Will Pressure Destroy Superconductivity?*

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(Received January 1967)

The question of whether the application of sufficient pressure can destroy superconductivity completely is considered for the superconductors Al, Cd, Zn, In, Sn, and Pb. The superconducting transition temperature T_c for these elements is found to vary linearly with volume over an appreciable range of volume. Extrapolation to $T_c=0$ yields critical pressures of 67, 38, and 41 kbar for the destruction of superconductivity in Al, Cd, and Zn, respectively. These values are compared with considerably higher estimates obtained in previous analyses. Measurements of T_c for lead, as a function of pressure up to a maximum pressure of 30 kbar, are presented. On combining these data with Bridgman's room-temperature compressibility measurements for lead, T_c is found to vary linearly with volume and $\partial T_c/\partial V=0.907°\text{K cm}^{-3}$, corresponding to $\partial T_c/\partial P=-3.86\pm0.12\times10^{-5}°\text{K bar}^{-1}$ at $P=0$.

I. INTRODUCTION

THE question of whether the application of sufficient pressure to a superconductor can eventually inhibit the transition to the superconducting state down to absolute zero has existed since the early discovery[1] that pressure could lower the superconducting transition temperature. The recent development[2,3] of high-pressure techniques at temperatures below 1°K has brought experimental observation to a point where it is now feasible to attempt to obtain an answer to this question. The transition temperature T_c has been determined over a relatively wide pressure range for a number of nontransition metal superconductors,[2,4–10] and it is found to vary nonlinearly with pressure, $\partial T_c/\partial P$ decreasing with increasing pressure. Thus, in order to determine whether there is a critical pressure at which T_c will eventually go to zero, some suitable form of extrapolation is required. To date, two independent approaches to this problem have been adopted.

Olsen and co-workers[11] have suggested a relationship of the form

$$\ln(T_c/\Theta) \propto V^{-\phi}, \tag{1}$$

where ϕ [$=\partial \ln(NJ)/\partial \ln V$; N is the density of electron states at the Fermi surface and J the phonon mediated attractive electron-electron interaction] is assumed to be a constant for any given nontransition metal. Levy and Olsen[7] have shown that this relationship can be fitted, with $\phi=3.7$, to their data for the T_c of Al measured to a maximum pressure of 21 kbar. Consequently, they conclude that for Al T_c will vary nonlinearly with both volume and pressure and that no amount of volume reduction will reduce T_c to zero. They point out, however, that because of uncertainties in fitting the data, they cannot rule out the possibility that superconductivity may be destroyed for pressures in excess of 0.5 mbar.

In the report of their earlier work on cadmium, Brandt and Ginzburg,[2] following a suggestion of V. L. Ginzburg,[12] proposed a relationship of the form

$$T_c(P)=A\exp[-a/(P_c-P)], \tag{2}$$

where A and a are constants and P_c is the critical pressure at which superconductivity disappears. Fitting this relationship to their extensive data for Cd, they estimated 57 kbar $\lesssim P_c \lesssim$ 70 kbar. More recently, Brandt and Ginzburg[10] replace A in (2) by $0.85\,\Theta(P)$ and obtain a value of P_c for Cd which is some 1.5 times greater than their original estimate. Furthermore, they point out that although both relationships (1) and (2) may be fitted equally well to the full range of the experimental data for Al, this is not the case for Cd and Zn, where the data can only be fitted over the entire pressure range with relationship (2). They conclude that the superconductivity of Cd and Zn will be destroyed for pressures in excess of 122 and 160 kbar,

* Research sponsored by the U. S. Air Force Office of Scientific Research, Office of Aerospace Research, U.S. Air Force, under Grant No. AF-AFOSR-631-64.

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1 G. J. Sizoo and H. K. Onnes, Leiden Commun. **180b** (1925); B. G. Lazarew and L. S. Kan, J. Phys. USSR **8**, 193 (1944); L. S. Kan, A. L. Sudorstov, and B. G. Lazarew, Zh. Eksperim. i Teor. Fiz. **18**, 825 (1948); Dokl. Akad. Nauk USSR **69**, 173 (1949).

