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SOME PROPERTIES OF SINGLE METAL CRYSTALS

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In this note I summarize the results of measurements of a number of the physical properties of single crystals of the more readily obtainable non-cubic metals, Zn, Cd, Bi, Sb, Te, and Sn. The detailed description of the measurements and the method of producing the crystals is to be given elsewhere (probably in *Proc. Amer. Acad. Arts Sci., Boston*). I also give a few measurements on a single crystal of tungsten (cubic system) which I owe to the courtesy of Dr. Langmuir of the General Electric Co. who obtained it from a German firm. The measurements given here include the elastic constants at room temperature, the linear compressibilities at 30° and 75° C. to 12,000 kg./cm.², the thermal expansion, the specific electrical resistance, the temperature coefficient of resistance, and the effect of pressure on resistance to 12,000 kg. at several temperatures.

All of the metals in the list above are characterized by an axis of rotational symmetry; Zn and Cd have a six-fold axis (hexagonal system), Bi, Sb, and Te a three-fold axis (trigonal system), and Sn a four-fold axis (tetragonal system). The rotational axis is taken as the datum line in the crystal; when, for example, a property is specified in the perpendicular direction, the direction perpendicular to the axis is understood. Besides the principal axis, there are principal planes. Zn, Bi, and Sb show perfect cleavage on a single plane perpendicular to the axis, Cd and Sn have no cleavage but the most important slip plane is also perpendicular to the axis, while Te, on the other hand, has three principal cleavage planes, intersecting in three lines parallel to the principal axis.

Of the properties above, the elastic constants are the most complicated; the trigonal and tetragonal systems have six independent constants, and the hexagonal system five. The notation of Voigt for the elastic constants is used in the following. All the other properties have rotational symmetry, so that the linear compressibility or thermal expansion or electrical

resistance is completely determined for all directions in the crystal if it is determined parallel and perpendicular to the axis.

There follows now the numerical summary.

ELASTIC CONSTANTS IN ABS. C. G. S. UNITS

CONSTANT	Zn	Cd	Br	Sb	Te	Sn	W
s_{11}	8.23×10^{-13}	12.9×10^{-13}	26.9×10^{-13}	17.7×10^{-13}	48.7×10^{-13}	18.5×10^{-13}	2.534×10^{-13}
s_{12}	+ .34	-1.5	-14.0	-3.8	-6.9	-9.9	-.726
s_{13}	-6.64	-9.3	-6.2	-8.5	-13.8	-2.5	s_{12}
s_{33}	26.38	36.9	28.7	33.8	23.4	11.8	s_{11}
s_{44}	25.0	64.0	104.8	41.0	58.1	57.0	6.55
s_{66}	$2(s_{11} - s_{12})$	$2(s_{11} - s_{12})$	$2(s_{11} - s_{12})$	$2(s_{11} - s_{12})$	$2(s_{11} - s_{12})$	135.	$2(s_{11} - s_{12})$
s_{14}	0	0	+16.0	-8.0	Not determined	0	0

LINEAR COMPRESSIBILITY, $\left(\frac{\Delta l}{l_0}\right)$

Pressure in kg./cm.² Range, 12,000 kg./cm.²

METAL	AT 30° c.		AT 75° c.	
Zn	$12.98 \times 10^{-7}p - 5.32 \times 10^{-12}p^2$		$13.55 \times 10^{-7}p - 7.82 \times 10^{-12}p^2$	
Zn ⊥	1.946	- 1.11	2.025	- 1.47
Bi	15.92	-11.1	15.80	-11.6
Bi ⊥	6.450	- 4.60	6.423	- 4.57
Sb	16.48	-20.5	16.37	-18.0
Sb ⊥	5.256	- 4.56	5.091	- 3.04
Te	-4.137	+ 9.6	-5.132	+13.2
Te ⊥	27.48	-52.7	27.77	- 53.6
Sn	6.719	- 4.07	6.956	- 3.91
Sn ⊥	6.022	- 4.20	6.144	- 4.26

From the directly measured linear compressibility the cubic compressibilities may be calculated.

CUBIC COMPRESSIBILITY, $\left(\frac{\Delta V}{V_0}\right)$

Pressure in kg./cm.² Range, 12,000 kg./cm.²

METAL	AT 30° c.		AT 75° c.	
Zn	$16.87 \times 10^{-7}p - 8.08 \times 10^{-12}p^2$		$17.60 \times 10^{-7}p - 11.35 \times 10^{-12}p^2$	
Bi	29.17	- 22.43	29.89	-31.13
Sb	26.99	- 31.6	26.55	-25.3
Te	50.82	-101.1	50.41	-85.6
Sn	18.76	- 13.6	19.24	-13.7
W	3.18	- 1.4	3.18	- 1.5

LINEAR THERMAL EXPANSION AT ROOM TEMPERATURE

METAL	PARALLEL	PERPENDICULAR
Zn	57.4×10^{-6}	12.6×10^{-6}
Cd*	52.5	20.2
Bi	13.96	10.36
Sb	15.56	7.96
Te	- 1.6	27.2
Sn	30.50	15.45

* Values for Cd from E. Grüneisen and E. Goens, *Phys. Z.*, **24**, 506-510, 1923.

