ULTRASONIC ATTENUATION IN
SUPERCONDUCTING CADMIUM

by

ROGER ALAN ROBBINS, B.S., M.S.

A DISSERTATION

IN

PHYSICS

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

DOCTOR OF PHILOSOPHY

Approved

Accepted

August, 1973

Copyright by
ROGER ALAN ROBBINS
1973

801
T3
1973
No. 76
Cic. 2

AEC-5a...

ACKNOWLEDGEMENTS

I am deeply indebted to Professor Billy J. Marshall for his direction of this dissertation and to the Robert A. Welch Foundation for financial support. I would also like to express my appreciation to Dr. Steven G. O'Hara and Dr. C. Rinn Cleavelin for helpful discussions and criticism, to Susie McCollar for typing the manuscript, and to my wife Anne, for her encouragement and support during this work.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.	Page ii
LIST OF TABLES.	v
LIST OF FIGURES	viii
I. INTRODUCTION	1
II. ULTRASONIC ATTENUATION METHOD AND EQUIPMENT	8
Introduction.	8
Ultrasonic Method	8
Electronic Equipment.	13
Equipment Performance	23
III. He ³ REFRIGERATOR DESIGN	31
He ³ Cryostat Design	34
Review of Literature.	34
Design Details.	38
Vacuum Systems	47
Thermometry	53
Superconducting Magnet.	55
Transmission Line Design.	60
IV. SAMPLE PREPARATION.	64
Preparation Requirements.	64
Spark Cutting Procedure	66
Spark Damage.	68
Transducer Bond	72
V. SAMPLE QUALITY INVESTIGATION.	74
Introduction.	74

	Page
Magnetoacoustics.	75
Outline of Theory	75
Magnetoacoustic Cryostat.	80
Magnetoacoustic Results	84
Magnetic Susceptibility	95
VI. RESULTS	99
Analysis Method	100
Results	107
Data for $\vec{q} [0001]$	108
Data for $\vec{q} [10\bar{1}0]$	115
Data for $\vec{q} [11\bar{2}0]$	115
Interpretation of Results	131
Summary	133
LIST OF REFERENCES.	135
APPENDIX A.	142
APPENDIX B.	149
APPENDIX C.	153
APPENDIX D.	158

LIST OF TABLES

Table	Page
1. Comparison of He ³ Cryostat.	36
C-1. Multiplying Factors	157
D-1. $\vec{q} [0001]$, Echo No. 1, 9.49 MHz	159
D-2. $\vec{q} [0001]$, Echo No. 1, 9.49 MHz	159
D-3. $\vec{q} [0001]$, Echo No. 1, 9.49 MHz	160
D-4. $\vec{q} [0001]$, Echo No. 2, 9.49 MHz	160
D-5. $\vec{q} [0001]$, Echo No. 2, 9.49 MHz	161
D-6. $\vec{q} [0001]$, Echo No. 3, 9.49 MHz	161
D-7. $\vec{q} [0001]$, Echo No. 3, 9.49 MHz	162
D-8. $\vec{q} [0001]$, Echo No. 2, 33.696 MHz	162
D-9. $\vec{q} [0001]$, Echo No. 1, 33.695 MHz	163
D-10. $\vec{q} [0001]$, Echo No. 1, 33.695 MHz	163
D-11. $\vec{q} [0001]$, Echo No. 1, 33.695 MHz	164
D-12. $\vec{q} [0001]$, Echo No. 2, 33.695 MHz	164
D-13. $\vec{q} [0001]$, Echo No. 2, 33.695 MHz	165
D-14. $\vec{q} [0001]$, Echo No. 2, 33.695 MHz	165
D-15. $\vec{q} [0001]$, Echo No. 1, 33.7 MHz	166
D-16. $\vec{q} [0001]$, Echo No. 1, 33.695 MHz	166
D-17. $\vec{q} [0001]$, Echo No. 1, 52.04 MHz.	167
D-18. $\vec{q} [10\bar{1}0]$, Echo No. 5, 10.3 MHz	167
D-19. $\vec{q} [10\bar{1}0]$, Echo No. 5, 10.3 MHz	168
D-20. $\vec{q} [10\bar{1}0]$, Echo No. 5, 10.3 MHz	168

Table	Page
D-21. $\vec{q} [10\bar{1}0]$, Echo No. 5, 10.3 MHz.	169
D-22. $\vec{q} [10\bar{1}0]$, Echo No. 5, 10.3 MHz.	169
D-23. $\vec{q} [10\bar{1}0]$, Echo No. 8, 10.3 MHz.	170
D-24. $\vec{q} [10\bar{1}0]$, Echo No. 8, 10.3 MHz.	170
D-25. $\vec{q} [10\bar{1}0]$, Echo No. 1, 33.7 MHz.	171
D-26. $\vec{q} [10\bar{1}0]$, Echo No. 1, 33.7 MHz.	171
D-27. $\vec{q} [10\bar{1}0]$, Echo No. 1, 33.7 MHz	172
D-28. $\vec{q} [10\bar{1}0]$, Echo No. 1, 33.7 MHz	172
D-29. $\vec{q} [10\bar{1}0]$, Echo No. 1, 54 MHz.	173
D-30. $\vec{q} [10\bar{1}0]$, Echo No. 1, 54 MHz.	173
D-31. $\vec{q} [10\bar{1}0]$, Echo No. 1, 54 MHz.	174
D-32. $\vec{q} [10\bar{1}0]$, Echo No. 1, 54 MHz.	174
D-33. $\vec{q} [10\bar{1}0]$, Echo No. 1, 70 MHz.	175
D-34. $\vec{q} [10\bar{1}0]$, Echo No. 1, 70 MHz.	175
D-35. $\vec{q} [10\bar{1}0]$, Echo No. 1, 70 MHz.	176
D-36. $\vec{q} [10\bar{1}0]$, Echo No. 1, 70 MHz.	176
D-37. $\vec{q} [10\bar{1}0]$, Echo No. 1, 94 MHz.	177
D-38. $\vec{q} [10\bar{1}0]$, Echo No. 1, 94 MHz.	177
D-39. $\vec{q} [10\bar{1}0]$, Echo No. 1, 94 MHz.	178
D-40. $\vec{q} [10\bar{1}0]$, Echo No. 1, 94 MHz.	178
D-41. $\vec{q} [11\bar{2}0]$, Echo No. 5, 8.7 MHz	179
D-42. $\vec{q} [11\bar{2}0]$, Echo No. 5, 8.7 MHz	179
D-43. $\vec{q} [11\bar{2}0]$, Echo No. 6, 8.7 MHz	180
D-44. $\vec{q} [11\bar{2}0]$, Echo No. 4, 8.7 MHz	180

Table	Page
D-45. $\vec{q} [11\bar{2}0]$, Echo No. 1, 31.2 MHz.	181
D-46. $\vec{q} [11\bar{2}0]$, Echo No. 1, 31.2 MHz.	181
D-47. $\vec{q} [11\bar{2}0]$, Echo No. 1, 51.2 MHz.	182
D-48. $\vec{q} [11\bar{2}0]$, Echo No. 1, 51.2 MHz.	182
D-49. $\vec{q} [11\bar{2}0]$, Echo No. 1, 70 MHz.	183
D-50. $\vec{q} [11\bar{2}0]$, Echo No. 1, 70 MHz.	183
D-51. $\vec{q} [11\bar{2}0]$, Echo No. 1, 70 MHz.	184
D-52. $\vec{q} [11\bar{2}0]$, Echo No. 1, 70 MHz.	184
D-53. $\vec{q} [11\bar{2}0]$, Echo No. 1, 70 MHz.	185
D-54. $\vec{q} [11\bar{2}0]$, Echo No. 1, 90 MHz.	185
D-55. $\vec{q} [11\bar{2}0]$, Echo No. 1, 90 MHz.	186
D-56. $\vec{q} [11\bar{2}0]$, Echo No. 1, 90 MHz.	186
D-57. $\vec{q} [11\bar{2}0]$, Echo No. 1, 90 MHz.	187
D-58. $\vec{q} [11\bar{2}0]$, Echo No. 1, 90 MHz.	187
D-59. $\vec{q} [11\bar{2}0]$, Echo No. 1, 90 MHz.	188
D-60. $\vec{q} [11\bar{2}0]$, Echo No. 1, 90 MHz.	188
D-61. $\vec{q} [11\bar{2}0]$, Echo No. 1, 108 MHz	189
D-62. $\vec{q} [11\bar{2}0]$, Echo No. 1, 108 MHz	189
D-63. $\vec{q} [11\bar{2}0]$, Echo No. 1, 108 MHz	190

LIST OF FIGURES

Figure	Page
1. Representative Oscilloscope Display of Exponential Pulse Echo Train.	10
2. Representative Echo on Expanded Time Scale with Display Scanner Marker on Top of Broad Echo Peak.	10
3. Instrumentation for Attenuation Measurements in the [0001] and [10 $\bar{1}$ 0] Directions in Cadmium	15
4. Instrumentation for Attenuation Measurements in the [11 $\bar{2}$ 0] Direction in Cadmium	20
5. Relative Timing Signals in Phase Sensitive Detection System of Figure 4.	22
6. Equipment Arrangement for Linearity Check of hp Scope, Display Scanner, and Arenberg Amplifier System.	25
7. HP 175A Oscilloscope and 1782A Display Scanner Linearity Check	26
8. Arenberg Pre-Amp and Wideband Linearity Check	27
9. Display Scanner Baseline Drift.	29
10. PAR Lock-in Amplifier Linearity Check	30
11. He ³ Cryostat.	33
12. He ³ Can and Associated Details (cm)	39
13. He ³ Vacuum System	48
14. High Vacuum System	51
15. Carbon Thermometer Calibration	56
16. Approximate Calibration of Superconducting Solenoid in He ³ Cryostat	57
17. Superconducting Solenoid	59
18. RF Transmission Line.	61

Figure	Page
19. Micrograph of Cadmium $[10\bar{1}0]$ Spark Planed Surface.	69
20. Laue X-Ray of Cadmium Surface Shown in Figure 19	69
21. Micrograph of Cadmium $[10\bar{1}0]$ Surface After First Etch Showing Striations Below Spark Craters	71
22. Laue X-Ray of $[10\bar{1}0]$ Surface After Last Etch Showing That the Strained Layer Has Been Removed.	71
23. Expansion of Surface and Origin of Striations	72
24. Magnetoacoustic Cryostat	81
25. Magnetoacoustic Zone Plot: $\vec{q} [0001]$, 30 MHz, 10 KG . . .	86
26. Magnetoacoustic Zone Plot: $\vec{q} [10\bar{1}0]$, 10 MHz, 10 KG . . .	87
27. Magnetoacoustic Zone Plot: $\vec{q} [11\bar{2}0]$, 10 MHz, 10 KG . . .	88
28. Attenuation vs. Magnetic Field $\vec{q} [10\bar{1}0]$, $H [0001]$, 50 MHz, $T = 1.5K$	89
29. Attenuation vs. $1/H^2$	90
30. High Field Attenuation vs. Frequency	91
31. Open Orbit Resonance Lines $\vec{q} [10\bar{1}0]$, $H [11\bar{2}0]$, 50 MHz, $T = 1.5K$	93
32. Electron Mean Free Path Length $\vec{q} [10\bar{1}0]$, $H [11\bar{2}0]$	94
33. Representative Graph of Magnitude of Resistance Mini- mum in Zn as a Function of Mn Impurity Content ⁷	96
34. Cd Magnetic Susceptibility vs. Temperature: 7 kg; x - Marcus ²⁷ , o - Present Work	98
35. Definition of Attenuation Terms and Their Relationships.	101
36. Effects of Ultrasonic Amplitude on Attenuation vs. Tem- perature Curve. Patterned After Lead Data of Tittman and Bommel ⁴	104
37. Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 9.49 MHz for $\vec{q} [0001]$	109

Figure

Page

38.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 33.7 MHz For $\vec{q} [0001]$	110
39.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 52 MHz For $\vec{q} [0001]$	111
40.	Energy Gap $2\Delta(0)$ vs. Frequency for $\vec{q} [0001]$	112
41.	Limiting Attenuation vs. Frequency for $\vec{q} [0001]$	113
42.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 10.3 MHz For $\vec{q} [10\bar{1}0]$	116
43.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 33.7 MHz For $\vec{q} [10\bar{1}0]$	117
44.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 54 MHz For $\vec{q} [10\bar{1}0]$	118
45.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 70 MHz For $\vec{q} [10\bar{1}0]$	119
46.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 94 MHz For $\vec{q} [10\bar{1}0]$	120
47.	Energy Gap $2\Delta(0)$ vs. Frequency For $\vec{q} [10\bar{1}0]$	121
48.	Limiting Attenuation vs. Frequency For $\vec{q} [10\bar{1}0]$	122
49.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 8.7 MHz For $\vec{q} [11\bar{2}0]$	123
50.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 31.2 MHz For $\vec{q} [11\bar{2}0]$	124
51.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 51.2 MHz For $\vec{q} [11\bar{2}0]$	125
52.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 70 MHz For $\vec{q} [11\bar{2}0]$	126
53.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ At 90 MHz For $\vec{q} [11\bar{2}0]$	127
54.	Plot of $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(T)/t$ At 108 MHz For $\vec{q} [11\bar{2}0]$	128

Figure	Page
55. Energy Gap $2\Delta(0)$ vs. Frequency For $\vec{q} [11\bar{2}0]$	129
56. Limiting Attenuation vs. Frequency For $\vec{q} [11\bar{2}0]$	130
57. Plot of α_S/α_{TC} vs. t^3 For Cadmium: $\vec{q} [10\bar{1}0]$, $\nu =$ 33.7 MHz, $K = .73$	143
58. Plot of α_S/α_{TC} vs. t^3 For Molybdenum: $\vec{q} [100]$, $\nu =$ 32.6 MHz, $K = .75$	144
59. Plot of α_S/α_{TC} vs. t^3 For Zinc: $\vec{q} [11\bar{2}0]$, $\nu = 10$ MHz, $K = .74$	145
60. Plot of α_S/α_{TC} vs. t^3 For Lead: $\vec{q} [110]$, $\nu = 30$ MHz, $K = .68$	146
61. Plot of α_S/α_n vs. t^3 For Lead Showing Nonlinearity.	147
62. AND Gate and Binary Frequency Divider	150
63. Power Supply for Frequency Divider and AND Gate	152
64. Constant Current Source for Thermometry	154
65. Regulated Power Supply for Constant Current Source.	156

CHAPTER I

INTRODUCTION

Superconductivity, for twenty two years after its discovery,¹ was considered as that property of certain materials which results in the loss of all measurable electrical resistance at cryogenic temperatures below a critical temperature T_c , characteristic of each particular material. A new property of superconductivity was found in 1933 when Meissner and Ochsenfeld² discovered that a metal in the superconducting state prevents any magnetic flux from existing in its interior. This property, now called the "Meissner effect," was thought to arise when a magnetic field was applied because electrical surface currents of appropriate magnitudes were spontaneously set up, which created magnetic fields exactly opposing the applied field. Because this current has no opposition from electrical resistance, it continues at a magnitude which cancels the applied field within the material indefinitely. However, it was found that if a magnetic field of sufficient strength was applied to a superconductor, its superconducting properties would be destroyed and the metal would return to its normal state.³ Results of investigations on the critical magnetic field of thin films of superconductive materials pointed to a penetration depth⁴ in which the magnetic field decreased to zero and in which the electrical surface currents flowed. Results of these and other experiments gave rise to the idea of a long range coherence length⁵ which results from a long range interaction between electrons participating in the superconducting state.

A significant advancement in understanding superconductivity came when low temperature specific heat experiments⁶ revealed the fact that the specific heat in the superconducting state followed an exponential law. This suggested that there was an energy gap between normal and superconducting electrons.⁷

A great break-through occurred with the discovery of the isotope effect in superconductors.^{8,9} These experiments showed that the transition temperature varied as the inverse square root of the isotopic mass of the superconducting element. This observation showed, for the first time, that the principle interaction causing superconductivity was concerned with an interaction between the electrons and the lattice vibrations (phonons).

With these and other facts known, Bardeen, Cooper, and Schrieffer,¹⁰ (BCS) succeeded in constructing a successful theory, based on a simple idealized model of a metal, which explained the principle effects produced by superconductivity. The basis of this theory rests on the recognition that in superconductors, electrons tend to attract each other through an exchange of virtual lattice phonons and form paired states (Cooper pairs).¹¹ By the nature of this interaction, the ensemble of electron pairs has less energy than that of the normal electron assembly. The BCS theory, along with experimental evidence, states that there is a definite energy gap between these electron ensembles and that a minimum amount of energy must be given to an electron pair in order to break it apart. This difference in energy between normal and superconducting electrons

is of an extraordinarily small size, on the order of 10^{-4} or less electron volts.¹⁰

Because of this small energy difference, as a superconductor cools below its transition temperature, some thermal phonons still have sufficient energy to break up Cooper pairs. As the material cools further, the lattice phonon spectrum shifts toward lower energies and fewer Cooper pairs are broken up. As more Cooper pairs form, there are more pair states available for pair interaction, and as a consequence of the Bose-like statistics involved, the pair excitation energy of the system increases to a limit, $2\Delta(0)$ at zero Kelvin.⁷ The BCS theory calculates this energy gap $2\Delta(0)$ to be $3.52 kT_c$ for all superconductors. The symbols k and T_c are used to represent Boltzmann's constant and the superconducting transition temperature, respectively. This energy gap value is supported to within 10-15% by most experimental determinations of the zero Kelvin energy gap for a large number of superconductors.¹⁰

BCS show that the magnitude of the superconducting energy gap can be determined by experimentally observing the ultrasonic attenuation as a function of temperature. For ultrasonic frequencies below 10^8 Hz, the energy associated with the applied phonons is less than 10^{-6} eV. Since phonons whose energy is less than the 10^{-4} eV energy gap cannot interact with Cooper pairs, they must scatter from electrons which have been thermally excited and are not in the paired state (quasiparticles). Thus, as the temperature is decreased and more electrons are able to form pairs, the number of unpaired electrons available to scatter the applied phonons decreases, and the ultrasonic

attenuation decreases. This is clearly seen in the BCS ultrasonic attenuation equation,

$$\frac{\alpha_s(T)}{\alpha_n(T)} = \frac{2}{e^{\Delta(T)/kT} + 1} \quad (1-1)$$

where $\alpha_s(T)$ and $\alpha_n(T)$ represent the ultrasonic attenuation in the superconducting and normal states, respectively, T is the temperature and $\Delta(T)$ is the BCS temperature-dependent energy gap. In fact, the right hand side of equation (1-1) is just a modified Fermi function which describes the probability distribution of quasiparticles available for ultrasonic phonon scattering at finite temperatures below T_c . Thus, by fitting the experimental attenuation data to equation (1-1), the temperature dependent energy gap can be found, and by extrapolation, the zero Kelvin energy gap can be determined.

Deviations from the BCS value of $2\Delta(0)$ in experimental data on superconductors whose electronic structure is composed of several bands, has given rise to the consideration of possible multiple energy gaps for these metals. A phenomenological proposal by Morse¹² suggests the existence of a different energy gap for each band in the electronically complex superconductors. According to this proposal, the effects of the energy gaps can be sampled by the ultrasonic technique, if the attenuation ratio of equation (1-1) is considered in terms of a sum over the bands contributing interacting quasiparticles,

$$\frac{\alpha_s(T)}{\alpha_n(T)} = \sum_i \frac{A_i}{e^{\Delta_i(T)/kT} + 1} \quad (1-2)$$

In this equation $\Delta_i(T)$ is the temperature dependent energy gap associated with the i -Th band, and the coefficients are subject to the condition,

$$\sum_i A_i = 2. \quad (1-3)$$

This idea has been advanced recently with a more rigorous theory by Tang,^{13,14} in which equation (1-2) is obtained from microscopic consideration in the form

$$\frac{\alpha_s(T)}{\alpha_n(T)} = \sum_i \left(\frac{N_i}{N} \right) \frac{2}{e^{\Delta_i(T)/kT} + 1} \quad (1-4)$$

for longitudinal ultrasonic waves in the limit $q\ell \gg 1$, where q is the phonon wave number and ℓ is the electron mean free path length. The coefficient N_i represents the number of electrons in the i -Th band and N is the total number of electrons. This equation shows that, if the energy gaps are different, each gap will dominate the attenuation in a different temperature region.¹⁵ However, the experimental evidence for this approach has been somewhat sparse and inconclusive.

Recent electronic specific heat data on the complex, multiband superconductors cadmium and zinc by Ducla-Soares and Cheeke¹⁶ seem to

indicate the presence of two energy gaps. This data was fit to a simple two gap model suggested by Cooper,¹⁷ where the low temperature electronic specific heat is given by

$$\gamma \ln \left[\frac{C_{es}}{\gamma T_c} \right] \approx C + \frac{3}{2} \ln \left(\frac{T_c}{T} \right) + \ln [a_1 e^{-\Delta_1(0)/kT} + a_2 e^{-\Delta_2(0)/kT}]. \quad (1-5)$$

In this equation C_{es} is the superconducting electronic specific heat, C is a constant, $\Delta_1(0)$ and $\Delta_2(0)$ are the respective zero Kelvin energy gaps, a_1 and a_2 are the corresponding relative electron populations, and

$$\gamma = \frac{2}{3} \pi^2 N(0) k^2, \quad (1-6)$$

where $N(0)$ is the density of Bloch states of one spin per unit energy at the Fermi surface, and k is Boltzmann's constant. Any energy gap determined from electronic specific heat data, however, represents an average gap arising from electrons on the entire Fermi surface, and is difficult to compare with an energy gap determined by ultrasonics. Also, because of the difficulty in obtaining accurate specific heat data, the error associated with the specific heat calculation is on the order of 25 per cent or more.¹⁶

In addition to the specific heat results cited above, recent ultrasonic attenuation measurements on the crystallographically similar metal zinc, by Cleavelin,¹⁸ indicated a connection between the presence of multiple energy gaps and the crystal purity. This connection was thought to arise through the magnitude of the $q\lambda$

product. Since the ultrasonic attenuation technique samples the energy gap of a selectable group of electrons on an effective zone about the equator of the Fermi surface,¹⁵ it was anticipated that an ultrasonic study of cadmium might supply additional evidence to indicate the nature of multiple energy gaps.

In order to accomplish this goal, a previously constructed He³ refrigerator¹⁹ was modified for ultrasonic work. An electronic system was assembled to accurately and continuously determine the ultrasonic attenuation as a function of temperature in both the normal and superconducting states. The single crystal of cadmium was carefully prepared so that ultrasonic measurements could be made in all three principle crystallographic directions. Supporting experiments were performed to determine the magnetic purity of the crystal and the electron mean free path lengths. The ultrasonic attenuation data were then analyzed so that, if the cadmium electron assembly contained multiple energy gaps, their presence and magnitude would be revealed. These results were then correlated with the range of $q\lambda$ values encountered in the experiment.

