



THE THEORY OF MAGNETISM MADE SIMPLE

An Introduction to Physical Concepts
and to Some Useful Mathematical Methods

Daniel C. Mattis

Department of Physics, University of Utah



NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Contents

| | |
|--|-----------|
| Prologue | v |
| Chapter 1. History of Magnetism | 1 |
| 1.1. Physics and Metaphysics | 3 |
| 1.2. Gilbert and Descartes | 6 |
| 1.3. Rise of Modern Science | 12 |
| 1.4. Electrodynamics | 16 |
| 1.5. The Electron | 23 |
| 1.6. The Demise of Classical Physics | 26 |
| 1.7. Quantum Theory | 31 |
| 1.8. Modern Foundations | 35 |
| 1.9. Magnetic Bubbles | 39 |
| 1.10. Ultimate Thin Films | 44 |
| 1.11. Dilute Magnetic Alloys | 47 |
| 1.12. New Directions | 49 |
| Chapter 2. Currents or Spins? | 53 |
| 2.1. Charge Currents or Spins? | 53 |
| 2.2. The Magnetic Dipole | 56 |
| 2.3. The Magnetic Dipole-Dipole Interactions | 57 |
| 2.4. The Exchange Interactions | 63 |
| 2.5. Metals and Their Alloys | 65 |
| 2.6. Superconductivity | 68 |
| 2.7. The Need to Study Spin Angular Momentum | 69 |

| | |
|---|------------|
| Chapter 3. Quantum Theory of Angular Momentum | 70 |
| 3.1. Kinetic Angular Momentum | 70 |
| 3.2. Spherical Harmonics | 74 |
| 3.3. Reason for Integer l and m | 78 |
| 3.4. Matrices of Angular Momentum | 80 |
| 3.5. Pauli Spin Matrices | 82 |
| 3.6. Compounding Angular Momentum | 83 |
| 3.7. Equations of Motion of Interacting Angular Momenta | 87 |
| 3.8. Coupled Boson Representation | 87 |
| 3.9. Rotations | 90 |
| 3.10. More on Compound Angular Momentum | 92 |
| 3.11. Other Representations | 95 |
| 3.12. Spins One-Half: Special Tricks | 96 |
| 3.13. Spins One | 98 |
| 3.14. Quadratic Forms | 100 |
| 3.15. Projection Operators | 101 |
| Chapter 4. Magnetism and the Many-Body Problem | 104 |
| 4.1. Hamiltonian Physics and Degeneracy | 104 |
| 4.2. The Pauli Principle | 107 |
| 4.3. The Two-Fermion Problem | 111 |
| 4.4. Electrons in One Dimension: A Theorem | 113 |
| 4.5. The Wronskian | 116 |
| 4.6. States of Three Electrons | 118 |
| 4.7. Eigenfunctions of Total S^2 and S_z | 120 |
| 4.8. Hund's Rules | 125 |
| 4.9. p^3 Configuration | 127 |
| 4.10. p^2 and p^4 Configurations | 133 |
| 4.11. Second Quantization | 139 |
| 4.12. Double Exchange | 143 |
| 4.13. Superexchange | 146 |
| 4.14. Jellium | 149 |
| 4.15. Hubbard Model: An Introduction | 154 |
| 4.16. Nagaoka's Ferromagnetism | 163 |
| 4.17. One Dimension: Exact Solutions | 167 |
| 4.18. Ferrimagnetism | 168 |
| 4.19. Spin-Dependent Tunneling | 172 |

