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OPTICAL AND ELECTRONIC PROPERTIES OF LUMINESCENT AND OF METASTABLE
JUL 82 D BERRY, F WILLIAMS

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OPTICAL AND ELECTRONIC PROPERTIES
OF LUMINESCENT AND OF METASTABLE SOLIDS

FINAL REPORT

DAVID BERRY AND FERD WILLIAMS

JULY 29, 1982

U. S. ARMY RESEARCH OFFICE

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PHYSICS DEPARTMENT, UNIVERSITY OF DELAWARE, NEWARK, DE 19711

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Theoretical and experimental studies have been completed on donor-acceptor pair spectra including effects of electron-phonon interaction and on the effects of hydrostatic pressure on the luminescence of point and molecular dopants. The direct effect of pressure on the adiabatic potentials of the dopants and effects of anharmonicity of these potentials are included. Effects on vibronic spectra are determined. The theory of effects of hydrostatic pressure is extended to effects of uniaxial stress, thus unifying theoretical analyses of applied mechanical stress. Specific materials investigated include GaP:Zn,S; SnSe:In, Li		

20. ABSTRACT (con't.)

ZnS:Cu; and alexandrite ($\text{BeAl}_2\text{O}_4:\text{Cr}^{3+}$). Both temperature and pressure dependence of the spectrum of alexandrite have been measured and interpreted. Also, the anisotropy and twinning of cubic ZnS and the effects of pressure on spectra of molecular crystals have been clarified. Collaboration with several ARRADCOM laboratories continues.

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I. Introduction

The aim of the research of this grant has been the study of electronic properties of materials through the use of optical techniques, in particular, using the luminescence of the materials. In conjunction with the use of the optical probing, we have studied the changes of optical properties when external stresses were applied to our samples. This research has involved a concerted effort in both theory and experiments.

The primary areas of research have been the study of material showing donor-acceptor pair sharp line spectra and the pressure effects on optical properties of solids. In the first area of research, we have investigated materials like GaP:C,S and ZnO:Cu; in the second area, we have looked at the properties of materials such as alexandrite ($\text{BeAl}_2\text{O}_4:\text{Cr}^{3+}$).

In both of these areas, we have added to the fundamental theoretical understanding and also carried on correlated experimental research. In the area of donor-acceptor pair work, we have advanced the understanding of the electron-phonon interaction as to its effects on the donor-acceptor pair spectra, both by theoretically deriving the form of the R-dependent terms arising from this interaction and by experimentally verifying the derived form. In the area of stress effects, we have clarified the present situation in the fields of uniaxial and hydrostatic stress effects, in particular, to the unity that is possible of the theoretical points of view and to some correction needed in each field. In addition, since the pressure effect plus the use of luminescence give details about the adiabatic potential, we have found that, although this combination can be a powerful additional tool for understanding electronic properties of solids, each type of spectrum must be individually analyzed using as much information available about the center

as possible with the general outline of the method of analysis of pressure effects within the adiabatic approximation used being that which we have developed.

This grant was a continuation of an ongoing research program here at the University of Delaware on the optical and electronic properties of solids. This present 3-year report is the updating of the last 5-year report that we completed on February 26, 1979⁽¹⁾.

The work of this grant has involved collaboration with the U.S. Army laboratories of ARADCOM and with American and foreign laboratories who were doing related types of research. These interactions have helped in the general work done on this grant, both by direct interactions done in concert with us on grant-oriented projects and in general stimulation of the research group.

In Section II, we give a brief review of the work done for this grant. For additional details of the work done, see the publications produced under this grant which are listed in Appendix I. In Section III, we list the laboratories and personnel with whom we have interacted. Section IV sums up the achievements and conclusions of the present grant, and Appendix II lists the group's personnel involved in the work done on the present grant/contract.

II. Research Done on Grant /Contract

A. Pressure Effects on Luminescent Spectra

In this part of the research program, we carried on concurrent theoretical and experimental efforts. The experimental aspect was concerned with the effects of hydrostatic pressure, whereas the theoretical aspect was concerned with both hydrostatic and uniaxial stress effects and their underlying unity.

