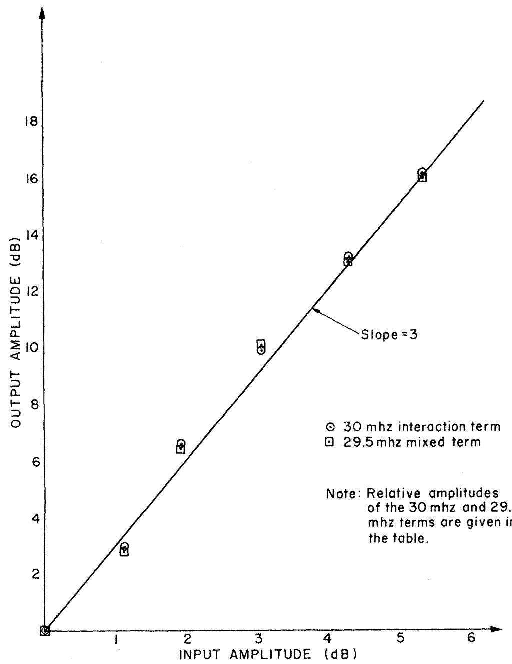

FIG. 2. Four-phonon process, outputs $S_{\omega_1+\omega_2+\omega_3}$ and $S_{2\omega_1+\omega_3}$ versus input amplitude $S_{\omega_1}+S_{\omega_2}+S_{\omega_3}$.

mentals. Then, by placing the illumination at its maximum, the sum-frequency amplitude was reduced by more than 18 dB while the fundamental amplitudes increased by about 10 dB. Similar results were obtained in the four-phonon case. Had this mixing been due to the transducers or the associated electronic equipment, then an increase in the fundamental amplitudes would have produced a corresponding increase in the amplitude of the sum-frequency term. As this relationship did not exist, and further, since the response of the 14-, 16-, and 30-MHz signals to changes in illumination correlates well with previous nonlinear electron-phonon interaction theories,[1,2] the observed mixing of the acoustic waves must have taken place within the cadmium sulfide.

In conclusion, by utilizing the ultrasonic amplifier under gain conditions, large-amplitude three- and four-phonon processes have been observed. The results obtained qualitatively confirm the nonlinear theory of multiple-wave interactions.

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[1]B. Tell, Phys. Rev. 136, A772 (1964).
[2]H. Kroger, Appl. Phys. Letters 4, 190 (1964).
[3]N. S. Shiren, Phys. Rev. Letters 11, 3 (1963).
[4]F. R. Rollins, Jr., L. H. Taylor, and P. H. Todd, Jr., Phys. Rev. 136, A597 (1964).
[5]D. L. White, J. Appl. Phys. 33, 2547 (1962).
[6]A. R. Hutson, Phys. Rev. Letters 9, 296 (1962).
[7]E. W. Prohofsky, J. Appl. Phys. 37, 4729 (1966).

ELASTIC MODULI AND DEBYE TEMPERATURES OF THE POLYCRYSTALLINE RARE-EARTH METALS AT 4.2 AND 300°K

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The low-temperature behavior of the rare-earth metals has been subjected to extensive studies from both theoretical and experimental points of view. However, interpretation of several experiments, for instance specific heat, magnetostriction, behavior under high pressure, etc., could be accomplished to a limited extent only because of the unavailability of data on the elastic moduli and Debye temperatures in the vicinity of the absolute zero. The lack of the low-temperature elasticity data on the rare-earth metals is mostly due to the difficulties in performing successful ultrasonic measurements in substances that undergo phase changes. In such cases, the choice of suitable ultrasonic couplants can be a difficult problem.

In the present Letter, we report the polycrystalline values of the Young's and shear moduli, the adiabatic compressibility, Poisson's ratio, and the Debye temperatures at 4.2 and 300°K. They are listed in Table I. These are preliminary results of a comprehensive study on the variation of the elastic moduli and ultra-

Table I. The elastic moduli and Debye temperatures of the rare-earth metals at 4.2 and 300°K.

Atomic No.	Element	Young's modulus (10^{11} dyn cm^{-2})		Shear modulus (10^{11} dyn cm^{-2})		Adiabatic compressibility (10^{-12} cm^2 dyn^{-1})		Poisson's ratio σ		Debye temperature (°K)	
		4.2°K	300°K	4.2°K	300°K	4.2°K	300°K	4.2°K	300°K	4.2°K	300°K
57	La	3.50	3.19	1.54	1.36	6.25	6.26	0.135	0.166	154	145
58	Ce[a]	3.25	3.37	1.33	1.36	5.09	4.64	0.223	0.240	139	144
59	Pr	3.62	3.60	1.39	1.39	3.34	3.48	0.297	0.291	146	146
60	Nd	4.52	4.07	1.78	1.58	3.01	3.19	0.272	0.283	163	153
62	Sm	5.18	4.80	2.03	1.87	2.62	2.64	0.273	0.284	169	164
63	Eu	2.07	1.82	0.90	0.79	10.2	11.3	0.144	0.155	117	109
64	Gd	6.27	5.57	2.53	2.22	2.51	2.63	0.237	0.254	184	173
65	Tb	6.02	5.79	2.37	2.29	2.26	2.47	0.272	0.260	179	174
66	Dy	6.16	6.29	2.47	2.57	2.46	2.65	0.248	0.223	178	181
67	Ho	7.37	6.63	3.08	2.73	2.46	2.56	0.198	0.216	195	184
68	Er	7.49	7.29	3.03	2.96	2.09	2.19	0.238	0.233	192	190
70	Yb	2.64	2.38	1.13	0.99	7.50	7.35	0.166	0.207	121	113

[a]The values of 4.2°K are for α-Ce. Those at 300°K are for γ-Ce.

sonic attenuations of the rare-earth metals, with particular emphasis on the effect of magnetic phase changes on these properties.

The high-purity (99.9+ %) rare-earth samples were supplied by Leytess Inc., New York, and by Johnson Mathey Company, England. An ultrasonic-pulse technique was employed at a frequency of 10 MHz. Experimental details and the method of data processing will be described elsewhere.[1] The estimated experimental error in the absolute values of the elastic moduli is 0.2 %. The Debye temperatures were determined to within 0.5°K.

It appears, from Table I, that the values of the elastic properties at 4.2 and at 300°K are quite close to each other. But between these extremal temperatures, the variation of the moduli and Debye temperatures with temperature displays peaks and humps that are much higher in magnitude than the values listed in Table I. Sharp peaks in the adiabatic compressibility appear at the magnetic transition temperatures in accord with the thermodynamic requirements.[2]

The variation of the elastic moduli at 4.2°K versus the atomic number, with the exception of Eu and Yb, exhibits a definite trend. The nature of this behavior is being studied in terms of the electronic structure of the rare-earth series. The room-temperature values tabulated in Table I can be compared with those given by Gschneider.[3] Discrepancies are probably due to the difference in metal purity.

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[1]M. Rosen, to be published.

[2]L. D. Landau and E. M. Lifshitz, Statistical Physics (Pergamon Press, London, England, 1958), Chap. 14, p. 430.

[3]K. A. Gschneider, Solid State Phys. 16, 275 (1964).