2 N. B. Brandt and N. I. Ginzburg, Zh. Eksperim. i Teor. Fiz. **44**, 1876 (1963) [English transl.: Soviet Physics—JETP **17**, 1262 (1963)].

3 M. Levy and J. L. Olsen, Rev. Sci. Instr. **36**, 233 (1965).

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

5 L. D. Jennings and C. A. Swenson, Phys. Rev. **112**, 31 (1958). The pressures quoted in the original report are 3% too low and corrected values have been given by Swenson in *Metallurgy at High Pressures and High Temperatures*, edited by K. A. Gschneidner, Jr., M. T. Hepworth, and N. A. D. Parlee (Gordon & Breach Science Publishers, Inc., New York, 1964), p. 190.

6 D. H. Bowen and G. O. Jones, Proc. Roy. Soc. (London) **A254**, 522 (1960).

7 M. Levy and J. L. Olsen, Solid State Commun. **2**, 137 (1964).

8 W. Buckel and W. Gey, Z. Physik **176**, 336 (1963).

9 J. Wittig, Z. Physik **195**, 228 (1966).

10 N. B. Brandt and N. I. Ginzburg, Zh. Eksperim. i Teor. Fiz. **50**, 1260 (1966) [English transl.: Soviet Physics—JETP **23**, 838 (1966)].

11 J. L. Olsen, E. Bucher, M. Levy, J. Muller, E. Corenzwit, and T. H. Geballe, Rev. Mod. Phys. **36**, 168 (1964).

12 V. L. Ginzburg, Zh. Eksperim. i Teor. Fiz. **44**, 2104 (1963) [English transl.: Soviet Physics—JETP **17**, 1415 (1963)].

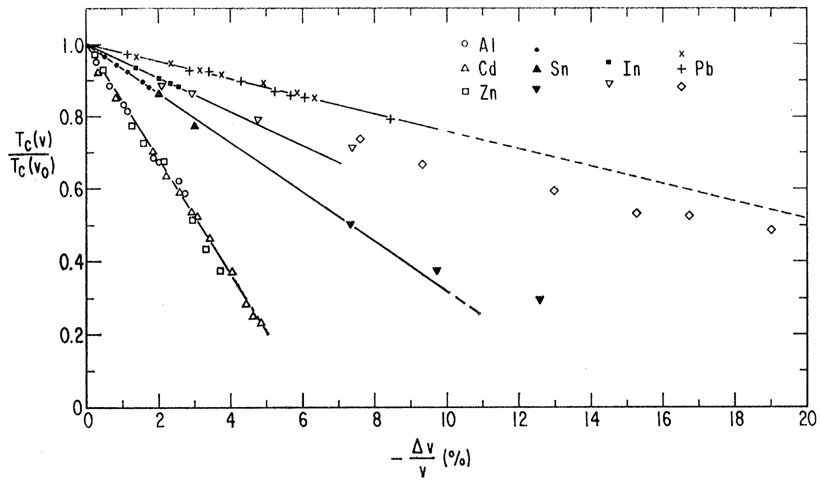

FIG. 1. The variation of the reduced superconducting transition temperature as a function of percentage volume change. Al: ○ (Ref. 7); Cd: △ (Ref. 2); Zn: □ (Ref. 10); Sn: ● (Ref. 5), ▲ (Ref. 4), ▼ (Ref. 9); In: ■ (Ref. 5), ▽ (Ref. 8); Pb: × (this work), + (Ref. 18), ◇ (Ref. 9). For clarity not all of the available data points have been plotted.

respectively; while for Al the question remains open, though they estimate a P_c of 220 kbar.

We wish to offer a different approach which is both simple and, in our opinion, more fundamental, namely, to plot T_c not as a function of pressure, as is usually the case, but directly as a function of *volume*, without attempting to fit the data to any preconceived relationship of pressure or volume. This concept is not new, being first adopted by Chester and Jones,[4] who showed that the T_c of tin varied *linearly* with volume up to 17.5 kbar. It was later shown by Jennings and Swenson[5] that the curvature of their plots of T_c as a function of pressure for indium and tin was removed when they considered T_c directly as a function of volume.

