PRESSURE DEPENDENCE OF THE SUPERCONDUCTING TRANSITION TEMPERATURE IN ZINC

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A study was made of the influence of uniform compression on the temperature T_c of the superconducting transition in zinc in the pressure range up to 26 000 atm. At a pressure of 26 000 atm, the superconducting transition temperature decreased by a factor of 2.7. It is shown that the pressure dependence of T_c of zinc is best described by an exponential function. The problem is discussed of the possibility of a transition of a superconductor to the normal state under the action of pressure.

ONE of the most interesting problems associated with the influence of pressure on superconductivity is the question whether pressure can destroy superconductivity without changing the crystal structure, i.e., whether superconductivity can be destroyed in that range of pressures where there are no first-order phase transitions. The possibility of destroying superconductivity by compression has been considered earlier.[1,2] It has been shown that the dependence of T_c on p for cadmium is described by the formula

$$T_c(p) = A \exp\left(-\frac{a}{p_{c0} - p}\right), \tag{1}$$

where A and a are some constants, and p_{c0} is the critical pressure at which the superconductivity disappears.

A different point of view has been based on an empirically established linear dependence for some metals[3-6]

$$\frac{\partial \ln [T_c(p)/0.85\Theta(p)]}{\partial \ln v} = \varphi_v \ln \frac{0.85\Theta(p)}{T_c(p)} \tag{2}$$

(v is the sample volume, Θ is the Debye temperature). According to the data of Olsen et al.,[5] the parameter $\varphi_V \equiv \partial \ln NV/\partial \ln v$ (N is the density of states on the Fermi surface, V is the electron—phonon interaction parameter) for non-transition metals (with the exception of thallium) is positive and has values from 1.8 to 3.7.

If it is assumed that φ_V is independent of pressure (as has been done in[5,6]), the dependence of T_c on p for non-transition metals should be described by the formula

$$\ln \frac{T_c(p)}{0.85\Theta(p)} = Cv^{-\varphi_v}, \tag{3}$$

where C is a constant. Hence it follows that T_c cannot vanish at any finite pressure, since the volume v does not vanish.

It seemed of interest to obtain additional data on the dependence of T_c on p for other superconductors in which relatively large changes in T_c could be obtained. Zinc was selected as a suitable object for these measurements.

As far as the authors are aware, there has been only one investigation[7] in which the ice-bomb method was used to study the influence of a pressure of p = 1700 atm on the $H_c(T)$ curve of zinc. From the displacement of the $H_c(T)$ curve on compression, the following value of the derivative was obtained

$$\partial T_c / \partial p = -(1.6 \pm 0.4) \cdot 10^{-5} \text{ deg/atm}.$$

MEASUREMENT METHOD

The measurements were carried out in the temperature range 0.06—0.8°K. Temperatures in this range were obtained by the adiabatic demagnetization of an iron—ammonium alum pellet, joined by a cold duct to a sample.

The transition to the superconducting state and the destruction of the superconductivity by a transverse magnetic field, produced by a Helmholtz system, was recorded by an electronic method at 22 cps. The general arrangement of the apparatus and the measurement method were described in detail in[1].

The pressure was applied by a booster (cf.[1,8]) without the use of any intermediate pressure-transmitting medium. As in[1], a copper rod of 6—8 mm

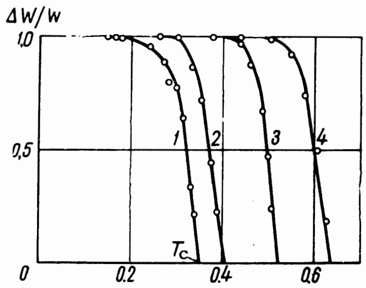

FIG. 1. Superconducting transition curves for zinc in the absence of a magnetic field at various pressures: 1) p = 26 200 atm; 2) p = 23 100 atm; 3) p = 15 500 atm; 4) p = 11 800 atm.

length was placed between a sample and a cemented tungsten carbide (VK-6) plunger.