During the initial stage of this 3-year period, work was completed on the basic theory of the effects of hydrostatic pressure effects on luminescent spectra. At that time, the current theory in the literature⁽²⁾ assumed that, when explaining the effects of pressure within the adiabatic approximation, the pressure only changed the most probable configuration but did not change the adiabatic potentials surfaces. We determined, from an analogy with a system consisting of a spring and an added mass, that this theory gave inconsistent results for the effects of pressure when the harmonic approximation to the adiabatic potentials was used. We developed a theory of the effects of pressure which included both the effects on the most probable configuration and on the adiabatic potentials. This theory was developed for anharmonic as well as harmonic adiabatic potentials and for broad band as well as vibronic structure spectra. This initial development made the simplifying assumption that both the pressure effect and the Stokes' shift take place along the same configurational coordinate axis.

In later development of the theory made by us, we clarified some of the changes that would arise within the context of this theory if more than a single configurational coordinate were involved when considering both the optical and pressure phenomena. In this connection, with each addition of

generalization, new parameters characterizing the more general adiabatic potential are introduced making the theory less valuable as a theoretical tool unless these additional parameters can be found from other experimental results. We then applied our theory to experimental results that are in the literature. The results of the application of our theory to some of the data in the literature, as compared to the Erickamer, Frank and Slichter (DFS) theory⁽²⁾, did not differentiate between the two theories, but instead indicated that the results of the pressure effects could not be predicted from a simple one-dimensional adiabatic model; and, on the other hand, the data were not accurate enough so that the use of a model having many parameters would have had much value. Therefore, we initiated an experimental program so that we could get a broad range of different types of data for a given material of an accuracy needed to use the new theoretical tool of the pressure effects and concurrently continued the application of our theory to the data in the literature by modification to our general theory. Both the experimental program and the application of our theory to particular systems are ongoing programs.

In the case of the application of our theory, we have recently completed work for some organic compounds in which an harmonic approximation is used for the adiabatic potential curves, but some anharmonic effects and/or multi-dimensional configurational coordinate effects are introduced. We then compared our results with similar results obtained for the DFS theory and found that neither theory gave a good explanation of the data, and that this is probably due to the incorrect incorporation of the anharmonic effects.

In addition, we looked at the stress data of Laisaar and of Rolfe and his coworkers on molecular defects in alkali halides. Some preliminary

results were obtained for these materials; however, the Laisaar work was done at room temperature with hydrostatic pressure and the work of Rolfe and coworkers was done at liquid helium temperature with uniaxial stress. From both data it could be seen that anharmonic effects were important and that the data did not correlate well. From the Rolfe data we could ascertain that each of the Laisaar peaks of the vibronic structure was composed of a zero-phonon line plus a phonon side band, and that the phonon side band did not follow the zero phonon line. Therefore, the reported Laisaar data were an averaging of the effect for the zero-phonon line and the side band, whereas the reported Rolfe data were for the zero-phonon line only. However, using the Laisaar data we were able to show a correlation between the determined value of the parameters defining the adiabatic potential for different alkali halides for the same molecular impurity and the orientation of the molecule in the lattice as determined by Rolfe.

On the experimental side of the program, we initially began with the study of the donor-acceptor pair spectra of GaP:Cd,O. We received from Dr. Harry Fair of ARADCOM some initial instruction in the use of the diamond anvil cell at room temperature, and with his help initiated work on the GaP:Cd,O. We later added to the system so that we could use the cell in the temperature range of 100^oK to 300^oK and in the pressure range of 1 Kbar to 40 Kbars.

The initial room temperature pressure study of GaP:Cd,O showed that the near-neighbors pair band of the Cd-O pairs in GaP showed a red shift. At room temperature this material does not show a sharp line pair spectra and, therefore, the analysis is complicated, in that the observed effects are average effects of the many-pair lines and the broad band

background. We are continuing this part of the experimental program by having pressure measurements on donor-acceptor pair spectra done at liquid helium temperature by Dr. Yersin in Regensburg, West Germany.