II. EXPERIMENTAL DATA

For the purpose of the present analysis, data over a sufficient pressure range were available for Al,[7] Cd,[2] Zn,[10] Sn,[4,5,9] In,[5,8] and Pb.[6,9] Pressure values were converted to relative volume changes using smooth curves drawn through Bridgman's room-temperature compressibility data.[13] Strictly, in such an analysis the relative volume changes considered should be those at the low temperature. However, we believe that the use of room-temperature data does not lead to any serious error in the analysis, as we discuss below.

Since data taken from different authors were expressed in different pressure units, care was taken to transpose all pressure values into a unified unit, the bar. The superconducting transition temperatures for all the elements considered are plotted, in reduced units of $T_c(V)/T_c(V_0)$ (where V_0 denotes values at zero pressure) against percentage volume change in Fig. 1. The linear variation of T_c with volume over the full range of the pressure measurements is immediately evident for Al, Cd, and Zn and, quite remarkably, the data for these elements fall on the same line. The situation for Sn, In, and Pb, where data from several authors are combined, is not so clear cut and we shall evaluate the individual data for these elements.

Chester and Jones[4] have previously reported that the T_c of tin varies linearly with volume for pressures up to 17.5 kbar. Jennings and Swenson[5] later showed that their careful measurements of T_c to 10 kbar are also linear in volume. Both sets of data, as plotted in Fig. 1, are seen to be in good agreement. The T_c value measured at 46 kbar by Wittig[9] lies on the line drawn through the lower-pressure data, but values measured at 64 and 88 kbar indicate a possible departure from linearity at these higher pressures. The deviation of the 64-kbar point from linearity (equivalent to the quoted pressure being some 8 kbar too high) is not sufficient to be considered significant in view of the $\pm 10\%$ uncertainty which was attached to the pressure determination. The departure of the point at 88 kbar, however, lies well outside the quoted uncertainty in the pressure determination and would indicate a significant deviation from a linear dependence of T_c upon volume. This deviation may well be associated with the proximity of the first-order phase change which occurs in tin in the region of 100 to 114 kbar[14] and results[9] in a dramatic increase of T_c.

Two sets of data are available for measurements on indium; the accurate measurements of Jennings and Swenson[5] to ~10 kbar and those of Buckel and Gey[8] to 36 kbar. These data are in reasonable agreement, those of Buckel and Gey lying a little below the more accurate measurements of Jennings and Swenson through which the line chosen to represent T_c as a function of volume was drawn. The deviation of the

[13] P. W. Bridgman, Proc. Am. Acad. Arts Sci. **74**, 425 (1942); **76**, 1 (1945); **76**, 9 (1945); **77**, 189 (1959); **84**, 111 (1955).

[14] R. A. Stager, A. S. Balchan, and H. G. Drickamer, J. Chem. Phys. **37**, 1154 (1962); H. D. Stromberg and D. R. Stephens, J. Phys. Chem. Solids **25**, 1015 (1964); W. Stark and G. Jura, American Society for Mechanical Engineers Report No. 64-WA/PT-28, 1964 (unpublished).

maximum pressure point of Buckel and Gey's data from this line cannot be considered significant because the equivalent pressure difference of $\sim$7 kbar falls within the $\pm 20\%$ uncertainty limits which the authors attach to their higher pressures.

The published data available for the T_c of lead at pressures below 40 kbar are sparse and limited to those of Hake and Mapother[15] and Garfinkel and Mapother[16] to maximum pressures of 0.3 and 0.65 kbar, respectively, and the single measurement of Bowen and Jones[6] at 9.5 kbar. The values of $\partial T_c/\partial P$ derived from these three sets of data are not in good agreement and are -4.14×10^{-5}, -3.89×10^{-5}, and -4.5×10^{-5} °K bar^{-1}, respectively. Further measurements were therefore desirable and these were undertaken both to resolve these differences in the value of $\partial T_c/\partial P$ and also with the view to using lead as a manometer at temperatures between 4 and 7°K. Measurements of T_c were made at a number of pressures to a maximum of $\sim$30 kbar. Pressures were determined from the change of T_c of a superconducting tin manometer using the empirical relationship

