

CONTENTS

CONTRIBUTORS	xv
FOREWORD	xvii
PREFACE	xix

1. Experimental Methods of Measuring High-Field Magnetoresistance in Metals

by W. A. REED

1.1. Introduction	1
1.1.1. Summary of the Monotonic Effects	1
1.1.2. Magnetic Breakdown	8
1.1.3. Quantum Oscillations	9
1.2. Sample Preparation and Evaluation	10
1.2.1. Methods for Cutting Samples	10
1.2.2. Methods for Attaching Leads	12
1.2.3. Sample Mounting	14
1.2.4. Sample Evaluation	15
1.3. Sample Holders	15
1.4. Magnetic Fields and Low Temperatures	20
1.5. Measurement Techniques	21
1.5.1. DC Method	21
1.5.2. AC Method	23
1.5.3. Pulsed Field Method	25
1.5.4. Inductive (Helicon) Method	26
1.5.5. Induced Torque Method	27
1.6. Data Collection and Processing	29
1.7. Special Topics	29
1.7.1. High-Pressure Measurements	29
1.7.2. Low-Field Effects	30
1.7.3. Anomalous Longitudinal Magnetoresistance .	30

2. Experimental Methods for the de Haas-van Alphen Effect

by J. R. ANDERSON and D. R. STONE

2.1. The de Haas-van Alphen Effect	33
2.2. dHvA Expressions	35
2.2.1. Frequencies	35
2.2.2. Amplitudes	37
2.2.3. B versus H	40
2.3. Field Modulation Technique	44
2.3.1. dHvA Frequency Selectivity	46
2.3.2. Block Diagram	47
2.3.3. Frequency Measurements	51
2.3.4. Amplitude Measurements	54
2.3.5. Computer Analysis	55
2.4. Examples of dHvA Experiments	56
2.4.1. dHvA Studies in Lead	56
2.4.2. Cyclotron Mass Measurements in Indium .	60
2.4.3. Ferromagnetic Metals	61
2.5. Summary	64

3. Experimental Techniques for Visible and Ultraviolet Photoemission

by G. F. DERBENWICK, D. T. PIERCE, and W. E. SPICER

3.1. Introduction	67
3.1.1. Photoemission Measurements Past and Present	67
3.1.2. Physics of the Photoemission Process	74
3.2. Photoelectric Quantum Yield	81
3.2.1. Definition and Measurement	81
3.2.2. Calibration of Reference Phototube	82
3.3. Measurement of Energy Distribution Curves	84
3.3.1. The Retarding Field Analyzer	84
3.3.2. Electronics for the Retarding Field Analyzer	89
3.3.3. Other Types of Energy Analyzers	99
3.3.4. Angular EDC Measurements	100
3.3.5. EDC Measurements As a Function of Temperature	101

3.4. Sample Preparation	102
3.4.1. Cleavage	103
3.4.2. Evaporation	104
3.4.3. Heat Cleaning	105
3.4.4. Ion Bombardment Cleaning	107
3.4.5. Lowering Electron Affinity by Applying Surface Layers	110
3.5 High Vacuum Photoemission Chambers	114
3.5.1. Vacuum Pumps	114
3.5.2. Photoemission Chambers	116
3.6. Monochromator and Light Sources	120
3.7. Directions for Future Research	121

4. Experiments on Electron Tunneling in Solids

by R. V. COLEMAN, R. C. MORRIS, and J. E. CHRISTOPHER

4.1. Introduction	123
4.2. Tunneling in Superconductors	126
4.2.1. Summary of Superconducting Tunnel Characteristics	126
4.2.2. Tunneling between Normal Metal and a Superconductor	128
4.2.3. Tunneling between Two Superconductors . .	132
4.2.4. Deviations from Ideal Tunneling Behavior .	133
4.2.5. Experimental Determination of the Energy Gap	135
4.2.6. Tunneling into Single Crystals	140
4.2.7. Tunneling Measurements of Density of States and Phonon Spectra	144
4.2.8. Tunneling Used as a Probe of the Electron-Phonon Interaction	149
4.2.9. Phonon Generation and Detection	150
4.2.10. Geometrical Resonances in Tunneling	152
4.2.11. Superconducting Tunneling in High Magnetic Fields	153
4.3. Normal-Metal Tunneling	157
4.3.1. Introduction to Normal-Metal Tunneling . .	157
4.3.2. Elastic Normal-Metal Tunneling	157
4.3.3. Dispersion Relations in the Barrier	161

4.3.4. High-Voltage Tunneling	161
4.3.5. Inelastic Tunneling	163
4.3.6. Molecular Excitations in Barriers	165
4.3.7. Barrier Excitations in Normal-Metal Tunneling	167
4.3.8. Electrode Excitations in Normal-Metal Tunneling	169
4.3.9. Zero-Bias Anomalies	170
4.4. Semiconductors in Tunnel Junctions	177
4.4.1. Summary	177
4.4.2. Metal-Insulator-Semiconductor Tunnel Junctions	178
4.4.3. Metal-Semiconductor Tunnel Junctions . . .	181
4.4.4. p-n Tunnel Junctions	184
4.4.5. Electrode-Semiconductor-Electrode Tunnel Junctions	187
4.5. Special Topics on Experimental Techniques	187
4.5.1. Junction Fabrication	187
4.5.2. Junction Testing	192
4.5.3. Measurement Circuits	193