A second phase of the experimental program on the hydrostatic pressure effects has been the study of alexandrite ($\text{BeAl}_2\text{O}_4:\text{Cr}^{3+}$). In this work, we looked at both the temperature and the pressure effects on the R_1 and R_2 lines, on the phonon side bands, and on the superimposed structure which overlap the phonon side bands. The pressure measurements have been done both at room temperature and at 100°K . The general results are:

(A) for the R_1 and R_2 lines, (1) that there is a red shift with pressure and with temperature and, therefore, both these shifts cannot be explained by assuming that the temperature variation and pressure cause a change in the specific volume, (2) that the pressure shift for the ruby R_1 and R_2 lines are larger than for alexandrite, (3) that the R_1 and R_2 lines shift linearly for alexandrite as they do for ruby, (4) that the ratio of the intensity of the R_1 line to the R_2 line increases with pressure, and (5) that the half-width decreases with pressure; (B) for the broad band that there is a blue shift with pressure and (C) for the superimposed line structure, e.g., the lines at 6500\AA , 6900\AA and at 6950\AA , (1) that there is a red shift which is linear with pressure, and (2) that there is a relative enhancement of this structure as compared to the broad band background.

From the temperature measurements on the R_1 and R_2 lines activation energy for transition between the lines is found to be 4.4 meV which is in agreement with their separation, and a non-radiative activation energy of 73 meV.

We have used a McCumber and Sturge⁽³⁾ analysis of the temperature dependent of the R_1 and R_2 line in the alexandrite and found that this theory

gives good agreement with the experimental results when the Debye temperature is chosen to be $\theta_D = 732\text{K}$ as compared to $\theta_D = 760\text{K}$ for ruby. However, when a simple extension of the McCumber and Sturge analysis is made to include the effects of pressure, it is found that the magnitude of the predicted effect is an order too small and the dependence is not linear. This research is still continuing, in particular, the analysis of the pressure effects on both alexandrite and ruby. For these systems, in order to explain the pressure effects, we believe we must involve more than one configurational coordinate and, therefore, use of more than just the optical pressure effects measurements is advisable.

In addition to the research on the hydrostatic pressure effect, we have begun theoretical research into the effects of uniaxial stress with the aim of having a combined theoretical-experimental research program on stress effects on luminescent materials. The initial theoretical work was to show the unity of the analyses for hydrostatic and uniaxial stress effects, and, in particular, to extend the basic procedure used for hydrostatic stress effect on single minimum adiabatic potential surfaces to multi-minimum Jahn-Teller adiabatic potential surfaces. From this work we have two initial results: First, the linear splitting between equivalent Jahn-Teller minimum arises because of the work done against the external pressure when changing configurations from one minimum to the other and not from induced strains. The second result involves the form of the Hamiltonian to be used for uniaxial stress. It is usually assumed that the stress Hamiltonian is the same as the strain Hamiltonian; however, from our general analysis, we have found that these Hamiltonians differ by a term which is the product of the pressure times the configurational coordinate, and that it is this term that represents

the work done against the pressure when we change configurations.

We have done an initial investigation of the F^+ center in CaO for which a large amount of information about the adiabatic potential surfaces is known. This center is a Jahn-Teller center. The form of the adiabatic potential surface is found by assuming that the T_2 and E modes are "equally coupled" to the F^+ center. However, our initial results using this assumption gave about equally accurate predictions, as does the usual theory. However, the result must be interpreted differently, that is, as to the cause of the splitting. On the other hand, we believe that both methods would give better results if we relax the condition that the T_2 and E modes are "equally coupled" to the condition that both modes are strongly coupled but not necessarily "equally coupled." This research is ongoing.

