NONLINEAR ELASTIC AND THERMOELASTIC PROPERTIES
OF HIGH TEMPERATURE MATERIALS

Final Report

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Abstract

The pressure dependence of the single crystal elastic constants has been measured at 300°K for RbCl, RbBr, RbI, NaI, KI, wurtzite, and UO_2 , between 300 and 500°K for CsI, between 37 and 300°K for V_3Si and between 13 and 300°K for V_3Ge . Except for UO_2 and for the longitudinal moduli in wurtzite the pressure dependence was found to be nonlinear in the pressure range up to about 4 kbar for the rubidium halides, or 10 kbar for the other materials. The complete set of third order elastic constants has been measured at 300°K for UO_2 single crystals, for Al_2O_3 single crystals and for Al_2O_3 polycrystals. For vitreous silica the complete sets of third and fourth order elastic constants have been measured at room temperature. The results for most of the nonmetallic materials could be satisfactorily explained on the basis of the rigid ion model (alkali halides) and the shell model (UO_2). The data were used for the calculation of first and second Grueneisen parameters, both in the anisotropic continuum approximation and (for alkali halides) on the basis of the shell model, for the isothermal equation of state at high pressure, to the discussion of crystal stability in relation to high pressure phase transformations, and for the calculation of the pressure coefficients of the superconducting transition temperatures in V_3Si and V_3Ge . In general, good to fair agreement between the calculated measured quantities was obtained.

1. INTRODUCTION

1.1 Objective of Work

The objective of this work was to study the nonlinearity of the interatomic forces with respect to atomic displacements in high temperature materials (such as uranium compounds and alkali halide model substances) and in superconducting intermetallic compounds and to investigate their effect on anharmonic material properties. In order to pursue this end it was proposed, first, to measure the third order elastic constants at room temperature and (for certain materials) as a function of temperature and pressure; second, to interpret these data theoretically in terms of models for the interatomic forces; and third, to apply and to utilize the results in theoretical investigations on the thermal equation of state (pressure versus volume relation at high pressure, dependence of thermal expansion and elastic constants on temperature), on the theoretical strength for brittle fracture, and on the strain dependence of phonon frequencies in relation to high pressure phase transformations and the pressure dependence of the superconducting transition temperature.

1.2 Nature of Achievements and Unfinished Work

This report covers the total length of the AEC contract AT(30-1)-3991 for the period of 3 years and 10 months from June 1, 1968, through March 31, 1972.

The achievements consist of experimental data on the pressure dependence of the elastic constants, of third order elastic constants and for one material (vitreous SiO_2) of the complete set of fourth-

order elastic constants, of the theoretical explanation of the experimental results for ionic materials in terms of models for the interatomic forces, and of applications of both experimental and theoretical result to the explanation of a variety of anharmonic properties as outlined in detail in subsequent sections.

The materials investigated included six alkali halides, several oxide materials (UO_2 , Al_2O_3 , vitreous SiO_2), wurtzite, and the superconducting intermetallic compounds V_3Ge and V_3Si . Most data were taken at room temperature, except for CsI , where the pressure dependence of the elastic constants was determined between 300 and 500°K , and for V_3Ge and V_3Si , where the pressure dependence of the elastic constants was measured at and below 300°K down to 13°K .

For most of the ionic materials the experimental data could be well accounted for on the basis of rigid ion and shell model calculations. For V_3Ge and V_3Si the observed unusual behavior appears to be qualitatively attributable to electronic band structure effects, but it cannot quantitatively be explained on the basis of the density of states model of Labbé and Friedel.

The application of the experimental and theoretical results to the explanation of a variety of anharmonic properties shows in general good agreement between theory and experiment. This demonstrates the adequacy of the theoretical framework and it contributes to the understanding of the effect of crystal structure, type of chemical bond, and of the size of the constituting ions on anharmonic properties.

As is discussed in more detail in Section 3, the scientific and technological relevance of this work arises mainly from the increase of knowledge and understanding of material behavior at high pressure, from the atomistic understanding of anharmonic properties of materials of engineering relevance, and of the engineering relevance of certain anharmonic properties for a variety of technological applications.