CHAPTER II

ULTRASONIC ATTENUATION METHOD AND EQUIPMENT

Introduction

The apparatus required to measure the ultrasonic attenuation in superconducting cadmium consists of electronic equipment capable of measuring the attenuation of ultra sound in the crystal and a refrigerator capable of producing and controlling the ultra low temperatures required by superconducting cadmium. Since the attenuation difference between the normal state and the superconducting state in cadmium is very small in some crystallographic directions, careful consideration must be given to the quality of the electronic system. Similarly, since the temperature range over which data is taken is small and very near the ultimate capability of the refrigerator, care must be taken in controlling and monitoring the temperature of the crystal. This chapter will present a thorough description of the electronic equipment used to measure the attenuation. Careful attention will be paid to the linearity, stability, and accuracy of the electronics. The refrigerator and thermometry will be discussed in detail in Chapter III.

Ultrasonic Method

The method used to obtain ultrasonic attenuation data in superconducting cadmium was the standard single transducer pulse-echo technique.²⁰ Briefly, this method consists of generating a short pulse of radio frequency electrical energy which is sent to the crystal in the test environment in the cryostat. At the crystal

the electrical signal is converted into a short pulse of ultrasonic energy by a piezoelectric quartz transducer bonded to the crystal. This ultrasonic pulse is transmitted through the crystal and reflected from the opposite face and returned to the transducer. At the transducer a very small portion of the ultrasonic energy is used in producing an electrical echo signal; the rest of the ultrasonic energy is reflected back through the crystal. Each time the ultrasound reaches the transducer, another electrical echo is produced. This electrical echo train is amplified, detected, and displayed on an oscilloscope screen as depicted in Figure 1.

In order to record the relative change in attenuation as a continuous function of temperature, the voltage of one echo was monitored, as a function of temperature. This was done with the aid of a display scanner which extracted from the expanded oscilloscope display a voltage proportional to the height of the selected echo shown in Figure 2. In general, this voltage was recorded on an X-Y recorder as a function of thermometer voltage. Data taken in this fashion were then converted into attenuation units of dB/cm.

The procedure for calculating the relative attenuation values from the observation of only one echo, in the echo train, is described in the following discussion. Assume that the ultrasonic wave produced by the transducer is a plane wave that is uniformly attenuated as it travels through the homogeneous single crystal of cadmium. This wave can be described in complex notation by the equation.

$$\sigma(x,t,T) = \sigma_0 e^{-\alpha x} e^{i(\omega t - kx)}, \quad (2-1)$$

Figure 1. REPRESENTATIVE OSCILLOSCOPE
DISPLAY OF EXPONENTIAL PULSE ECHO TRAIN

Figure 2. REPRESENTATIVE ECHO ON EXPANDED
TIME SCALE WITH DISPLAY SCANNER MARKER ON
TOP OF BROAD ECHO PEAK

where $\sigma(x,t,T)$ represents the stress wave amplitude as a function of distance traveled in the crystal, x time, t , and crystal temperature, T . The amplitude of the initial stress pulse at the transducer is given by σ_0 . The total attenuation of the wave by all causes is characterized by α in the real exponential. In anticipation of effects to be described later, this total attenuation will be written as the sum of a temperature dependent attenuation $\alpha^*(T)$, and a temperature independent, residual attenuation, α_r ,

$$\alpha = \alpha^*(T) + \alpha_r. \quad (2-2)$$

In this representation, $\alpha^*(T)$ characterizes all the mechanisms contributing to the total attenuation which vary with temperature. The residual attenuation α_r describes the attenuation contribution by all nonelectric interactions such as binder losses and dislocation losses which are assumed to be temperature independent below the transition temperature of cadmium.

Since the attenuation is determined by monitoring the height of the envelope of the j -th high frequency echo $\sigma_j(x,T)$ the attenuation may be specified by the equation,

$$\sigma_j(x,T) = \sigma_0 e^{-j(2\ell)[\alpha^*(T) + \alpha_r]}, \quad (2-3)$$

where ℓ is the length of the crystal and $(2\ell)j$ represents the total distance traveled by the stress wave of the j -th echo. The natural log of equation (2-3) yields a more explicit expression for the

attenuation,

$$\ln \sigma_j(x, T) = \ln \sigma_0 - 2j\ell[\alpha^*(T) + \alpha_r]. \quad (2-4)$$

In order to establish a temporary reference point of the stress magnitude of the j -th echo, consider the stress at the transition temperature, T_c . In the form of equation (2-4),

$$\ln \sigma_j(x, T_c) = \ln \sigma_0 - 2j\ell[\alpha^*(T_c) + \alpha_r]. \quad (2-5)$$

The relative attenuation $\alpha^*(T)$, is determined by comparing the stress magnitude at any temperature, equation (2-4), with that at the transition temperature, equation (2-5). Subtracting equation (2-4) from equation (2-5) yields the comparison,

$$\ln \sigma_j(x, T_c) - \ln \sigma_j(x, T) = 2j\ell[\alpha^*(T) - \alpha^*(T_c)], \quad (2-6)$$

or upon rearranging,

$$\alpha^*(T) - \alpha^*(T_c) = \frac{1}{2j\ell} \ln \frac{\sigma_j(x, T_c)}{\sigma_j(x, T)}. \quad (2-7)$$

Because the data was taken with linear amplifiers, the stress amplitude can be taken as proportional to the amplified electrical echo signal,^{20,21}

$$\sigma_j = kV_j \quad (2-8)$$

When this relationship is substituted into equation (2-7), the relative attenuation can be calculated from the recorded voltage data.

Thus,

$$\alpha^*(T) - \alpha^*(T_c) = \frac{1}{2j\ell} \ln \frac{V_j(x, T_c)}{V_j(x, T)}, \quad (2-9)$$

where the relative attenuation is expressed in nepers per unit length. The most common units used to describe experimental attenuation data in this field are units of decibels (dB) per centimeter. In terms of this notation, the attenuation equation becomes

$$\alpha^*(T) - \alpha^*(T_c) = \frac{20}{2j\ell} \log_{10} \frac{V_j(x, T_c)}{V_j(x, T)} \quad (2-10)$$

where α^* is in units of dB/cm.

Electronic Equipment

In order to obtain the maximum amount of data from the experiment, it was decided to measure the relative attenuation as a continuous function of temperature by monitoring the relative changes in the magnitude of one echo. Of the many methods in use today,²² this one has the most sensitivity. However, it is susceptible to drift in amplitude or gain in any section of the entire electronic system. In view of this possible source of error, the electronics was continually maintained within the manufacturers specification during this series of experiments.

The ultrasonic attenuation in the hexagonal close packed crystal structure of cadmium is highly anisotropic.²³ In anticipation of this, several instrumentation configurations were selected to provide the optimum sensitivity over the range of attenuation magnitudes expected.

Figure 3 shows a block diagram of the electronics used to obtain data in the $[0001]$ and $[10\bar{1}0]$ directions in cadmium. Briefly, the operation is as follows. The Hewlett-Packard model 214A pulse generator produces short square wave pulses which trigger the Arenberg Pulsed RF Oscillator (model PG 650C) at the rate of 800 pulses per second. It should be noted that the Hewlett-Packard pulse generator is used to externally trigger the Arenberg pulsed oscillator in order to achieve better time stability in the RF pulses than that produced with the Arenberg internal trigger system. The trigger output of the Hewlett-Packard pulse generator, with its variable time delay/advance control, is used to synchronize the horizontal sweep on the Hewlett-Packard oscilloscope, model 175A. The RF pulse is sent to the crystal and to the Arenberg pre-amplifier, PA-620-SN. The first stage in the pre-amplifier clips the high voltage RF pulse so that the amplifier will not overload and saturate later stages. The RF pulse that reaches the transducer is converted into an ultrasonic pulse which reflects from the ends of the crystal a number of times and results in a series of echoes. These ultrasonic echoes are reconverted into electrical signals at the transducer and amplified as an echo train at the Arenberg pre-amplifier, type PA-620-SN. This pre-amplifier also serves as an impedance matching tuner which can be adjusted manually to match the transducer impedance at frequencies up to a maximum of 50 MHz. This pre-amplifier and the Arenberg wide band amplifier, type WA 600 D, are used for frequencies at or below 50 MHz. For frequencies above 50 MHz the Arenberg VHF amplifier, model VR 720,

Figure 3. INSTRUMENTATION FOR ATTENUATION MEASUREMENTS IN THE [0001] AND $[10\bar{1}0]$ DIRECTIONS IN CADMIUM.

is substituted for both the pre-amplifier and the wide band amplifier. The VHF amplifier can be tuned from 50 MHz to 210 MHz. This instrument has an impedance matching circuit at its input which can also be manually adjusted to match the transducer impedance. In the output section of both amplifier systems the amplified RF echo train is detected and reamplified. This video signal, as depicted in Figure 1, is fed to the vertical amplifier, type 1752B, of the Hewlett-Packard oscilloscope. This signal is displayed on the oscilloscope screen as an aid to tuning the amplifiers and to checking the quality of the transducer-crystal binder. The amplifier tuning is adjusted in conjunction with the RF oscillator frequency to obtain transducer resonance, which is immediately observable on the scope. The transducer bond is adjusted until an exponential echo train is observed on the scope.

In order to facilitate stability of the echo height voltage extracted from the scope display by the display scanner, the sweep speed of the oscilloscope is greatly increased. The trigger delay on the Hewlett-Packard pulse generator is then adjusted so that the selected echo appears on the center of the scope screen with a broad peak as shown in Figure 2. The display scanner, model 1782A, is then adjusted manually to extract the voltage of the echo at the center of the broad peak. In this manner, any jitter in pulse position or small instabilities in the sweep speed will not cause any significant change in amplitude of the extracted echo height voltage. In addition to these precautions, both the Arenberg RF pulse generator, and the

Arenberg wide band amplifier system were always operated with a Sorensen type R3010 solid state ac voltage regulator supplying the ac power. This reduced the RF pulse amplitude drift due to power line variations by an appreciable amount, and the drift was thereafter considered negligible.

When longitudinal ultrasonic waves are propagated in the [0001] direction in cadmium, relative attenuation changes on the order of 10 to 60 dB are expected between the normal and the superconducting states in the frequency range from 10 MHz to 70 MHz.²⁴ In this case, a logarithmic converter, Hewlett-Packard model 7561A, was used to convert the large voltage changes into decibel changes which could be conveniently recorded on the Y axis of the Moseley X-Y recorder, model 2X2A, as a function of thermometer voltage on the X-axis. It should be noted that the height of the displayed echo was maintained in the linear range of the amplifiers, scope, and display scanner. This was done by stabilizing the temperature so that the echo height became constant, then adjusting the amplifier gain so that the echo voltage was returned to the other end of the linear range of the electronics. The temperature was then varied until the echo voltage had again traversed the linear range. This was repeated as many times as necessary to record the entire change in attenuation. This procedure is allowable since the displayed voltage is the actual RF echo voltage V^* , multiplied by the combined amplifier gain A ,

$$V_j(x,T) = AV_j^*(x,T) \quad (2-11)$$

and

$$V_j(x, T') = AV_j^*(x, T') \quad (2-12)$$

where $V_j^*(x, T)$ and $V_j^*(x, T')$ are the actual echo voltages at a temperature T and T' , respectively. The relative attenuation change, as determined from equation (2-10), does not depend on the amplifier gain,

$$\alpha^*(T') - \alpha^*(T) = \frac{20}{2j\ell} \log_{10} \frac{AV_j^*(x, T)}{AV_j^*(x, T')} \quad (2-13)$$

For longitudinal ultrasonic waves propagated in the $[10\bar{1}0]$ direction in cadmium, the 10 MHz to 90 MHz frequency range, the relative attenuation change between the normal and superconducting state is expected to be on the order of 2 to 15 dB.²⁴ In this situation more sensitive data can be achieved by recording the echo height voltage changes directly from the Hewlett-Packard display scanner onto the Y-axis of the X-Y recorder. This voltage data is then converted to decibel changes in the data analysis computer program.

When longitudinal sound waves are propagated in the $[11\bar{2}0]$ direction of cadmium, the difference in attenuation between the normal state and the superconducting state is much smaller than it is in the other directions. In the frequency range of 10 MHz to 170 MHz, this attenuation change was expected to be in the range of .5 to 8 db.²⁴ Because of the very small change in attenuation at the low

frequency range, rather large errors may be expected from the relative insensitivity and the noise of the equipment configuration just described.

In order to overcome the problems associated with the conventional electronics, a phase sensitive detection system was set up. This basic method has been well developed and extensively analyzed in other fields, but only recently have workers in the ultrasonic field begun to use this idea.²⁵⁻²⁸ This detection system uses sampling integration and phase sensitive detection to enhance the signal-to-noise ratio in the echo train. The electronic configuration used in this work is modeled after the circuits described by Claiborne and Einsprich,²⁸ and Hemphill.²⁷ The beauty of this more sophisticated detection system is that it uses all of the equipment in the more conventional circuit of Figure 3 and requires only an additional lock-in amplifier and a binary frequency divider-AND gate interface unit. The lock-in amplifier was used in a previous magnetic thermometry system,¹⁹ and the interface unit was designed and constructed in the lab (see Appendix B).

The block diagram of the phase sensitive system is shown in Figure 4. The Hewlett-Packard pulse generator P1 was used to set the repetition rate R of the system. The delayed trigger signal from P1 was used to trigger the horizontal sweep of the oscilloscope. This variable trigger delay feature is used to vary the position of the echo train on the scope screen so that an individual echo can be centered on the screen when the horizontal sweep speed of the scope

Figure 4. INSTRUMENTATION FOR ATTENUATION MEASUREMENTS IN THE [1120] DIRECTION IN CADMIUM.

is increased to broaden the echo peak, as in the conventional circuit. The pulse output of P1, (less than 4 volts) is sent to the N-stage binary frequency divider and the AND gate. The output of the binary frequency divider is a square wave with a frequency of

$$f_2 = 2^{-N}R, \quad (2-14)$$

where R is the repetition rate of the system. This output, Figure 5(a), serves as a reference signal for the Princeton Applied Research model 121 lock-in amplifier. This signal is also supplied internally to the AND gate as a control signal. The AND gate then allows pulses from P1 to pass to the second Hewlett-Packard pulse generator P2 only during the positive half of the control signal. Pulse generator P2 serves only as a pulse amplifier and triggers the RF pulse generator 2^{N-1} times in the positive duration of the control signal, as shown in Figure 5(b) for a four stage binary. This RF pulse travels to the crystal and the resulting echoes are amplified and detected as in the system of Figure 3. Since the horizontal sweep of the oscilloscope is triggered 2^N times in the period $T_2 = 1/f_2$, the picture appearing on the screen consists of 2^{N-1} traces of only the amplifier noise. Now, when the display scanner samples an echo as before, the output is an ac signal of frequency f_2 approximating a square wave proportional to the echo height as shown in Figure 5(c). The steplike leading and trailing edges of this signal occur because of the practical efficiency of the storage circuit in the display scanner. This signal is phase coherent with the lock-in reference

(a) BINARY FREQUENCY DIVIDER OUTPUT FOR LOCK-IN AMPLIFIER REFERENCE SIGNAL.

(b) RF PULSE OUTPUT FOR 4 STAGE BINARY FREQUENCY DIVIDER.

(c) DISPLAY SCANNER OUTPUT TO LOCK-IN AMP.

Figure 5. RELATIVE TIMING SIGNALS IN PHASE SENSITIVE DETECTION SYSTEM OF FIGURE 4.

signal as indicated in Figures 5(a-c). The lock-in amplifier reflects any signals occurring at a frequency other than the reference frequency f_2 , and provides a dc output proportional to the RMS voltage of the display scanner. This signal is recorded on the X-Y recorder as a function of thermometer voltage.

In order to gain maximum effectiveness from this type of detection system, several things must be considered. In general, the signal-to-noise ratio is improved when many samples are taken, thus the repetition rate R should be as high as possible. However, in practice this is limited by the amount of RF heating that can be absorbed by the crystal without measurably affecting the temperature, and by the power output capability of the RF pulse generator. A second consideration is that the time constant of the output of the lock-in amplifier should be large so that random signals will average to zero. This is limited also because data is taken as a function of temperature which is varied with time. In view of these considerations, the basic repetition rate R , was set at an accurately measured 800 Hz. The binary frequency divider was constructed as a four stage counter so that $N = 4$ and the reference frequency f_2 , was 50 Hz. The output filter time constant on the lock-in amplifier was usually set at one second. The RF frequency was measured on a Hewlett-Packard model 5245L electronic counter.

Equipment Performance

The performance of each of these electronic systems was measured in controlled experiments. The theoretical significance in the

experimental data is concerned with the change in the echo voltage. Thus, the absolute amplifier gain is not important, but the linearity of the amplifier circuitry is extremely important.

The circuit shown in Figure 6 was set up to determine the linearity of the Hewlett-Packard oscilloscope and display scanner in the system of Figure 3. The linearity of the Hewlett-Packard scope and display scanner system was investigated by varying the pulse height from the Arenberg amplifier system with an Arenberg 93 ohm attenuator, and then comparing the input voltage to the vertical amplifier of the scope with the corresponding output voltage of the display scanner. This voltage measurement was made with a type W plug-in unit and a Tektronix type 547 oscilloscope, which is accurate to 0.1%. The results of this comparison are shown in Figure 7.

Attenuation data on cadmium was always taken when the echo height was between 1 and 10 volts to insure linearity. In order to compare the input and output of the wide band amplifier system using available equipment, a Tektronix type 1121 fixed gain amplifier was used to amplify the input signal so that its magnitude could be measured on the type W comparator. The 93 ohm terminator at the output of the type 1121 amplifier was required for impedance matching so that the proper amplitude could be measured. The results of this measurement are shown in Figure 8. The relatively large error indication is a result of difficulty in making voltage measurements due to low level signals and poor signal-to-noise ratio.

When the display scanner is used to record the echo height

Figure 6. EQUIPMENT ARRANGEMENT FOR LINEARITY CHECK OF HP SCOPE, DISPLAY SCANNER, AND ARENBERG AMPLIFIER SYSTEM.

Figure 7. HP 175A OSCILLOSCOPE AND 1782A DISPLAY SCANNER LINEARITY CHECK

Figure 8. ARENBERG PRE-AMP AND WIDEBAND LINEARITY CHECK.

directly onto the X-Y recorder graph, baseline drift becomes a small source of error. When the log converter is included in the circuit, this error becomes more significant, especially for low level signals. The significant increase in this case because the log converter characteristically amplifies low level signals more than larger signals. In order to minimize this error, the display scanner was calibrated to put out 200 mV for each centimeter signal height on the scope screen. In addition, the echo was always maintained above the one centimeter mark on the screen. Thus, the minimum voltage put out by the display scanner was 200 mV. This insured that the 7 mV baseline drift was less than 1% of the signal output. An actual amplified recording of this baseline drift as a function of time is shown in Figure 9.

The linearity of the PAR model 121 lock-in amplifier was investigated by measuring its input and resulting output voltage with the Tektronix type W comparator. The test signal in this case was derived from an audio oscillator operating at the reference frequency of 50 Hz. The results of this test are shown in Figure 10. This instrument appeared quite linear over the appropriate range.

Figure 9. DISPLAY SCANNER BASELINE DRIFT.

Figure 10. PAR LOCK-IN AMPLIFIER LINEARITY CHECK

CHAPTER III

He^3 REFRIGERATOR DESIGN

In order to study the ultrasonic attenuation in superconducting cadmium, temperatures of 0.5K and well below must be produced and easily controlled. This can be accomplished by using a He^3 refrigerator which conveniently produces temperatures down to 0.3K. This refrigeration method operates on the principle that if the vapor pressure over a liquid is reduced, the temperature of the liquid will fall until its vapor comes into dynamic equilibrium with the liquid. This approach to the production of controlled low temperatures is particularly convenient because of the relatively large cooling capacity of a liquid and the ease with which the temperature can be controlled.

Liquid He^3 is used as the refrigerant because it exhibits properties which overcome the principle difficulties encountered with a liquid He^4 refrigerant, but which allow the use of the well established He^4 refrigeration techniques. As a coolant, He^3 has two major advantages over He^4 . First, at the same vapor pressure, the temperature of liquid He^3 is much lower than that of He^4 .^{29,30} Second, the evaporation rate of He^3 is much smaller than that of He^4 since it does not become a superfluid which will climb the walls of the container and rapidly evaporate on warmer surfaces.

The refrigerator used in this work was a modified He^3 refrigerator which was originally designed and constructed in the laboratory for use in measuring specific heat and magnetic susceptibility.³¹ Several

changes in design were made in the original cryostat so that ultrasonic measurements could be performed. The uninterrupted running time was greatly extended by removing the twelve inch long induction coils originally used for magnetic susceptibility measurements. These coils were so long and massive and occupied so much volume in the He^4 dewar that a significant proportion of the liquid He^4 was evaporated in cooling the cryostat. This left only enough He^4 to maintain low temperatures for about three hours before a new charge of liquid He^4 was required. The new design placed the high vacuum can at the bottom of the He^4 dewar, thus allowing about twelve inches more working space for the liquid He^4 . This space, plus the reduced mass allowed an increase to twelve hours uninterrupted He^4 running time. A drawback to this improvement, however, proved to be a rise in the ultimate temperature of about 0.1K due primarily to the lengthening of the He^3 pumping line. Another modification required was the installation of an RF coaxial transmission line to transmit and receive the ultrasonic attenuation information. This line was a source of considerable trouble during the experiment and will be discussed in detail later.

In this refrigeration system, as shown in Figure 11, the entire cryostat is precooled to 77K by filling the outer glass dewar with liquid nitrogen. When the cryostat has precooled, liquid He^4 , at 4.2K is transferred into the inner glass dewar. The He^4 is then cooled to about 1.5K by reducing its vapor pressure with the high volume Stokes 105 CFM vacuum pump. At this temperature gaseous He^3

Figure 11. He³ CRYOSTAT

is introduced into the He^3 duct whereupon the gas condenses and begins to trickle into the thermally isolated He^3 can. When the liquid He^3 first reaches the relatively warm He^3 can, it immediately evaporates and then recondenses in the He^3 duct during what is commonly called the reflux stage. When the gaseous He^3 has liquified and filled the He^3 can, its vapor pressure is reduced by a mechanical vacuum pump and the gas thus removed is stored in a seven liter storage tank. The vapor pressure, and thus the temperature of the liquid He^3 is controlled by controlling the pumping rate of the vacuum pump. This is easily accomplished by carefully adjusting the two parallel needle valves which bleed He^3 gas from the reservoir back into the pumping line.