$$\Delta T_c = -4.63\times10^{-5}P + 2.16\times10^{-10}P^2 \quad (P \text{ in bars}), \qquad (3)$$

obtained from a combination of the linear plot of T_c as a function of volume and Bridgman's compressibility data[13] for tin expressed in the form[17]

$$\Delta V/V_0 = -18.45\times10^{-7}P + 8.58\times10^{-12}P^2 \quad (P \text{ in bars}). \qquad (4)$$

The use of (3) is restricted to pressures below 30 kbar because this is the limit of the pressure range for which (4) is valid. However, an expression similar to (3) may be derived for pressures in excess of 30 kbar by fitting a suitable relationship to the compressibility data at these pressures. This procedure is limited solely by the departure from a linear dependence between T_c and V at pressures in excess of $\sim$60 kbar. Pressure values calculated from the relationship given by Jennings and Swenson[5] deviate rapidly from those obtained using (3) for pressures above 10 kbar and are some 10% higher at 30 kbar.

Measurements of T_c as a function of pressure for lead have also been made to a maximum pressure of $\sim$45 kbar by Köhnlein.[18] The pressure in this case was determined by a strain-gauge technique[8] and is therefore an absolute determination. Both sets of data are shown in Fig. 1 and are in reasonable agreement. The single measurement of Bowen and Jones[6] lies somewhat lower than these data. Again T_c has a linear dependence upon volume over the pressure range of these measurements.

From the slope of the line through our data we find directly $[V_0/T_c(V_0)]\partial T_c/\partial V = 2.31$. Combining this value with the slope of the compressibility curve at $P=0$, which we take[17] to be 23.3×10^{-7} bar^{-1} and $T_c(V_0) = 7.193$°K,[19] we calculate $\partial T_c/\partial P = (-3.86\pm 0.12)\times10^{-5}$ °K bar^{-1}. This value is in excellent agreement with that of Garfinkel and Mapother[16] from their measurements to 0.65 kbar.

Upon comparing the T_c values for lead at pressures below 45 kbar with the measurements of Wittig[9] at pressures above 40 kbar, it is evident that a discrepancy exists between the data taken in the two pressure ranges. Wittig's measurements would imply a much more rapid initial decrease of T_c than that actually observed at the lower pressures. Since the problem of pressure determination below 40 kbars is considerably less severe than at higher pressures, particularly when using a superconducting manometer, the lower-pressure measurements are considered to be more reliable. A comparison of Wittig's data with that taken at the lower pressures would suggest that his lowest pressure is some 20 kbar greater than the quoted value. So large a discrepancy at this particular pressure is surprising in view of its proximity to the calibration point taken at the Tl(II)→Tl(III) transition (37 kbar). The same calibration procedure when applied for the measurements on tin[9] produced data which fitted smoothly on to those taken at lower pressures. Arbitrarily assigning a "correction" of +21 kbar to all of the higher-pressure data brings them into better agreement with the extrapolation of the line drawn through the lower-pressure data. However, we do not wish to imply that this agreement would be taken as evidence for the continued linear dependence of T_c upon volume out to pressures of the order of 160 kbar. Further absolute measurements at pressures above 40 kbar will be required to resolve this.

III. DISCUSSION

Before discussing the implications of the above data, we will consider the effect of using room-temperature compression data in the present analysis. The available compressibility data for metals at liquid-helium temperatures are extremely limited. Swenson[20] has shown that for indium and thallium $\Delta V/V_0$ at $\sim$10 kbar decreases upon cooling. However, if it is assumed that the shape of the P-V curve remains relatively unaltered as the temperature changes, the decrease in $\Delta V/V_0$ will merely result in an increase in the slope of the T_c-V relationship. From a consideration of Swenson's measurements on In and Tl we may expect that the values of $[V_0/T_c(V_0)]\partial T_c/\partial V$ derived using room-temperature compressibility data will be some 10–20% too low.