ELECTRICAL RESISTANCE

METAL	SP. RESISTANCE AT 20° C.	AVERAGE TEMPERATURE COEFF. OF SP. RESISTANCE 0-100° C.	INITIAL PRESSURE COEFF. OF SP. RESISTANCE AT 0° C.
Zn	6.13×10^{-6}	.00419	-10.87×10^{-4}
Zn ⊥	5.91	418	- 6.55
Cd	8.30	428 (?)	-13.1
Cd ⊥	6.80		- 8.7
Bi	13.8	445	+24.5
Bi ⊥	10.9	445	+ 7.5
Sb	35.6	595	+17.2
Sb ⊥	42.6	511	+ 1.05
Te	56,000		
Te ⊥	154,000		
Sn	14.3	447	-10.96
Sn ⊥	9.9	469	-10.28
W	5.48		

The elastic constants are seen to vary greatly with direction, so that these single crystals do not by any means approach the behavior of isotropic bodies. The linear compressibility of Zn is nearly 7 times greater parallel to the axis than at right angles, and the linear compressibility of Te is *negative* parallel to the axis. The effective Young's moduli (s_{11} and s_{33}) also vary greatly with direction, although not so much as the linear compressibilities. Notice that in all cases the deformability is greatest across the principal cleavage or slip plane, except in the case of the effective Young's modulus of Sn. Since the separation of atomic centers is greatest across the cleavage or slip planes, we should expect in general a greater deformability in this direction.

Successful measurements of the compressibility of Cd were not obtained, owing to the existence of two new polymorphic forms under pressure. The transitions are reversible, and at 20° C. take place at about 3000 and 6000 kg./cm.² In addition to changes of dimensions there is also a very slight change in the electrical resistance at the transition. The average in all directions in the crystal of the properties of the new modifications is very close indeed to those of the ordinary modification,

which explains why these modifications have escaped me in previous measurements on crystalline aggregates of Cd.

The thermal expansion is also in all cases greatest across the cleavage or slip planes. Notice the negative expansion of Te along the axis. It is interesting that the variation with direction of the elastic constants and thermal expansion is much greater in Zn and Cd than in Bi and Sb, which by ordinary standards have a much more strongly developed crystalline character. For the sake of completeness I have included in the table of thermal expansions the recent values of Grüneisen and Goens for Cd, who have also given values for all the other properties of Zn and Cd listed here, except the behavior under pressure. The samples of Cd which I had intended for these measurements were ruined by an exposure to pressure, which produced a disorientation on crossing the transitions points.

The differences of electrical conductivity in different directions are much less pronounced than the differences of elastic deformability, but follow the same general rule, namely the resistance is greatest *across* the plane of easiest cleavage or slip, that is, in the direction in which the atoms are most separated. The only exception to this rule is Sb. The temperature coefficient of resistance does not vary greatly with direction; the pressure coefficient varies much more. The resistance of Zn, Cd, and Sn decreases under pressure; the decrease is greatest parallel to the axis, that is, in the direction in which the atoms are brought closest together by pressure. Under high pressure the variations of resistance with direction become less accentuated for these three metals. Bi, on the other hand, increases in resistance under pressure, and the increase is more rapid parallel to the axis, so that the variation of resistance with direction becomes accentuated under pressure. The behavior of the resistance of Sb under pressure is very unusual and striking. Briefly, the effect of pressure is to compel a return to the normal type of behavior, so that under 12,000 kg. the resistance is greatest across the cleavage planes, as is normal. The return to normality is most rapid at the higher temperatures. The details of the pressure effect are complicated. (In the detailed paper, the resistance of all these metals is given as a function of pressure to 12,000 kg. and between 0° and 95° C.; the results are too complicated to be summarized here.) At the higher temperatures the sign of the pressure coefficient in the perpendicular direction reverses, and there are intermediate temperatures where the resistance passes through a maximum with increasing pressure, the only example known of such an effect. After pressure has compelled a return to normality, the effect of further increasing pressure is to accentuate still further the greater resistance across the cleavage planes. The fact that ultimately the preponderance of resistance across the cleavage planes of both Bi and Sb becomes accentuated as the atoms are brought closer together shows that the resistance is determined by

something more specific than the mere distance apart of the atoms, and that without doubt the details of atomic structure are involved.

I am indebted to my assistant, Mr. W. Koenig, for many of the readings on which these results are based.

EFFECT OF INSULIN ON THE LACTIC FERMENTATION

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A difficulty which seriously retards the progress of experimental investigations on insulin, as well as its preparation for clinical use, is that of determining even relatively the quantity present in solutions containing it. This research on its effect on the lactic fermentation was undertaken in the hope of developing a more satisfactory assay of insulin preparations than the animal-testing method affords. It was also thought that any effects observed might throw light on the mechanism of its physiological action. The research seemed promising since preliminary experiments had shown that addition of insulin considerably increased the total acid produced by the lactic fermentation as brought about by the organism *Lactobacillus bulgaricus*.

This research was made possible by a grant from the Carnegie Corporation of New York. We are also indebted to Eli Lilly and Company of Indianapolis for a supply of their purest insulin, to the Vitalait Laboratory of Pasadena for furnishing pure cultures of the lactic bacteria, to Miss Emma B. Mundy and Mr. John R. Adams of the Pasadena High School for bacteriological assistance, and to Messrs. G. A. Alles and A. L. Raymond of this Institute for valuable suggestions and for aid in preparing and testing the insulin preparations.

The fermentation experiments were made with mixtures that contained in 100 cc. of solution, 1 g. of glucose, 10 cc. of skimmed milk, 2 drops of a milk culture of *Lactobacillus bulgaricus* and varying amounts of insulin solution (or of a blank solution). The solutions were made up in glass-stoppered bottles, which were placed in a water thermostat at 32°, and which were either rotated on a horizontal shaft within the thermostat, or shaken by hand at fifteen-minute intervals for the first four hours and then occasionally till the solutions coagulated.

Two insulin samples were used, both of which were prepared from a highly concentrated aqueous solution furnished by Eli Lilly and Company. One (here called no. 1) was the precipitate obtained by adding a large