We note that the analysis which was developed by Curie, Berry and Williams⁽⁴⁾ (see also papers 5,6,7,9 and 13 of Appendix I) yields in the harmonic approximation a quadratic dependence on pressure of zero-phonon transitions but including the effect of anharmonicity yields in addition a linear pressure dependence. We have now identified this linear dependence on pressure as arising from the differences in the changes of zero-point energies for the two electronic states with pressure. In order to fit the experimental pressure dependence of the R-lines of alexandrite and of ruby two conditions must be satisfied:

(1) The differences in anharmonicity of the excited and ground states must be big enough to explain the linear pressure coefficient, and

(2) The force constants and coupling constants must both be almost the same for the two electronic states in order for the quadratic dependence on pressure to not be evident, at least up to 100 k bars.

We have estimated the anharmonicity difference on the basis of anharmonicity contributing 10% of the zero point energy for the excited state and find that this yields a pressure coefficient adequate to explain the linear pressure dependence; since the excited and ground states for the same electronic configuration and differ only in ν_{sp} , force constants as well as coupling constants with the applied pressure are expected to be very nearly the same for the two states, although no quantitative estimate of differences has as yet been made.

B. Donor-Acceptor Pairs

The research program on donor-acceptor pairs has been an ongoing research project of the present group for many years. Within this subsection of the research, we have a strong, direct interaction of the theory and experiment. The basic theoretical and experimental aspects of the donor-acceptor pair spectra were well understood by the mid-1960's. However, since these spectra contain so much detailed information about the interactions within the solid, the complete analysis of the data is not possible at the present time. For example, the energy difference for inequivalent pairs having the same separation distance is not well understood at this time. The R dependence of the energy spacing of the pair lines beyond the simple one over R term is just now being understood. It is this latter problem which we have worked on during the present period of this grant.

At the beginning of this grant, Kartheuser, Evrard and Williams worked out the details of the effects of the electron-phonon interaction on the donor-acceptor pair spectra showing that the additional R -dependent terms for the transition energy of the donor-acceptor pair involved a term which was a product of a power function of R times an exponential term. They gave the explicit form of this term for several different situations, for example, for pairs having unequal Bohr radii. (See the paper number 4 in Appendix I.) In this work they explicitly gave results of computer analysis of their theory for the material ZnSe:Li,In , from which they improved the determined value of the static dielectric constant by using data in the literature and showed that this improved theory gave a better fit to the data for near-neighbor pairs than the one over R term alone does.

In addition, experimental research was carried out on GaP:C,S to verify the explicit form of these additional terms in the expression for the transition energy, as well as showing that these terms would give a better fit to the data. At present, we have been able to show that these additional terms are exponential with R. However, both the explicit form of the R-dependent coefficient of the exponential term and, therefore, the explicit value of the constant in the exponential have not been verified because of difficulties in the numerical analysis. This part of the research is continuing.

Another aspect of the experimental research on the material GaP:C,S is the explicit temperature dependence of explicit pairs. In particular, the comparison is made of the temperature dependence of two different pairs having approximately the same separation but which have different characteristics as to being composed of a singlet or doublet of inequivalent pairs. In particular, during this period we have been investigating the 21st and 22nd nearest-neighbor pairs. We have studied earlier, in a similar manner, the 14th and 15th nearest-neighbor pairs and plan to compare the two results to find variation of this temperature variation with R. The 21st pair is a doublet and the 22nd is a singlet for this system. This analysis is continuing in conjunction with the work on the overall aspect of the spectrum mentioned above. We expect to find that the de-activation energy for each pair is R-dependent, from which we expect to verify the fact that the de-activation process is the thermal activation from the pair excited state in which either the electron or hole is first captured, followed by recapture in a different pair having deeper energy levels, that is, deeper relative to the band edge because of a larger R-separation.