[15] R. R. Hake and D. E. Mapother, J. Phys. Chem. Solids **1**, 199 (1956).
[16] M. Garfinkel and D. E. Mapother, Phys. Rev. **122**, 459 (1961).
[17] K. A. Gschneidner, Jr., Solid State Phys. **16**, 275 (1964).
[18] D. Köhnlein (private communication).
[19] J. P. Frank and D. L. Martin, Can. J. Phys. **39**, 1320 (1961).
[20] C. A. Swenson, Phys. Rev. **100**, 1607 (1955).

TABLE I. Estimated critical pressures and volume changes for $T_c=0$.

Element	This work P_c (kbar)	This work $-\Delta V_{crit}/V_0$ (%)	Brandt and Ginzburg[a] P_c (kbar)	Brandt and Ginzburg[a] $-\Delta V_{crit}/V_0$ (%)	Levy and Olsen[b] P_c (kbar)	Levy and Olsen[b] $-\Delta V_{crit}/V_0$ (%)
Al	67	6.3	220	~16.3	>500	>26
Cd	38	6.3	122	~13.9		
Zn	41	6.3	160	~14.2		
In	163	21.8				
Sn	110	14.8				
Pb	≳1000	~40				

[a] Reference 10. [b] Reference 7.

It is evident from Fig. 1 that plotting T_c directly as a function of volume affords a simple and reliable means of extrapolating to zero T_c, providing that T_c continues to vary linearly with volume as $T_c \to 0$. It is important that this provision be kept in mind throughout the following analysis.[21] In view of the large relative depressions of T_c, the data for Cd and Zn, and to a lesser extent Al, are particularly suitable for such an extrapolation, which yields a critical volume change $\Delta V_{crit}/V_0 = -6.3\%$ for $T_c=0$. This value of $\Delta V_{crit}/V_0$ is equivalent to critical pressures of 67, 38, and 41 kbar for Al, Cd, and Zn, respectively. The various estimates of P_c, and the equivalent $\Delta V_{crit}/V_0$, for the destruction of superconductivity are collected in Table I, where it can be seen that the present estimates are considerably lower than those obtained in previous analyses.

While the extrapolations are by no means as reliable as for Al, Cd, and Zn, because of the smaller relative decreases in T_c and the uncertainties associated with the higher pressures involved, values of critical volume and pressure for In, Sn, and Pb are also listed in Table I. For tin the extrapolation would indicate that P_c is ~110 kbar. It is interesting to note that this pressure is associated with a crystallographic phase change[14] which results in a dramatic increase of T_c.[9] However, since crystallographic phase changes have not been detected[22] for Al, Cd, and Zn to pressures considerably in excess of P_c, there is no reason, at present, to suppose that T_c for these elements could not go to zero.

Of course, we are not able to rule out the possibility that at higher pressures than at present investigated T_c may deviate from a linear volume dependence. However, the measurements on Cd and Zn extend to low enough values of reduced T_c to indicate that if T_c for these elements is not to go to zero, a rapid decrease in $\partial T_c/\partial V$ would be required. Thus, even a modest extension of the pressure range of the measurements for Cd and Zn would be of considerable interest.

It is instructive to consider the implications of a linear volume dependence for T_c within the framework of the simple BCS[23] relationship

$$T_c(V) = 0.85\Theta(V) \exp[-1/g(V)], \quad (5)$$

where $\Theta(V)$ is the Debye temperature and $g(V) = N(V)J(V)$, [$N(V)$ is the density of electron states at the Fermi surface and $J(V)$ is the phonon mediated attractive electron-electron interaction] is a reasonable approximation for the nontransition metal superconductors. Volume-dependent quantities are denoted by V in parenthesis, V_0 indicating zero pressure values. We obtain directly from (5)

$$1/g(V) = \ln[0.85\Theta(V)/T_c(V)], \quad (6)$$

and hence

$$J(V) = \{N(V) \ln[0.85\Theta(V)/T_c(V)]\}^{-1}. \quad (7)$$

Thus, with a knowledge of the volume dependences of $N(V)$, $\Theta(V)$, and $T_c(V)$ we may readily obtain $J(V)$ as a function of volume.