As stated in a letter from Dr. D.K. Stevens to the Principal Investigator of February 19, 1971, the decision for the early termination of the contract "was to a large extent the result of budgetary stringencies imposed on the AEC budget by the President's FY 1972 Budget Request to Congress." Although continued funding was obtained for a period of one year from the National Science Foundation, this drop out support was at a reduced funding level and did not permit the orderly continuation or completion of all aspects of the work in progress. Among the projects which had to be discontinued due to lack of funds were:

- (1) Calibration and use of a newly acquired beta-press for extending the range for elastic constant measurements under purely hydrostatic pressure to about 30 to 35 kbar at room temperature. This would have permitted to determine the nonlinearity of the pressure dependence of elastic constants for materials less compressible than alkali halides, such as oxides and intermetallic compounds.
- (2) Use of a newly acquired pressure vessel for gas pressure up to about 15 kbar at room temperature with a bellows system

for the simultaneous generation of uniaxial compression and hydrostatic pressure. This would have permitted to measure the pressure dependence of the third order elastic constants of more compressible materials with applications to the theoretical understanding of the pressure dependence of the theoretical strength.

- (3) Theoretical work on the temperature dependence of the elastic constants, on the ionic size effect on anharmonic properties in a wider class of materials, and on the anisotropy and the pressure dependence of the theoretical strength for brittle fracture.

1.3 Graduate Student Training

At the time of the inception of this contract most government agencies, including the U.S. Atomic Energy Commission, requested the use of graduate students for performing a substantial portion of the proposed research. Consequently, a number of graduate students have been supported and trained under this contract. Three PhD degrees have been or will be awarded on the basis of research sponsored exclusively or predominantly under this contract. One graduate student was inducted into Military Service after a promising initial period of work under this contract. For two more graduate students the termination of this contract ultimately resulted in the loss of Federal support for their graduate research work.

2. SUMMARY OF WORK

2.1 Experimental Investigations

2.1.1 Pressure Dependence of Elastic Constants of Alkali Halides,

Wurtzite, UO_2 , V_3Si and V_3Ge

Rubidium Halides. The pressure dependence of the three second order elastic constants c_{11} , c_{12} and c_{44} has been measured for single crystals of RbCl, RbBr and RbI at 300°K. The measurements were restricted to the pressure range below the phase transition from the NaCl to the CsCl structure, which occurs between 4 to 7 kbar. Due to the high precision of the ultrasonic interferometer used it has been possible to observe the nonlinearity of the pressure dependence and to determine the second pressure derivatives in addition to the first pressure derivatives. The first pressure derivatives of c_{44} is negative for all three rubidium halides.

NaI and KI. The pressure dependence of the single crystal elastic constants has been measured at 300°K up to 10 kbar for NaI and KI and found to be nonlinear, so that the second pressure derivatives and three linear combinations of fourth order elastic constants could be determined in addition to the first pressure derivatives. The pressure coefficient of c_{44} is positive for NaI, but negative for KI.

CsI. The variation of the pressure dependence of the second order elastic constants of CsI with temperature has been measured between 300 and 500°K. From these measurements the temperature dependence of three linear combinations of the third and fourth-order elastic constants could be determined.

Wurtzite and Sphalerite. The five single crystal elastic constants of wurtzite (ZnS) have been measured at 25°C as a function of pressure, and at 1 bar as a function of temperature between 25 and 100°C. Within experimental accuracy the pressure dependence in the range up to 10 kbar was found to be linear for the longitudinal modes and quadratic for the shear modes. The elastic constants and their first pressure derivatives agree approximately with theoretical values for the hcp structure with first nearest neighbor central force interaction.

The elastic properties of sphalerite (ZnS) have been calculated from the data for wurtzite in the "equivalent sphalerite approximation" of Sullivan and used for discussing the dependence on ionic radii of the pressure coefficients of the elastic constants in sphalerite-type II-VI compounds.

UO₂. The pressure dependence of the three elastic constants of UO₂ have been measured up to 10 kbar at room temperature and found to be linear. All pressure derivatives are positive.

V₃Si and V₃Ge. The pressure dependence of the single-crystal elastic constants of V₃Si and V₃Ge has been measured from 37 to 298°K and 13 to 298°K, respectively. For V₃Si the first pressure derivative of the shear modulus $c_s = (1/2)(c_{11} - c_{12})$ is strongly temperature dependent and becomes negative at intermediate temperatures (between about 50 and 80°K). This behavior differs qualitatively from predictions based on the density of states model of Labbé and Friedel. For V₃Ge the first pressure derivatives of the longitudinal modulus c_{11}

and of the shear modulus are strongly temperature dependent and show deep minima at low temperatures.