| | |
|---|------------|
| Chapter 5. From Magnons to Solitons: Spin Dynamics | 175 |
| 5.1. Spin Waves as Harmonic Oscillators | 176 |
| 5.2. One-Magnon Eigenstates in Ferromagnets | 185 |
| 5.3. Two-Magnon States and Eigenstates in Ferromagnets | 186 |
| 5.4. Bound States in One Dimension | 195 |
| 5.5. Bound States in Two and Three Dimensions | 196 |
| 5.6. Antiferromagnetic Magnons: The One-Dimensional XY Model . | 200 |
| 5.7. Bethe's Solution of One-Dimensional Heisenberg Antiferromagnet | 206 |
| 5.8. Linearized Antiferromagnetic Magnons | 215 |
| 5.9. Ferrimagnetism | 224 |
| 5.10. Some Rigorous Notions in Antiferro- and Ferri-Magnetism . . | 226 |
| 5.11. Vortices | 228 |
| 5.12. Solitons and Bloch Domain Walls: Introductory Material . . | 231 |
| 5.13. Solitary Wave Solution | 235 |
| 5.14. More on Magnetic Domains | 241 |
| 5.15. Time-Dependent Phenomena | 242 |
| 5.16. Majumdar-Ghosh Model and “Quantum Frustration” | 247 |
| 5.17. Integer Spins | 250 |
| 5.18. The AKLT Spin One Chain | 254 |
| 5.19. Defective Antiferromagnets | 255 |
| Chapter 6. Magnetism in Metals | 257 |
| 6.1. Bloch and Wannier States | 259 |
| 6.2. Tight-Binding | 260 |
| 6.3. Weak Magnetic Properties | 267 |
| 6.4. Exchange in Solids: Construction of a Model Hamiltonian . | 273 |
| 6.5. Perturbation-Theoretic Derivation of Heisenberg Hamiltonian | 281 |
| 6.6. Heisenberg Hamiltonian in Metals | 284 |
| 6.7. Ordered Magnetic Metals: Deriving the Ground State | 287 |
| 6.8. Kondo Effect | 296 |
| 6.9. Spin Glasses | 304 |
| 6.10. Magnetism without Localized Spins: Preliminaries | 310 |
| 6.11. Degenerate Bands and Intra-Atomic Exchange Forces | 314 |
| 6.12. Magnons in Metals | 320 |
| 6.13. Marginal Magnetism of Impurities | 327 |
| 6.14. Correlations and Equivalence to <i>s-d</i> Model | 337 |
| 6.15. Periodic Anderson Model | 342 |

| | |
|--|------------|
| Chapter 7. Statistical Thermodynamics | 344 |
| 7.1. Spins in a Magnetic Field | 344 |
| 7.2. The Partition Function | 349 |
| 7.3. The Concept of the Molecular Field | 354 |
| 7.4. Discontinuity in Specific Heat | 358 |
| 7.5. Magnetic Susceptibility and Spontaneous Magnetization | 361 |
| 7.6. Adiabatic Demagnetization | 365 |
| 7.7. Antiferromagnetism | 366 |
| 7.8. Short-Ranged versus Long-Ranged Interactions | 369 |
| 7.9. Fermions, Bosons, and all that | 375 |
| Fermions | 375 |
| Bosons | 375 |
| Gaussian | 376 |
| Legendre Transformations | 377 |
| 7.10. Gaussian and Spherical Models | 378 |
| Gaussian Model | 379 |
| Spherical Model | 382 |
| Watson's Integrals Generalized | 387 |
| 7.11. Magnetic Susceptibility in Gaussian and Spherical Models | 389 |
| 7.12. Spherical Antiferromagnet | 392 |
| 7.13. Spherical Model Spin Glass | 395 |
| Magnetic Properties of Spin Glass | 399 |
| 7.14. Thermodynamics of Magnons | 407 |
| 7.15. Magnetism in Two Dimensions | 414 |
| 7.16. The XY Model: 1D | 418 |
| 7.17. The XY Model: 2D | 426 |
| 7.18. Transfer Matrix of Plane Rotator Model | 433 |
| Chapter 8. The Ising Model | 438 |
| 8.1. High Temperature Expansions | 441 |
| 8.2. Graph Theory | 445 |
| 8.3. Low Temperature Expansions and the Duality Relations | 448 |
| 8.4. Peierls' Proof of Long Range Order | 452 |
| 8.5. 1D Ising Model in Longitudinal Fields | 454 |
| 8.6. 1D Ising Model in Transverse Fields | 462 |
| 8.7. Concerning Quadratic Forms of Fermion Operators | 474 |
| 8.8. Two-Dimensional Ising Model: The Transfer Matrix | 478 |
| 8.9. Solution of Two-Dimensional Ising Model in Zero Field | 485 |

| | |
|---|------------|
| 8.10. Spontaneous Magnetization and Magnetic Susceptibility | 494 |
| 8.11. Zeros of the Partition Function | 502 |
| 8.12. Miscellania, Including 2D Antiferromagnets | 507 |
| 8.13. The Three-Dimensional Ising Model | 517 |
| 8.14. Ising Gauge Glass | 526 |
| 8.15. Frustration | 528 |
| Chapter 9. Miscellaneous Advanced Topics | 533 |
| 9.1. Critical Phenomena | 533 |
| 9.2. Green Functions Formalism | 536 |
| 9.3. Nonlinear Responses and Chaos | 539 |
| 9.4. Kondo Phenomenon: The <i>s-d</i> Model Redux | 539 |
| 9.5. Scaling, Renormalization and Information Theory | 547 |
| Bibliography | 549 |
| Index | 561 |