Another aspect on the donor-acceptor pair research is our return to doing experimental work on ZnS:Cu,Ga crystals. On an earlier grant of which this grant is a continuation, we had grown single crystals of ZnS with various impurities including donor-acceptor pairs. Although we saw evidence for donor-acceptor pair recombination in the spectra from these crystals, e.g., ZnS:Cu,Ga, we never saw the primary evidence for donor-acceptor pair recombination of a distinct, sharp multi-line spectrum having the characteristic structure in the energy separation of the donor-acceptor pair spectrum. Although this type of sharp line spectrum has been seen in IV-IV compound, e.g., Si; III-V compound, e.g., GaP, and II-VI compound, e.g., ZnSe, it has not been seen in the important luminescent host material ZnS. Therefore, the question arises as to the reason that this type of spectrum is not seen in this material. The most likely answer is that most of the acceptors in ZnS are very deep, therefore, leading to a small overlap of the electron and hole wavefunctions and, therefore, to a small transition probability. If this is the case, then the interesting experiment to be performed to verify this assumption and to learn more about the acceptor properties in ZnS, is to do a combined band-to-band optical pumping and infrared excitation of the acceptor in order to see an excited state sharp line donor-acceptor pair spectra. This work was initiated near the end period of the present grant by Visiting Professor Kramer of Hunter College. This research is still ongoing.

Another material looked at in connection with donor-acceptor pair spectra is the material ZnO:Cu. Here the copper goes in both substantially and interstitially forming acceptors and donors, respectively. The infrared

radiation can be explained as arising from near neighbor donor-acceptor pair transitions. The particulars of this explanation and the experimental data are now being put together for publication in cooperation with Professor Broser of the Technical University of West Berlin.

C. Other Research

In addition to the research mentioned above, we have investigated two other peripheral aspects of luminescent phenomenon. The first involves a survey of the non-radiative transition and the second the effects of isotopes on luminescence.

In connection with the non-radiative processes, we have surveyed both the general situation of the theory of radiationless processes in molecules and solids and the particular situation for semiconductors. See Appendix I, papers 1 and 2. This survey allowed the group to become more acquainted with the present understanding of the radiationless processes. The conclusion we have drawn is that, although the present understanding is quite advanced, there is need for some critical experiments to pin down some specific points about the process. On the other hand, because of the new experimental techniques becoming available, for example, because of the superconducting bolometer, new experiments which can directly detect the phonons created will enable researchers to do some of the needed experiments. In particular, the question exists as to whether the non-radiative process is a simple transition from a low vibrational state of the excited electronic state to a high vibrational state of the ground electronic state followed by a cascade process or is the process one which goes through several intermediate electronic states. Since the non-radiative process is a process competing with the radiative one, it is important to understanding why given materials show the luminescence phenomenon and others do not.

The other peripheral research looked at was the isotope effect on zero-phonon spectra. With today's spectrometers very accurate measurements of the narrow zero-phonon lines can be made and, therefore, we can

measure the variation of these lines when the mass of the impurity and/or the mass of the ligands are changed, from which we can determine the effects of each of these masses on the effective mass of the mode. Because the effective mass is not independently measurable from the effective force constant for the mode, it is of interest to determine the effect of variations of the effective mass and of the variations of the force constant with respect to the masses of the different particles, both for the zero pressure, zero-phonon line shift and for the changes in the pressure effect coefficient. An initial consideration of these effects has been made.

As this grant is the continuation of an earlier grant to our same group, we have completed work begun on an earlier grant, in particular, the publication of the research done on the anisotropy and twinning in cubic zinc sulfide crystals. In this work, using X-ray crystallography and thermal conductivity measurements, we have interpreted the structure of single crystals of zinc sulfide grown from the vapor as having the X-ray pattern of a face centered cubic structure with a pair of overlapping lattices due to rotational twinning in the [111] direction which we have interpreted as due to an inverted twinning. This research was done in collatoration with Dr. Garrett of ARADCOM (now with Bell Laboratories) and with Professor Ruban of the Free University of West Berlin.

III. Interactions

During the period of this grant, we have had many ongoing interactions which have helped with the work on this grant. In addition, we have interacted with personnel of ARADCOM on problems of interest to them.