He^3 Cryostat Design

Review of Literature

This cryostat was designed after careful consideration of published designs and performance characteristics. Certainly the object of the design is to produce the lowest possible temperature and have the capability to pump out an adequate amount of heat for a reasonable time. In addition, the design must provide for a method of smoothly controlling the temperature. The lowest temperature attainable depends on the amount of heat leaking into the He^3 bath and the rate at which the vapor can be pumped from the liquid He^3 . The length of time that the lowest temperatures can be maintained depends on the quantity of liquid He^3 , the heat leak, and the amount of liquid He^3 boiled off in initially cooling the He^3 can and sample holder structure

to its lowest temperature. The optimum cryostat design results from the proper compromise between the pumping speed, the heat leak, and several other lesser considerations.

Table I gives a brief comparison of the major design and performance characteristics of a number of He^3 cryostats which were described in some detail in the literature. The refrigeration system described by Reich and Garwin³² illustrates a method of continuous refrigeration in which a small amount of He^3 can remove a very large amount of heat and still maintain a very low temperature. The He^3 gas which is boiled off is compressed at room temperature and then recondensed at 1K by the He^4 bath. This recondensed liquid is then returned to the low temperature He^3 bath to complete the cycle. Note that the returning warm liquid He^3 tends to produce thermal gradients in the He^3 liquid.

Since He^3 gas has become more readily available, He^3 refrigerator design has shifted to the single condensation type in which the He^3 is liquified at the beginning of the run and the experiment is concluded before the He^3 is completely evaporated. This type allows a lower and more uniform temperature to be attained for a somewhat limited time. Seidel and Keesom,³³ using a small diffusion pump to reduce the He^3 vapor pressure, and pumping through a fairly small He^3 transfer line were able to reach 0.3K, the ultimate temperature could be maintained for over 80 hours. The refrigeration system of Esel'son et al³⁴ is similar to the one above except that the diffusion pump is backed by a charcoal adsorption pump cooled by liquid

TABLE I
Comparison of He³ Cryostats

Cryostat	Type	Amt. of He ³ Gas at S.T.P.	He ³ Pumping Line
Reich & Garwin ³² Columbia: 1958	Continuous Refrigeration	.08 ℓ	---
Seidel & Keesom ³³ Purdue: 1958	Single Shot	3 ℓ	.4 cm Dia. .01 cm Wall 6 cm Long German Silver
Esel'son ³⁴ USSR: 1962	Single Shot Charcoal Ad- sorption	2 ℓ	---
Walton ³⁵ Oak Ridge: 1966	Single Shot	3-4 ℓ	1.27 cm Dia. Stainless 5 cm Long
Mallon ⁴⁸ Rice: 1966	Single Shot	2 1/3 ℓ	.32 cm O.D. .015 cm Wall 7 cm Long Stainless
Fruneau ³⁶ France: 1967	Single Shot Charcoal Ad- sorption	2 1/2 ℓ	---
Robbins Texas Tech: 1970	Single Shot	4.5 ℓ	1.24 cm Dia. .01 cm Wall 12.5 cm Long Stainless

TABLE I (continued)

Cryostat	He ³ Pump	Ultimate Temp.	Heat Pumping Rate at Ultimate Temp.	Running Time
Reich & Garwin ³² Columbia: 1958	Rotary Oil Pump	.35 K	$>10^3 \frac{\text{ergs}}{\text{sec}}$	Indefinite
Seidel & Keesom ³³ Purdue: 1958	Rotary Oil Pump & 25 μ /S Diff. Pump	.30 K	$50 \frac{\text{ergs}}{\text{sec}}$	>80 hrs.
Esel'son ³⁴ USSR: 1962	Adsorption Pump & 15 μ /S Diff. Pump	.30 K	---	>6 hrs.
Walton ³⁵ Oak Ridge: 1966	Rotary Oil & 300 μ /S Diff. Pump	.21 K	$47 \frac{\text{ergs}}{\text{sec}}$	---
Mallon ⁴⁸ Rice: 1966	Rotary Oil Pump	.40 K	$23 \frac{\text{ergs}}{\text{sec}}$	---
Fruneau ³⁶ France: 1967	Adsorption Pump	.33 K	---	As long as He ⁴ bath lasts
Robbins Texas Tech: 1970	Rotary Oil Pump	.27 K*	$72 \frac{\text{ergs}}{\text{sec}}$	>80 hrs.

*Modified Cryostat reaches .37 K

hydrogen. The advantage in this system is that heat generating mechanical vibrations are considerably reduced, and the system can be constructed with less chance of vacuum leaks. There could be some danger in this method if the highly combustible hydrogen gas were to be mishandled. Walton³⁵ designed his refrigerator with large pumps and large pumping lines in order to maximize the rate of He^3 removal. This was done in such a way that the heat leak into the liquid He^3 was not unduly increased. Thus, he was able to reach the unusually low temperature of 0.21K. Fruneau et al³⁶ pumped on the liquid He^3 bath in their refrigerator with only a zeolite 5A adsorption pump which was cooled with liquid He^4 . This refrigerator was able to maintain its ultimate temperature of .33K for as long as the He^4 bath lasted.

Design Details

This cryostat was carefully designed to produce the lowest possible temperatures while using only a mechanical vacuum pump as the compressor. It was decided originally that the use of an oil diffusion pump in the He^3 line would be more cumbersome in the precise control of temperature than it would help in lowering the ultimate temperature. The details of the low temperature portion of the modified He^3 cryostat developed from the pump limitation consideration are shown in Figure 12.

The first major consideration was the size of the He^3 pumping line and the He^3 transfer line. The point in question is that a small diameter line offers the advantage of a small heat leak into

Figure 12. He³ CAN AND ASSOCIATED DETAILS (cm)

the He^3 can but a small diameter line reduces the pumping rate and thus limits the ultimate temperature. This point was resolved in favor of a larger pumping line by considering the heat flow equations and the pumping rate expressions. Many of the He^3 cryostats in the literature used 1/4 inch diameter, 2 1/2 inch long, thin wall stainless steel tubing for the He^3 transfer line. Using the value of the approximate mean thermal conductivity of stainless steel between zero K and 1K as reported by Berman,⁴⁰

$$K = 1.8 \times 10^3 \frac{\text{erg}}{\text{sec.cm.K}}$$

the heat leak rate due to conduction in a 6 cm long, 1/4 inch diameter stainless steel tube of wall thickness 0.01 cm would be 14 ergs/sec. In considering an equal length transfer line of 1/2 inch diameter to increase the pumping speed, it is obvious that because of the greater amount of material in the walls, the heat leak will be considerably larger. However, if the length of the transfer line is increased to 12.5 cm, the conduction heat leak will be $Q = 9.4$ ergs/sec, 33 per cent less than that of the smaller, shorter line. The 6.5 cm additional length should not significantly affect the pumping rate since it represents less than ten per cent of the pumping line length.

A more important source of energy influx to the liquid He^3 bath is due to heat conduction from the 1.5K He^4 bath through the low pressure He^3 vapor in the He^3 transfer line. Experimental data given by Fokkens, et al³⁷ and theoretical calculations by

Buckingham and Scriven³⁸ show that the thermal conductivity of low pressure He³ vapor in the temperature range of 0.3K to 1.5K is very nearly linear and is rapidly changing. This thermal conductivity, $K(T)$ can be expressed as

$$K(T) = 489T + 123, \quad (3-1)$$

in units of ergs/ (sec cm K).³⁹ Fokkens also states that this conductivity is pressure independent in the range above and below 150×10^{-3} mm mercury. The heat leak between the He⁴ bath at 1.5K and the He³ bath at 0.4K is calculated from the integral

$$\dot{Q} = \frac{\pi r^2}{\Delta y} \int_{.4}^{1.5} K(T) \alpha T, \quad (3-2)$$

where $\dot{Q}$ is the rate of heat leaking into the He³ bath, r is the inner radius of the transfer line, and Δy is the length of the transfer line (between the high vacuum line and the He³ can). The resulting heat leak through the He³ gas in the 1/4 inch diameter, 6 cm long transfer line is about $\dot{Q} = 34$ ergs/sec., compared to $\dot{Q} = 62$ ergs/sec in the 1/2 inch diameter, 12.5 cm long line. Thus, the larger line allows almost twice the heat leak as the smaller line. However, this is offset by the increased pumping speed.

In order to compare the pumping speed of He³ through the two sizes of pumping lines, consider the expression given by Walton³⁵ for the ultimate low pressure P_0 , at the lowest temperature T_0 of the liquid He³,

$$P_o = \dot{Q}_m \frac{3}{4} \frac{R}{2\pi} \sqrt{T_o} \sum_i \frac{\ell_i}{r_i^3} . \quad (3-3)$$

The quantity $\dot{Q}_m$ is the rate of He^3 mass flow through the pumping line, R is the universal gas constant, ℓ_i represents the lengths of series pumping lines of radii r_i . This equation shows that the pumping rate $\dot{Q}_m$, the ultimate pressure P_o , and thus the ultimate temperature T_o , are all enhanced by the cube of the radius of the pumping lines. Thus, by doubling the diameter of the pumping line, the pumping rate is increased by 2^3 times. Therefore, the efficiency of the refrigerator is indeed enhanced by using the larger pumping line. In addition, by installing the 1/2 inch diameter line as a continuous section from the He^3 can all the way to the top of the cryostat, the chances of having vacuum leaks develop at ' soldered pipe joints is considerably reduced.

Another possible, but lesser source of heat conduction into the He^3 bath is that through the electrical leads which run from the leads chimneys to a thermal ground on the He^3 can. These leads were made of a 0.0065 inch diameter copper sheathed superconducting wire of niobium-48% titanium alloy called SUPERCON T48B, type S, (copper to superconductor ratio of 0.67:1).³⁹ By using these small superconducting wires, no heat is developed in them by the electrical currents and their thermal conductivity drops as the temperature drops below the superconducting transition temperature of about 10K. However, since the thermal conductivity of these alloy

wires is not known, a 2.5 cm section of AWG number 38 manganin wire (82% Cu, 15% Mn, 3% Ni) was inserted in all the leads except the two higher current superconducting solenoid leads in order to insure that the heat conduction was kept to a minimum. The electrical resistance in 2.5 cm of the manganin is about .5 ohm so that with the microamp current, less than 10^{-12} watts are developed in the manganin section. But using the mean low temperature thermal conductivity of manganin given by Berman,⁴⁰

$$K = 1.8 \times 10^3 \frac{\text{ergs}}{\text{sec cm K}},$$

the maximum heat leak through the twelve leads is less than 1 erg/sec. Incidentally, the electrical leads running from the room temperature ceramic vacuum feed-through to the low temperature high vacuum feed-throughs are made of AWG number 36 copper wire coated with formvar insulation. The two solenoid current leads are formvar insulated AWG number 32 copper wire.

Convection in the He^3 gas column should not occur between the room temperature and the He^4 temperature region because the gas density is greater at the lower, cooler end. However, contrary to Seidel and Keesom,³³ there may be convection currents between the 1.5K region and the low temperature He^3 can because the He^3 gas density at 1.5K is about an order of magnitude greater than that below 1K.⁴¹ However, this source of heat influx is probably not too significant in view of the agreement between calculated and experimental values of total heat leak.

The rate of heat influx to the He^3 can due to radiation from the walls of the high vacuum can was calculated from the Stefan-Boltzmann law applied to energy exchange between two surfaces,

$$\dot{Q} = \sigma AE[T_2^4 - T_1^4], \quad (3-4)$$

where T_1 and T_2 are the temperature of the cold and warm surfaces, respectively, σ is the Stefan-Boltzmann radiation constant, A is the surface area of the He^3 can, and E is the total emissivity factor. This quantity E can be calculated for concentric cylinders from

$$E = \frac{e_1 e_2}{e_2 + \frac{A_1}{A_2} (e_1 - e_2) e_1} \quad (3-5)$$

where e_1 and e_2 are the individual emissivities of the cold He^3 can surface and the warmer high vacuum can surfaces, of areas A_1 and A_2 , respectively. Scott⁴² indicates that Eq. (4-5) is a good approximation for practical geometries such as short cylinders with flat ends, where A_1 and A_2 are taken as the total areas facing the insulating space of the inner and outer surfaces respectively. The radiation heat leak calculated from Eq. (4-5) and including the radiation traveling down the He^3 transfer line from the radiation trap is

$$\dot{Q} \leq 0.7 \times 10^{-3} \text{ ergs/sec.}$$

This is seen to be insignificant compared to other types of heat leaks.

The rate of heat produced in the He^3 bath by mechanical vibration is difficult to estimate but is reduced by mounting all vibrating pumps on platforms separate from the He^3 refrigerator table and using some means of vibration dampening such as bellows in the pumping lines.

The calculated total rate of energy influx to the He^3 bath due to all previously mentioned sources is

$$\dot{Q} \leq 72 \text{ ergs/sec.}$$

Since many of the constants in the above heat equations were extrapolated or estimated, the resulting value of the total heat leak is only an estimate. The experimental value of this total heat leak can be obtained by maintaining the liquid He^3 at its lowest temperature and measuring the rate of increase in pressure in the seven liter He^3 storage tank. Since the amount of gas in the tank is known as a function of pressure, the liquid evaporation rate can be determined. This information, in conjunction with the latent heat of evaporation of liquid He^3 , given by Hammel⁴³

$$L_{\text{He}^3} = 25 \times 10^7 \text{ ergs/mole,}$$

yields the experimentally determined total heat leak into the He^3 liquid at peak efficiency of

$$\dot{Q}_T \leq 80 \text{ ergs/sec.}$$

There were other important considerations which influenced the design of the cryostat. For example, in order to enhance the rate of evaporation of the liquid He^3 and thus lower the ultimate temperature of the refrigerator, the He^3 can was constructed as a shallow, large diameter can so that a maximum liquid surface area would be exposed to the vacuum. Also, the volume of the He^3 can is somewhat greater than that of the liquid He^3 so that the flow of He^3 vapor is not unduly constricted. As an added advantage, the shallowness of the He^3 can plus its construction of high conductivity copper provide for a good, short thermal link between the liquid He^3 and the specimen to be cooled, which is mounted on a high purity copper pedestal as shown in Figure 2. This pedestal is composed of a copper tube with a manganin wire heater noninductively wound and stycasted⁴⁶ onto it. This tube, 0.81 cm long with a wall thickness of 0.016 cm, is stycasted to the He^3 can lid in such a way as to maintain good electrical contact with the can. Stycasted in good electrical contact to the top of this tube is a high conductivity copper block used as the crystal platform and the electrical thermometer housing. This arrangement was designed so that the temperature range of the cryostat could be accurately controlled to about 10K in order to study higher transition temperature superconductors.

The overall design of the He^3 system was such that 93% of the 4.5 liters STP of He^3 gas condensed. This efficiency allowed about the longest possible He^3 running time. In practice, liquid He^3 temperatures have been maintained for over 28 hours, or until

the 25 liters of liquid He^4 in the storage dewar were used up. This was more than sufficient time to complete the superconducting experiments.

Vacuum Systems

Figure 13 is a schematic drawing of the He^3 vacuum system. The thin wall He^3 pumping line of type 304 stainless steel was silver soldered into the lid of the He^3 can, to the lid of the high vacuum can and to a junction with the room temperature pumping system. This line branches immediately above the cryostat in a removable copper tee which is sealed to the pumping lines with neoprene O-ring seals. This tee was made removable in case future experiments required direct access to the liquid He^3 . The bellows sealed connecting valve on one side of the tee connects the He^3 system to the high vacuum system so that the He^3 pumping lines may be vacuum cleaned after the system has been open to the atmosphere. This is a critical valve and it must be used carefully since there is the possibility of losing the He^3 gas to the atmosphere through its misuse.

Into the top of the tee is silver soldered a 3.8 inch diameter copper tube which leads to a precision Wallace and Tiernan absolute pressure indicator, type FA 160, which measures absolute pressure from .1 mm to 20 mm mercury. This is the pressure indicator used to calibrate the carbon resistance thermometer.

The other side of the tee as shown in Figure 13 is connected to a one inch diameter copper pumping line approximately three feet

Figure 13. He³ VACUUM SYSTEM

long. A Hastings model T thermocouple vacuum gauge was soft soldered into this line in order to directly observe the rate at which the He^3 pressure and thus the He^3 temperature was changing during the experiment. This gauge was designed to measure pressures between one torr and 1×10^{-3} torr, but was not sufficiently accurate to calibrate the carbon thermometer. This pumping line ended in a nominal one inch diameter stainless steel bellows which serves to reduce mechanical vibrations in the He^3 can from the mechanical vacuum pump.

The He^3 gas is pumped through the bellows cut-off valve by a specially sealed, 50 FM Welch Duo-Seal mechanical vacuum pump, model 1402. This pump has a special oil seal on the pulley shaft. This seal was manufactured by the Welch Scientific Company and is described in detail by Reich and Garwin.³² The He^3 gas is stored in a seven liter tank under a pressure of 6.8 inches of mercury less than one atmosphere, as measured by an Ashcroft Bourdon vacuum gauge. This gauge is the means by which the operator can tell when the He^3 gas has all condensed and by which the level of liquid in the He^3 can be estimated. By storing the gas at slightly less than one atmosphere, the significance of small leaks is reduced, since any air which may leak into the system will freeze out in the low temperature section of the cryostat. The gas pressure in the He^3 pumping line is regulated by pumping gas through the wide open cut-off valve and bleeding it back into the low pressure system through the parallel set of needle valves. For coarse adjustment, one of the bleedback valves is a Hoke Vee-type valve. The other valve is used

for fine control and is a precision Whitey micrometer needle valve, type 316. The fine control is quite good in that the pressure can be controlled closely enough to maintain the He^3 temperature within a few millikelvin of a given value.

Figure 14 shows the high vacuum insulation pumping system and the vacuum system used to pump on the liquid He^4 . The high vacuum is created by a restored six inch Distillation Products diffusion pump backed with an old model 1.5 CFM Welch Duo-Seal mechanical vacuum pump. The cryostat is protected from diffusion pump oil by a one liter liquid nitrogen cold trap constructed in the lab. The valve labeled "Diffusion Pump Isolation Valve" in Figure 14 is used as an isolation valve during leak checking, or in rare occasions when the vacuum lines must be brought up to atmospheric pressure briefly while not desiring to shut down the diffusion pump. The high vacuum pressure is monitored by a CVC cold-cathode ionization vacuum gauge, model PGH-100A. According to this gauge, the pressure normally drops to about 10^{-6} mm mercury when the cryostat is at room temperature. However, during a He^3 run, when the cryostat is cooled with liquid He^4 , the cryostat high vacuum insulation region is sealed off from the diffusion pump by the "Hi-Vac Isolation Valve." According to Garfunkel and Wexler,⁴⁵ the insulation pressure should cryopump to the order of 10^{-10} mm mercury in this situation.

The high vacuum can is constructed of moderate gauge copper with all permanent joints silver soldered. All electrical leads and vacuum piping are fed into the high vacuum can through the lid for

Figure 14. HIGH VACUUM SYSTEM.

operator convenience. The can is sealed with a low temperature (77 degrees C) solder called Woodsmetal.⁴⁶ This is a somewhat cumbersome procedure, but once the technique was mastered, no vacuum leak occurred at the joint.

The electrical leads were fed into the high vacuum can through a leads chimney as shown in Figure 2. This chimney consists of a short 1/2 inch diameter thin wall stainless steel tube silver soldered to the can lid. An ordinary 5/8 to 1/2 inch copper reducer was silver soldered to the top of the stainless steel tube and a lid made of thin copper was silver soldered across the open end of the reducer. Holes were drilled in this lid with a number 60 drill for the superconducting wire electrical leads. These wires were inserted through individual holes and Stycast was spread across this lid as a vacuum seal. The only reason for this configuration was to prevent accidental overheating of this stycast seal. Since stainless steel conducts heat poorly, a relatively brief overheating of the copper can will not overheat the stycast. In this form no leaks have ever been detected in these electrical feed throughs.

The vapor pressure of the liquid He^4 is reduced by a high volume, 105 CFM Stokes mechanical vacuum pump as shown in Figure 14. The He^4 vapor pressure is monitored with a mercury manometer. The vent for the He^4 bath, used primarily to vent He^4 gas during a liquid He^4 transfer, is made to allow the addition of an auxiliary vacuum pump to help lower the He^4 bath temperature. A parallel set of valves is also provided for fine control of the He^4 bath temperature if required.

Thermometry

The thermometer used to measure the temperature of the cadmium crystal was a nominal 2.7 ohm, 1/2 watt untreated carbon resistor manufactured by Allen Bradley, Inc.⁴⁷ The resistor was mounted snugly in a hole in the copper crystal mount just under the crystal as shown in Figure 12. Since most of the heat enters and leaves the resistor through its leads⁴⁸ one lead was soldered directly to the copper crystal mount. Thermal coupling to the other lead was provided by soldering a 750 pF silver mica capacitor from this lead to the copper mount. Because of the large plate area to separation ratio, the capacitor provides a good thermal path while blocking the flow of dc electrical current. In addition, the capacitor prevents RF heating in the resistor by providing an electrical short circuit across the resistor for any stray radio frequency signals picked up by the leads outside the cryostat.⁴⁹

The resistance of the carbon resistor thermometer is measured by the conventional four lead dc method. In this method a regulated constant current is sent through the resistor and the voltage measured directly across the resistor is correlated to the resistance through Ohms law. The thermometer current was supplied by a constant current power supply modeled after a design published by Kroeger and Rhinehart.⁵⁰ See Appendix C for details. This power supply was stable to better than 0.2% over its 0.5 μ A to 10 mA range. In order to prevent Joule heating from raising the temperature in the thermometer, a current of 0.5 μ A was used during the experiment. This

insured that the Joule heating was always less than 2×10^{-9} watts. This heating was sufficiently small so that no effect of self-heating in the thermometer was observed.⁴⁸ The voltage across the carbon thermometer was amplified by a precision Leeds and Northrup model 9835-B dc microvolt amplifier. The input impedance of this amplifier was 1.1×10^7 ohms compared to the maximum thermometer resistance of less than 10^3 ohms. Thus, the voltage measurement was essentially potentiometric. The output of this amplifier was used to drive the x-axis of the Moseley X-Y recorder on which the attenuation data was being recorded.