Zinc samples were single-crystal cylinders of 2—3 mm diameter and 3—4 mm long, grown in quartz ampoules by the Bridgman method from spectroscopically pure zinc.

RESULTS OF MEASUREMENTS

The temperature of the superconducting transition was determined by two methods: from the superconducting transition curves without an external magnetic field and by extrapolating the critical field curves until they intersected the abscissa. By way of example, Fig. 1 gives some temperature dependences of the relative change in the signal W at the output of an electronic amplifier in the absence of a magnetic field. Both methods of determining T_c gave results which agreed well, if the value of T_c in Fig. 1 was assumed to be the point of intersection between the extension of the steepest part of the curve and the abscissa.

The dependence of T_c on p is shown in Fig. 2. It is quite clear that this dependence is not linear. The derivative $\partial T_c/\partial p$ decreases from the value -2.4×10^{-5} deg/atm at low pressures to -1.7×10^{-5} deg/atm in the region of 20 000—26 000 atm.

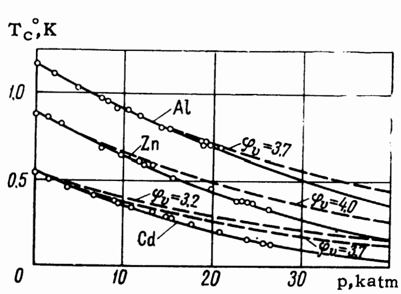

FIG. 2. Pressure dependence of the superconducting transition temperature of zinc, cadmium, and aluminum. Continuous curves are the results of calculation using Eq. (7), while dashed curves are the results of calculation using Eq. (4) for various values of φ_V.

At 26 000 atm the temperature of the superconducting transition decreases by a factor of 2.7.

DISCUSSION OF RESULTS

We shall determine first of all how well the obtained dependence of T_c of zinc on p is described by Eqs. (1) and (3). For convenience in calculations, we shall write Eq. (3) in the form

$$\ln\frac{T_c(p)}{0.85\Theta(p)} = \ln\frac{T_c(0)}{0.85\Theta(0)}\left[\frac{v(p)}{v(0)}\right]^{-\varphi_v}. \tag{4}$$

The values of v(p)/v(0) and Θ(p), which occur in this formula, are given for various pressures in the adjoining table.

p, atm	Zinc		Aluminum		Cadmium	
	v (p)/v(0)	Θ (p)	v (p)/v (0)	Θ (p)	v (p)/v (0)	Θ (p)
0	1.000	235	1.000	418	1.000	188
5000	0.992	239	0.9935	425.5	0.99	192.5
10 000	0.985	243	0.987	432.8	0.981	197
15 000	0.978	246.7	0.980	440	0.972	201
20 000	0.971	250.5	0.975	446.8	0.963	205
25 000	0.964	254	0.969	452.4	0.955	209
30 000	0.958	257.2	0.964	459.5	0.947	212.6
40 000	0.946	263.4	0.954	471.5	0.933	219.5

The data on the dependence of the volume on the pressure were taken from Bridgman's investigations on the assumption that they were not affected greatly by low temperatures. To estimate the change in Θ on compression we used the Grüneisen formula[9,10] from which it follows that

$$\Theta(p) = \Theta(0)\,[1 + p\alpha / C_v], \tag{5}$$

where $\alpha = v^{-1}(\partial v/\partial T)_p$, C_V is the specific heat per unit volume. It is known that, under compression, α decreases and C_V increases. In the first approximation, the decrease in α/C_V as the pressure is increased is allowed for by the factor v(p)/v(0).

