¹ have shown that $(\partial H_c / \partial p)_T$ is independent of pressure to 17 500 atmos, we are justified in replacing $\Delta H_c / \Delta p$ at constant temperature with the more concise notation $(\partial H_c / \partial p)_T$. The least-squares fit for the data in Figs. 6 and 7 gives

$$\left(\frac{\partial H_c}{\partial p}\right)_T / \left(\frac{\partial H_c}{\partial p}\right)_{T_c} = 0.61 + 0.029T^2, \quad (\text{Sn})$$

$$\left(\frac{\partial H_c}{\partial p}\right)_T / \left(\frac{\partial H_c}{\partial p}\right)_{T_c} = 0.77 + 0.020T^2. \quad (\text{In})$$

In the effort to determine small pressure displacements in critical field curves, the zero pressure critical field data were determined with some accuracy. These data are given in Table II. The indium critical field curve is determined from 45 data points from 1°K to

TABLE I. $10^6 \times (\partial T_c / \partial p)$ ($^{\circ}\text{K}/\text{atmos}$).

Sn	In	Tl	Al	Pressure (atmos)	Author
-3	-4			100	Sizoo and Onnes ^a
		+0.6		1370	Lazarev and Kan ^b
-5.8	-4.8	+1.4		1750	Lazarev and Kan ^b
		-0.4		13 400	Chester and Jones ^c
-4.3				11 500	Chester and Jones ^c
-4.5				17 500	Chester and Jones ^c
$-4.58^d \pm 0.09$		+1.3 \pm 0.2		100	Fiske ^e
-4.4				100	Garbor and Mapother ^f
-4.7 ± 0.2	-4.0 ± 0.3			100	Present work
		+0.6 \pm 0.3	-2.0 ± 0.2	1900	Present work

^a See reference 1.^b See reference 5.^c See reference 11.^d Unpublished.^e See reference 13.^f See reference 12.

T_c which yield an rms deviation of 0.25 gauss. The tin curve is determined from 38 data points with an rms deviation of 0.9 gauss.

IV. DISCUSSION

We confine our remarks to two aspects of our subject: first, the temperature dependence of $(\partial H_c / \partial p)_T$, and second, the relation between stress and isotope effects. The temperature dependence of $(\partial H_c / \partial p)_T$ is analogous in some respects to the temperature dependence of the isotope shift which has been studied in detail.^{16,17} We first outline the expected form of the temperature dependence of $(\partial H_c / \partial p)_T$. We assume that in the expression,

$$H_c(T) = H_0 [1 + \alpha(T/T_c)^2 + \beta(T/T_c)^3], \quad (1)$$

the ratio H_0/T_c and the coefficients α and β are independent of pressure. This assumption constitutes what is called the "similarity principle"; we will later discuss

its justification. Differentiating Eq. (1) and substituting $(\partial H_0 / \partial p)_T = (H_0/T_c)(\partial T_c / \partial p)_T$ obtained from the similarity principle, we obtain

$$(\partial H_c / \partial p)_T = (\partial H_0 / \partial p)_T [1 - \alpha(T/T_c)^2 - 2\beta(T/T_c)^3]. \quad (2)$$

As is well known, the Third Law of Thermodynamics when applied to the superconducting transition requires that $(\partial H_c / \partial T)_p = 0$ for all pressures at $T = 0^{\circ}\text{K}$. Therefore we have that $(\partial^2 H_c / \partial p \partial T) = (\partial^2 H_c / \partial T \partial p) = 0$ at $T = 0^{\circ}\text{K}$. The expression of Eq. (2) for $(\partial H_c / \partial p)_T$ does satisfy this Third Law requirement. It is convenient to deal with the ratio

$$R = \left(\frac{\partial H_c}{\partial p} \right)_T / \left(\frac{\partial H_c}{\partial p} \right)_{T_c} = \frac{1 - \alpha(T/T_c)^2 - 2\beta(T/T_c)^3}{1 - \alpha - 2\beta}.$$

The solid curves in Figs. 6 and 7 represent this ratio with the values of α and β determined by least squares fit with zero pressure data. We observe from Fig. 6