Since the temperature-resistance calibration of carbon resistor thermometers is commonly reported to shift upon cycling between room temperature and low temperature,⁵¹ the carbon thermometer was recalibrated before each run and during some especially long runs. The calibration was accomplished by correlating the resistance of the thermometer as measured by the dc amplifier-X-Y recorder system, with the temperature of the liquid He³ as measured by the Wallace and Tiernan absolute pressure indicator. The liquid He³ temperature was determined from the T₆₂ He³ temperature scale prepared by Sherman et al.²⁹ This procedure calibrated the thermometer between the temperature of 1.2K and 0.65K. In order to extend this calibration to lower temperatures, a least squares fit was made to the well known Clement-Quinnell⁵² semi-empirical equation relating resistance R and temperature T,

$$\log_{10} R + \frac{C}{\log_{10} R} = A + \frac{B}{T}, \quad (3-6)$$

where A, B, and C are arbitrary constants determined from the least squares fit to the calibration data. The fit was found to be considerably better than 1.0% in each calibration run. The extrapolation at low temperatures was found to be consistent to better than 2% from run to run. The temperature resolution at the transition temperature of cadmium was found to be about 0.002K. A temperature-resistance calibration and extrapolation curve is shown in Figure 15.

In addition to this thermometer, a germanium probe thermometer was placed in another hole in the crystal mount to measure temperatures above 1.2K. This thermometer was purchased as a calibrated unit from CryoCal Inc.⁵³ The accuracy of this thermometer is stated by the manufacturer to be 0.001K with a repeatability of better than 0.0005K.

The estimation of temperature from room temperature down to 10K for the purpose of observing the precooling rate of the crystal, was accomplished by measuring the resistance in the superconducting magnet which is mounted on the sample mount coaxially with the cadmium crystal. The resistance was measured in the same manner as the carbon thermometer by a convenient switching arrangement except that the magnet voltage was displayed on a digital voltmeter for viewing. A graph of the approximate temperature-resistance characteristic of this superconducting wire is shown in Figure 16.

Superconducting Magnet

In order to produce a magnetic field which would quench superconductivity in cadmium and in other crystals studied in this cryostat,

Figure 15. CARBON THERMOMETER CALIBRATION

Figure 16. APPROXIMATE CALIBRATION OF SUPERCONDUCTING SOLENOID IN He³ CRYOSTAT

a superconducting solenoid was constructed. It was desired that this solenoid be small enough to be mounted directly on the copper sample mount and yet be able to produce a magnetic field of several thousand gauss if necessary. Another critical requirement was that the coil must not affect the temperature of the sample. The details of the coil are shown in Figure 17. In order to conserve space, the coil form was constructed by making right angle flanges on a 1/2 inch diameter thin wall nonmagnetic stainless steel tube of the same stock used for the He³ pumping line. The solenoid was wound with a 0.0065 inch diameter, copper sheathed (for stability) superconducting wire of niobium-48% titanium alloy called SUPERCON T48B, type S, (copper to superconductor ratio of 0.67:1).³⁹ Thirteen layers of wire with about 86 turns per layer for an actual number of 1139 turns were wound on the coil form. The coil was then coated with Stycast 2850FT epoxy. Because of the geometry of the sample-coil configuration, Figure 12, no effort was made to produce a uniform field over the entire crystal volume. Simple calculations show that 1.2 amps will produce a field of about 1200 gauss in the center of the solenoid. This allowed an approximate meter calibration of one gauss per milli-amp. In practice ample extra current was used to insure sufficient magnetic field strength over the crystal volume to insure that the entire crystal was in the normal state. The magnet control circuit was designed so that the magnet current was delivered to the solenoid through two AWG number 32 enameled copper wires and two AWG number 36 copper wires were available for voltage leads across the solenoid for

Figure 17. SUPERCONDUCTING SOLENOID

a magnet protection circuit. A rotary switch in the control circuit allowed these four wires to be used as leads to measure the resistance in the solenoid by the four wire dc method. This was a convenient way to watch the precooling rate of the cryostat and to determine if the solenoid was in its superconducting state before attempting to actuate the magnet.

Transmission Line Design

The coaxial RF transmission line, used to transmit and receive the ultrasonic attenuation information was designed and constructed as shown in Figure 18. The outer conductor was made from 1/4 inch diameter type 304 stainless steel of 0.01 inch wall thickness. The inner conductor was made from a 0.040 inch diameter, 0.002 inch wall thickness capillary tube of cupro-nickel alloy of 30% copper, 70% nickel. A female BNC cable connector, type UG-261B/U, was soldered onto the upper end of the transmission line. The inner capillary tube was soldered to the center conductor pin of the BNC connector so that a vacuum seal was obtained in the capillary. The vacuum seal for the upper end of the annular region was effected with a short plug of Stycast epoxy. The transmission line was operated with a vacuum in this annular region.

Since the Arenberg pulsed RF oscillator and receiver impedances were 93 ohms, the transmission line was designed to use available materials which would yield a matching characteristic impedance as close as possible to 93 ohms. In practice, an impedance of 105 ohms was achieved. Annular teflon spacers were placed about every three

Figure 18. RF TRANSMISSION LINE

inches according to standard techniques⁵⁴ in order to support the center conductor and achieve an operating range up to the cut off frequency of about one gigahertz.

The center conductor was chosen as a thin wall capillary in order to reduce the heat leak from room temperature down to the crystal. However, since this conductor runs from room temperature to the sample in a vacuum, it is absolutely necessary to thermally short this line to something at liquid He⁴ temperature before the line reaches the sample. This was accomplished as shown in Figure 18, by injecting Stycast epoxy into a section of the annular region at the high vacuum lid. However, difficulties were encountered with this geometry because of apparent changes in the electrical properties of stycast during thermal cycling from room to liquid He⁴ temperatures. In an apparently successful attempt to circumvent this problem, the transmission line was replaced and installed in the same configuration except that the inner conductor was first coated in the region of the thermal short with a moderate coat of baked-on GE 7031 varnish⁵⁵ before the Stycast epoxy was injected. The upper annular region of the line was evacuated by punching a hole in the center conductor above and below the thermal short so that air could be pumped out by the high vacuum system. Stycast plugs were injected into the center conductor just above and below the pump out holes to serve as radiation traps. The brass sleeve was soft soldered to the high vacuum can lid and to the transmission line to help insure that the Stycast thermal ground would not break loose from

the outer stainless steel conductor during thermal cycling.⁵⁶

A number 00-90 brass screw was soldered into the open end of the center conductor. A nonmagnetic spring loaded ultrasonic plunger was threaded onto this screw so that various crystal sizes could be accommodated and the transducer-plunger tension could be adjusted. The RF electric circuit was completed to ground through the metal crystal, sample mount, and cryostat.

CHAPTER IV

SAMPLE PREPARATION

Many of the properties of superconductors are affected by crystallographic dislocations and imperfections.⁵⁷⁻⁵⁹ Probably the most serious of these effects pertaining to this study are those caused by dislocations. In the superconducting state these dislocations tend to vibrate like resonating strings under the stimulation of ultrasonic waves.⁶⁰ This produces a dependence of the shape of the superconducting ultrasonic attenuation curve on the strength of the initial ultrasonic pulse.⁶¹⁻⁶⁴ These effects, if present, will naturally influence the energy gap calculations.⁶⁵ This chapter will present a detailed description of the sample preparation with special emphasis on strains introduced by the cutting process.

Preparation Requirements

In order to study the superconducting properties of cadmium, with a minimum effect from dislocations and impurities, a zone refined single crystal, grown from better than 99.999 per cent pure cadmium melt, was purchased from Metals Research Ltd.⁶⁶ This crystal came in the form of a half inch diameter right circular cylinder about one inch long. Preparation for the ultrasonic study required that the crystal be cut into a rectangular parallelepiped exposing the three independent crystallographic directions.

There are several requirements which the sample must meet in order that meaningful data may be obtained. The most obvious of these is that the crystal must be small enough to fit inside the

superconducting solenoid in the He^3 refrigerator. This limits the size to something less than 1.2 cm in diameter by less than 0.9 cm in length. The minimum length is established from sound velocity considerations. It is necessary that the ultrasonic echo train consist of distinctly separate echoes as shown in Figure 1. Since the echoes are just less than 2 sec in width, the minimum time between echo peaks should be at least 2.5 sec. From the anisotropic sound velocities in cadmium at 4.2K given by Deaton,⁶⁷

$$\begin{aligned} v_{[10\bar{1}0]} &= 3.85 \times 10^5 \text{ cm/sec} \\ v_{[11\bar{2}0]} &= 3.88 \times 10^5 \text{ cm/sec} \\ v_{[0001]} &= 2.52 \times 10^5 \text{ cm/sec,} \end{aligned}$$

the minimum lengths should be about 0.48 cm in the $[10\bar{1}0]$ and $[11\bar{2}0]$ directions and about 0.32 cm in the $[0001]$ direction. Because of the high ultrasonic attenuation in the $[0001]$ direction, this length must be as short as possible so that the sound wave will not be entirely absorbed by the crystal before the first echo can be produced. In the other two directions, the attenuation is quite low, requiring that the crystal be correspondingly long, so that the attenuation change in the superconducting state will be sufficiently large to be accurately measured by the ultrasonic instrumentation. Based on these considerations, the cadmium sample was cut to the following lengths at 25°C:

$$\begin{aligned} l_{[10\bar{1}0]} &= 0.4767 \text{ cm} \\ l_{[11\bar{2}0]} &= 0.7276 \text{ cm} \\ l_{[0001]} &= 0.4093 \text{ cm.} \end{aligned}$$

In addition to the above requirements, the quality of the echo train depends on several other significant factors, which are discussed quantitatively in the book by Truell, Elbaum and Chick.⁶⁸ Briefly, the crystal faces must be accurately parallel so that sound wave interference at the transducer will not produce modulations in the echo train. Secondly, the crystal faces must be wider than the ultrasonic quartz transducer so that wall reflections will not modulate the echo train. This problem is circumvented by using a small transducer. Thirdly, the crystal faces must be accurately parallel to the crystallographic planes so that a pure longitudinal mode ultrasonic wave can be transmitted. Fourthly, the crystal surface must be sufficiently smooth so that the ultrasound waves will not be unduly scattered. Finally, the cutting process must introduce a minimum of strain into the crystal.

Spark Cutting Procedure

Since a cadmium single crystal is very soft and liable to mechanical twinning when strained, extreme care must be exercised in cutting processes. For this reason, it was decided to use a spark erosion method to prepare the sample. The electrical discharge machine (EDM) used in this work was an Elox TQH-31 machine tool⁶⁹ especially modified for low energy spark machining. This machine consists basically of a large trough in which the crystal stock is mounted and immersed in a dielectric cooling oil, catalog number 400773-55. The cutting tool is mounted in a rotatable chuck which is hydraulically controlled to maintain a certain vertical distance

away from the crystal depending on the average voltage between the tool and the work. A 250 kHz square wave voltage is applied to the tool-crystal gap causing a series of electrical discharges which slowly erode the crystal without any mechanical contact with the tool. The work is positioned under the cutting tool by moving the entire trough with micrometer screws. At the finest setting on this machine, the average energy per spark is estimated to be less than 100 ergs at 65 volts between tool and work.

Since spark damage in the crystal in a slicing operation depends not only on the spark energy, but also on the type of tool used, a stainless steel feeler gauge 0.003 inches thick was chosen. This decision was made according to suggestions by Luke and Puttick.⁷⁰

The crystal was mounted on the work holder in the trough with graphite-doped Duco cement so that good electrical contact was maintained between crystal could be removed and repositioned without strain by dissolving the cement in acetone. The cadmium sample was first cut into a rectangular parallelepiped roughly along the corresponding crystallographic planes by first slicing the stock crystal with the stainless steel blade tool. Fine adjustments were made on the orientation of the surfaces by mounting the sample on a goniometer table in the EDM trough and spark planing with a rotating brass disc tool. In this manner the sides were aligned to within 0.5 degrees of the appropriate direction as verified by Laue back reflection X-ray photographs.⁷¹ The X-ray machine used in this study was the type CN4001 X-ray generator from the Rigaku Denki Company of Japan, with

a Polaroid XR-7 Land Diffraction Cassette. Once the proper direction was established, the opposite sides of the crystal were planed parallel to a precision of about 0.0005 cm over the crystal faces.

Spark Damage

Although the spark planed surfaces appeared quite smooth to the naked eye, the micrograph of Figure 19 reveals the even, crater-like surface. Each crater represents a small area where a spark has melted the surface and part of the melt has resolidified on the crystal. During the routine Laue X-ray alignment procedure, it was noted that the X-ray spots were streaked as shown in Figure 20. The circular tendency of the spots is a well known feature and is attributed to the amorphous layer of the resolidified cadmium due to the spark melting.

In order to reveal the cause of the longitudinal streaks, the crystal was etched to remove this thin amorphous layer. A search of literature produced the following etching solutions:⁷²

1. Nitric acid, 1-2% in alcohol.
2. Ammoniacal ammonium persulphate in water-various strengths.
3. Dilute alcoholic feric chloride-various strengths.

This etching procedure required the successive use of each of these three solutions. In practice the crystal was cleaned with acetone to remove the EDM dielectric oil and then completely immersed in the first solution and carefully buffed with a cotton swab. After

Figure 19. MICROGRAPH OF CADMIUM $[10\bar{1}0]$ SPARK PLANED SURFACE. (0.01 mm BETWEEN SCALE LINES)

Figure 20. LAUE X-RAY OF CADMIUM SURFACE SHOWN IN FIGURE 19.

ten to thirty seconds the crystal was picked up with a plastic coated tweezer and immersed in distilled water. This procedure was successively repeated for the second and third etching solutions.

Figure 21 shows the $[10\bar{1}0]$ surface after the first etch. This micrograph reveals striations under the spark crater layer. These striations are all parallel to the basal plane and occurred in both the $[10\bar{1}0]$ and $[11\bar{2}0]$ surfaces, but not in the $[0001]$ surface. This suggests that the rapid surface heating of the sparks has caused sudden expansion of the surface layer which overcame the weak binding between basal planes and caused extensive shallow crystal distortion. This suggestion is also supported by the streaks in the Laue photograph of Figure 20. The fact that these continuous streaks follow the $[0001]$ axis zone lines indicates that the surface has expanded, causing the crystal lattice to "bend" as depicted schematically in Figure 23. However, the appearance of definite spots indicates that the surface damage is shallow enough that some X-rays are able to penetrate to the normal crystal structure below.

In order to eliminate this effect, the crystal was immersed in the nitric acid-alcohol solution and etched until 0.004 cm of cadmium had been removed from the surface shown in Figure 19. After this etch, the crystal surface appeared mirror-like and contained no striations. The Laue photograph of Figure 22 also indicates the absence of any strain. Thus, the crystal used in the ultrasonic study had no detectable strain introduced by the cutting process.

Figure 21. MICROGRAPH OF CADMIUM $[10\bar{1}0]$ SURFACE AFTER FIRST ETCH SHOWING STRIATIONS BELOW SPARK CRATERS. (0.01 mm BETWEEN SCALE LINES)

Figure 22. LAUE X-RAY OF $[10\bar{1}0]$ SURFACE AFTER LAST ETCH SHOWING THAT THE STRAINED LAYER HAS BEEN REMOVED.

Figure 23. EXPANSION OF SURFACE AND ORIGIN OF STRIATIONS

Transducer Bond

In the single transducer pulse-echo method of ultrasonic study, the quartz transducer must be rigidly bonded to the sample in order to transmit a clean plane-wave ultrasonic pulse to the crystal. Because of the relatively long recycling time required by the He^3 refrigerator used in this study, this bond must be extremely reliable and immune to severe temperature changes. That is, the bond must not break when the temperature is lowered and the crystal and transducers contract at different rates. It was found by experience that a reliable bond could be made with a very small amount of Dow Corning DC-11 compound.⁷³ A thin film of this grease was spread onto the cadmium crystal and the transducer was gently worked onto the surface so that no air bubbles were trapped in the bond. The crystal was then cooled to liquid nitrogen temperature and the ultrasonic echo

train was checked for quality. The system was then ready for liquid helium temperatures. It was found that if a good echo train was obtained at liquid nitrogen temperature then good echoes would also appear at liquid helium temperatures.

The quartz transducers used in this work were obtained from the Valpey-Fisher Company.⁷⁴ They were 0.2 inch diameter, 10 MHz, X-cut transducers polished for overtone operation and plated with chromium and gold on both sides.

CHAPTER V

SAMPLE QUALITY INVESTIGATION

Introduction

In electron-phonon studies in superconductors it is essential to know the product of the electron mean free path, ℓ , and the sound propagation vector $\vec{q}$. The most pertinent method of measuring the electron mean free path is that of magnetoacoustics. In this method the applied phonons interact with electrons on the same portion of the Fermi surface as in the ultrasonic attenuation experiment on superconducting cadmium. The electron mean free path length was calculated from the magnetoacoustic data using the method of Deaton,⁷⁵ in which $q\ell = 6.8$ when the high magnetic field saturation attenuation is equal to the attenuation in zero magnetic field. This method allows a rather direct determination of ℓ using the free electron model which applies to the Fermi surface of cadmium.⁷⁶

During these measurements, note was taken of the open orbit resonance absorption of ultrasonic waves as first reported by Gavenda.⁷⁷ Since the crystal used in this work showed higher order submultiple resonance lines than reported by either Gavenda⁷⁷ or Deaton,^{78,79} it was believed that the present crystal had less impurity content than that of Deaton's crystal. However, in further investigations, a plot of the electron mean free path length, determined from the open orbit resonance lines, as a function of temperature showed a maximum at 3.5K similar to that reported by Deaton.⁷⁹

He attributed this effect to the presence of certain magnetic impurities. A spectroscopic analysis of his crystal indicated major impurities of a few parts per million of iron and lead. This result, plus similar anomalies in the resistance of zinc and cadmium reported by Hedgecock⁸⁰ and Muir⁸¹ caused him to conclude that, for extremely pure crystals, magnetic impurities even on the order of a few parts per million could have noticeable effects on the transport properties.⁷⁹

Small amounts of impurities, especially magnetic materials, are also known to affect superconducting properties such as transition temperature²³ and energy gap anisotropy.³³ If the energy gap is affected by these impurities, it is conceivable that the presence or absence of multiple energy gaps could also be affected. In order to investigate this possibility and the possible effects of any bulk magnetic properties on the superconducting transition temperature, the magnetic susceptibility of this cadmium crystal was also measured.

Magnetoacoustics

Outline of Theory

In extremely pure metals at low temperatures when the electron mean free path length becomes comparable to or longer than the ultrasound wavelength, the ultrasonic attenuation oscillates as a function of the magnitude of an externally applied magnetic field whose orientation is perpendicular to the sound propagation direction. This is commonly called the magnetoacoustic effect. However, in addition to the oscillatory effects, the attenuation tends to a limiting value for high magnetic fields. The difference between this high field

attenuation and that at zero magnetic field at various frequencies represents the data which, through Deaton's method,⁷⁵ yields the electron mean free path length.

In zero magnetic field, the mechanism of attenuation of longitudinal ultrasonic waves by the conduction electrons is the interaction of these electrons with the electric fields produced by the motion of the lattice atoms under the influence of the sound wave. The electrons absorb the sound energy and after a short relaxation time dissipate it as heat to the lattice in electron-lattice collisions.⁸² For a longitudinal ultrasonic wave propagating through a metal crystal in zero magnetic field, it is found in terms of the free electron model that the ultrasonic attenuation for arbitrary $q\ell$ values is^{82,83}

$$\alpha_L(q\ell) = \frac{nm}{pv_s\tau} \left\{ \frac{(q\ell)^2 \tan^{-1}(q\ell)}{3[q\ell - \tan^{-1}(q\ell)]} \right\}. \quad (5-1)$$

In this expression n is the number of free electrons per unit volume, m is the electron rest mass, v_s is the sound velocity, p is the metal density, τ is the electron relaxation time, q is the magnitude of the sound wave vector ($q = \frac{2\pi}{\lambda}$), λ is the sound wavelength, and ℓ is the electron mean free path length.

From the results of derivations by Cohen⁸⁴ and Pippard,⁸² the behavior of the longitudinal attenuation in the limit of high magnetic fields is given by the expression

$$\lim_{H \rightarrow \infty} \alpha_L(H) = \frac{nmvq_\ell^2}{15pv_s}, \quad (5-2)$$

where v is the electron velocity on the Fermi surface. This limit is approached as H^{-2} as indicated by Pippard.⁸² Experimentally, data are taken so that a plot of high field relative attenuation values can be made against H^{-2} for a number of frequencies. These data will fall on a straight line which can then be extrapolated to $H = \infty$ to find $\alpha_L(\infty)$.

When the high field attenuation is equal to the attenuation in zero field,

$$\frac{nmvq_\ell^2}{15pv_s} = \frac{nm}{pv_s \tau} \left\{ \frac{(q_\ell)^2 \tan^{-1}(q_\ell)}{3[(q_\ell) - \tan^{-1}(q_\ell)]} \right\}. \quad (5-3)$$

A numerical calculation by Kjeldaas and Holstein⁸⁵ shows that

$$q_\ell = 6.8. \quad (5-4)$$

Thus, if the frequency at which $\alpha_L(H = 0)$ is equal to $\alpha_L(H = \infty)$ can be found, then the electron mean free path length can be calculated. From these data the general range of the anisotropic q_ℓ values can be determined.

The mean free path lengths as a function of temperature are also taken from the temperature dependence of the open orbit resonance-line half-widths. Since the microscopic theory explaining this

effect is quite complicated and is explained in the literature,⁸⁶ only a brief discussion relating to the present data will be given here. Galken, Kaner, and Korolyuk⁸⁷ first showed that open orbit electrons would absorb ultrasonic energy resonantly when the period of the open orbit is a multiple of the sound wavelength. The mechanism of resonance absorption is similar to cyclotron resonance in metals but is related to the spatial periodicity of the field in the metal instead of the temporal periodicity.⁸⁶ In the model of the cadmium Fermi surface proposed by Harrison⁸⁸ and corrected by Cohen and Falicov⁸⁹ for spin-orbit coupling effects, the columns of the second band monster are coupled along the [0001] direction. This model allows for electrons to travel from one Brillouin zone to another by following an average straight line along these connecting columns. This motion is induced when a magnetic field is applied in a direction perpendicular to this direction. Thus, in cadmium, the open orbit resonance phenomenon is observed in transverse magnetic fields for longitudinal sound propagation in the [11 $\bar{2}$ 0] and [10 $\bar{1}$ 0] directions. These open-orbit electrons cause a sharp resonant type of attenuation maximum because all to the open orbits must have the same period in the connected crystallographic direction. This period, of course, is determined by the dimensions of the reciprocal lattice. The amplitude of the subharmonics is determined by the shape of the open orbit.⁸⁶

Even without the orbit details, the resonance character of the absorption can be shown to be⁸⁷

$$\alpha \sim \frac{\alpha_0 \gamma}{\gamma^2 + \left(\frac{Ggc}{2\pi eH} - n\right)^2}, \quad (5-5)$$

or, in equivalent terms,

$$\alpha \sim \frac{\alpha_0 \gamma}{\gamma^2 + n^2(1 + H_n/H)^2} \quad (5-6)$$

where

$$H_n = \frac{Ggc}{2\pi ne}, \quad n = 1, 2, 3, \dots \quad (5-7)$$

and

$$\gamma = \frac{\pi n}{q} \quad (5-8)$$

In this equation H is the magnetic field at which the n th order resonance occurs, G is the period of the open orbit in momentum space, α_0 is the ultrasonic absorption in zero magnetic field, c is the speed of light, and e is the electron charge. Close to the resonance, the absorption line has a Lorentz shape independent of the order n , and the relative width is shown to be

$$\frac{\Delta H}{H} = \frac{\pi}{q\ell}. \quad (5-9)$$

The height of the resonance maximum is given as

$$\alpha_n = \frac{\alpha_0 q \ell}{\pi n} . \quad (5-10)$$

Thus, both the height and width of the open orbit resonance line are related to the electronic mean free path length. This provides a convenient method for observing ℓ as a function of temperature. As found by Deaton, the values of ℓ calculated by equation (5-9) and (5-10) are of the same order of magnitude as those determined from the high field attenuation analysis and would show essentially the same temperature dependence. Thus, the relative purity of the over-all sample can be readily indicated by this method.