1. Dr. Harry Fair of ARADCOM (Picatinny): With Dr. Fair, we have had ongoing interactions concerned with many different problems. For example, during the initial stages of this grant, we interacted with Dr. Fair in the initiation of our experimental hydrostatic pressure program. Present address: DARPA.

2. Dr. Sharma of ARADCOM (Picatinny): With Dr. Sharma, we have interacted on the question of the development and procurement of tritium lamps. Present address: Naval Weapons Lab.

3. Dr. Wiegand of ARADCOM (Picatinny): With Dr. Wiegand, we advised him on the growth of single crystal of NH_4NO_3 .

4. R. Tompkins of ARADCOM (Aberdeen Proving Ground): With Mr. Tompkins, we have interacted on the theory of the effects of pressure on luminescent spectra, particularly on an explicit application of the theory to organic materials. See publication 15 of Appendix I.

5. Dr. D. Curie of the Laboratoire de Luminescence (University of Paris, France): With Dr. Curie, we have interacted on a continuing bases on the theory of hydrostatic pressure in connection with work done on the grant.

6. Dr. I. Broser of the Institute für Festkörperphysik (Technical University of Berlin, Germany): With Dr. Broser, we have interacted on the effects of uniaxial stress and on isotope effects.

7. Dr. Evrard of the Institute of Physics (University of Liege, Belgium): With Dr. Evrard, we have interacted on the theory of electron-phonon interaction effects for donor-acceptor pair transitions.

8. Dr. B. Kramer of Hunter College (City University of New York):

With Dr. Kramer, we have interacted on the experimental investigation of the effects of infrared radiation on the luminescence of ZnS:Cu,Ga.

Many of these interactions are continuing at this time and will be kept ongoing in the future.

IV. Achievements and Conclusions

The main achievements of the research performed in connection with this grant are the following: (1) The determination that single cubic zinc sulfide crystals grown from the vapor have inverted twinning in the [111] direction, (2) the determination ϵ_0 to be 9.42 and $E_g - (E_A + E_D)$ to be 2.6823 eV for ZnSe:In,Li, (3) have confirmed that ϵ_0 is 11.02 for GaP, (4) have, in collaboration with the Laboratoire de Luminescence at the University of Paris, France, found that the pressure shift of the individual vibronic peak position of the S_2^- emission in scapolite is between 0.6 to 1.2 meV/kilo bars, depending on the vibronic peak, (5) have elaborated the different pressure effects involved in the pressure shift of the individual donor-acceptor pair line spectrum, in particular, for the case of ZnS phosphors, (6) have developed and applied an improved theory of the effects of pressure, both uniaxial and hydrostatic, on optical properties, (7) developed and applied an improved theory of the transition energies of donor-acceptor pairs which include the effects of electron-phonon interactions, and (8) have participated in several international forums related to luminescence.

In general, we have concluded that the use of pressure effects on optical properties can be a powerful tool for determining properties of the adiabatic potential. However, even though we have improved the general method of analysis which must be used in this study, each application of this analysis must be tailored, at present, to the particular situation under consideration. As of yet, the data and the theoretical understanding do not allow for broad classes of general analyses of the pressure effect on electronic properties. In connection with the work on donor-acceptor pair spectra, in general, we

have concluded that the inclusion of the electron-phonon interaction in the interpretation of the spectrum has allowed for a more accurate prediction of the spectrum. From this improved prediction, we are then able to determine more accurate values of the parameters involved in the modelling of the system and also more detail modelling. However, there are still some small variations which, as of yet, are not predictable by the application of this improved theory, which might be due to limitations of the adiabatic approximation and/or due to correlation effects. We also note that in both of these fields of research we are now probably pushing the adiabatic approximation to its limit of applicability within the present formulation of the approximation. This implies the need for a fundamental re-evaluation of the adiabatic approximation with an eye to its extension or development of a new type of approximation which has a wide use and ease of handling that will allow for approximate analytic solutions.