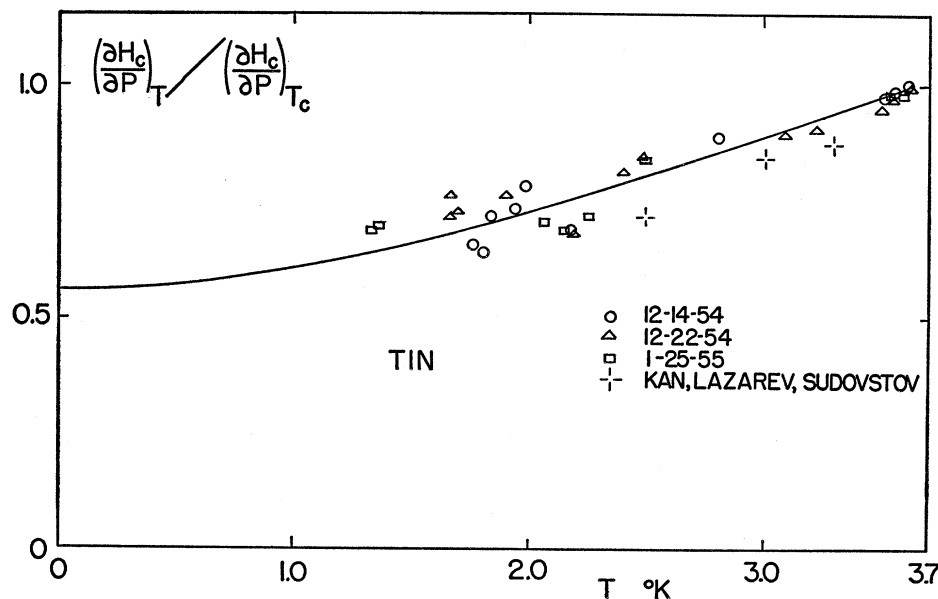


FIG. 6. Temperature dependence of $(\partial H_c / \partial p)_T$ for Sn. The solid line is derived from the similarity principle. The experimental apparatus was disassembled, reassembled, and zero pressure data were taken before and after the dates indicated for pressure data.

¹⁶ Lock, Pippard, and Shoenberg, Proc. Cambridge Phil. Soc. 47, 811 (1951).

¹⁷ E. Maxwell, Phys. Rev. 86, 235 (1952).

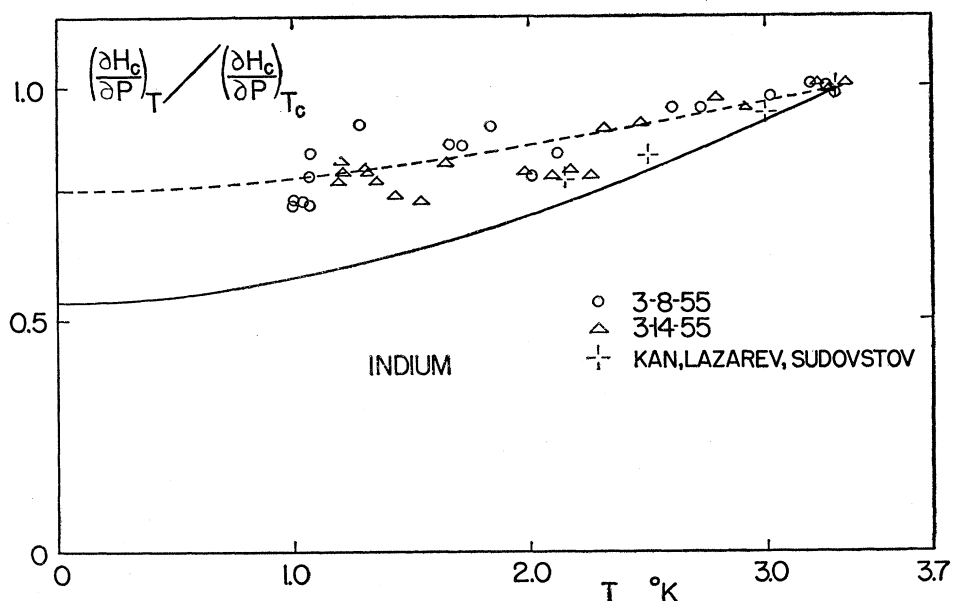


FIG. 7. Temperature dependence of $(\partial H_c/\partial P)_T$ for In. The solid line is derived from the similarity principle. The dashed line is derived by assuming the similarity principle in error by 0.7 percent at 1.9×10^8 atmos.