Magnetoacoustic Cryostat

The magnetoacoustic cryostat, which was designed and constructed in the laboratory for this project, is shown schematically in Figure 24. The upper portion of the cryostat consists of a brass housing, silver soldered to a round brass plate. The brass plate is vacuum sealed to the metal Janis double dewar system⁹⁰ by a removable O-Ring seal. The brass housing serves as a base for the electrical feedthroughs and the vacuum ports. A Hastings model T thermocouple vacuum gauge is also mounted in this housing in order to monitor the He⁴ exchange gas pressure in the cryostat. There are two 3/8 inch diameter copper vacuum ports for rubber hose connections to a vacuum pump and a He⁴ exchange gas supply. The AWG #34 wire leads from the thermometer and heater on the crystal mount at the bottom of the cryostat are fed through stycaast seals at the top of the brass housing.

Figure 24. MAGNETOACOUSTIC CRYOSTAT

The wires are then soldered to a multi-pin electrical connector fastened to an aluminum frame which is stycasted to the housing. This provides convenience in moving the cryostat.

The RF energy is fed to the crystal through a stainless steel coaxial transmission line which is soldered into the lid of the brass housing with soft eutetic solder. A specially machined brass flange sleeve was soldered at an appropriate position at the top of the coaxial line so that a type 7682 UHF connector body could be screwed on after the center pin had been soldered to the line's center conductor. The center conductor of the coaxial transmission line was made from a 1/8 inch diameter thin wall type 304 stainless steel tube. It was stycasted vacuum tight at the top of the line and was held away from the outer conductor along its length by appropriately spaced⁵⁵ Teflon spacers. The outer conductor was made from a 1/4 inch diameter type 304 stainless steel thin wall tube. The transmission line length is about two meters. This line is enclosed by a 3/4 inch diameter thin wall type 304 stainless steel vacuum jacket for thermal insulation between the liquid He⁴ bath and the cryostat mount. However, in order to obtain the lowest possible temperature at the crystal, three sets of thermal links are mounted along the length of the transmission line. These links consist of a copper sleeve soft soldered to the transmission line and three spring copper contacts soldered to the sleeve which make sliding contact with the vacuum jacket. These contacts are positioned so that a significant portion of the thermal energy traveling down the line from

the relatively hot room temperature end is diverted to the liquid helium bath before it can reach the crystal. These links are made to have some thermal resistance however, so that the temperature of the crystal can be efficiently varied with the electrical heating system on the crystal mount. The lower end of the center conductor terminates in a nonmagnetic brass spring onto which a small copper plunger has been soldered. This copper "button" serves as an electrical contact for the transducer.

The crystal mount is attached to the coax line by a copper sleeve containing a set screw, described as the plunger tension adjust in Figure 24. This feature allows the whole crystal mount to be moved vertically so that the spring tension on the transducer can be manually adjusted without having a complex plunger adjustment mechanism. The sleeve supports the crystal mount with two thick wall stainless steel support tubes silver soldered to the body so that the plane of the crystal mount is as nearly perpendicular to the vertical transmission line as possible. The crystal mount itself is a single piece machined out of high thermal conductivity copper stock. The crystal platform surface is a highly polished flat surface so that good thermal contact can be established with the sample. A hole is drilled in the copper block just below the sample surface so that a CryoCal germanium probe thermometer⁵⁴ fits in snugly to monitor the temperature. A manganin wire heater is non-inductively wound and stycasted onto the lower portion of the mount so that the crystal temperature may be stabilized electronically.

A set of three spring copper thermal links are screwed onto the bottom of the crystal mount to aid in cooling this mass. The thermometer and heater wires are stycasted to each of the three upper thermal shorts to cut down on the amount of heat conducted to the sample mount through these wires. A copper-constantan thermocouple is included to monitor higher temperatures of the crystal if desired.

The crystal is situated in the small tail section of the Janis dewar system between the 12 inch diameter flat pole faces of a Varian model V 3603 electromagnet.⁹¹ This magnet produces a highly uniform magnetic field up to 13,000 gauss. The magnet can be rotated manually and its direction determined from a scale at its base. The field is controlled by a Fieldial V-FR 2501 magnetic Field Regulator,⁹¹ which controls the magnet current by a feedback circuit which senses the field strength with a Hall probe.

Magnetoacoustic Results

The magnetoacoustic data were taken with the ultrasonic electronic system described in Chapter II. In particular, the logarithmic converter was used as shown in the block diagram in Figure 3. The X-axis of the X-Y recorder was driven by an output from the Fieldial magnet power supply system which indicated the magnetic field strength.

In order to gauge the relative anisotropy of the electron mean free path lengths, the first data were taken as a function of magnetic field angle for a fixed magnetic field of 10 kilogauss. Equation (5-2) shows that this attenuation is directly proportional to the mean

free path length to within a few per cent. Figures 25, 26, and 27 show these zone plots for the three sound directions. The pertinent crystallographic directions are indicated on the plots.

The general range of electron mean free paths was found for several magnetic field orientations from the following procedure used by Deaton. First, the ultrasonic attenuation as a function of magnetic field, for a given phonon and magnetic field direction, Figure 28, was taken for several frequencies. Since the high field attenuation approaches its limit as H^{-2} , a plot of high field attenuation versus H^{-2} was made for all frequencies measured. The extrapolated values were found as shown in Figure 29. These extrapolated high field attenuation values were then plotted as a function of frequency as shown in Figure 30. At the frequency where the attenuation curve crosses 0 dB, the product $q\ell$ equals 6.8.

This method has limitations in that if the $q\ell$ product is quite large, the curve of Figure 30 may not cross the 0 dB line until low ultrasonic frequencies are used. In this experiment frequencies below about 10 MHz were not used. Thus, the mean free path lengths in the $\vec{q}||[0001]$ direction could not be quantitatively measured. However, the high attenuation measured in this direction implies that the $q\ell$ product is quite large.

In the perpendicular sound direction shown in Figures 26 and 27, the minimum mean free path length is labeled. The shortest mean free path length measured is that marked as $\ell = .0105$ cm in Figure 26. At the lowest ultrasonic frequency used, 10 MHz,

Figure 25. MAGNETOACOUSTIC ZONE PLOT:
 $\vec{q} \parallel [0001]$, 30 MHz, 10 KG.

Figure_26. MAGNETOACOUSTIC ZONE PLOT:
 $\vec{q} || [10\bar{1}0]$, 10 MHz, 10 KG.

Figure 27. MAGNETOACOUSTIC ZONE PLOT: $\vec{q} \parallel [11\bar{2}0]$,
10 MHz, 10 KG

Figure_28. ATTENUATION vs. MAGNETIC FIELD
 $\vec{q} || [10\bar{1}0]$, $H || [0001]$, 50 MHz, $T = 1.5K$.

Figure 29. ATTENUATION vs. $1/H^2$.

Figure 30. HIGH FIELD ATTENUATION vs. FREQUENCY.

$q = 162 \text{ cm}^{-1}$, and the smallest $q\ell$ product in effect at any time in this experiment is 1.6. Thus, at no time does the superconducting ultrasonic attenuation data result from interactions in the region where $q\ell \sim 1$.

The possible presence of extremely small amounts of magnetic impurities in the cadmium sample was indicated by the anomalous maximum in the electron mean free path length as a function of temperature. This indication was observed in the mean free path lengths as measured from the data of open orbit resonance lines. Figure 31 clearly shows the presence of a fundamental and a second order open orbit resonance line. A third order line is present but is almost completely obscured by the large increase in attenuation due to the ordinary magnetoacoustic attenuation.

The electron mean free path length is determined from the half width of the resonance line according to equation (5-9). In this process the background absorption is subtracted, leaving a Lorentz shape resonance line from which ΔH can be easily obtained. Figure 32 shows the ℓ values calculated by this method. Except for the higher values of ℓ and a smaller magnitude of the maximum in Figure 32, this curve is very similar in form to that obtained by Deaton.⁷⁹ Deaton also presents data which show that the electron mean free path length exhibits this maximum in the same form regardless of whether ℓ is determined from open orbit resonance data or from the high field attenuation data. The spectrographic analysis of Deaton's cadmium crystal was reported to contain on the order of 10 parts per million

Figure 31. OPEN ORBIT RESONANCE LINES
 $\vec{q} || [10\bar{1}0]$, $H || [11\bar{2}0]$, 50 MHz, $T = 1.5K$

Figure 32. ELECTRON MEAN FREE PATH LENGTH $\vec{q} || [10\bar{1}0]$, $H || [11\bar{2}0]$.

of iron with lesser amounts of lead as impurities. Deaton⁷⁹ suggests that this anomalous behavior in the electron mean free path length is related to the same processes causing the electrical resistance minimum observed in lightly alloyed crystals.^{80,81} If this is true, then for extremely pure crystals such as the present cadmium sample, the effects of these impurities should rapidly diminish as the impurity concentration is diminished. This can be inferred from the shape of the curve shown in Figure 33. This curve, taken from the work of Hedgecock and Muir⁸⁰ on Mn impurity in zinc shows that for extremely pure crystals, the magnitude of the electrical resistance minimum diminishes rapidly as the impurity concentration is decreased. Thus, since the magnitude of the mean free path maximum in the present sample is less than that of Deaton's crystal, it is concluded that there is less impurity content in the present sample than that stated for Deaton's cadmium sample.

Magnetic Susceptibility

The bulk magnetic susceptibility of the cadmium stock crystal was measured using the standard Faraday method. In this study, a sample of the cadmium was spark machined from the stock crystal immediately adjacent to the site where the sample used for ultrasonic study was taken. This sample was cut in the shape of a short parallelepiped with a small hole spark machined through one end. A glass hook was inserted through the hole and the sample was then suspended from the Cahan Electrobalance⁹³ in the susceptibility cryostat such that the [0001] axis was vertical. The magnetic field gradient was supplied

Figure 33. REPRESENTATIVE GRAPH OF MAGNITUDE OF RESISTANCE MINIMUM IN Zn AS A FUNCTION OF Mn IMPURITY CONTENT.⁷

by a Varian six inch electromagnet⁹⁴ with special pole faces machined such that the field gradient was vertical. According to the Faraday method, a vertical force will be exerted on a magnetic sample when the magnetic field gradient is applied. The electrobalance is calibrated to measure this force as an apparent change in mass, Δm of the sample. The magnetic susceptibility χ_x is then calculated from the relation

$$\chi_x = \frac{\Delta m}{\frac{H_x}{g} \frac{dH_z}{dz} m}, \quad (5-11)$$

where the field character $H_x \frac{dH_z}{dz}$ was previously determined in a calibration experiment using a sample of Mohr's salt ($\text{Fe}(\text{NH}_4)_2(\text{SO}_4) \cdot 6\text{H}_2\text{O}$), whose magnetic properties are well known.

Figure 34 shows the results of the magnetic susceptibility measurements. It is seen that these measurements agree fairly well with those of Marcus.⁹⁵ The slightly greater diamagnetism in the present crystal is probably due to a higher purity. A slight tendency toward paramagnetism was noted at liquid helium temperature but it was discovered that the glass hook used to suspend the cadmium sample contributed sufficient paramagnetism to cause the total measurement to tend toward paramagnetic values. The data point at 4.2K was corrected for the glass contribution.⁹⁶

Thus, it is seen that if there are magnetic impurities in this sample of cadmium, they are so dilute as to not affect the bulk magnetic properties of the cadmium sample.

Figure 34. Cd MAGNETIC SUSCEPTIBILITY vs. TEMPERATURE: 7 kg; x - MARCUS²⁷, o - PRESENT WORK.

CHAPTER VI

RESULTS

The normal state attenuation data were taken below the transition temperature by applying a magnetic field of sufficient strength to quench superconductivity in cadmium. The maximum magnetic field strength necessary to quench superconductivity in cadmium was found by Goodman and Mendoza¹⁰⁷ to be about 30 gauss. A field somewhat larger than this was supplied by the superconducting solenoid described in Chapter II. This field was parallel to the sound direction in the crystal. It was noted that the normal state attenuation was a function of the strength of the magnetic field. This effect was discovered in cadmium earlier by Mackinnon and Daniel¹⁰⁸ and others¹⁰⁹ and is known as the parallel-field magnetoacoustic effect. The normal state data in this work were corrected for this effect from the results presented in the paper by Mackinnon and Daniel.¹⁰⁸

The temperature of the crystal was varied as described in Chapter III by manually controlling the He^3 vapor pressure. In order to insure thermal equilibrium between the cadmium sample and the thermometer, the temperature was varied quite slowly. The time for one temperature traverse over the range 0.5K to 0.3K was always 15 to 20 minutes or more. In addition, for every crystal-sound configuration, several sets of data were taken for both rising and falling temperatures. The speed of temperature change was controlled such that a minimum of attenuation hysteresis was observed.

The transition temperature of this cadmium sample was determined

from the ultrasonic attenuation data for each crystallographic direction by observing the temperature at which the attenuation abruptly changed from normal to superconducting. The transition temperature was found to be isotropic within the limits of the thermometer accuracy, and to have the value,

$$T_c = 0.503K \pm 0.005K$$

Analysis Method

The ultrasonic attenuation measurements as a function of temperature were made as described in Chapter II. Figure 35 illustrates the definition of the various attenuation values used in the analysis of the cadmium data. The term $\alpha_n^*(T)$ represents the total absolute attenuation in the normal state. This term includes the normal state electron-phonon electronic attenuation $\alpha_n(T)$, and attenuation α_r^* due to all other non-electronic interactions such as binder losses, impurity scattering, and dislocation losses. Since at these very low temperatures the crystal is in the impurity limited attenuation region, as evidenced by the fact that the normal state attenuation $\alpha_n^*(T)$ is constant in temperature, then it is assumed that the total residual attenuation α_r^* is constant. The total absolute attenuation in the superconducting state is designated by $\alpha_s^*(T)$. The term $\alpha_s(T)$ is the ultrasonic attenuation due to electron-phonon interactions in the superconducting state. The quantity actually measured experimentally, $\alpha_m^*(T)$ is the relative electronic attenuation derived in Chapter II as equation (2-10).

Figure 35. DEFINITION OF ATTENUATION TERMS AND THEIR RELATIONSHIPS.

In order to correlate the experimental data with the BCS theory, the ratio $\alpha_n(T)/\alpha_s(T)$ must be calculated. This can be done by considering the relationships between the terms identified in Figure 35. From this it is seen that

$$\alpha_n(T) = \alpha_n^*(T) - \alpha_r^* \quad (6-1)$$

and

$$\alpha_s(T) = \alpha_n^*(T) - \alpha_m^*(T) - \alpha_r^*. \quad (6-2)$$

Then the BCS ratio becomes

$$\frac{\alpha_n(T)}{\alpha_s(T)} = \frac{\alpha_n^*(T) - \alpha_r^*}{\alpha_n^*(T) - \alpha_m^*(T) - \alpha_r^*}. \quad (6-3)$$

But, in this form, the ratio cannot be numerically evaluated because the residual attenuation is not experimentally measured. From Figure 35, α_r^* can be related to known values,

$$\alpha_r^* = \alpha_n^*(0) - \alpha_m^*(0), \quad (6-4)$$

where $\alpha_n^*(0)$ is the normal state electronic attenuation at zero Kelvin. A computer program, to be described, extrapolates the superconducting relative attenuation to zero Kelvin to find $\alpha_m^*(0)$. Substituting the relation (6-4) into the ratio (6-3) results in

$$\frac{\alpha_n(T)}{\alpha_s(T)} = \frac{\alpha_n^*(T) - \alpha_n^*(0) + \alpha_m^*(0)}{\alpha_n^*(T) - \alpha_m^*(T) - \alpha_n^*(0) + \alpha_m^*(0)} \quad (6-5)$$

However, since $\alpha_n^*(T)$ is independent of temperature in these measurements on cadmium,

$$\alpha_n^*(T) = \alpha_n^*(0), \quad (6-6)$$

and equation (6-5) becomes

$$\frac{\alpha_n(T)}{\alpha_s(T)} = \frac{\alpha_m^*(0)}{-\alpha_m^*(T) + \alpha_m^*(0)} \quad (6-7)$$

This shows that the normal to superconducting electronic ultrasonic attenuation ratio used in the BCS theory can be derived from the relative attenuation and the extrapolated value, $\alpha_m^*(0)$. It should be noted that this method can be used for only those weak coupling superconductors whose normal state attenuation is a constant value independent of temperature below the transition temperature. Cadmium, zinc, and molybdenum, for example, fit this category.

Equation (6-7) shows that the accuracy of the attenuation ratio depends on the precision with which the superconducting relative attenuation can be extrapolated to zero Kelvin. This extrapolation process can be severely affected by crystallographic dislocations as first discovered in lead by Bommel^{97,98} and later by others^{61,62,65,99,100} and explained theoretically by Granato and Lucke.⁶⁰ The general pattern of amplitude dependence, as depicted in Figure 36, is that for large ultrasonic amplitude. In this case the superconducting attenuation-temperature plot curves upward and away from the BCS theoretical

Figure 36. EFFECTS OF ULTRASONIC AMPLITUDE ON ATTENUATION vs. TEMPERATURE CURVE. PATTERNED AFTER LEAD DATA OF TITTMAN AND BOMMEL.⁴

plot. It can be immediately seen that if this effect is present, the above extrapolation to find $\alpha_m^*(0)$ may produce severe errors in the ratio of equation (6-7). Thus, during this work, the ultrasonic amplitude was varied considerably for every crystallographic direction studied in an effort to detect the presence of amplitude dependence. No amplitude dependence was found. However, as a precaution, the data presented here were taken at a relatively small ultrasonic pulse amplitude.

Of the several methods discussed by Perz¹⁰¹ for analyzing attenuation data, the following modified method is most appropriate for observing the presence of more than one energy gap in cadmium. From the BCS attenuation equation

$$\frac{\alpha_s(T)}{\alpha_n(T)} = \frac{2}{e^{\Delta(T)/kT} + 1}, \quad (6-8)$$

the temperature dependent energy gap can be found,

$$\ln\left[\frac{2\alpha_n(T)}{\alpha_s(T)} - 1\right] = \frac{\Delta(T)}{kT}. \quad (6-9)$$

Since there is a non-zero energy gap only at temperatures below the transition temperature T_c , let $\Delta(T)$ be described as a function of reduced temperature t ,

$$t = \frac{T}{T_c}. \quad (6-10)$$

Since the ultrasonic attenuation in cadmium is found to follow the BCS curve fairly well, the ratio $G(t)$ is introduced,

$$G(t) = \frac{\Delta(t)}{\Delta(0)}, \quad (6-11)$$

where $\Delta(t)$ is the temperature dependent energy gap of an ideal BCS superconductor, and $\Delta(0)$ is the zero Kelvin energy gap for a BCS superconductor. The values of $G(t)$ were tabulated by Mühlischlegel,¹⁰² but for convenience in the computer program the power series expansion given by Ferrell¹⁰³ and Clem¹⁰⁴ was used to approximate the BCS relation,

$$G(t) = 1.7367(1 - t)^{1/2} [1 - 0.4095(1 - t) - 0.0626(1 - t)^2 + \dots] \quad (6-12)$$

The values calculated from this series are within 0.1% of the values reported by Mühlischlegel. Now, by substituting equation (6-11) into equation (6-9), the following equation in terms of reduced temperature is obtained,

$$\ln \left[\frac{2\alpha_n(t)}{\alpha_s(t)} - 1 \right] = \left[\frac{\Delta(0)}{kT_c} \right] \frac{G(t)}{t}. \quad (6-13)$$

By plotting the ultrasonic attenuation data in the form

$\ln[2\alpha_n(t)/\alpha_s(t) - 1]$ as a function of the calculated BCS values of $G(t)/t$, the resulting curve should be linear if the data follows the

BCS theory. The slope of this line should be equal to the zero Kelvin superconducting energy gap divided by kT_c . However, if the cadmium crystal possessed several energy gaps, each effective over a given temperature range, the curve should show several slopes from which the individual gaps could be determined.¹⁰⁵

A Fortran computer program for the IBM 360/50 computer was written so that the attenuation (or voltage, as in equation 2-10) data could be fit to equation (6-13) by the method of least squares. From equation (6-7) it can be seen that the attenuation ratio used in equation (6-13) depends on the extrapolated value of the measured relative superconducting attenuation $\alpha_m^*(0)$. The computer program found this value by treating it as an adjustable parameter and varying it until the best least squares fit to equation (6-13) was obtained for the low temperature portion of the data. Testing the fit to the low temperature data was done so that in the possible event of more than one energy gap, the extrapolation process would find the best value of $\alpha_m^*(0)$. This value is then used in fitting the higher temperature data which may contain other energy gaps.¹⁰⁶

Results

The results of the computer analysis presented in the following section are divided into groups corresponding to the three principle crystallographic directions studied. The graphs shown in Figures 37 through 56 are representative data from typical experimental runs. Numerical data for all of the experimental runs are presented in Appendix D.

Data for $\vec{q}||[0001]$

Representative ultrasonic attenuation data for $\vec{q}||[0001]$ are plotted in Figures 3 through 5. The data in these plots are expressed in terms of $\ln[2\alpha_n(t)/\alpha_s(t) - 1]$ versus $G(t)/t$, so that the slope of the line would represent $\Delta(0)/kT_c$ as shown in equation (6-13). These data clearly show that within the scatter, there is only a single slope in each individual data set for the higher values of $G(t)/t$, (lower temperatures). The curvature evident in the first three or four data points in some of the graphs is thought to arise from the non-BCS like character of the attenuation data just below the transition temperature. This effect is typical and pronounced in transverse wave ultrasonic work and to a much smaller extent in longitudinal wave ultrasonic experiments, but its origin is not well known. David¹¹⁷ attempts to attribute this effect to small shear components in the longitudinal sound waves. The effect in shear wave attenuation is associated with a screening of the electron-phonon interaction by the supercurrents.^{12,118,119} Thus, these first few data points have been deleted in calculating the superconducting energy gaps, so that for frequencies of 9.49, 33.7, and 52 MHz, only one zero Kelvin limiting energy gap is indicated in this direction.