Because we have shown in the above analysis that T_c is linear in volume, we may write

$$T_c(V) = T_c(V_0)[1+\gamma_s(V_0)(V/V_0-1)], \quad (8)$$

where $\gamma_s(V_0) = [V_0/T_c(V_0)]\partial T_c/\partial V$ (effectively the zero-pressure superconducting "Grüneisen constant"). Expressing $N(V)$ and $\Theta(V)$ as expansions in powers of (V/V_0-1), we have

$$N(V) = N(V_0)[1+a_1(V/V_0-1) + a_2(V/V_0-1)^2 + \cdots], \quad (9)$$

and

$$\Theta(V) = \Theta(V_0)[1+b_1(V/V_0-1) + b_2(V/V_0-1)^2 + \cdots]. \quad (10)$$

[21] From a purely thermodynamic standpoint there is no inconsistency in a finite, nonzero pressure dependence for T_c (in zero magnetic field) at absolute zero since for a second-order transition $\partial T/\partial P \to 0/0$ as $T \to 0$ and therefore becomes indeterminate. If indeed $\partial T_c/\partial P$ remains finite and nonzero, the T_c-P line is expected to terminate on the P axis in a third-order transition. A similar situation exists for the normal to mixed-state transition in type-II superconductors as $T_c \to 0$, and this case has been considered by C. J. Gorter, Physica **30**, 2175 (1964). If, on the other hand, the T_c-P line for the first-order transition in a magnetic field is considered, this must terminate on the P axis with $\partial T_c/\partial P = \infty$. Thus, we may expect T_c as a function of pressure to go to zero more rapidly in a magnetic field.

[22] R. W. Lynch and H. G. Drickamer, J. Phys. Chem. Solids **26**, 63 (1965); M. H. Rice, R. G. McQueen, and J. M. Walsh, Solid State Phys. **6**, 1 (1958).

[23] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).

TABLE II. Parameters used in the calculation of ϕ and $J(V)$.

Element	$N(V_0)$[a] States/eV atom	$\Theta(V_0)$[a] (°K)	$\gamma_s(V_0)$	$\gamma_e(V_0)$	$\gamma_g(V_0)$
Al	0.456	423±5	15.9	2.0±0.5[b]	2.3±0.5[b]
Cd	0.286	252±48	15.9	0.7±1.5[b]	2.7±0.4[b]
Zn	0.272	316±20	15.9	···	2.01±0.14[a]
In	0.720	109	4.6	1.0±0.2[c]	2.37±0.16[a]
Sn	0.754	196±9	6.75	1.7±0.3[d]	2.00±0.14[a]
Pb	1.310	102±5	2.31	1.7±0.5[e]	2.7±0.2[e]

[a] Reference 17.
[b] K. Andres, Phys. Condensed Material **2**, 294 (1964).
[c] H. Rohrer, Phil. Mag. **4**, 1207 (1959).
[d] C. Grenier, Compt. Rend. **240**, 3202 (1955).
[e] G. K. White, Phil. Mag. **7**, 271 (1962).

Restricting the analysis to relatively small volume changes, say $\Delta V/V_0 \lesssim -10\%$, and to a first-order approximation neglecting terms higher than first order, it follows directly that

$$a_1 = \gamma_e(V_0) = [V_0/N(V_0)][\partial N(V)/\partial V], \qquad (11)$$

and

$$b_1 = -\gamma_g(V_0) = [V_0/\Theta(V_0)](\partial\Theta/\partial V), \qquad (12)$$

where $\gamma_e(V_0)$ and $\gamma_g(V_0)$ are the zero-pressure electronic and lattice Grüneisen constants, respectively. $J(V)$ as a function of volume for Al, Cd, and Sn is plotted with reduced coordinates in Fig. 2 and the pertinent zero-pressure quantities used in the calculation are listed in Table II. The limit to which the linear volume dependence of T_c for each element has been observed is indicated. $J(V)$ varies slowly with volume over the range of volumes so far examined experimentally, but if T_c continues to vary linearly with volume down to absolute zero there must be a rapid decrease of $J(V)$ for $\Delta V > 0.9\Delta V_{\text{crit}}$. To reach this critical-volume region for Cd would require T_c measurements at pressures of ~34 kbar at temperatures in the neighborhood of 50 mdeg.