that for tin the solid curve obtained on the assumption of the similarity principle agrees with the data within experimental error. However, from Fig. 7 we see that for indium all data points lie above the solid curve obtained from the similarity principle. It is clear that the similarity principle does not apply for pressure effects in indium. The dashed curve through the data points in Fig. 7 was obtained on the assumption that α and β are constant, but that H_0/T_c decreases by 0.7% under the ice pressure of 1.9×10^8 atmos. The volume change produced by this pressure is 0.35% for tin and 0.7% for indium.

To review the theoretical basis for the similarity principle ($H_0/T_c = \text{constant}$), we write the Gibbs potential based on the Gorter-Casimir two fluid model.¹⁸ We assume an energy gap Δ per unit volume between normal and superconducting electron energy levels and a fraction $f = n_s(T)/n_s(0^\circ\text{K})$, where $n_s(T)$ is the number of superconducting electrons per unit volume at $T^\circ\text{K}$:

$$G_s = U_0 - (V/V_m)(1-f)^{x/2}\gamma T^2 + \Delta V f + G(T)_{\text{lattice}}.$$

Here γT is the electronic specific heat per mole, V_m is molar volume, and x is chosen to fit experiment. For example, $x = \frac{1}{2}$ for a parabolic curve of $H_c(T)$ vs T . For

stable equilibrium we have $\partial G_s/\partial f = 0$. Performing the differentiation, we obtain $f = 1 - (\Delta V_m/x\gamma T^2)^{1/(x-1)}$. At T_c , f is zero. Also Δ is given by $\frac{1}{2}\mu_0 H_0^2$. We obtain finally:

$$H_0/T_c = (x\gamma/\mu_0 V_m)^{\frac{1}{x}}. \quad (3)$$

This is the similarity principle providing $x\gamma/V_m$ is constant. The exponent x can be expressed as a function of α and β only,¹⁷ and thus its pressure dependence is expected to be small. The electronic specific heat γ can be expressed as the free-electron specific heat by replacing the electron mass with an effective mass m^* . Thus, we have

$$\gamma/V_m = 3.26 \times 10^{-5} (m^*/m) (n^{\frac{1}{3}} V_m^{\frac{2}{3}}/V_m) \text{ cal/deg-mole}^2,$$

where n is the number of valence electrons per atom. To explain the observed dependence of H_0/T_c on volume in the case of indium one must assume that m^* is approximately proportional to V_m^2 .

From another standpoint, we have empirical evidence for the dependence of H_0/T_c or γ/V_m on T_c . The value of H_0/T_c or γ/V_m for each superconductor can be plotted as a function of T_c . One finds that the soft superconductors fall approximately along a straight line (with a branch line below 2°K) with positive slope.

TABLE II. Zero-pressure data.

Metal	T_c ($^\circ\text{K}$)	$(\partial H_c/\partial T)_{T=T_c}$ (gauss/ $^\circ\text{K}$)	$H_c = H_c(T)$ (gauss)
Sn	3.728 ± 0.0015	-147.4 ± 1	$H_c = 307.3 - 26.80T^2 + 1.225T^3$ $= H_0[1 - 1.2117(T/T_c)^2 + 0.2117(T/T_c)^3]$
In	3.412 ± 0.003	-155.8 ± 1	$H_c = 284.5 - 27.68T^2 + 0.9489T^3$ $= H_0[1 - 1.1325(T/T_c)^2 + 0.1325(T/T_c)^3]$
Tl	2.385 ± 0.004	-135.5 ± 2	...
Al	1.174 ± 0.003	-163 ± 3	...

¹⁸ P. L. Bender and C. J. Gorter, *Physics* **18**, 597 (1952).