Figure 40 shows that, within the indicated error, the energy gap is frequency independent. The indicated error represents the repeatability of the absolute value of the energy gap. The error arises from the difficulty in extrapolating the attenuation data over the relatively large temperature range of about $.7T_c$ to find

Figure 38. PLOT OF $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ AT 33.7 MHz FOR $\vec{q} \parallel [0001]$.

Figure 40. ENERGY GAP $2\Delta(0)$ vs. FREQUENCY
FOR $q \parallel [0001]$

Figure 41. LIMITING ATTENUATION vs. FREQUENCY FOR $\vec{q} || [0001]$.

$\alpha_m^*(0)$. Any small error in the actual attenuation data will be exaggerated in the value of the energy gap because of this large extrapolation.

Figure 41 shows the extrapolated total electronic ultrasonic attenuation values $\alpha_m^*(0)$, as a function of frequency. The linearity of this curve indicates that the electron mean free path length is so long in this direction that for the frequencies studied, $q\ell \gg 1$. This is inferred from the limiting value of the attenuation given by Pippard,¹¹⁰

$$\alpha_m^*(0) = \frac{\pi N m v_o q}{6 M v_{s\ell}}, \quad q\ell \gg 1, \quad (6-14)$$

where v_o is the Fermi velocity, $v_{s\ell}$ is the longitudinal sound velocity in the crystal, M is the density, m is the mass of a free electron, and N is the number of free electrons per unit volume. This equation shows a linear dependence of the electronic ultrasonic attenuation on the frequency ν , ($q = \frac{2\pi\nu}{v_s}$), as compared to the limiting region of small $q\ell$ where $\alpha_m^*(0)$ depends on the square of the frequency,¹⁰⁹

$$\alpha_m^*(0) = \frac{4 N m v_o q^2 \ell}{15 M v_{s\ell}}, \quad q\ell \ll 1 \quad (6-15)$$

or the region of $q\ell \sim 1$ where $\alpha_m^*(0)$ is non linear in frequency,¹¹⁰

$$\alpha_m^*(0) = \frac{N m}{M v_{s\ell} \tau} \left[\frac{(q\ell)^2 \tan^{-1}(q\ell)}{3\{(q\ell) - \tan^{-1}(q\ell)\}} - 1 \right], \quad q\ell \sim 1 \quad (6-16)$$

where τ is the electron-lattice relaxation time. This indication is corroborated by the magnetoacoustic measurements shown in Chapter V.

The data indicate that in the $[0001]$ direction there is only one energy gap. This gap is frequency independent and apparently represents the limiting minimum energy gap.

Data for $\vec{q}||[10\bar{1}0]$

Figures 42 through 46 are representative plot of $\ln[2\alpha_n(t)/\alpha_s(t) - 1]$ versus $G(t)/t$ for $\vec{q}||[10\bar{1}0]$. This data again clearly shows that for all frequencies studied there is only one straight line and thus only one indicated energy gap. As Figure 47 indicates, this energy gap is also frequency independent within the repeatability error. The limiting attenuation data shown in Figure 48 is seen to fit Pippard's equation (6-14) for large $q\ell$ values. This again implies that the single indicated energy gap in this direction is the limiting minimum energy gap.

Data for $\vec{q}||[11\bar{2}0]$

Representative plots of $\ln[2\alpha_n(t)/\alpha_s(t) - 1]$ versus $G(t)/t$ for frequencies of 8.7 to 108 MHz for $\vec{q}||[11\bar{2}0]$ are shown in Figures 49 through 54. This data also clearly indicates the presence of only one energy gap for all frequencies studied. As before, the energy gap is frequency independent within the repeatability error, as seen in Figure 55. The abnormally high energy gap at 50 MHz is believed to be scatter due to the smaller number of data sets taken at that frequency. Figure 56 indicates that the limiting ultrasonic attenuation due to electronic absorption is linear in frequency in accordance with

Figure 47. ENERGY GAP 2 (0) vs. FREQUENCY FOR $\vec{q} \parallel [10\bar{1}0]$.

Figure 48. LIMITING ATTENUATION vs. FREQUENCY
for $q||[10T0]$.

Figure 50. PLOT OF $\ln[2\alpha_\eta/\alpha_s - 1]$ vs. $G(t)/t$ AT 31.2 MHz FOR $\vec{q} \parallel [11\bar{2}0]$.

Figure 51. PLOT OF $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ AT 51.2 MHz FOR $q||[11\bar{2}0]$.

Figure 52. PLOT OF $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$
AT 70 MHz FOR $q||[1120]$.

Figure 53. PLOT OF $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ AT 90 MHz FOR $q||[1120]$.

Figure 54. PLOT OF $\ln[2\alpha_n/\alpha_s - 1]$ vs. $G(t)/t$ AT 108 MHz FOR $\vec{q} \parallel [11\bar{2}0]$.

Figure 55. ENERGY GAP $2\Delta(0)$ vs. FREQUENCY FOR $q||[1120]$.

Figure 56. LIMITING ATTENUATION vs.
FREQUENCY FOR $q||[11\bar{2}0]$.

the Pippard equation (6-14). This again corroborates the magnetoacoustic data in showing the $q\lambda$ product to be greater than one.

Interpretation of Results

The extremely high purity of this cadmium crystal has been indicated in the high field magnetoacoustic data, the open orbit resonances, the very shallow maximum in the electron mean free path length data, and the magnetic susceptibility data in Chapter V. As a result of this high purity, the magnetoacoustic data and the linearity of the limiting ultrasonic attenuation versus ultrasonic frequency curves shown in Figures 41, 48, and 56 indicates that the $q\lambda$ values are much larger than unity for all crystallographic orientations and all frequencies used in this study. Noting this range of $q\lambda$ values, it is seen that the data indicate a single, frequency independent, superconducting energy gap associated with each crystallographic direction studied.

Results of recent ultrasonic measurements on the crystallographically similar crystal zinc by Cleavelin¹⁸ indicate that ultrasonic measurements tend to detect multiple energy gaps when the electron mean free path length and the ultrasonic frequency are such that the $q\lambda$ product is near unity. He also notes that the multiple energy gaps tend to merge into one limiting energy gap when $q\lambda$ becomes much greater than one. Thus, the cadmium and zinc data seem to indicate that for large $q\lambda$ values, only one energy gap is detected in each direction. Comparing this result with the multiband theory of Tang,¹³ equation (1-4), it would appear that the ultrasonic

measurements in the high $q\ell$ region are actually sampling the energy gaps of electrons in only one band in these metals.

Perhaps for low $q\ell$ values, the effective zone of the Fermi surface seen by the ultrasonic phonons is large enough to include contribution to several energy gaps by electrons in more than one band. This seems to be consistent with the low temperature specific heat data of Ducla-Soares and Cheeke¹⁶ which indicated a double energy gap for both cadmium and zinc. Since specific heat data obtains contributions to $2\Delta(0)$ from electrons in all populated bands,¹¹⁵ it is thought that if sufficiently low ultrasonic frequencies were available, the presence of multiple energy gaps in the $q\ell \sim 1$ region would be an interesting consideration for future work.

With the exception of Ducla-Soares¹⁶ there has been no reported indication of the presence of multiple energy gaps in cadmium. In the work on niobium by Tsuda and Suzuki,¹¹¹ a somewhat unsatisfying fit of their data to a two energy gap model was obtained for $q\ell$ values less than one. The fit seemed to improve as the crystal purity was increased and $q\ell$ approached one. An attempt was made by Wu et al¹¹² to fit the ultrasonic data of superconducting mercury to a two gap model for high values of $q\ell$, but an unrealistic set of energy gaps resulted. They concluded that the assumption of a double energy gap did not satisfactorily explain their results and more theoretical work was needed to explain the discrepancies of their data from the BCS theory. The tendency toward the existence of multiple energy gaps in the ultrasonic data on lead by Randorff and Marshall¹¹³

occurred for a $q\lambda$ range estimated from later magnetoacoustic data to be near one. O'Hara¹¹⁴ suggests the possibility of multiple energy gaps in the two directions in his molybdenum crystal for which the $q\lambda$ product was near one. The third direction, in which $q\lambda > 1$, indicated a single energy gap.

Summary

The question of multiple superconducting energy gaps in pure cadmium suggested by the low temperature specific heat measurements of Ducla-Soares and Cheeke¹⁶ has prompted this ultrasonic study. Recent ultrasonic measurements on zinc by Cleavelin¹⁸ had linked the presence of multiple energy gaps to the crystal purity through the $q\lambda$ product. Since the ultrasonic attenuation technique samples the energy gap of a selectable group of electrons on the Fermi surface, it was anticipated that this study might supply evidence to indicate the origin and nature of multiple energy gaps.

In order to accomplish this goal a major effort was put forth to determine the purity of the crystal and to measure the electron mean free path lengths. Once the range of $q\lambda$ values was determined, the ultrasonic attenuation as a function of temperature was measured in the normal and superconducting states for the three principle crystallographic directions.

Analysis of these data indicates the presence of a single, frequency independent, superconducting energy gap associated with each crystallographic direction studied. Based on the experimental results of Cleavelin¹⁸ on zinc, this result is to be expected for

the large values of $q\lambda$ encountered in the present cadmium crystal. As indicated by the multiple energy gap theory of Tang,¹³ equation (1-4), the origin of the energy gaps detected in this work is thought to be due to electrons of only one band.

LIST OF REFERENCES

1. K.H. Ones, Comm. Phys. Lab. Univ. Leiden, Nos. 119, 120, 122 (1911).
2. W. Meissner and R. Ochsenfeld, Naturwiss. 21, 787 (1933).
3. W.J. de Haas and J. Voogd, Leiden Comm. 214c, 149 (1931).
4. J.M. Lock, Proc. Roy. Soc. 208A, 391 (1951).
5. A.B. Pippard, Proc. Roy. Soc. 216A, 547 (1953).
6. W.S. Corak, B.B. Goodman, C.B. Satterwhite, and A. Wexler, Phys. Rev. 96, 1442 (1954).
7. H.M. Rosenberg, Low Temperature Solid State Physics, (Oxford University Press, London, 1963), p. 196.
8. E. Maxwell, Phys. Rev. 78, 487 (1950).
9. Reynolds, Serin, Wright, and Nesbitt, Phys. Rev. 78, 487 (1950).
10. J. Bardeen, L.N. Cooper, and J.R. Schrieffer, Phys. Rev. 108, 1175 (1957).
11. L.N. Cooper, Phys. Rev. 104, 1189 (1956).
12. R.W. Morse, IBM Journ. Res. Dev. 6, 58 (1962).
13. I.M. Tang, Lettere Al Nuovo Cimento 1, 949 (1971).
14. I.M. Tang, Phys. Rev. B 2, 129 (1970).
15. J.R. Leibowitz, Phys. Rev. 133, A84 (1964).
16. E. Ducla-Soares and J.D.N. Cheeke, Proc. Twelfth Intl. Conf. on Low Temp. Phys., Kyoto, Japan, 305 (1971).
17. L.N. Cooper, Phys. Rev. Letters 3, 17 (1959).
18. C.R. Cleavelin, Unpublished Ph.D. Dissertation, Texas Tech University, (1973).

19. R.A. Robbins and B.J. Marshall, J. Appl. Phys. 42, 2562 (1971).
20. R. Truell, C. Elbaum, and B.B. Chick, Ultrasonic Methods in Solid State Physics, (Academic Press, New York, 1969), pp. 62-70.
21. R.L. Roderick and R. Truell, J. Appl. Phys. 23, 267 (1952).
22. Truell, Elbaum, Chick, pp. 134-144.
23. D.R. Peck and E.R. Dobbs, Phys. Letters 35A, 196 (1971).
24. Peck and Dobbs, Phys. Letters 35A, 196 (1971).
25. R.J. Blume, Rev. Sci. Instr. 34, 1400 (1963).
26. R.C. Williamson, Rev. Sci. Instr. 40, 666 (1969).
27. R.B. Hemphill, Rev. Sci. Instr. 39, 910 (1968).
28. L.T. Claiborne and N.G. Einspruch, Phys. Rev. 151, 229 (1966).
29. R.H. Sherman, S.G. Sydoriak, and T.R. Roberts, Los Alamos Scientific Laboratory Report 2701, July 30, 1962.
30. National Bureau of Standards, NBS Monograph 10, (1960).
31. R.A. Robbins and B.J. Marshall, J. Appl. Phys. 42, 2562 (1971).
32. H.A. Reich and R.L. Garwin, Rev. Sci. Instr. 30, 7 (1959).
33. G. Seidel and P.H. Keesom, Rev. Sci. Instr. 29, 606 (1958).
34. B.N. Esel'son, A.D. Shvets, and N.G. Bereznyak, Cryogenics 2, 361 (1962).
35. D. Walton, Rev. Sci. Instr. 37, 734 (1966).
36. M. Fruneau, A. Lacaze, and L. Weil, Cryogenics 7, 135 (1967).
37. K. Fokkens, K.W. Taconis, and R. de Bruyn Ouboter, "The Heat Conductivity of Gaseous He^3 and He^4 Between 0.4K and 3.0K," Proceedings of the Eighth International Conference on Low Temperature Physics, ed. by R.O. Davies (Washington: Butterworths, 1963), p. 34.

38. R.A. Buckingham and R.A. Scriven, Proc. Phys. Soc., London, A65, 376 (1952).
39. Norton Company, Supercon Division, P.O. Box 143, Greendale Station, Worcester, Mass. 01606.
40. R. Berman, Phil. Mag. 42, 642 (1951).
41. E.C. Kerr, Phys. Rev. 96, 551 (1954).
42. R.B. Scott, Cryogenic Engineering, (D. van Nostrand Company, New Jersey, 1959), p. 148.
43. E.F. Hammel, Prog. in Low Temperature Physics, Vol. I, (Interscience Publishers, Inc., New York, 1955), p. 70.
44. Stycast 2850Ft from Emmerson & Cuming, Inc., Dielectric Materials Division, Gardena, Calif.
45. M.P. Garfunkel and A. Wexler, Rev. Sci. Instr. 25, 170 (1954).
46. Sargent-Welch Company, Chicago, Illinois.
47. Allen Bradley, Inc., Milwaukee, Wisconsin.
48. R.G. Mallon and H.E. Rorschach, Jr., Phys. Rev. 158, 418 (1967).
49. J.E. Zimmerman, A. Arrott, and J. Skalyo, Rev. Sci. Instr. 29, 1148 (1958).
50. F.R. Kroeger and W.A. Rhinehart, Rev. Sci. Instr. 42, 1532 (1971).
51. W.L. Johnson and A.C. Anderson, Rev. Sci. Instr. 42, 1296 (1971).
52. J.R. Clement and E.H. Quinnell, Rev. Sci. Instr. 23, 213 (1952).
53. CryoCal Inc., 1371 Avenue "E" Riviera Beach, Florida.
54. T. Moreno, Microwave Transmission Design Data, (Dover Publications Inc., New York, 1948), p. 60.
55. General Electric, Company, Schenectady, New York.

56. W.O. Hamilton, D.B. Greene, and D.E. Davidson, Rev. Sci. Instr. 39, 645 (1968).
57. E.W. Collings, F.T. Hedgecock and Y. Muto, Phys. Rev. 134, A1521 (1964).
58. D. Farrell, J.G. Park, and B.R. Coles, Phys. Rev. Letters 13 328 (1964).
59. G. Boato, G. Gallinaro, and C. Rizzuto, Phys. Rev. 148, 353 (1966).
60. A. Granato and K. Lucke, J. Appl. Phys. 27, 583 (1956); 27, 789 (1956).
61. R.E. Love, R.W. Shaw, and W.A. Fate, Phys. Rev. 138, A1453, (1965).
62. B.R. Tittmann and H.E. Bommel, Phys. Rev. 151, 178 (1966).
63. C.A. Wert, J. Appl. Phys. 20, 29 (1949).
64. R.H. Chambers and R. Smoluchowski, Phys. Rev. 117, 725 (1960).
65. R.E. Love and R.W. Shaw, Rev. Mod. Phys. 136, 260 (1964).
66. Metals Research Ltd., Melbourn, Royston, England.
67. B.C. Deaton, Ph.D. Thesis, University of Texas, (1962).
68. R. Truell, C. Elbaum, and Chick, Ultrasonic Methods in Solid State Physics, (Academic Press, New York, 1969), ch. 2.
69. Elox Corp., 1830 Stephenson Highway, Troy, Michigan.
70. C. Luke and Puttick, J. Phys. D: Appl. Phys. 4, 967 (1971).
71. C. Kittel, Introduction to Solid State Physics, 3rd Ed., (John Wiley & Sons, Inc., New York, 1966), ch. 2.
72. Metals Reference Book, 3rd Ed., (Butterworths, Washington, 1962), p. 236.

73. Dow Corning Corporation, Midland, Michigan.
74. Valpey-Fisher Corporation, 1015 First Street, Holliston, Massachusetts 01746.
75. B.C. Deaton and J.D. Gavenda, Phys. Rev. 129, 1990 (1963).
76. H. Schwarz, Phys. Stat. Sci. 39, 507 (1970).
77. J.D. Gavenda and B.C. Deaton, Phys. Rev. Letters 8, 208 (1962).
78. B.C. Deaton and J.D. Gavenda, Phys. Rev. 136, A1096 (1964).
79. B.C. Deaton, Phys. Rev. 140, A2051 (1965).
80. F.T. Hedgecock and W.B. Muir, Phys. Rev. 129, 2045 (1963).
81. W.B. Muir, J. Phys. Soc. Japan 16, 2598 (1961).
82. A.B. Pippard, Proc. Roy. Soc. A257, 165 (1960).
83. T. Holstein, Westinghouse Research Memo. 60-94698-3-M17 (1956).
84. M.H. Cohen, M.J. Harrison, and W.A. Harrison, Phys. Rev. 117, 937 (1960).
85. T. Kjeldaas and T. Holstein, Phys. Rev. Letters 2, 340 (1959).
86. A.B. Pippard, Low Temperature Physics, (Gordon and Breach Publishers, London, 1962), p. 126.
87. A.A. Galkin, E.A. Kaner, and A.P. Korolyuk, Zh. Eksperim. i. Theor. Fiz. 39, 1517 (1960). [Transl: Soviet Phys. JETP 12, 1055 (1961)].
88. W.A. Harrison, Phys. Rev. 126, 497 (1962).
89. M.H. Cohen and L.M. Falicov, Phys. Rev. Letters 5, 544 (1960).
90. Janis Dewar Model 10DT from Janis Research Company, Inc., 22 Spencer Street, Stoneham, Massachusetts.
91. Varian Associates, Palo Alto, California.

92. B.C. Deaton, Phys. Letters 7, 7 (1963).
93. Cahn RM Automatic Electrobalance, Cahn Instrument Company, Paramount, California.
94. Model V 3700-1 Electromagnet, Varian Associates, Palo Alto, California
95. J.A. Marcus, Phys. Rev. 76, 621 (1949).
96. G.L. Salinger and J.C. Wheatly, Rev. Sci. Instr. 32, 872 (1961).
97. H.E. Bommel, Phys. Rev. 96, 220 (1954).
98. W.P. Mason and H.E. Bommel, J. Acoust. Soc. Am. 28, 930 (1956).
99. B.R. Tittman and H.E. Bommel, Phys. Rev. Letters 14, 296 (1965).
100. A. Hikata and C. Elbaum, Phys. Rev. Letters 18, 750 (1967).
101. J.M. Perz, J. Phys. C (Solid State Phys.) 3, 438 (1970).
102. B. Mühlischlegel, Zietschrift fur Physik 155, 313 (1959).
103. R.A. Ferrell, Z. Physik 182, 1 (1964).
104. J.R. Clem, Ann. of Phys. 40, 268 (1966).
105. R.W. Morse and H.V. Bohm, Rev. Mod. Phys. 108, 1094 (1957).
106. B.C. Deaton, Phys. Rev. 177, 688 (1969).
107. B.B. Goodman and E. Mendoza, Phil. Mag. 42, 594 (1951).
108. L. Mackinnon and M.R. Daniel, Phys. Letters 1, 157 (1962).
109. L. Mackinnon, M.T. Taylor and M.R. Daniel, Phil. Mag. 7, 523 (1962).
110. A.B. Pippard, Repts. of Prog. in Phys. 23, 176 (1960).
111. N. Tsuda and T. Suzuki, J. Phys. Chem. Solids 28, 2487 (1967).
112. H.C. Wu, H.V. Bohm, and R.L. Thomas, Phys. Rev. B 2, 122 (1970).
113. J.E. Randorff and B.J. Marshall, Phys. Rev. B 2, 100 (1970).
114. S.G. O'Hara, Ph.D. Dissertation, Texas Tech University, Unpublished, (1973).

115. A.C. Rose-Innes and E.H. Rhoderick, Introduction to Superconductivity, (Pergamon Press, Oxford, 1969), p. 116.
116. R. David, Phillips Res. Repts. 1964, p. 524.
117. R.W. Morse and H.V. Bohm, J. Acoust. Soc. Amer. 31, 1523 (1959).
118. R. David, H.R. Van der Laan, and N.J. Poulis, Commun. Kamerlingh Onnes Lab., Leiden No. 331c; Physica 28, 330 (1962).
119. J.W.F. Woo, Phys. Rev. 155, 429 (1967).
120. J.W.F. Woo, Phys. Rev. 172, 423 (1968).
121. R.T. Beyer and S.V. Letcher, Physical Ultrasonics, (Academic Press, New York, 1969), pp. 255, 329.
122. H.V. Malmstadt and C.G. Enke, Electronics for Scientists, (W.A. Benjamin, Inc., New York, 1963), pp. 423-431.
123. E.J. Angelo, Jr., Electronic Circuits, (MC Graw-Hill Book Company, New York, 1964), p. 17.
124. J. Millman and C.C. Halkias, Electronic Devices and Circuits, (Mc Graw-Hill Book Company, New York, 1967), pp. 621-632.
125. F.R. Kroeger and W.A. Rhinehart, Rev. Sci. Instr. 42, 1532 (1971).
126. C.L. Alley and K.W. Atwood, Electronic Engineering, (John Wiley & Sons, Inc., New York, 1963), ch. 17.

