

---

# Contents

<b>1. The Magnetic Field</b>	<b>1</b>
1. Historical	1
2. The Magnetic field Vector $H$	1
3. The Magnetization Vector $M$	3
4. Magnetic Induction, the Vector $B$	6
5. The Demagnetization Factor $D$	8
6. Energy of Interaction	11
7. Magnetic Effects of Currents. The Magnetic Shell. Faraday's Law	15
8. Maxwell's and Lorentz's Equations	22
9. The Magnetic Circuit	25
10. Dipole in a Uniform Field	27
<b>2. Diamagnetic and Paramagnetic Susceptibilities</b>	<b>31</b>
1. Introduction	31
2. Review of Quantum Mechanical and Other Results	32
<b>Diamagnetism</b>	<b>38</b>
3. The Langevin Formula for Diamagnetic Susceptibility	38
4. Susceptibility of Atoms and Ions	39
5. Susceptibility of Molecules	42
<b>Paramagnetism</b>	<b>46</b>
6. Curie's Law	46
7. Theoretical Derivations of Curie's Law	47
8. Quantum Mechanical Treatment	51
9. Susceptibility of Quasi-free Ions: the Rare Earths	54
10. The Effect of the Crystalline Field	57

11. The Iron Group Salts	63
12. Covalent Binding and the <i>3d</i> , <i>4d</i> , <i>5d</i> , and <i>5f-6d</i> Transition Groups	68
13. Saturation in Paramagnetic Substances	70
14. Paramagnetic Molecules	73
15. Paramagnetic Susceptibility of the Nucleus	75
<b>3. Thermal, Relaxation, and Resonance Phenomena in Paramagnetic Materials</b>	<b>78</b>
1. Introduction	78
<b>Thermal Phenomena</b>	79
2. Summary of Thermodynamic Relationships	79
3. The Magnetocaloric Effect: The Production and Measurement of Low Temperatures	83
<b>Paramagnetic Relaxation</b>	87
4. The Susceptibility in an Alternating Magnetic Field	87
5. Spin-Lattice Relaxation	90
6. Spin-spin Relaxation	101
<b>Paramagnetic Resonance</b>	106
7. Conditions for Paramagnetic Resonance	106
8. Line Widths: the Effect of Damping	111
9. Fine and Hyperfine Structure: the Spin-Hamiltonian	119
10. The Spectra of the Transition Group Ions	127
The <i>3d</i> group ions	128
Covalent binding and the <i>3d</i> , <i>4d</i> , <i>5d</i> , and <i>5f-6d</i> groups	130
<i>4f</i> rare earth ions in salts	130
Transition ions in various host lattices	132
11. The Spectra of Paramagnetic Molecules and Other Systems	133
Paramagnetic gases	133
Free radicals	134
Donors and acceptors in semiconductors	138
Traps, <i>F</i> -centers, etc.	140
Defects from radiation damage	141
12. The Three-Level Maser and Laser	142
<b>4. Nuclear Magnetic Resonance</b>	<b>149</b>
1. Introduction	149
2. Line Shapes and Widths	158
3. Resonance in Nonmetallic Solids	161
4. The Influence of Nuclear Motion on Line Widths and Relaxations	164
5. The Chemical Shift: Fine Structure	170
6. Transient Effects: the Spin-Echo Method	171

## CONTENTS

xiii

7. Negative Temperatures	177
8. Quadrupole Effects and Resonance	181
9. Nuclear Orientation	183
10. Double Resonance	185
11. Beam Methods	186
<b>5. The Magnetic Properties of an Electron Gas</b>	<b>194</b>
1. Statistical and Thermodynamic Functions for an Electron Gas	194
2. The Spin Paramagnetism of the Electron Gas	204
3. The Diamagnetism of the Electron Gas	211
4. Comparison of Susceptibility Theory with Experiment	220
5. The De Haas-Van Alphen Effect	224
6. Galvanomagnetic, Thermomagnetic, and Magnetoacoustic Effects	228
7. Electron Spin Resonance in Metals	231
8. Cyclotron Resonance	232
9. Nuclear Magnetic Resonance in Metals	238
10. Some Magnetic Properties of Superconductors	240
<b>6. Ferromagnetism</b>	<b>259</b>
1. Introduction	259
2. The Classical Molecular Field Theory and Comparison with Experiment	261
The spontaneous magnetization region	262
The paramagnetic region	268
Thermal effects	270
3. The Exchange Interaction	275
4. The Series Expansion Method	284
5. The Bethe-Peierls-Weiss Method	287
6. Spin Waves	292
7. Band Model Theories of Ferromagnetism	300
8. Ferromagnetic Metals and Alloys	307
9. Crystalline Anisotropy	310
10. Magnetoelastic Effects	321
<b>7. The Magnetization of Ferromagnetic Materials</b>	<b>332</b>
1. Introduction	332
2. Single-Domain Particles	340
Critical size	340
Hysteresis loops	344
Incoherent rotations	354
Some experimental results	356
Other effects	359

