MATERIALS RESEARCH SOCIETY
SYMPOSIA PROCEEDINGS

VOLUME 22

High Pressure in Science and Technology

PART I

Collective Phenomena and Transport Properties

EDITORS

C. Homan

R. K. MacCrone

E. Whalley

NORTH-HOLLAND

High Pressure in Science and Technology

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MATERIALS RESEARCH SOCIETY SYMPOSIA PROCEEDINGS VOLUME 22

High Pressure in Science and Technology

Proceedings of the 9th AIRAPT International High Pressure Conference, Albany, New York, U.S.A., July 24-29, 1983

PART I

Collective Phenomena and Transport Properties

EDITORS:

C. Homan
Bénet Weapons Lab., USARRDC, Watervliet, New York, U.S.A.

R. K. MacCrone
Materials Engineering Department, Rensselaer Polytechnic Institute, Troy, New York, U.S.A.

E. Whalley
Division of Chemistry, National Research Council, Ottawa, Canada

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PREFACE

The 9th AIRAPT High Pressure Conference was held in Albany, N.Y., U.S.A. on 1983 July 24-29. The first conference was organized by Boris Vodar and was held in Le Creusot, France in 1965 August. It was followed by a second in Schloss Elmau, West Germany, in 1967, the third in Aviemore, U.K., in 1970, the fourth in Kyoto, Japan, in 1974, the fifth in Moscow, U.S.S.R., in 1975, and the sixth in Boulder, Colorado, U.S.A., in 1977. The seventh returned to the birthplace, Le Creusot, in 1979, and the eighth was held in Uppsala, Sweden, in 1981.

The ninth conference is, therefore, the second to be held in the U.S.A. Tentative plans had been made to have it in Canada, when a group from Albany independently proposed to have one there. Eventually the two groups met, and agreed to pool their resources and organize a joint U.S.A.-Canada conference. It departed from the preceding conferences by including four specialized symposia, on Collective Phenomena, Transport Properties, Fluids under Pressure, and High Pressure Engineering and Safety, as well as general sessions on all aspects of high pressure in science and technology. The two related symposia, Collective Phenomena and Transport Properties, were held in sequence, and they and the symposia on Fluids under Pressure each occupied a single sequence of sessions throughout the Conference. The symposium on High Pressure Engineering and Safety was also the Third International High Pressure Engineering Conference, which was the first held outside of the U.K. The first conference was held in London in 1967, and the second was in Brighton in 1975. Papers submitted to the general program were arranged in sessions according to subject. There were five plenary papers presented at the Conference, one for each of the four symposia and one for the general sessions. Invited and submitted papers were presented in both oral and poster sessions, except the papers in the symposium on Fluids under Pressure, which was presented orally.

Although there was an American and a Canadian Co-Chairman, and the organization of the sessions was done jointly by the American and Canadian organizers, the organization of the Conference itself was done largely by the American organizers in Albany, as it had to be because they were on the spot, and all the financial support came from the U.S.A. The staffs of the Department of Physics of the State University of New York at Albany and the Material Engineering Department of Rensselaer Polytechnic Institute contributed greatly to the organization and smooth running and deserve the wholehearted thanks of all of us.

During the Conference, the fourth award of the Bridgman Medal was made to Francis Birch for his major contributions to geophysics by measuring the equations of state of solids at high pressure, by analyses of the elastic properties of the earth's interior, and by his study of the heat flux in the deep earth. He has also received the Vetlesen Prize, the Arthur L. Day and Penrose Medals for the Geological Society of America, the William Bowie Medal of the American Geophysical Union, and the National Medal of Science. He was elected a member of the U.S. National Academy of Science in 1968 and was awarded its Legion of Merit Award.

C.G. Homan
R.K. MacCrone
E. Whalley

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CONTENTS OF PART I

COLLECTIVE PHENOMENA AT HIGH PRESSURE

TRANSPORT PROPERTIES AT HIGH PRESSURE

COLLECTIVE PHENOMENA

AT

HIGH PRESSURE

COLLECTIVE PHENOMENA AT HIGH PRESSURE

C. W. CHU AND M. K. WU
Department of Physics and Energy Laboratory, University of Houston, Houston, Texas 77096

ABSTRACT

The role of high pressure in the study of collective phenomena is briefly discussed by presenting the following four examples: (1) the destruction of superconductivity, (2) the creation of superconductivity, (3) instabilities and superconductivity, and (4) magnetism and superconductivity.

I. INTRODUCTION

In a condensed matter, there exist many types of interactions among the many particles present, resulting in the presence of many collective phenomena. In spite of the diversity of the interactions, almost all are electromagnetic in nature. An electromagnetic force is known to depend on the inter-particle distance and thus, to be pressure-sensitive. Even the quantum force which keeps condensed matter from totally collapsing due to the Heisenberg uncertainty principle has been shown to be pressure-dependent [1]. Consequently, the application of high pressure to a condensed matter is the most effective and simplest tool to probe and to modify its physical properties and sometimes even to create a new physical state which cannot be realized otherwise. The information obtained from high pressure studies has not only provided important bases for the testing of existing theories but also laid the foundations for the development of new models.