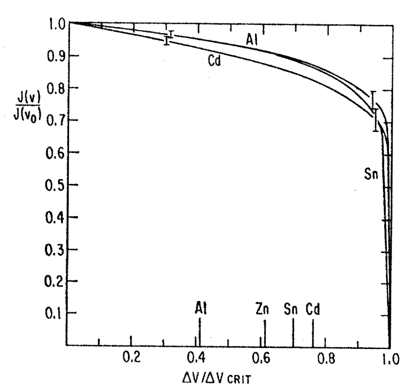

FIG. 2. Variation of $J(V)$ as a function of volume. Vertical lines on horizontal axis indicate the limit of the volume range for which T_c has been experimentally observed to vary linearly with volume. The error bars are associated with the uncertainty in γ_e.

The volume derivative of the BCS relationship (5), first given by Lüthi and Rohrer,[24] and which may be expressed in the form

$$\frac{\partial \ln[T_c(V)/\Theta(V)]}{\partial \ln V} = \ln\left[\frac{0.85\Theta(V)}{T_c(V)}\right]\frac{\partial \ln g(V)}{\partial \ln V}, \qquad (13)$$

has been extensively applied to studies of superconductivity at high pressure. It was shown by Rohrer[25] that the quantity $\phi = \partial \ln g(V)/\partial \ln V$ calculated from (13) was roughly constant for the nontransition metal superconductors. This observation lead Olsen and coworkers[11] to assume that ϕ would be constant for any given nontransition metal superconductor over a wide range of pressure and by integration of (13) they arrived at the expression (1).

However, in calculating ϕ from (13) the implicit volume dependence of the quantities involved was not considered, i.e., $\partial \ln T_c$ was calculated as $[1/T_c(V_0)]\partial T_c$, and therefore the values of ϕ so obtained are only applicable at $P=0$. Retaining the instantaneous values of $T_c(V)$, $\Theta(V)$, and $g(V)$ in (13) and using relation-

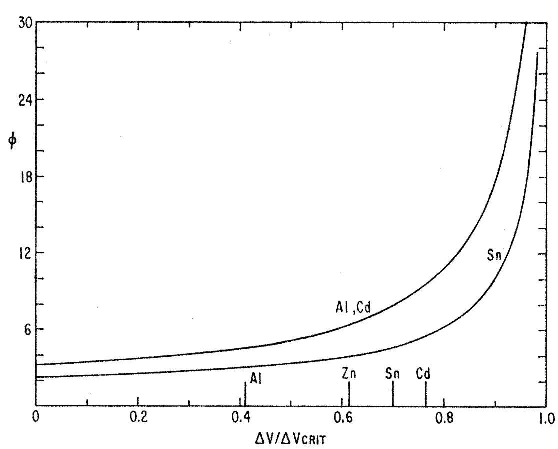

FIG. 3. Variation of ϕ as a function of relative volume change. The vertical lines on the horizontal axis indicate the limit of the volume range for which T_c has been experimentally observed to vary linearly with volume.

[24] B. Lüthi and H. Rohrer, Helv. Phys. Acta **31**, 294 (1958).
[25] H. Rohrer, Helv. Phys. Acta **33**, 675 (1960).