5. Experiments Using Weakly Linked Superconductors

by B. S. DEAVER, Jr., and D. A. VINCENT

5.1. Introduction	199
5.2. Experiments That Study the Josephson Effects . . .	201
5.2.1. The Josephson Effects	201
5.2.2. General Comments on Experiments	208
5.2.3. The dc Supercurrent	212
5.2.4. Microwave-Induced Steps on the I - V Curve	217
5.2.5. Frequency Dependence of the Josephson Current and the Riedel Singularity	225
5.2.6. Self-Induced Supercurrent Steps—Cavity Modes	229
5.2.7. Radiation from the Oscillating Supercurrent .	233
5.2.8. Plasma Resonance	238
5.2.9. Subharmonic Structure on the I - V Curve	239
5.2.10. Phonon Generation by the Josephson Effect	243
5.2.11. Effects of Thermodynamic Fluctuations and Noise	245

5.3. Characteristics of Various Types of Weakly Linked Superconductors	251
5.3.1. Types of Weak Links	251
5.3.2. Current-Phase Relation and Various Phenomenological Descriptions of Weak Links	262
5.3.3. Equivalent Circuit Models	268
5.4. Applications of Weakly Linked Superconductors	273
5.4.1. Measurements of e/h	273
5.4.2. Voltage Standard	274
5.4.3. Superconducting Rings Containing a Single Weak Link	275
5.4.4. Superconducting Rings Containing Two Weak Links	289
5.4.5. The Clarke Slug	296
5.4.6. Detection, Mixing, Harmonic Generation, and Parametric Amplification	299
5.4.7. Digital Devices	304

6. Experimental Methods in Mössbauer Spectroscopy

by R. L. COHEN and G. K. WERTHEIM

6.1. Introduction to Mössbauer Spectroscopy	307
6.1.1. The Measurables	311
6.2. Mössbauer Spectrometers	316
6.2.1. Drives and Data Collection	316
6.2.2. Gamma-Ray Detection	346
6.2.3. Radioactive Sources for Mössbauer Experiments	350
6.3. Auxiliary Equipment	352
6.3.1. Low-Temperature Techniques	352
6.3.2. Furnaces	359
6.3.3. Magnets	361
6.3.4. High-Pressure Mössbauer Experiment	363
6.3.5. Data Handling	365
Appendix A. Data Analysis	366
Appendix B. Useful Graphs	367
Bibliography	368

7. Ultrasonic Studies of the Properties of Solids

by E. R. FULLER, Jr., A. V. GRANATO, J. HOLDER,
and E. R. NAIMON

7.1. Introduction	371
7.2. Ultrasonic Waves in Solids	374
7.2.1. Longitudinal Waves in an Isotropic Solid . .	375
7.2.2. Small-Amplitude Waves in Cyrstals	376
7.2.3. Finitely Strained Solids	381
7.2.4. Attenuation and Dispersion	389
7.3. Experimental Techniques	391
7.3.1. Generation of Ultrasonic Waves	391
7.3.2. Sample Preparation	396
7.3.3. Velocity and Attenuation Measurements . .	397
7.4. Applications of Ultrasonic Waves to Measuring Phys- ical Properties	410
7.4.1. Elastic Constants	410
7.4.2. Real Materials	421
Appendix A. Thermoelasticity Theory and Related Elastic Coefficients	433
A.1. Thermoelasticity	433

8. The Use of Ions in the Study of Quantum Liquids

by FRANK E. MOSS

8.1. Review of the Structure of Ions in Liquid Helium .	443
8.1.1. The Bubble Model for the Negative Ion and the Positronium Atom	443
8.1.2. The Electrostriction Model for the Positive Ion	445
8.2. Production of Ions in Liquid Helium	446
8.2.1. Radioactive Sources	446
8.2.2. Photoelectric Injection of Electrons	448
8.2.3. Injection of Hot Electrons by Tunnel Diodes	449
8.2.4. Injection of Electrons from Thermionic Cath- odes	451
8.2.5. Field Emission	452
8.2.6. Gaseous Discharges and Laser Breakdown .	453

8.3. Methods for Measurement of the Ionic Drift Velocity	454
8.3.1. The Velocity Spectrometer	454
8.3.2. The Cunsolo Method	456
8.3.3. Velocity Measurements Using Signal Averagers	458
8.3.4. The Space-Charge Limited Diode	461
8.4. The Use of Ion Mobility Measurements in the Study of Microscopic Excitations in Liquid Helium	463
8.4.1. Introduction	463
8.4.2. The Roton Region	465
8.4.3. The Phonon Region	467
8.4.4. $\text{He}^3\text{-He}^4$ Solutions	468
8.4.5. Pure He^3	468
8.5. Ion Techniques for Studying Macroscopic Quantum Excitations	469
8.5.1. Rotating Superfluid He^4	469
8.5.2. Capture of Ions by Quantized Vortex Lines .	470
8.5.3. Escape of Ions from Quantized Vortex Lines .	474
8.5.4. Creation of Vortex Rings with Ions	476
8.5.5. The Use of Ions in Studies on the Structure of Turbulent Superfluid Helium	479
8.5.6. Mobility of Ions along Linear Vortex Lines .	481
8.6. Studies of Superfluid Surfaces and Films	481
8.6.1. Interaction of Ions with the Free Liquid Surface	481
8.6.2. Motion of Ions in Superfluid Films	483