APPENDIX A

THE t^3 PROBLEM

During the data analysis for this dissertation and that of O'Hara¹¹⁴ and Cleavelin,¹⁸ one aspect of the low temperature ultrasonic attenuation was found to be linear in the cube of the reduced temperature. This was first noted by Cleavelin in his zinc data in the form of $\log_{10}(V_s)$ versus t^3 , where V_s is the ultrasonic echo voltage height in the superconducting state and t is the reduced temperature, (equation 6-10). This linear relationship also seemed to be characteristic of the data of cadmium, molybdenum, and lead. A more straightforward relationship was found by the author in the form of

$$\frac{\alpha_s}{\alpha_{T_C}} = Kt^3 \quad (A-1)$$

where α_s is the superconducting attenuation, α_{T_C} is the attenuation at the transition temperature, and K is a proportionality constant. Figures 57, 58, and 59 show examples of how data from cadmium, molybdenum, and zinc fit the relationship of equation (A-1). The linearity of the data appears to become established below a reduced temperature of about .94. The slope K , of this curve seems to be similar for each of the superconductors shown, and suggests the possibility of a form of correspondence between superconductors.

Figure 60 shows a similar plot of ultrasonic attenuation data

Figure 58. PLOT OF α_s/α_{Tc} vs. t^3 FOR MOLYBDENUM:
 $\vec{q} \parallel [100]$, $\nu = 32.6$ MHz, $K = .75$.

Figure 61. PLOT OF α_s/α_n vs. t^3 FOR LEAD SHOWING NONLINEARITY.

for lead as a function of t^3 . Lead, characterized as a strong coupling superconductor,^{119,120} has relatively high transition temperature of 7.2K. Because of this high T_c and the purity of the lead sample used to obtain this data, at its transition temperature, the crystal is in the transition region where the electron-phonon scattering process is rapidly increasing the ultrasonic attenuation as the temperature decreases. This means that the normal state ultrasonic attenuation is increasing at and below the transition temperature, as depicted in Figure 36. This differs from that of the cadmium, molybdenum, and zinc crystals whose normal state attenuation is constant as in Figure 35. These crystals have transition temperatures so low that the electron-phonon scattering process is limited by impurities. The lead data suggested the form of equation (A-1) because of its increasing normal state attenuation below T_c . Figure 61 shows that the ratio α_s/α_n does not follow the t^3 proportionality. It has been our experience that equation (A-1) remains valid for all frequencies and all crystallographic directions studied in the four crystals discussed above.

Since this problem was not related directly to the dissertation goals, it is mentioned here only as a suggested problem for future inquiry.

APPENDIX B

AND GATE AND BINARY FREQUENCY DIVIDER

This interface unit was designated and constructed to synchronize and reference the trigger signals to the various electronic instruments in the phase sensitive ultrasonic detection system described in Chapter II.

The operation of this circuit can be described with the aid of the schematic diagram shown in Figure 62. The four volt trigger signals at 800 Hz from pulse generator P1 are received through the 47 ohm matching resistor and split in order to trigger the frequency divider and the AND gate. The frequency divider is composed of four standard bistable multivibrator circuits.¹²² The multivibrators feature trigger steering diodes (D1-D12) to improve and insure stable triggering. The "speed up" capacitors (100 pF) also help insure stable triggering and improve the waveform by increasing the regenerative transition rate.

Frequency division is achieved because the multivibrator circuits are triggered only when a positive going pulse arrives at the steering diode junction. For example, two positive triggering signals are required to cause the first multivibrator to change states twice, yet only one positive pulse is sent to the next multivibrator. This occurs when the collector voltage of Q_2 changes from -4.4 volts to -0.2 volts. Four stages, each dividing the frequency by two, yield a total division by 2^4 , or 16.

Figure 62. AND GATE AND BINARY FREQUENCY DIVIDER

After the four stages of binary division, the resulting waveform, which is a square wave of -0.2 volts to -4.4 volts, is fed into a voltage clamper circuit¹²³ which raises these voltages to -0.2 volts to +3.5 volts. This 50 Hz signal is available as a square wave reference signal for the lock-in amplifier as shown in Figure 4. This square wave is also sent to the AND gate (diodes D14 and D15) as the chopping control signal. When the 50 Hz waveform is in the +3.5 volt state, the 800 Hz trigger signal can raise the base voltage of transistor Q_9 so that they are amplified and sent out. When the 50 Hz waveform is in the -0.2 volt state, the 800 Hz trigger signals cannot raise the base voltage of Q_9 sufficiently, and no signal is sent out. Thus, the output waveform consists of eight negative going trigger pulses followed by no output for eight cycles.

The power supply for this interface unit is shown in Figure 63. Since transistor bistable multivibrators are somewhat sensitive to the power supply voltage, a Zener regulated voltage supply was constructed to insure reliable operation of the frequency divider. The operation of this circuit can be found in any standard first level electronic engineering textbook.¹²⁴

Figure 63. POWER SUPPLY FOR FREQUENCY DIVIDER AND AND GATE.

APPENDIX C

CONSTANT CURRENT SUPPLY FOR THERMOMETRY

A low cost constant current supply was constructed in the lab by C.R. Cleavelin in order to facilitate the automatic recording of the resistance of the carbon resistance thermometer. The circuit, modeled after a design by Kroeger and Rhinehart,¹²⁵ is shown in Figure 64. The heart of the design is the Motorola MC 1439G operational amplifier set up in the form of a voltage comparator. The amplifier compares the reference voltage derived from the IN430A Zener voltage reference diode, with the feedback voltage produced by the output current flowing through the range resistor, (1K through 10M). The op amp then adjusts the output current so that this feedback voltage equals the reference voltage. By changing the value of the range resistor more or less output current must be produced in order to maintain the reference voltage across the range resistor. This is the method used to change the current output range of the circuit. Since the feedback voltage is sampled across the fixed range resistor, when the load resistance changes (i.e., thermometer resistance changes with temperature), the op amp automatically varies the output voltage so that the output current is maintained constant. In other words, regardless of the resistance of the thermometer, the same current flowing through the thermometer flows through the range resistor and by Ohms law, if the voltage across the fixed range resistor is maintained constant, then the output current must also be constant. Continuous fine adjustment of the output current is

Figure 64. CONSTANT CURRENT SOURCE FOR THERMOMETRY.

obtained with the 5K ten turn potentiometer controlling the reference voltage. The absolute value of the output current is monitored by observing the voltage across a 1K or a 10K, .05% precision standard resistor in series with the thermometer.

The values of the range resistors and the current standard resistors were chosen so that the resistance of the thermometer and the output current could be conveniently obtained by simply moving the decimal place of the voltage read across the thermometer and the current standard resistor. Table C-1 lists the multiplying factors required to convert the voltage across the thermometer into thermometer resistance along with other pertinent data. The column labeled "current DVM voltage" lists the voltage across the current standard resistor required for the corresponding output current listed in the previous column. Small errors in the 1% accuracy of the range resistors may require fine adjustments of the reference voltage to produce the proper output current.

The schematic of the regulated power supply used to power the constant current circuit is shown in Figure 65. This is a standard Zener regulated dc power supply circuit which can regulate the dc voltage to within 5%.¹²⁶ This regulation circuit was used so that effects due to line voltage fluctuations would be minimized.

Figure 65. REGULATED POWER SUPPLY FOR CONSTANT CURRENT SOURCE.

TABLE C-1
Multiplying Factors

Range Resistor (Ohms)	Output Current (μ A)	Current DVM Voltage (mV)	Multiplying Factor
10M	0.1	1.0	10^2
1M	1.0	10	10^3
100K	10	100	10^4
10K	100	100	10^5
1K	1000	1000	10^6

Appendix D

Experimental Data

This appendix contains the experimental data which was taken directly from the X-Y recorder tracings. The carbon resistance values were converted to temperature readings by the He^3 vapor pressure calibration curves and the Clement-Quinnell extrapolation procedure. The temperature was then normalized to the transition temperature T_c so that the column labeled t is the reduced temperature,

$$t = T/T_c. \quad (\text{D-1})$$

The first set of data tables list the ultrasonic attenuation in dB/cm for sound propagating in the $[0001]$ direction for all frequencies measured. The second and third set of tables list the actual echo height voltages as a function of reduced temperature for sound propagating in the $[10\bar{1}0]$ and $[11\bar{2}0]$ directions, respectively.

For convenience the low temperature crystal lengths are repeated here.

$$\ell_{[0001]} = 0.4030 \text{ cm} \quad (\text{D-2})$$

$$\ell_{[10\bar{1}0]} = 0.4752 \text{ cm} \quad (\text{D-3})$$

$$\ell_{[11\bar{2}0]} = 0.7255 \text{ cm} \quad (\text{D-4})$$

Table D-1

 $\vec{q}||[0001]$, Echo No. 1, 9.49 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	3.94	.78	5.13
.99	1.60	.88	4.10	.77	5.20
.98	2.00	.87	4.22	.76	5.25
.97	2.35	.86	4.35	.75	---
.96	2.63	.85	4.48	.74	---
.95	2.85	.84	4.60	.73	---
.94	3.06	.83	4.70	.72	---
.93	3.25	.82	4.80	.71	---
.92	3.45	.81	4.90	.70	---
.91	3.61	.80	4.98		
.90	3.78	.79	5.05		

Table D-2

 $\vec{q}||[0001]$, Echo No. 1, 9.49 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	3.94	.78	5.13
.99	1.60	.88	4.10	.77	5.20
.98	2.00	.87	4.22	.76	5.25
.97	2.35	.86	4.35	.75	---
.96	2.63	.85	4.48	.74	---
.95	2.85	.84	4.60	.73	---
.94	3.06	.83	4.70	.72	---
.93	3.25	.82	4.80	.71	---
.92	3.45	.81	4.90	.70	---
.91	3.61	.80	4.98		
.90	3.78	.79	5.05		

Table D-3

 $\vec{q} || [0001]$, Echo No. 1, 9.49 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	3.91	.78	5.00
.99	1.80	.88	4.04	.77	5.06
.98	2.08	.87	4.16	.76	5.14
.97	2.41	.86	4.26	.75	---
.96	2.66	.85	4.37	.74	---
.95	2.91	.84	4.47	.73	---
.94	3.10	.83	4.56	.72	---
.93	3.30	.82	4.66	.71	---
.92	3.47	.81	4.75	.70	---
.91	3.64	.80	4.83		
.90	3.77	.79	4.91		

Table D-4

 $\vec{q} || [0001]$, Echo No. 2, 9.49 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	7.88	.78	10.40
.99	3.40	.88	8.16	.77	10.58
.98	4.15	.87	8.41	.76	10.75
.97	4.75	.86	8.69	.75	10.93
.96	5.28	.85	8.94	.74	11.10
.95	5.75	.84	9.16	.73	---
.94	6.16	.83	9.38	.72	---
.93	6.54	.82	9.60	.71	---
.92	6.91	.81	9.80	.70	---
.91	7.25	.80	10.00		
.90	7.58	.79	10.20		

Table D-5

 $\vec{q} || [0001]$, Echo No. 2, 9.49 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	8.08	.78	10.58
.99	3.90	.88	8.33	.77	10.80
.98	4.60	.87	8.58	.76	11.00
.97	5.14	.86	8.85	.75	---
.96	5.63	.85	9.07	.74	---
.95	6.09	.84	9.30	.73	---
.94	6.50	.83	9.51	.72	---
.93	6.87	.82	9.74	.71	---
.92	7.20	.81	9.95	.70	---
.91	7.50	.80	10.16		
.90	7.80	.79	10.36		

Table D-6

 $\vec{q} || [0001]$, Echo No. 3, 9.49 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	12.40	.78	15.63
.99	5.74	.88	12.80	.77	15.86
.98	7.05	.87	13.14	.76	16.06
.97	7.91	.86	13.50	.75	16.26
.96	8.60	.85	13.81	.74	---
.95	9.35	.84	14.13	.73	---
.94	10.00	.83	14.40	.72	---
.93	10.55	.82	14.68	.71	---
.92	11.05	.81	14.93	.70	---
.91	11.55	.80	15.18		
.90	12.00	.79	15.42		

Table D-7

 $\vec{q} || [0001]$, Echo No. 3, 9.49 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	12.60	.78	16.10
.99	6.60	.88	13.00	.77	16.38
.98	7.74	.87	13.35	.76	---
.97	8.55	.86	13.68	.75	---
.96	9.25	.85	14.00	.74	---
.95	9.86	.84	14.31	.73	---
.94	10.40	.83	14.61	.72	---
.93	10.91	.82	14.92	.71	---
.92	11.39	.81	15.22	.70	---
.91	11.84	.80	15.51		
.90	12.22	.79	15.81		

Table D-8

 $\vec{q} || [0001]$, Echo No. 2, 33.696 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	28.60	.78	37.30
.99	12.00	.88	29.60	.77	37.90
.98	15.00	.87	30.60	.76	38.40
.97	17.20	.86	31.60	.75	38.90
.96	19.00	.85	32.40	.74	---
.95	20.80	.84	33.30	.73	---
.94	22.30	.83	34.20	.72	---
.93	23.90	.82	34.90	.71	---
.92	25.00	.81	35.50	.70	---
.91	26.30	.80	36.20		
.90	27.50	.79	36.80		

Table D-9

 $\vec{q}||[0001]$, Echo No. 1, 33.695 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	13.88	.78	17.64
.99	6.20	.88	14.30	.77	17.90
.98	7.60	.87	14.70	.76	18.20
.97	8.70	.86	15.10	.75	---
.96	9.75	.85	15.48	.74	---
.95	10.52	.84	15.82	.73	---
.94	11.22	.83	16.15	.72	---
.93	11.80	.82	16.48	.71	---
.92	12.40	.81	16.80	.70	---
.91	12.92	.80	17.10		
.90	13.40	.79	17.36		

Table D-10

 $\vec{q}||[0001]$, Echo No. 1, 33.695 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	13.16	.78	16.70
.99	6.80	.88	13.60	.77	16.98
.98	7.90	.87	13.94	.76	---
.97	8.75	.86	14.30	.75	---
.96	9.54	.85	14.64	.74	---
.95	10.20	.84	14.96	.73	---
.94	10.80	.83	15.28	.72	---
.93	11.38	.82	15.60	.71	---
.92	11.87	.81	15.88	.70	---
.91	12.32	.80	16.16		
.90	12.76	.79	16.43		

Table D-11

 $\vec{q}||[0001]$, Echo No. 1, 33.695 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	12.65	.78	16.11
.99	6.00	.88	13.05	.77	16.39
.98	7.30	.87	13.40	.76	16.63
.97	8.37	.86	13.78	.75	---
.96	9.15	.85	14.10	.74	---
.95	9.85	.84	14.41	.73	---
.94	10.42	.83	14.72	.72	---
.93	10.94	.82	15.02	.71	---
.92	11.40	.81	15.31	.70	---
.91	11.85	.80	15.60		
.90	12.28	.79	15.88		

Table D-12

 $\vec{q}||[0001]$, Echo No. 2, 33.695 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	25.90	.78	34.00
.99	11.5	.88	26.90	.77	34.50
.98	13.7	.87	27.80	.76	35.00
.97	15.30	.86	28.70	.75	---
.96	16.90	.85	29.50	.74	---
.95	18.40	.84	30.30	.73	---
.94	19.80	.83	31.00	.72	---
.93	21.20	.82	31.60	.71	---
.92	22.50	.81	32.30	.70	---
.91	23.70	.80	32.90		
.90	24.90	.79	33.40		

Table D-13

 $\vec{q}||[0001]$, Echo No. 2, 33.695 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	26.10	.78	---
.99	13.20	.88	27.00	.77	---
.98	15.00	.87	27.80	.76	---
.97	16.80	.86	28.60	.75	---
.96	18.50	.85	29.40	.74	---
.95	19.80	.84	30.20	.73	---
.94	21.00	.83	30.90	.72	---
.93	22.10	.82	31.60	.71	---
.92	23.20	.81	32.40	.70	---
.91	24.20	.80	33.00		
.90	25.20	.79	33.60		

Table D-14

 $\vec{q}||[0001]$, Echo No. 2, 33.695 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	25.90	.78	33.80
.99	12.20	.88	26.80	.77	---
.98	14.20	.87	27.60	.76	---
.97	16.20	.86	28.50	.75	---
.96	17.80	.85	29.20	.74	---
.95	19.30	.84	30.00	.73	---
.94	20.60	.83	30.70	.72	---
.93	21.90	.82	31.40	.71	---
.92	23.00	.81	32.00	.70	---
.91	24.00	.80	32.60		
.90	25.00	.79	33.20		

Table D-15

 $\vec{q}||[0001]$, Echo No. 1, 33.7 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	14.10	.78	---
.99	7.60	.88	14.40	.77	---
.98	8.70	.87	14.78	.76	---
.97	9.60	.86	15.15	.75	---
.96	10.30	.85	15.53	.74	---
.95	10.95	.84	15.90	.73	---
.94	11.60	.83	16.25	.72	---
.93	12.15	.82	16.60	.71	---
.92	12.70	.81	16.90	.70	---
.91	13.20	.80	17.25		
.90	13.70	.79	17.60		

Table D-16

 $\vec{q}||[0001]$, Echo No. 1, 33.695 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	12.70	.78	16.82
.99	5.70	.88	13.17	.77	17.12
.98	6.90	.87	13.60	.76	---
.97	7.75	.86	14.00	.75	---
.96	8.50	.85	14.43	.74	---
.95	9.20	.84	14.81	.73	---
.94	9.95	.83	15.20	.72	---
.93	10.60	.82	15.58	.71	---
.92	11.16	.81	15.90	.70	---
.91	11.70	.80	16.25		
.90	12.20	.79	16.54		

Table D-17

 $\vec{q} || [0001]$, Echo No. 1, 52.04 MHz

t	Attenuation (dB/cm)	t	Attenuation (dB/cm)	t	Attenuation (dB/cm)
1.00	0.00	.89	22.60	.78	28.10
.99	9.80	.88	23.20	.77	28.50
.98	12.70	.87	23.80	.76	28.80
.97	14.80	.86	24.30	.75	29.20
.96	16.30	.85	24.80	.74	---
.95	17.60	.84	25.30	.73	---
.94	18.60	.83	25.80	.72	---
.93	19.60	.82	26.30	.71	---
.92	20.40	.81	26.75	.70	---
.91	21.20	.80	27.20		
.90	21.90	.79	27.60		

Table D-18

 $\vec{q} || [10\bar{1}0]$, Echo No. 5, 10.3 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.28	.89	2.07	.78	2.41
.99	1.56	.88	2.10	.77	2.43
.98	1.64	.87	2.13	.76	2.47
.97	1.71	.86	2.17	.75	2.49
.96	1.77	.85	2.21	.74	2.51
.95	1.82	.84	2.24	.73	2.54
.94	1.86	.83	2.27	.72	2.57
.93	1.91	.82	2.29	.71	---
.92	1.95	.81	2.32	.70	---
.91	1.98	.80	2.35		
.90	2.03	.79	2.38		

Table D-19

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 5, 10.3 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.38	.89	2.16	.78	2.48
.99	1.67	.88	2.18	.77	2.50
.98	1.75	.87	2.23	.76	2.53
.97	1.82	.86	2.25	.75	2.56
.96	1.87	.85	2.28	.74	2.58
.95	1.92	.84	2.32	.73	2.61
.94	1.97	.83	2.35	.72	2.63
.93	2.01	.82	2.38	.71	---
.92	2.05	.81	2.40	.70	---
.91	2.08	.80	2.43		
.90	2.12	.79	2.46		

Table D-20

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 5, 10.3 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.38	.89	2.17	.78	2.52
.99	1.64	.88	2.21	.77	2.55
.98	1.76	.87	2.24	.76	2.58
.97	1.82	.86	2.28	.75	2.61
.96	1.88	.85	2.32	.74	2.63
.95	1.92	.84	2.35	.73	2.66
.94	1.97	.83	2.38	.72	---
.93	2.02	.82	2.41	.71	---
.92	2.06	.81	2.43	.70	---
.91	2.10	.80	2.46		
.90	2.13	.79	2.49		

Table D-21

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 5, 10.3 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.38	.89	2.18	.78	2.57
.99	1.66	.88	2.23	.77	2.61
.98	1.74	.87	2.27	.76	2.64
.97	1.81	.86	2.30	.75	2.66
.96	1.87	.85	2.34	.74	2.68
.95	1.93	.84	2.38	.73	2.70
.94	1.98	.83	2.42	.72	2.73
.93	2.02	.82	2.44	.71	---
.92	2.07	.81	2.48	.70	---
.91	2.11	.80	2.51		
.90	2.15	.79	2.54		

Table D-22

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 5, 10.3 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.40	.89	2.18	.78	2.54
.99	1.69	.88	2.22	.77	2.57
.98	1.78	.87	2.25	.76	2.60
.97	1.84	.86	2.28	.75	2.63
.96	1.90	.85	2.32	.74	2.66
.95	1.95	.84	2.35	.73	2.68
.94	1.99	.83	2.38	.72	2.71
.93	2.03	.82	2.42	.71	---
.92	2.08	.81	2.44	.70	---
.91	2.12	.80	2.48		
.90	2.15	.79	2.51		

Table D-23

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 8, 10.3 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	2.30	.89	3.99	.78	4.89
.99	2.81	.88	4.08	.77	4.98
.98	3.03	.87	4.17	.76	5.05
.97	3.16	.86	4.26	.75	5.13
.96	3.28	.85	4.34	.74	5.21
.95	3.39	.84	4.43	.73	5.30
.94	3.50	.83	4.50	.72	5.38
.93	3.61	.82	4.58	.71	---
.92	3.71	.81	4.66	.70	---
.91	3.81	.80	4.73		
.90	3.90	.79	4.81		

Table D-24

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 8, 10.3 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	2.28	.89	4.03	.78	4.90
.99	2.80	.88	4.12	.77	4.98
.98	2.99	.87	4.21	.76	5.04
.97	3.12	.86	4.30	.75	5.12
.96	3.26	.85	4.38	.74	5.19
.95	3.39	.84	4.46	.73	5.26
.94	3.51	.83	4.54	.72	5.32
.93	3.62	.82	4.61	.71	---
.92	3.73	.81	4.69	.70	---
.91	3.85	.80	4.75		
.90	3.95	.79	4.83		

Table D-25

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 33.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	5.50	.89	7.40	.78	8.19
.99	6.20	.88	7.48	.77	8.25
.98	6.39	.87	7.55	.76	8.31
.97	6.53	.86	7.62	.75	8.39
.96	6.69	.85	7.70	.74	8.46
.95	6.80	.84	7.79	.73	8.51
.94	6.91	.83	7.87	.72	---
.93	7.01	.82	7.93	.71	---
.92	7.11	.81	8.00	.70	---
.91	7.21	.80	8.08		
.90	7.31	.79	8.13		

Table D-26

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 33.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	5.44	.89	7.33	.78	8.16
.99	6.10	.88	7.41	.77	8.21
.98	6.34	.87	7.49	.76	8.28
.97	6.49	.86	7.57	.75	8.35
.96	6.62	.85	7.66	.74	8.41
.95	6.75	.84	7.72	.73	8.47
.94	6.86	.83	7.80	.72	---
.93	6.96	.82	7.88	.71	---
.92	7.05	.81	7.95	.70	---
.91	7.14	.80	8.01		
.90	7.24	.79	8.10		