2.1.2 Third Order Elastic Constants of UO_2 and Al_2O_3

The complete set of six third order elastic constants of single crystal UO_2 was determined at 300°K from ultrasonic velocity measurements under hydrostatic pressure and uniaxial stress. For Al_2O_3 the fourteen single crystal third order elastic constants and the three isotropic polycrystal third order elastic constants have also been measured.

2.1.3 Fourth Order Elastic Constants of Vitreous Silica

For vitreous silica the complete set of the second, third and fourth order elastic constants were determined experimentally at room temperature. This is the first material for which all fourth order elastic constants have been measured. The results agree within experimental error with a value for certain linear combinations of these constants which were obtained before by Powell and Skove from tensile experiments with whiskers.

The data will be used for an analysis of some anharmonic properties of vitreous silica and should add to the understanding of the unusual physical properties of noncrystalline solids in general.

2.2 Theoretical Investigations

2.2.1 Determination of Fourth Order Elastic Constants from Ultrasonic Wave Propagation in Stressed Crystals

From the Christoffel tensor for a crystal of cubic symmetry or for an isotropic material under hydrostatic and/or uniaxial stress

expressions have been derived for $(\rho_0 W^2)_{pp}$, $(\rho_0 W^2)_{p\sigma}$ and $(\rho_0 W^2)_{\sigma\sigma}$, where ρ_0 denotes the density at the undeformed state, W the natural velocity introduced by Thurston and Brugger, and the subscripts denote derivatives with respect to pressure p and/or stress σ . These equations permit the determination of the complete sets of 14 or 4 fourth order elastic constants from ultrasonic velocity measurements in crystals of cubic symmetry (classes O_h , O and T_d) and of isotropic materials under uniaxial stress and under hydrostatic pressure.

2.2.2 Isothermal Equation of State

All quantitative experimental work at high pressure has been hampered until today by the lack of an accurate high pressure scale. At a symposium on the "Accurate Characterization of the High Pressure Environment" (National Bureau of Standards, October 1968) it was estimated, for example, that the accuracy of the 100 kbar fixed point based on the phase transition in Sn is not more accurate than 6 percent. On the other hand, it is possible to set up a pressure scale on the basis of an equation of state, and to use the ultrasonic data on the pressure dependence of the elastic constants for calculating an empirical "ultrasonic equation of state" on the basis of a truncated Birch equation of state. This has been done for CsCl and CsBr at 300°K, and for CsI between 300 and 530°K. It is very significant that the ultrasonic equation of state turns out to be very accurate over a much larger pressure range than that used in the ultrasonic measurements themselves. A careful error analysis also shows that for example, at 400 kbar the accuracy of the ultrasonic

equation of state is comparable to, or even greater than, direct lattice constant measurements by means of a high pressure x-ray camera. The ultrasonic equation of state of CsI proposed on the basis of our work should therefore be useful as an independent pressure standard up to about 500 kbar and in the temperature range between 300 and 530°K and, through extrapolation, even above this temperature range.

2.2.3 Lattice Theory of Higher Order Elastic Constants

Theoretical investigations on the pressure dependence of the second-order elastic constants, on the third-order elastic constants and on the temperature dependence of these quantities have been carried out. The fact that for alkali halides the first pressure derivatives of the shear moduli depend on the cation only, but are virtually independent of the anion could be explained semiquantitatively on the basis of a Born-Mayer short range repulsive potential between first and second nearest neighbors. The ionic size effect is taken into account through the pre-exponential factors $b_{ij} = \beta_{ij} \exp(r_i + r_j)/\rho$, where r_i denotes the ionic radii, β_{ij} the Pauling factors ($\beta_{+-} = 1$, $\beta_{++} = 1.25$, $\beta_{--} = 0.75$) and $i, j = +, -$.

For UO_2 the experimental results can be explained on the basis of the shell model of Axe extended to the third order elastic constants of the fluorite structure by Srinivasan. The internal strain contributions are found to be significant.

2.2.4 Applications of the Anisotropic Continuum Model

The anisotropic elastic continuum model has been found to hold well for many materials in the high temperature limit for first and second-order anharmonic effects, such as the first Grueneisen parameter, the pressure dependence of the Grueneisen parameter and the temperature derivatives of the elastic constants. This is in part even true for materials with such complex crystal structure as the β -tungsten structure (V_3Si and V_3Ge). The anisotropic continuum model has also been used to calculate the pressure dependence of the superconducting transition temperature T_c in V_3Si and V_3Ge . It was found that the microscopic Grueneisen parameter of the transverse acoustic mode propagating in $[110]$ with polarization in $[1\bar{1}0]$ is necessary for the explanation of the large positive pressure coefficient of T_c in V_3Ge and for the explanation of the difference in behaviour between V_3Ge and V_3Si .