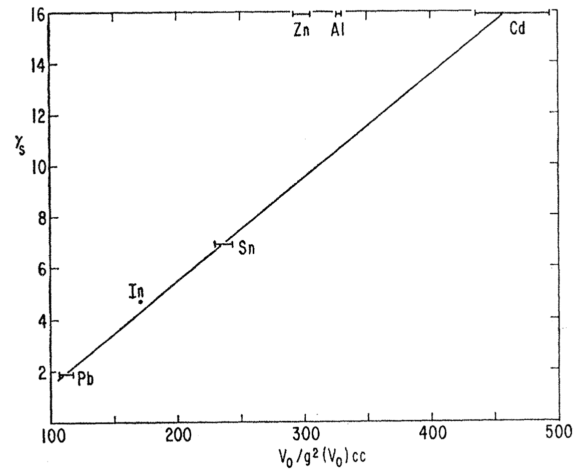

FIG. 4. γ_s plotted as a function of $V_0/g^2(V_0)$. The error bars are associated with the uncertainty in $\Theta(V_0)$.

ships (8), (11), and (12), it may be readily shown that

$$\phi=\left[\frac{\gamma_s(V_0)}{1+\gamma_s(V_0)(V/V_0-1)}+\frac{\gamma_g(V_0)}{1-\gamma_g(V_0)(V/V_0-1)}\right]\times\left[\ln\left\{\frac{0.85\Theta(V_0)[1-\gamma_g(V_0)(V/V_0-1)]}{T_c(V_0)[1+\gamma_s(V_0)(V/V_0-1)]}\right\}\right], \quad (14)$$

where we define

$$\phi=[V_0/g(V)][\partial g(V)/\partial V].$$

Values of ϕ for Al, Cd, and Sn are shown plotted as a function of reduced volume change in Fig. 3. The volume ranges for which T_c has been experimentally observed to vary linearly with volume are again indicated. We see from Fig. 3 that to consider ϕ to be volume-independent is only a reasonable approximation for $\Delta V<0.4\,\Delta V_{\text{crit}}$. However, as the measurements of Levy and Olsen[7] for Al do not extend beyond $0.41\Delta V_{\text{crit}}$ their ability to fit their data to the relationship (1) is understood. Furthermore, the failure[10] of (1) to fit the data for Cd and Zn with fixed values of ϕ is also accounted for.

Rewriting (13) in the form

$$[T_c(V)]^{-1}[\partial T_c(V)/\partial V]=[\Theta(V)]^{-1}[\partial\Theta(V)/\partial V]+[g^2(V)]^{-1}[\partial g(V)/\partial V], \quad (15)$$

we may express $\gamma_s(V_0)$ as

$$\gamma_s(V_0)=-\gamma_g(V_0)+[V_0/g^2(V_0)][\partial g(V)/\partial V]_{V=V_0}. \quad (16)$$

From (16), assuming all nontransition metal superconductors to have much the same value for $[\partial g(V)/\partial V]_{V=V_0}$, we would expect that $\gamma_s(V_0)\propto V_0/g^2(V_0)$ because $\gamma_g(V_0)$ is roughly constant. This assumption is borne out for Cd, Sn, In, and Pb for which $\gamma_s(V_0)$ varies linearly with $V_0/g^2(V_0)$ (see Fig. 4). The values for Zn and Al, however, do not fall on this line and would imply a stronger volume dependence of $g(V)$ for these elements. Furthermore, we would conclude from (16) that Al and Zn have the same value of $\gamma_s(V_0)$ as a consequence of the closeness of their values for $V_0/g^2(V_0)$. However, no such simple explanation is forthcoming to account for the same value of $\gamma_s(V_0)$ being observed for Cd.

IV. CONCLUSION

Examination of the available data on T_c as a function of pressure for Al, Cd, and Zn has revealed that T_c has a linear volume dependence over the entire experimental range of pressures. With the assumption that T_c continues to vary linearly with volume to absolute zero, extrapolated values of the critical pressure required to destroy superconductivity have been determined and are found to be considerably lower than those of previous predictions. The T_c data for In, Sn, and Pb have also been considered and for pressures up to 40 kbar, T_c for these elements also varies linearly with volume. At higher pressures the situation is more uncertain due to difficulties in pressure determination.

ACKNOWLEDGMENTS

We are indebted to D. Köhnlein for a report of his work prior to publication. Comments and criticism by S. Gygax and G. Knapp, and conversations with H. Suhl and W. Klement, Jr., were greatly appreciated. Correspondence with C. A. Swenson is gratefully acknowledged.