9. Thermometry at Ultralow Temperatures

by WALTER WEYHMANN

9.1. Introduction	485
9.2. Resistance Thermometers	489
9.3. Susceptibility Thermometers	502
9.3.1. Paramagnetic Susceptibility of Localized Atomic Moments	504
9.3.2. Paramagnetic Susceptibility of Nuclear Moments	511

9.4. Miscellaneous Thermometers	533
9.4.1. Thermocouples	534
9.4.2. ^3He Melting Curve	535
9.4.3. Superconductors	536
9.4.4. Capacitors	538
9.5. Conclusions	538
10. Superconducting Microwave Resonators	
by JOHN M. PIERCE	
10.1. Introduction	541
10.2. Microwave Properties of Superconductors	544
10.2.1. The Surface Impedance of Normal and Superconducting Metals	544
10.2.2. The Superconducting Surface Resistance . .	550
10.2.3. The Superconducting Surface Reactance . .	552
10.2.4. The Residual Surface Resistance	553
10.2.5. Dependence of the Surface Impedance on rf Field Level	560
10.2.6. The rf Critical Field	562
10.3. Methods of Fabricating High- Q Superconducting Resonators and Measuring Their Properties	567
10.3.1. Design and Fabrication of High Q Resonators	567
10.3.2. Materials for High- Q Superconducting Resonators	570
10.3.3. Measurement Techniques for High- Q Resonators	575
10.3.4. Frequency Measurement and Control	580
10.3.5. Coupling Networks for Superconducting Resonators	581
10.3.6. Special Cryogenic Microwave Techniques . .	584
10.4. Brief Review of Experiments Using Superconducting Resonators	584
10.4.1. Frequency Stability in Superconducting Resonators	585
10.4.2. Tuning Superconducting Resonators	587
10.4.3. Frequency Standards Referenced to Superconducting Resonators	588

10.4.4. High-Field Applications	590
10.4.5. Material Property Studies	591
10.4.6. Miscellaneous Applications	592

11. Superconducting Device Technology

11.1. Superconducting Magnets	595
---	-----

by C. D. GRAHAM, Jr.

11.1.1. Introduction	595
11.1.2. General Considerations	596
11.1.3. Materials	598
11.1.4. Stabilization	600
11.1.5. Field Uniformity	600
11.1.6. Field Measurement	602
11.1.7. Power Supply Considerations	603
11.1.8. Operation in Swept Field	604
11.1.9. Reversed Field	605
11.1.10. Liquid Helium Consumption	605
11.1.11. Operating Procedure	606
11.1.12. Costs	607

11.2. Superconducting Shielding	609
---	-----

by W. O. HAMILTON

11.2.1. Introduction	609
11.2.2. Shielding against Time-Varying Fields	610
11.2.3. Shielding against dc Fields	612
11.2.4. Conclusions	617

12. Experimental Methods in the Preparation and Measurement of Thin Films

by: D. C. LARSON

12.1. Preparation of Thin Films	620
---	-----

12.1.1. Introduction	620
12.1.2. Thermal Evaporation	622
12.1.3. Sputtering	637
12.1.4. Chemical Deposition	645

12.2. Thin Film Measurements	652
12.2.1. Introduction	652
12.2.2. Thickness Measurements	653
12.2.3. Mechanical Measurements	660
12.2.4. Optical Measurements	665
13. The Observation of Magnetic Domains	
by D. J. CRAIK	
13.1. Introduction	675
13.2. Principles Governing Domain Formations	676
13.3. Survey of Methods	683
13.3.1. Specimen and Specimen Surface Preparation	684
13.4. Powder Pattern (Colloid) Technique	687
13.5. Specialized Techniques and Pattern Formation	692
13.5.1. Replica Method for Electron Microscopy	692
13.5.2. Vapor Condensation Method	693
13.5.3. The Formation of Powder Patterns	695
13.6. Optical and Magneto-optical Properties	697
13.6.1. Faraday and Birefringence Methods	707
13.6.2. Magnetic Birefringence	715
13.6.3. The Polar Kerr Method	718
13.6.4. Longitudinal Kerr Method	721
13.6.5. Transverse Kerr Method	726
13.7. Lorentz (Electron) Microscopy	726
13.8. Scanning Electron Microscopy	734
13.9. X-Ray Method	736
13.10. Methods for Antiferromagnetic Domains	740
13.11. Further Methods	743
AUTHOR INDEX	745
SUBJECT INDEX	768