The reason for this correlation is not understood.¹⁹ However, one might anticipate from the correlation that if T_c for a particular metal is reduced, then H_0/T_c and γ/V_m would decrease. On this basis the expected decrease in H_0/T_c for indium when submitted to a pressure of 1.9×10^3 atmos is 0.6%, in close agreement with the observed decrease of 0.7%. This agreement is perhaps fortuitous, since the same magnitude decrease in H_0/T_c should then be expected for Sn, whereas no change greater than 0.15% is observed for tin.

We now turn to the relation between the stress and isotope effects. By combining the data from these effects, one may estimate the relative importance of changes in lattice spacing and lattice vibration amplitude in altering T_c or H_0 . This is accomplished by assuming $H_c = H_c(T, V, q^2)$, where V is molar volume and q^2 represents the mean square amplitude of zero point lattice vibrations. If we regard isotopic mass M as a continuous thermodynamic variable, we may write

$$\left(\frac{\partial H_c}{\partial p}\right)_T = \left(\frac{\partial H_c}{\partial \ln q^2}\right)_V \left(\frac{\partial \ln q^2}{\partial p}\right)_T + \left(\frac{\partial H_c}{\partial \ln V}\right)_{q^2} \left(\frac{\partial \ln V}{\partial p}\right)_T \quad (4)$$

$$\left(\frac{\partial H_c}{\partial M}\right)_T = \left(\frac{\partial H_c}{\partial \ln q^2}\right)_V \left(\frac{\partial \ln q^2}{\partial M}\right)_T + \left(\frac{\partial H_c}{\partial \ln V}\right)_{q^2} \left(\frac{\partial \ln V}{\partial M}\right)_T \quad (5)$$

The left members are measured experimentally. The coefficients of $(\partial H_c/\partial \ln q^2)_V$ and $(\partial H_c/\partial \ln V)_{q^2}$ can be estimated, with the result that Eqs. (4) and (5) become

$$\left(\frac{\partial H_c}{\partial p}\right)_T = \left(\frac{\partial H_c}{\partial \ln q^2}\right)_V (-\Gamma B) + \left(\frac{\partial H_c}{\partial \ln V}\right)_{q^2} (-B) \quad (4A)$$

¹⁹ J. G. Daunt, *Progress in Low Temperature Physics*, edited by C. J. Gorter (Interscience Publishers, Inc., New York, 1955), Vol. I, p. 202.

$$\left(\frac{\partial H_c}{\partial M}\right)_T = \left(\frac{\partial H_c}{\partial \ln q^2}\right)_V \left(-\frac{1}{2M}\right) + \left(\frac{\partial H_c}{\partial \ln V}\right)_{q^2} \left(-\frac{1}{2M}\right) \left(\frac{9 N k \theta_D \Gamma}{8 V}\right), \quad (5A)$$

where Γ is Grüneisen's constant,²⁰ B compressibility, θ_D the Debye temperature at 0°K, N Avogadro's number, and k the Boltzmann constant. If we insert experimental values for $(\partial H_c/\partial p)_T$, $(\partial H_c/\partial M)_T$, B , Γ , θ_D , and V , we have for tin:

$$(\partial H_c/\partial \ln V)_{q^2} = +5.5(\partial H_c/\partial \ln q^2)_V,$$

and for thallium:

$$(\partial H_c/\partial \ln V)_{q^2} = -3.3(\partial H_c/\partial \ln q^2)_V.$$

That is, fractional changes in V , holding q^2 constant, are much more effective in displacing H_c than are fractional changes in q^2 , holding V constant. Alternately, one may consider $H_c = H_c(T, V, \theta_D)$. In this case similar expressions are obtained, with the result that $(\partial H_c/\partial \ln V)_{\theta_D} = 10(\partial H_c/\partial \ln \theta_D)_V$ for tin.

Since the energy gap Δ between normal and superconducting energy levels on the two-fluid model is given by $\frac{1}{2}\mu_0 H_0^2$, this analysis seems to indicate that the energy gap Δ , and therefore the interaction mechanism responsible for superconductivity, is more sensitive to changes in lattice dimension than to zero-point lattice vibration amplitude.

V. ACKNOWLEDGMENTS

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²⁰ J. C. Slater, *Introduction to Chemical Physics* (McGraw-Hill Book Company, Inc., New York, 1939), p. 219.