3.	Superparamagnetic Particles	360
4.	Permanent Magnet Materials	363
5.	Domain Walls	367
6.	Domain Structure	374
7.	The Analysis of the Magnetization Curves of Bulk Material	382
	Domain wall movements	383
	Coercive force	385
	Initial permeability	392
	Picture frame specimens	393
	The approach to saturation	394
	Remanence	395
	Nucleation of domains: whiskers	396
	Barkhausen effect	398
	Preisach-type models	399
	External stresses	400
	Minor hysteresis loops	403
8.	Thermal Effects Associated with the Hysteresis Loop	404
9.	Soft Magnetic Materials	407
10.	Time Effects	411
11.	Thin Films	416
<b>8.</b>	<b>Antiferromagnetism</b>	<b>432</b>
	1. Introduction	432
	2. Neutron Diffraction Studies	433
	3. Molecular Field Theory of Antiferromagnetism	447
	Behavior above the Néel temperature	448
	The Néel temperature	449
	Susceptibility below the Néel temperature	450
	Sublattice arrangements	454
	The paramagnetic-antiferromagnetic transition in the presence of an applied magnetic field	457
	Thermal effects	458
	4. Some Experimental Results for Antiferromagnetic Compounds	459
	5. The Indirect Exchange Interaction	464
	6. More Advanced Theories of Antiferromagnetism	467
	The series expansion method	467
	The Bethe-Peierls-Weiss method	468
	Spin waves	469
	7. Crystalline Anisotropy: Spin Flopping	470
	8. Metals and Alloys	476
	9. Canted Spin Arrangements	479
	10. Domains in Antiferromagnetic Materials	481
	11. Interfacial Exchange Anisotropy	483

<b>9. Ferrimagnetism</b>	<b>486</b>
1. Introduction	486
2. The Molecular Field Theory of Ferrimagnetism	490
Paramagnetic region	491
The ferrimagnetic Néel temperature	494
Spontaneous magnetization	494
Extension to include additional molecular fields	498
Triangular and other spin arrangements	499
Three sublattice systems	500
Ferromagnetic interaction between sublattices	501
3. Spinels	503
4. Garnets	511
5. Other Ferrimagnetic Materials	521
6. Some Quantum Mechanical Results	526
7. Soft Ferrimagnetic Materials	529
8. Some Topics in Geophysics	532
<b>10. Resonance in Strongly Coupled Dipole Systems</b>	<b>539</b>
1. Introduction	539
2. Magnetomechanical Effects	539
3. Ferromagnetic Resonance	542
4. Energy Formulation of the Equations of Motion	551
5. Resonance in Ferromagnetic Metals and Alloys	556
6. Ferromagnetic Resonance of Poor Conductors	559
7. Magnetostatic Modes	563
8. Relaxation Processes	568
Relaxation via spin waves in insulators	569
Relaxation via spin waves in conductors	574
Fast relaxation via paramagnetic ions	574
Slow relaxation via electron redistribution	577
9. Nonlinear Effects	578
10. Spin-Wave Spectra of Thin Films	588
11. Electromagnetic Wave Propagation in Gyromagnetic Media	593
12. Resonance in Unsaturated Samples	599
13. Ferrimagnetic Resonance	607
14. Antiferromagnetic Resonance	616
15. Nuclear Magnetic Resonance in Ordered Magnetic Materials	624
16. The Mössbauer Effect	629
<b>Appendix I. Systems of Units</b>	<b>641</b>
<b>Appendix II. Demagnetization Factors for Ellipsoids of Revolution</b>	<b>645</b>
<b>Appendix III. Periodic Table of the Elements</b>	<b>646</b>
<b>Appendix IV. Numerical Values for Some Important Physical Constants</b>	<b>649</b>
<b>Author Index</b>	<b>651</b>
<b>Subject Index</b>	<b>671</b>