According to Olsen et al.,[5,6] $\varphi_V = 2.2$ for zinc. The dependence of T_c on p, plotted using Eq. (4) with this value of φ_V, differs strongly from the experimental data over the whole range of pressures. This difference is the consequence of the use in calculations of a too-low value of $\partial T_c/\partial p = -(1.6 \pm 0.4) \times 10^{-5}$ deg/atm which, as pointed out by the authors themselves, is inaccurate.

According to our data, $\varphi_V = 4 \pm 0.1$ for zinc. Using this value in Eq. (4) we obtain the dependence of T_c on p shown dashed in Fig. 2. In the pressure range up to ≈5000 atm it agrees with the experimental data. Above 5000 atm an increasing deviation from the experimental curve is observed.

Before comparing the experimental data with Eq. (1), we must draw attention to the following points. Formula (1), in the form used in[1], contains three unknown parameters: A, a, and p_{c0}, where $A \approx 5.6$ for cadmium. However, because formula (1) follows directly from the formula

$$T_c = 0.85\Theta e^{-1/NV}, \tag{6}$$

it is more natural to assume that the parameter A is of the order of the Debye temperature. Therefore, we shall use a modified formula (3) in the form

$$T_c(p) = 0.85\Theta(p) \exp\left(-\frac{a}{p_{c0} - p}\right). \tag{7}$$

The continuous curve in Fig. 2 gives the dependence of T_c on p for zinc, plotted using Eq. (7) and the values a = 85 700 and p_{c0} = 158 000 atm. Clearly, formula (7) agrees better with experiment than formula (3).

In the same figure the experimental data for cadmium[1] and aluminum[11] are compared with the curves calculated using formula (3) (dashed curves) and formula (7) (continuous curves). For aluminum, we used the value $\varphi_V = 3.7$,[6] while for cadmium, we used the values $\varphi_V = 3.2$ and $\varphi_V = 3.7$. For the latter value the curve is in better agreement with experiment at low pressures. The agreement with Eq. (7) is obtained using the values a = 680 000 and p_{c0} = 120 000 atm for cadmium, and a = 1234×10^3 and p_{c0} = 216 000 atm for aluminum. We note that the value of p_{c0} obtained for cadmium from Eq. (7) is about 1.5 times larger than the value of p_{c0} calculated in[1] using Eq. (1).

These data show that, in the case of zinc and cadmium, formula (4) does not agree with the experimental dependence of T_c on p even at very high values of φ_V. For aluminum, both formulas agree with experiment in the pressure range up to ≈20 000 atm. In order to find which formula describes better the dependence of T_c on p for aluminum it is necessary to carry out experiments at pressures considerably higher than 20 000 atm. However, it is already clear that formula (4) describes the dependence of T_c on p for aluminum over a considerably greater range of changes in T_c, than in the case for zinc and cadmium.

Thus, so far the experimental data on the dependence of T_c on p, obtained for zinc and cadmium agree with the hypothesis of the existence of a critical pressure p_{c0} at which the superconductivity disappears. It is at present difficult to judge how generally this hypothesis applies to nontransition metals, including aluminum. However, if we assume that there is a p_{c0} at which T_c vanishes, then the function

$$\varphi_v = -\frac{\partial(NV)}{\partial v}\frac{v}{NV}$$

should increase with increase of pressure because NV decreases.

We also note that some difference is to be expected between the experimental points (Fig. 2) and the curves plotted using Eq. (7) because this formula is valid only near p_{c0}. Agreement is improved by inclusion of the second-order and higher terms from the expansion of NV in terms of $(p_{c0} - p)/p_{c0}$.

Since the superconductivity can be destroyed by compression only if the parameter V vanishes, it is very important to determine the pressure dependence of this parameter over a sufficiently wide range of pressures. For this purpose it is necessary to carry out precision measurements of the critical field curves. We are of the opinion that the data for cadmium, obtained earlier by us,[1] are not sufficiently accurate for such calculations. The results of more accurate measurements of the critical field curves for cadmium, zinc, tin, and indium at pressures up to 25 000 atm will be published in the near future.

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