1. Final Report for grant numbers DAA-G29-76-G-0098 and DA-ARO-D-31-124-73-G83 on "Optical and Electronic Transport Properties of Luminescent Semiconductors, Amorphous Materials and Metastable Solids, Feb. 26, 1979 for U.S. Army Research Office.
2. H. G. Drickamer, C. W. Frank, and C. P. Slichter, Proc. Nat. Acad. Sc. U.S.A. 69, p. 933 (1972).
3. D. E. McCumber and M. D. Sturge, J. Appl. Phys. 34, p. 1682 (1963).

Appendix IPublications Completed under Grant since 1979

1. F. Williams, D. E. Berry and J. E. Bernard, "Present Trends in the Theory of Radiationless Processes," chapter in Radiationless Processes, edited by B. Di Bartolo (Plenum Press, N.Y., 1980) p. 1.
2. F. Williams, D. E. Berry and J. E. Bernard, "Radiationless Processes in Semiconductors," chapter in Radiationless Processes, edited by B. Di Bartolo (Plenum Press, N.Y., 1980) p. 409.
3. D. Curie, D. E. Berry and F. Williams, "Theory of the Effects of Hydrostatic Pressure on the Radiative Transitions of Crystals," Physical Review B20, p. 2323 (1979).
4. E. Kartheuser, R. Evrard and F. Williams, "Radiative Recombination of Donor-Acceptor Pairs in Polar Semiconductors," Physical Review B21 p. 648 (1980).
5. D. Curie, D. E. Berry and F. Williams, "The Franck-Condon Principle for Ions and Molecules in Crystals," Physical Review B22, p. 4109 (1980).
6. D. Curie, B. Canny, H. K. Liu, P. Jaszczyn-Kopec, D. E. Berry and F. Williams, "The Effects of Hydrostatic and Uniaxial Pressure on Vibronic Spectra," J. of Luminescence 24/25, p. 145 (1981).
7. D. Berry and F. Williams, "Theory on the Effect of Applied Stress on Luminescent Spectra Based on a Stress Hamiltonian," J. of Luminescence 24/25, p. 329 (1981).
8. F. Williams, "Review of Present Trends in Luminescence Research," J. of Luminescence 24/25, p. 929 (1981).
9. F. Williams, "Theory of Pressure-Dependent Spectra of Ions and Molecules in Crystals," chapter in the International Symposium on the Physics of High Pressure in Solids, edited by Shelton (North Holland, N.Y., 1981) p. 15.
10. F. Williams, "Quantum Mechanical Description of Solids," chapter in Collective Excitations in Solids, edited by B. Di Bartolo (Plenum Press, N.Y. 1982) in press.
11. F. Williams, "Present Trends in Collective Excitations in Solids," chapter in Collective Excitations in Solids, edited by B. Di Bartolo (Plenum Press, N.Y., 1982) in press.

12. W. L. Garrett, G. Ruban and F. Williams "Anisotropy and Twinning in Cubic Zinc Sulfide Crystals," J. of Physics and Chemistry of Solids 43, p. 497 (1982).
13. D. E. Berry, R. C. Tompkins and F. Williams, "Analysis of the Effects of High Pressure on the Spectra of Molecular Crystals," J. of Chemical Physics 76, p. 3362 (1982).
14. T. Kottke and F. Williams, "Effect of Hydrostatic Pressure on Luminescence of Alexandrite", to be submitted.

Appendix IIDegrees Granted and Personnel Supported by Grant 1979-PresentPresent affiliation shown in parentheses.

D. E. Berry (Research Associate)

D. Hoover, M. S. (1981) (Current Graduate Student)

T. Kottke, M. S. (1979), Ph.D. (1982)

R. Morillo-Soto, M. S. (1979) (Professor University Zulia, Maracaibo)

M. Martens (Research Associate)

F. Williams (H. Fletcher Brown Professor) summer support 1979, 1980, 1981