Collective phenomena consist of a large collection of interesting phenomena and form the bulk of discussions of this Conference. Fortunately, many of them have been discussed in this Symposium and many others will be covered in other Symposia of this Conference. Therefore, we decided to discuss the collective phenomena at high pressures by presenting only four examples involving superconductivity where pressure has played and will continue to play an important role. The examples are: (1) the destruction of superconductivity, (2) the creation of superconductivity, (3) instabilities and superconductivity, and (4) magnetism and superconductivity. Superconductivity has been established to be a common phenomenon in Nature. It is interesting not just in its own right but also for the insights that one can get in using superconductivity as a probe to other phenomena. The presentation of these examples should not lose its generality in demonstrating the important role of high pressure in the study of collective phenomena.

II. DISCUSSION

The use of high pressure techniques in the study of superconductivity is not new and can be traced back to Onnes and Sizoo [2] a few years after the discovery of superconductivity. However, the study then was only on Hg and restricted to about 1 kb and close to 4.2 K. Together with the advancement on material and our understanding of superconductivity, the availability of ultrahigh pressure and ultralow temperature today brings us to a new horizon in the study of superconductivity and other collective phenomena.

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II-1. The Destruction of Superconductivity

One of the triumphs of modern physics is the development of the microscopic theory of superconductivity, or the BCS theory [3]. The theory is based on the fundamental concept of pair-formation between electrons with a net attractive interaction, regardless of the strength or nature of the interaction. For an isotropic superconductor, by assuming that the attractive interaction V = constant for $|\varepsilon| < \hbar\omega_0$ and = 0 otherwise, and that the cutoff energy $\hbar\omega_0 \ll$ the Fermi energy ε_F (thus the electron density of states can be replaced by that at the Fermi surface N(0)) one obtains the well known BCS gap equation, the universal constant $\Delta(0)/(k_B T_C) = 1.75$ with $\Delta(0)$ being the superconducting gap at 0°K and k_B the Boltzmann constant, and the superconducting temperature

$$k_B T_C = 1.14\, \hbar\omega_0 \exp[-1/N(0)V] \qquad (1)$$

in the weak-coupling limit. By further assuming that such an attractive interaction arises from an electron-phonon interaction and the cutoff frequency ω_0 will then be replaced by the Debye frequency ω_D which, in general, is $\ll \varepsilon_F/\hbar$, Eq. (2) then becomes the well-known BCS T_C-expression

$$T_C = 1.14\, \Theta_D \exp[-1/N(0)V] \qquad (2)$$

The theory accounts for not only the fundamental properties of a superconductor but also the isotope effect of many superconductors although not all. Unfortunately, it gives a lower T_C than observed. By taking into consideration the time-dependent electron pairing interaction, McMillan [4] obtained a modified T_C

$$T_C = (\Theta_D/1.45) \exp\left[\frac{-1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}\right] \qquad (3)$$

with the effective electron-phonon interaction $\lambda = N(0)\langle I^2\rangle/M\langle\omega^2\rangle$, $\mu^* \sim 0.1$ being the Coulomb repulsion, $\langle I^2\rangle$ an average of the electron-phonon matrix element over the Fermi surface, M the atomic mass, and $\langle\omega^2\rangle$ a weighted average of the square of the phonon frequency. Presently, Eq. (3) is the most popular T_C-expression [5].

It has been shown [6] that, at least for low pressure, $\partial\ln\lambda/\partial\ln V = \partial\ln[N(0)\langle I^2\rangle]/\partial\ln V + \partial\ln[1/\langle\omega^2\rangle]/\partial\ln V = s + 2\gamma \equiv \phi$ where s is a negative constant and γ the Grüneisen constant. By neglecting the small pressure effect on μ^*, the volume dependence of T_C, is then given as

$$T_C = \frac{\Theta_D (V/V_0)^{-\lambda}}{(1.45)} \exp\left\{\frac{-1.04[1+\lambda_0(V/V_0)^{\phi}]}{\lambda_0(V/V_0)^{\phi} - \mu^*[1+0.62\lambda_0(V/V_0)^{\phi}]}\right\} \qquad (4)$$

The attempt to understand the occurrence of superconductivity through its destruction by pressure has existed for a long time [7]. However, not until recently have the limits of high pressure and low temperature made the attempt meaningful without extrapolation (to a certain extent). A few years ago, by incorporating the high pressure diamond cell with a dilution refrigerator, Gubser and Webb [8] measured the T_C of Al (1.17K at 1 b), which is known to be a well-behaved superconductor in the BCS sense, up to 62 kb down to 0.075 K. T_C was found to decrease with pressure continuously and follow well the simple relation obtained previously [7] for sp superconductors at lower pressures, $T_C/T_0 = 1 + \alpha\Delta V/V_0$, where T_0 is T_C at 1 b, α is a constant depending on material, ΔV the pressure induced volume