2.2.5 Lattice Dynamical Calculation of First and Second Grueneisen Parameters

General expressions for the thermal second Grueneisen parameter of Davies and Parke, $\xi = (1/pC_V)(\partial B^S/\partial T)_V$ are presented in the quasi-harmonic approximation, and the microscopic second Grueneisen parameter $\gamma'_\lambda(\vec{q}) = (V^2/\omega_\lambda(\vec{q}))(\partial\omega_\lambda(\vec{q})/\partial V^2)$ is derived from second order perturbation theory in the approximation of a general quasi-harmonic shell model with pressure dependent parameters. Numerical application is made to the calculation of the dispersion of $\gamma'_\lambda(\vec{q})$ and to temperature dependence of ξ , of the pressure derivative of the first Grueneisen parameter, and of the Anderson-Grueneisen parameter

$\delta_S = (1/\beta B^S)(\partial B^S/\partial T)_P$ for NaI, KI, RbCl, RbBr, and RbI. The parameters of the shell model were determined from experimental values of the elastic constants, of the static and optical dielectric constants, of the infrared absorption frequency, and from the first and second pressure derivatives of the first five of these quantities. The dispersion of the microscopic second Grueneisen parameter and the temperature variation of the thermal second Grueneisen parameters are considerably larger than for the corresponding first order quantities. The agreement with experimental data is fair to good.

2.2.6 Ionic Size Effects in Anharmonic Properties

An interesting sequence of interrelated ionic size effects occurs in the sign and magnitude of the pressure coefficients of the elastic constants, in the magnitude and temperature dependence of the thermal Grueneisen parameter, and in the transition pressure of high pressure phase transformations, such as from the wurtzite or sphalerite to the rocksalt structure, and from the rocksalt to the cesium chloride structure. For the alkali halides these effects could be semiquantitatively explained on the basis of Pauling's expression for the short range repulsive forces in terms of ionic radii. These effects are of considerable interest for a systematization and for the prediction of materials properties on the basis of crystal structure, type of chemical bond and ionic size effects.

3. SCIENTIFIC AND TECHNOLOGICAL RELEVANCE

While the work pursued under this contract belongs in the category of basic physical research and is primarily of scientific interest, it has also direct and indirect bearing on important technological applications.

First, basic physical property data characteristic of anharmonic behavior have been experimentally determined for a variety of materials, several of which are of considerable technological importance.

Second, for the ionic materials investigated, these data have been explained semiquantitatively in terms of theoretical models for the interatomic forces which in turn can now be used more confidently to explain other physical phenomena and materials properties.

Third, the application of the above data and/or models to the explanation of some anharmonic properties and effects has lead to a better qualitative and quantitative understanding of material properties at high pressure, and of the role of crystal structure, chemical bond and ionic size in determining anharmonic materials properties.

Anharmonic effects in general, arising from the nonlinearity of the interatomic forces and characterized by the higher order elastic constants, are related to various technological applications. Any understanding of these properties on an atomistic scale and the application of this knowledge to the development of materials more suitable for a given application could therefore benefit greatly

from the availability of these experimental data and of theoretical work devoted to the quantitative understanding of the materials investigated under this contract. The anharmonic properties referred to are thermal expansion and thermal conductivity, theoretical strength for brittle fracture, the melting temperature and the vapor pressure at high temperature, the phase diagram and the mechanism of displacive phase transformations and their dependence on hydrostatic and nonhydrostatic stress. A quantitative understanding of structure-sensitive and defect-controlled properties such as diffusion, radiation resistance, and corrosion resistance, also requires prior knowledge of the interatomic forces and anharmonic properties of the ideal crystal. Finally, it is obvious that a prerequisite for the understanding and prediction of the mechanical and thermal properties of composites (including, for example, surface coatings) is that the corresponding data for the single phase materials are available.

The materials investigated under this contract belong to six different crystal structures: rocksalt, fluorite, wurtzite, tungsten, corundum and vitreous silica.

