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Pressure Derivatives of the Elastic Constants of Copper, Silver, and Gold to 10 000 Bars

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The pressure derivatives of the elastic constants of the homologous series of metals, copper, silver, and gold have been measured over the pressure range from 0 to 10 000 bars, using a modified ultrasonic pulse-echo method. Means have been devised to measure the *change* of elastic constant with pressure as directly as possible. The values found for the pressure derivatives of the elastic constants are as follows:

	Cu	Ag	Au
dB_s/dP	5.59	6.18	6.43
dC/dP	2.35	2.31	1.79
dC'/dP	0.580	0.639	0.438

The notation $C=C_{44}$, $C'=(C_{11}-C_{12})/2$, and $B_s=(C_{11}+2C_{12})_s/3$ has been used. The data for each metal, of the three elastic constants and their pressure derivatives, have been interpreted in terms of conventional theory. The theoretical contributions of long-range interactions have been subtracted off and the remainder attributed to short-range nearest-neighbor interaction. The analysis indicates that these must be noncentral, many-body interactions in order to account for the shear constants and especially their pressure derivatives. The many-body character of the interactions is of rapidly increasing importance in the sequence copper, silver, and gold.

INTRODUCTION

IT is well known that in the theory of the cohesion of copper it is necessary to introduce a short-range repulsive interaction between ion cores in order to account for the observed value of the compressibility. This interaction is generally represented empirically by a two-parameter exponential potential which is a function of ion separation only. It is an important interaction in theories of the mechanism of diffusion in this metal and several workers have followed the procedure of evaluating the parameters by means of the observed values of the single crystal elastic stiffnesses.[1–3] This procedure is quite satisfactory for the purpose, but the reverse procedure of attempting to account in detail for the elastic stiffnesses in terms of a two-parameter exponential repulsion is less satisfactory. This failure is seldom pointed out explicitly; it becomes more and more apparent, however, when one examines the single-crystal elastic stiffnesses of the similar metals, silver and gold.

The contribution of a short-range interaction becomes more and more important relative to long-range interactions as one successively examines the binding energy, the equilibrium condition, and the elastic stiffnesses. Going one step further, the pressure derivatives of the elastic stiffnesses will be determined almost entirely by the short-range interactions, and it is with a view to studying such interactions under these favorable circumstances that the present work was undertaken. It was felt that it would be desirable to study the entire homologous series, copper, silver, and gold, since the interpretation for these metals is expected to be qualitatively similar.

[1] H. B. Huntington and F. Seitz, Phys. Rev. 61, 315 (1942).
[2] H. B. Huntington, Phys. Rev. 91, 1092 (1953).
[3] C. Zener, Acta Cryst. 3, 346 (1950).

The pressure derivative of the bulk modulus is a primary result in the classic work of Bridgman[4]; the dependence on pressure of the shear modulus of a few polycrystalline materials has been studied by Birch.[5] The only previous study of the pressure dependence of the elastic constants of single crystals is that of Lazarus,[6] who, in a pioneering paper, reported on KCl, NaCl, CuZn, Cu, and Al. The present work follows Lazarus in using the ultrasonic pulse-echo technique of elastic constant determination. This technique is ideal for observations in the ambient of a liquid under high pressure since it is a nonresonant method. Our observational procedure has, however, been different from that of Lazarus. The high-pressure apparatus has been constructed and the measuring equipment has been modified in such a way that the method is essentially a differential one, in which the *change* in elastic stiffness is observed directly.

EXPERIMENT

High-Pressure System

The high-pressure system consisted of an hydraulic pump operating on a 7.4:1 piston intensifier. The apparatus is based on a system used by Jacobs[7] for optical absorption studies.[8] Following a suggestion by Dr. D. P. Johnson of the National Bureau of Standards, Octoil-*S* was used as the high-pressure fluid. The superior lubricating properties of this oil as well as its low-pressure coefficient of viscosity make it an ideal

[4] P. W. Bridgman, *The Physics of High Pressures* (G. Bell and Sons, London, 1952), Chap. VI.
[5] F. Birch, J. Appl. Phys. 8, 129 (1937).
[6] D. Lazarus, Phys. Rev. 76, 545 (1949).
[7] I. S. Jacobs, Phys. Rev. 93, 993 (1953).
[8] We wish to thank Professor A. W. Lawson of the University of Chicago for the blue prints of Jacobs' apparatus and for many valuable suggestions.