Table D-27

 $\vec{q} || [\bar{1}010]$, Echo No. 1, 33.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	5.49	.89	7.36	.78	8.17
.99	6.15	.88	7.45	.77	8.21
.98	6.34	.87	7.53	.76	8.29
.97	6.50	.86	7.61	.75	8.36
.96	6.63	.85	7.69	.74	8.44
.95	6.75	.84	7.78	.73	8.49
.94	6.86	.83	7.83	.72	---
.93	6.98	.82	7.91	.71	---
.92	7.09	.81	7.98	.70	---
.91	7.18	.80	8.03		
.90	7.28	.79	8.11		

Table D-28

 $\vec{q} || [\bar{1}010]$, Echo No. 1, 33.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	6.46	.89	8.35	.78	9.17
.99	7.19	.88	8.42	.77	9.22
.98	7.40	.87	8.50	.76	9.29
.97	7.53	.86	8.57	.75	9.34
.96	7.65	.85	8.66	.74	9.40
.95	7.76	.84	8.75	.73	9.46
.94	7.87	.83	8.81	.72	9.52
.93	7.98	.82	8.89	.71	---
.92	8.07	.81	8.96	.70	---
.91	8.16	.80	9.02		
.90	8.26	.79	9.10		

Table D-29

 $\vec{q} \parallel [10\bar{1}0]$, Echo No. 1, 54 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	3.48	.89	5.60	.78	6.60
.99	4.26	.88	5.70	.77	6.66
.98	4.48	.87	5.79	.76	6.75
.97	4.63	.86	5.88	.75	6.82
.96	4.76	.85	5.98	.74	6.89
.95	4.90	.84	6.07	.73	---
.94	5.05	.83	6.18	.72	---
.93	5.16	.82	6.25	.71	---
.92	5.29	.81	6.35	.70	---
.91	5.40	.80	6.44		
.90	5.50	.79	6.51		

Table D-30

 $\vec{q} \parallel [10\bar{1}0]$, Echo No. 1, 54 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.25	.89	6.83	.78	8.10
.99	5.08	.88	6.96	.77	8.20
.98	5.40	.87	7.08	.76	8.31
.97	5.62	.86	7.19	.75	8.42
.96	5.81	.85	7.31	.74	8.56
.95	5.99	.84	7.43	.73	8.68
.94	6.14	.83	7.54	.72	---
.93	6.30	.82	7.66	.71	---
.92	6.43	.81	7.77	.70	---
.91	6.58	.80	7.88		
.90	6.71	.79	7.99		

Table D-31

$\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 54 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.33	.89	6.88	.78	8.11
.99	5.24	.88	7.01	.77	8.22
.98	5.50	.87	7.11	.76	8.33
.97	5.70	.86	7.22	.75	8.46
.96	5.89	.85	7.33	.74	8.57
.95	6.03	.84	7.45	.73	8.67
.94	6.20	.83	7.56	.72	---
.93	6.35	.82	7.68	.71	---
.92	6.50	.81	7.79	.70	---
.91	6.62	.80	7.90		
.90	6.77	.79	8.01		

Table D-32

$\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 54 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.36	.89	6.88	.78	8.20
.99	5.30	.88	7.00	.77	8.30
.98	5.52	.87	7.12	.76	8.40
.97	5.71	.86	7.25	.75	8.50
.96	5.88	.85	7.38	.74	8.58
.95	6.04	.84	7.50	.73	8.68
.94	6.18	.83	7.64	.72	---
.93	6.33	.82	7.75	.71	---
.92	6.48	.81	7.88	.70	---
.91	6.61	.80	7.99		
.90	6.74	.79	8.10		

Table D-33

 $\vec{q} || [10\bar{1}0]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	.870	.89	1.94	.78	2.53
.99	1.16	.88	1.99	.77	2.58
.98	1.27	.87	2.05	.76	2.63
.97	1.37	.86	2.10	.75	2.68
.96	1.46	.85	2.15	.74	2.73
.95	1.53	.84	2.20	.73	2.78
.94	1.61	.83	2.26	.72	---
.93	1.68	.82	2.31	.71	---
.92	1.75	.81	2.36	.70	---
.91	1.82	.80	2.42		
.90	1.88	.79	2.48		

Table D-34

 $\vec{q} || [10\bar{1}0]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	.950	.89	2.00	.78	2.62
.99	1.31	.88	2.06	.77	2.68
.98	1.43	.87	2.11	.76	2.75
.97	1.51	.86	2.17	.75	---
.96	1.59	.85	2.22	.74	---
.95	1.66	.84	2.27	.73	---
.94	1.72	.83	2.33	.72	---
.93	1.78	.82	2.38	.71	---
.92	1.84	.81	2.44	.70	---
.91	1.90	.80	2.50		
.90	1.95	.79	2.56		

Table D-35

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	.960	.89	2.13	.78	2.83
.99	1.29	.88	2.19	.77	2.90
.98	1.44	.87	2.25	.76	---
.97	1.56	.86	2.31	.75	---
.96	1.66	.85	2.37	.74	---
.95	1.75	.84	2.43	.73	---
.94	1.83	.83	2.50	.72	---
.93	1.88	.82	2.56	.71	---
.92	1.96	.81	2.64	.70	---
.91	2.02	.80	2.70		
.90	2.08	.79	2.76		

Table D-36

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.02	.89	2.07	.78	2.73
.99	1.19	.88	2.12	.77	2.79
.98	1.36	.87	2.17	.76	2.86
.97	1.48	.86	2.22	.75	---
.96	1.60	.85	2.27	.74	---
.95	1.69	.84	2.33	.73	---
.94	1.77	.83	2.38	.72	---
.93	1.84	.82	2.45	.71	---
.92	1.90	.81	2.51	.70	---
.91	1.96	.80	2.58		
.90	2.02	.79	2.65		

Table D-37

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 94 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	.49	.89	1.96	.78	2.97
.99	.80	.88	2.05	.77	3.07
.98	.96	.87	2.14	.76	3.15
.97	1.09	.86	2.23	.75	---
.96	1.22	.85	2.33	.74	---
.95	1.35	.84	2.42	.73	---
.94	1.46	.83	2.52	.72	---
.93	1.56	.82	2.61	.71	---
.92	1.67	.81	2.70	.70	---
.91	1.76	.80	2.79		
.90	1.86	.79	2.88		

Table D-38

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 94 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	.93	.89	2.56	.78	3.47
.99	1.26	.88	2.65	.77	3.55
.98	1.48	.87	2.74	.76	3.64
.97	1.65	.86	2.83	.75	---
.96	1.78	.85	2.90	.74	---
.95	1.93	.84	2.98	.73	---
.94	2.04	.83	3.07	.72	---
.93	2.15	.82	3.14	.71	---
.92	2.26	.81	3.23	.70	---
.91	2.36	.80	3.31		
.90	2.47	.79	3.38		

Table D-39

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 94 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.09	.89	2.95	.78	3.86
.99	1.60	.88	3.04	.77	---
.98	1.88	.87	3.13	.76	---
.97	2.04	.86	3.22	.75	---
.96	2.20	.85	3.30	.74	---
.95	2.32	.84	3.38	.73	---
.94	2.43	.83	3.46	.72	---
.93	2.55	.82	3.53	.71	---
.92	2.65	.81	3.62	.70	---
.91	2.76	.80	3.70		
.90	2.86	.79	3.78		

Table D-40

 $\vec{q} || [\bar{1}0\bar{1}0]$, Echo No. 1, 94 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.10	.89	2.96	.78	3.89
.99	1.65	.88	3.05	.77	3.97
.98	1.87	.87	3.14	.76	---
.97	2.03	.86	3.23	.75	---
.96	2.18	.85	3.31	.74	---
.95	2.33	.84	3.40	.73	---
.94	2.45	.83	3.48	.72	---
.93	2.56	.82	3.56	.71	---
.92	2.67	.81	3.64	.70	---
.91	2.77	.80	3.72		
.90	2.87	.79	3.81		

Table D-41

$\vec{q}||[\bar{1}120]$, Echo No. 5, 8.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	12.78	.89	16.88	.78	18.77
.99	13.82	.88	17.09	.77	18.89
.98	14.45	.87	17.29	.76	19.01
.97	14.86	.86	17.48	.75	19.12
.96	15.18	.85	17.67	.74	19.26
.95	15.49	.84	17.85	.73	19.38
.94	15.73	.83	18.02	.72	---
.93	16.00	.82	18.18	.71	---
.92	16.22	.81	18.33	.70	---
.91	16.46	.80	18.49		
.90	16.66	.79	18.62		

Table D-42

$\vec{q}||[\bar{1}120]$, Echo No. 5, 8.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	12.42	.89	16.54	.78	18.62
.99	13.50	.88	16.74	.77	18.77
.98	14.05	.87	16.96	.76	18.90
.97	14.48	.86	17.16	.75	19.02
.96	14.80	.85	17.36	.74	19.17
.95	15.12	.84	17.55	.73	19.31
.94	15.39	.83	17.73	.72	---
.93	15.63	.82	17.92	.71	---
.92	15.86	.81	18.11	.70	---
.91	16.10	.80	18.28		
.90	16.31	.79	18.45		

Table D-43

 $\vec{q} || [\bar{1}120]$, Echo No. 6, 8.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.50	.89	7.62	.78	8.88
.99	5.58	.88	7.75	.77	8.98
.98	5.96	.87	7.88	.76	9.06
.97	6.22	.86	8.01	.75	9.14
.96	6.44	.85	8.13	.74	9.23
.95	6.64	.84	8.25	.73	9.31
.94	6.84	.83	8.37	.72	---
.93	7.02	.82	8.48	.71	---
.92	7.18	.81	8.58	.70	---
.91	7.33	.80	8.68		
.90	7.47	.79	8.78		

Table D-44

 $\vec{q} || [\bar{1}120]$, Echo No. 4, 8.7 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	22.50	.89	29.13	.78	31.03
.99	25.60	.88	29.34	.77	31.16
.98	26.30	.87	29.57	.76	31.29
.97	26.80	.86	29.78	.75	31.43
.96	27.10	.85	29.97	.74	31.55
.95	27.47	.84	30.13	.73	31.66
.94	27.80	.83	30.31	.72	---
.93	28.05	.82	30.47	.71	---
.92	28.36	.81	30.64	.70	---
.91	28.65	.80	30.77		
.90	28.88	.79	30.91		

Table D-45

 $\vec{q} || [\bar{1}120]$, Echo No. 1, 31.2 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	22.08	.89	26.40	.78	27.93
.99	23.09	.88	26.57	.77	28.03
.98	23.87	.87	26.74	.76	28.13
.97	24.38	.86	26.90	.75	28.23
.96	24.80	.85	27.04	.74	28.34
.95	25.11	.84	27.19	.73	28.42
.94	25.38	.83	27.32	.72	28.51
.93	25.61	.82	27.45	.71	28.60
.92	25.85	.81	27.57	.70	28.69
.91	26.02	.80	27.70		
.90	26.22	.79	27.82		

Table D-46

 $\vec{q} || [\bar{1}120]$, Echo No. 1, 31.2 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	22.49	.89	27.31	.78	29.07
.99	23.53	.88	27.50	.77	29.20
.98	24.38	.87	27.69	.76	29.31
.97	24.98	.86	27.87	.75	29.43
.96	25.43	.85	28.05	.74	29.54
.95	25.79	.84	28.23	.73	29.65
.94	26.15	.83	28.39	.72	29.75
.93	26.43	.82	28.53	.71	29.85
.92	26.68	.81	28.68	.70	29.94
.91	26.90	.80	28.81		
.90	27.12	.79	28.95		

Table D-47

 $\vec{q} || [\bar{1}1120]$, Echo No. 1, 51.2 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.82	.89	2.88	.78	3.38
.99	2.05	.88	2.94	.77	3.42
.98	2.25	.87	3.00	.76	3.46
.97	2.33	.86	3.05	.75	3.48
.96	2.42	.85	3.09	.74	3.52
.95	2.49	.84	3.13	.73	3.56
.94	2.57	.83	3.18	.72	3.59
.93	2.63	.82	3.22	.71	3.62
.92	2.70	.81	3.26	.70	---
.91	2.76	.80	3.30		
.90	2.82	.79	3.34		

Table D-48

 $\vec{q} || [\bar{1}1120]$, Echo No. 1, 51.2 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.78	.89	2.43	.78	2.68
.99	1.94	.88	2.46	.77	2.70
.98	2.04	.87	2.49	.76	2.72
.97	2.12	.86	2.51	.75	2.74
.96	2.18	.85	2.54	.74	2.76
.95	2.23	.84	2.56	.73	2.77
.94	2.28	.83	2.58	.72	2.80
.93	2.32	.82	2.60	.71	2.81
.92	2.35	.81	2.62	.70	2.83
.91	2.38	.80	2.64		
.90	2.41	.79	2.66		

Table D-49

 $\vec{q} || [\bar{1}1120]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.73	.89	3.72	.78	4.49
.99	2.17	.88	3.80	.77	4.55
.98	2.50	.87	3.88	.76	4.60
.97	2.75	.86	3.97	.75	4.66
.96	2.93	.85	4.03	.74	4.71
.95	3.08	.84	4.11	.73	4.76
.94	3.20	.83	4.17	.72	4.83
.93	3.32	.82	4.23	.71	4.87
.92	3.44	.81	4.30	.70	4.93
.91	3.53	.80	4.37		
.90	3.62	.79	4.42		

Table D-50

 $q || [\bar{1}1120]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	2.37	.89	4.30	.78	5.09
.99	2.80	.88	4.39	.77	5.13
.98	3.12	.87	4.47	.76	5.18
.97	3.32	.86	4.54	.75	5.24
.96	3.52	.85	4.62	.74	5.31
.95	3.68	.84	4.70	.73	5.37
.94	3.82	.83	4.78	.72	5.43
.93	3.93	.82	4.84	.71	5.49
.92	4.03	.81	4.91	.70	5.57
.91	4.13	.80	4.97		
.90	4.22	.79	5.03		

Table D-51

 $\vec{q} || [\bar{1}1120]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.42	.89	6.70	.78	7.52
.99	5.03	.88	6.79	.77	7.57
.98	5.43	.87	6.88	.76	7.62
.97	5.66	.86	6.98	.75	7.68
.96	5.86	.85	7.05	.74	7.72
.95	6.00	.84	7.13	.73	7.78
.94	6.13	.83	7.20	.72	7.83
.93	6.27	.82	7.27	.71	7.89
.92	6.39	.81	7.33	.70	---
.91	6.49	.80	7.40		
.90	6.61	.79	7.46		

Table D-52

 $\vec{q} || [\bar{1}1120]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.87	.89	7.18	.78	8.18
.99	5.55	.88	7.29	.77	8.26
.98	5.88	.87	7.39	.76	8.33
.97	6.10	.86	7.49	.75	8.42
.96	6.29	.85	7.59	.74	8.48
.95	6.46	.84	7.68	.73	8.55
.94	6.59	.83	7.76	.72	8.63
.93	6.72	.82	7.85	.71	8.71
.92	6.86	.81	7.94	.70	---
.91	6.97	.80	8.02		
.90	7.09	.79	8.10		

Table D-53

$\vec{q}||[\bar{1}1120]$, Echo No. 1, 70 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	3.60	.89	5.89	.78	6.83
.99	4.17	.88	6.00	.77	6.89
.98	4.51	.87	6.11	.76	6.94
.97	4.71	.86	6.21	.75	7.00
.96	4.91	.85	6.31	.74	7.06
.95	5.08	.84	6.40	.73	7.10
.94	5.26	.83	6.49	.72	7.14
.93	5.40	.82	6.57	.71	7.20
.92	5.52	.81	6.63	.70	---
.91	5.66	.80	6.71		
.90	5.77	.79	6.77		

Table D-54

$\vec{q}||[\bar{1}1120]$, Echo No. 1, 90 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	2.03	.89	4.73	.78	5.86
.99	2.56	.88	4.86	.77	5.92
.98	3.05	.87	4.98	.76	5.98
.97	3.37	.86	5.10	.75	6.05
.96	3.61	.85	5.20	.74	6.12
.95	3.83	.84	5.31	.73	6.19
.94	4.00	.83	5.40	.72	6.27
.93	4.16	.82	5.50	.71	6.33
.92	4.33	.81	5.59	.70	6.41
.91	4.47	.80	5.68		
.90	4.60	.79	5.77		

Table D-55

 $\vec{q} || [\bar{1}120]$, Echo No. 1, 90 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.63	.89	7.15	.78	8.12
.99	5.53	.88	7.25	.77	8.20
.98	5.86	.87	7.35	.76	8.26
.97	6.05	.86	7.44	.75	8.34
.96	6.24	.85	7.53	.74	8.41
.95	6.41	.84	7.63	.73	8.47
.94	6.56	.83	7.71	.72	8.54
.93	6.68	.82	7.80	.71	8.61
.92	6.82	.81	7.88	.70	8.68
.91	6.92	.80	7.97		
.90	7.04	.79	8.05		

Table D-56

 $\vec{q} || [\bar{1}120]$, Echo No. 1, 90 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	3.08	.89	5.82	.78	6.62
.99	4.03	.88	5.91	.77	6.67
.98	4.40	.87	6.00	.76	6.73
.97	4.73	.86	6.08	.75	6.78
.96	4.95	.85	6.15	.74	6.84
.95	5.13	.84	6.23	.73	6.89
.94	5.26	.83	6.30	.72	6.94
.93	5.40	.82	6.37	.71	6.98
.92	5.52	.81	6.43	.70	7.03
.91	5.62	.80	6.50		
.90	5.73	.79	6.56		

Table D-57

 $\vec{q} || [\bar{1}1120]$, Echo No. 1, 90 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	3.70	.89	5.95	.78	6.88
.99	4.40	.88	6.05	.77	6.94
.98	4.72	.87	6.15	.76	7.01
.97	4.93	.86	6.24	.75	7.07
.96	5.11	.85	6.32	.74	7.13
.95	5.26	.84	6.41	.73	7.19
.94	5.40	.83	6.50	.72	7.25
.93	5.52	.82	6.57	.71	7.31
.92	5.65	.81	6.65	.70	---
.91	5.75	.80	6.72		
.90	5.85	.79	6.80		

Table D-58

 $\vec{q} || [\bar{1}1120]$, Echo No. 1, 90 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.76	.89	3.50	.78	4.28
.99	2.26	.88	3.58	.77	4.33
.98	2.53	.87	3.66	.76	4.44
.97	2.71	.86	3.72	.75	4.48
.96	2.86	.85	3.80	.74	4.52
.95	2.98	.84	3.88	.73	4.56
.94	3.08	.83	3.95	.72	4.60
.93	3.18	.82	4.01	.71	---
.92	3.27	.81	4.08	.70	---
.91	3.35	.80	4.16		
.90	3.42	.79	4.21		

Table D-59

$\vec{q}||[\bar{1}1120]$, Echo No. 1, 90 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	1.80	.89	3.56	.78	4.16
.99	2.35	.88	3.63	.77	4.20
.98	2.60	.87	3.69	.76	4.25
.97	2.78	.86	3.75	.75	4.28
.96	2.92	.85	3.80	.74	4.33
.95	3.03	.84	3.86	.73	4.37
.94	3.15	.83	3.92	.72	4.41
.93	3.23	.82	3.97	.71	4.45
.92	3.33	.81	4.02	.70	4.48
.91	3.41	.80	4.07		
.90	3.49	.79	4.12		

Table D-60

$\vec{q}||[\bar{1}1120]$, Echo No. 1, 90 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	4.63	.89	6.96	.78	7.78
.99	5.38	.88	7.06	.77	7.84
.98	5.69	.87	7.15	.76	7.88
.97	5.90	.86	7.24	.75	7.93
.96	6.07	.85	7.32	.74	7.98
.95	6.24	.84	7.40	.73	8.02
.94	6.38	.83	7.47	.72	8.06
.93	6.51	.82	7.54	.71	8.09
.92	6.63	.81	7.61	.70	---
.91	6.75	.80	7.67		
.90	6.86	.79	7.73		

Table D-61

 $\vec{q}||[\bar{1}120]$, Echo No. 1, 108 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	2.88	.89	7.62	.78	9.53
.99	3.60	.88	7.82	.77	9.68
.98	4.41	.87	8.02	.76	9.82
.97	5.08	.86	8.19	.75	9.97
.96	5.61	.85	8.39	.74	10.12
.95	6.03	.84	8.56	.73	10.25
.94	6.30	.83	8.74	.72	10.40
.93	6.62	.82	8.90	.71	10.53
.92	6.90	.81	9.06	.70	10.65
.91	7.15	.80	9.22		
.90	7.40	.79	9.37		

Table D-62

 $\vec{q}||[\bar{1}120]$, Echo No. 1, 108 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	3.46	.89	8.17	.78	9.89
.99	4.35	.88	8.37	.77	10.01
.98	5.05	.87	8.56	.76	10.13
.97	5.70	.86	8.74	.75	10.23
.96	6.24	.85	8.92	.74	10.35
.95	6.68	.84	9.07	.73	10.45
.94	6.98	.83	9.22	.72	10.55
.93	7.27	.82	9.37	.71	10.66
.92	7.52	.81	9.51	.70	10.75
.91	7.75	.80	9.64		
.90	7.97	.79	9.76		

Table D-63

 $\vec{q} \parallel [11\bar{2}0]$, Echo No. 1, 108 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	3.53	.89	8.77	.78	11.11
.99	4.35	.88	9.01	.77	11.28
.98	5.35	.87	9.25	.76	11.45
.97	6.00	.86	9.47	.75	11.62
.96	6.53	.85	9.71	.74	11.78
.95	6.99	.84	9.92	.73	11.94
.94	7.35	.83	10.13	.72	12.10
.93	7.70	.82	10.34	.71	12.22
.92	8.00	.81	10.54	.70	---
.91	8.24	.80	10.74		
.90	8.51	.79	10.92		

Table D-63

 $\vec{q} || [11\bar{2}0]$, Echo No. 1, 108 MHz

t	Voltage (Volts)	t	Voltage (Volts)	t	Voltage (Volts)
1.00	3.53	.89	8.77	.78	11.11
.99	4.35	.88	9.01	.77	11.28
.98	5.35	.87	9.25	.76	11.45
.97	6.00	.86	9.47	.75	11.62
.96	6.53	.85	9.71	.74	11.78
.95	6.99	.84	9.92	.73	11.94
.94	7.35	.83	10.13	.72	12.10
.93	7.70	.82	10.34	.71	12.22
.92	8.00	.81	10.54	.70	---
.91	8.24	.80	10.74		
.90	8.51	.79	10.92		