Rocksalt-type materials that have been investigated are alkali halides which are well suited as model substances to study the properties of this class of materials. The mono-carbides and mono-nitrides of uranium and plutonium (UC, PuC, UN and PuN) which are actual or potential fuel materials in nuclear reactors occur in the rocksalt structure. Other mono-carbides and mono-nitrides occurring in the rocksalt structure are TiC, ZrC, TaC, which have found

important applications as high temperature hard materials, and NbC and NbN which have relatively high superconducting transition temperatures and are therefore promising starting materials for developing high transition temperature composite-superconductors. In this connection one should remember that the superconducting transition temperature depends sensitively on the phonon spectrum, which includes for strongly coupled and strongly anharmonic superconductors the higher order coupling parameters that determine the phonon-phonon interaction. In addition, the pressure dependence of the superconducting transition temperature depends on the anharmonic properties of the crystal. For a quantitative understanding of the high superconducting transition temperature and systematic attempts to raise this temperature, full information on the anharmonic properties is therefore required.

The only fluorite-type material investigated experimentally under this contract is UO_2 . While the technical importance of this compound follows, of course, from its use as reactor fuel, a specific question of scientific interest is, for example, whether UO_2 undergoes an as-yet-undiscovered high pressure phase transformation to the $\beta\text{-PbCl}_2$ structure, as some earth-alkali halides do.

Wurtzite-type materials are of interest because of their unusually low thermal expansion coefficient, their large thermal conductivity, and their high melting temperature. They exhibit an anomalously high vapor pressure which frequently exceeds one atmosphere before these materials melt. All these properties are related to the very unusual

pressure dependence of the phonon frequencies and the details of the high pressure phase diagram. Both materials find practical use in numerous industrial applications. ZnO, for example, is used as a constituent in polymer composites. Other wurtzite-type materials of technical interest are SiC, which is characterized by its high temperature hardness and NbN and TaN, which are also potentially useful starting materials for the development of high transition temperature superconductors.

The materials occurring in the beta-tungsten structure which have been investigated are V_3Ge and V_3Si . Interest in these materials originates from the fact that the beta-tungsten structure seems to be the most favorable one for high temperature superconductivity. The superconducting transition temperature of V_3Si is 17°K and that of $Nb_{0.79}(Ge_{0.25}Al_{0.75})_{0.21}$ 20.98°K. As mentioned above in connection with the carbides and nitrides of niobium, the superconducting transition temperature is related to the anomalously large anharmonicity of the phonon system and can be studied in terms of the higher order elastic constants.

The corundum structure consists of a slightly distorted hexagonal close-packed structure of oxygen ions with the Al-cations occupying two thirds of the octahedral interstices. Practical applications of corundum-type materials range from high strength ceramics to acousto-optic and ultrasonic devices and use as a laser host. Fundamental physical property data, such as the third order elastic constants are necessary for the theoretical understanding of many of the favorable properties of this material.

Vitreous silica consists of an open network of interlinked SiO_4 tetrahedra which give rise to many unusual physical properties (low thermal expansion and thermal conductivity, high mechanical strength, low ultrasonic attenuation) with numerous technological applications. Third and fourth order elastic constant data are a prerequisite for the theoretical understanding of many of the unusual properties of this material and for testing any theoretical model purporting to explain these properties.

4. PERSONNEL

The following personnel have been employed under this contract during at least some part of the total contract period from June 1, 1968 to March 31, 1972:

Principal Investigator:

G.R. Barsch, Professor of Physics

Postdoctoral Assistants:

B.N.N. Achar, Research Associate

Z.P. Chang, Research Associate

S.Y. La, Research Associate

H.E. Shull, Research Associate

Graduate Assistants:

P.F. Carcia, Graduate Student in Solid State Science

L. Bonczar, Graduate Student in Physics

E. Chang, Graduate Student in Physics

M. Duffy, Graduate Student in Physics

D.C. Miller, Graduate Student in Solid State Science*

H.E. Shull, Graduate Student in Engineering Mechanics

Research Assistant:

J. Schiff, Computer Programmer

Technical Assistant:

E. Jones, Technician

*Inducted into Military Service, July 1969

5. PUBLICATIONS

1. G.R. Barsch and Z.P. Chang, "Ultrasonic and Static Equation of State for Cesium Halides," in: E.C. Lloyd, Ed., Accurate Characterization of the High Pressure Environment, p.173-186, NBS Special Publications 326, Washington (1971).
2. Z.P. Chang and G.R. Barsch, "Pressure Dependence of the Elastic Constants of RbCl, RbBr, and RbI," J. Phys. Chem. Sol. 32, 27-40 (1971).
3. G.R. Barsch and H.E. Shull, "Pressure Dependence of Elastic Constants and Crystal Stability of Alkali Halides: NaI and KI," phys. stat. sol. (b) 43, 637-649 (1971).
4. P.F. Carcia, G.R. Barsch and L.R. Testardi, "Pressure Dependence of Elastic Constants and of Shear-Mode Instability in V_3Si and V_3Ge ," Phys. Rev. Lett. 27, 944-947 (1971).
5. G.R. Barsch and B.N.N. Achar, "Shell Model Calculation of Second Gruneisen Parameters and of Pressure Dependence of First Gruneisen Parameters for Alkali Halides," in M.G. Graham and H.E. Nagy, Eds., Thermal Expansion-1971, AIP Conf. Proc. No. 3, p. 211-230, Am. Inst. Phys., New York (1972).
6. E. Chang and G.R. Barsch, "Pressure Dependence of Single Crystal Elastic Constants and Anharmonic Properties of Wurtzite," J. Phys. Chem. Sol. 34 (1973, in press).
7. P.F. Carcia and G.R. Barsch, "Pressure Dependence of Elastic Constants and of Superconductivity for V_3Ge ," Phys. Rev. (submitted, 1973)*.
8. P.F. Carcia and G.R. Barsch, "Pressure Dependence of Elastic Properties in Relation to Soft Mode Behaviour and Superconductivity in V_3Si ," phys. stat. sol. (to be submitted, 1973)*.
9. H.E. Shull and G.R. Barsch, "Determination of Fourth-Order Elastic Constants from Ultrasonic Wave Propagation in Stressed Crystals," J. Acoust. Soc. Am. (to be submitted, 1973).
10. H.E. Shull and G.R. Barsch, "Fourth Order Elastic Constants of Vitreous Silica," J. Acoust. Soc. Am. (to be submitted, 1973).
11. Z.P. Chang and G.R. Barsch, "Third Order Elastic Constants and Anharmonic Properties of UO_2 ," Phys. Rev. (to be submitted, 1973).

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12. J.H. Gieske and G.R. Barsch, "Third-Order Elastic Constants of Single Crystal and Polycrystal Sapphire," J. Appl. Phys. (to be submitted, 1973)**.
13. Z.P. Chang and G.R. Barsch, "Pressure Dependence of Elastic Constants of CsI as a Function of Temperature," J. Phys. Chem. Solids (to be submitted, 1973)*.
14. G.R. Barsch, S.Y. La, Z.P. Chang and H.E. Shull, "On the Validity of the Anisotropic Elastic Continuum Approximation for the Calculation of First and Second Grueneisen Parameters," J. Appl. Phys. (to be submitted, 1973)*.
15. R. Srinivasan and G.R. Barsch, "Exchange Charge Model for Third Order Elastic Constants of Diamond, Silicon and Germanium," Phys. Rev. (to be submitted, 1973).

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6. PAPERS PRESENTED

1. G.R. Barsch and Z.P. Chang, "Ultrasonic and Static Equation of State of Cesium Halides," Symposium on the Accurate Characterization of the High Pressure Environment, National Bureau of Standards, Gaithersburg, Md., Oct. 1968.
2. G.R. Barsch, "Third Order Elastic Constants of Nonmetallic Solids," Gordon Research Conference on "Solid State Studies in Ceramics," Meriden, N.H., August, 1969.
3. G.R. Barsch and B.N.N. Achar, "Shell Model Calculation of Second Grüneisen Parameters and of Pressure Dependence of First Grüneisen Parameters for Alkali Halides," Symposium on Thermal Expansion, Corning, N.Y., Oct. 1971.
4. P.F. Carcia and G.R. Barsch,* "Pressure Dependence of Elastic Constants and Anharmonic Properties of V_3Ge and V_3Si ," 1973 March Meeting of the American Physical Society, San Diego, Calif., March 1973.

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7. THESES COMPLETED, DEGREES GRANTED

1. H.E. Shull, PhD in Engineering Mechanics, December 1969.
"Higher Order Elastic Constants and Anharmonic Properties of Cubic Crystals with Application to NaI, KI and Vitreous Silica."
2. P.F. Carcia,* PhD in Solid State Science, December 1972.
"Pressure Dependence of Elastic Properties in Relation to Soft Mode Behaviour and Superconductivity in V_3Ge and V_3Si ."
3. E. Chang,* PhD in Physics, September 1973. "Pressure Dependence of Elastic Constants in Relation to High Pressure Phase Transformations and Anharmonic Properties of Wurtzite, Sphalerite and Zinc Oxide."

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