

# Contents of Volume II

|                                                                   |          |
|-------------------------------------------------------------------|----------|
| <b>10. Quantum Gases Without Interactions</b>                     | <b>1</b> |
| 10.1 The Indistinguishability of Quantum Particles                | 3        |
| 10.1.1 Exchange of Two Identical Particles                        | 3        |
| 10.1.2 The Pauli Principle                                        | 5        |
| 10.1.3 Bosons and Fermions;<br>Elementary and Composite Particles | 8        |
| 10.1.4 Effects Connected with Indistinguishability                | 11       |
| 10.2 Fock Bases                                                   | 14       |
| 10.2.1 Single-Particle States                                     | 15       |
| 10.2.2 Occupation Numbers                                         | 17       |
| 10.2.3 Operators in the Fock Representation                       | 20       |
| 10.3 Equilibrium of Quantum Gases                                 | 24       |
| 10.3.1 Grand Canonical Partition Function                         | 24       |
| 10.3.2 Occupation Factors                                         | 26       |
| 10.3.3 Large Volume Limit; Density of States                      | 27       |
| 10.3.4 Classical Limit; Low Densities                             | 31       |
| 10.4 Fermi-Dirac Statistics                                       | 33       |
| 10.4.1 Examples of Fermion Gases                                  | 33       |
| 10.4.2 Fermion Gas at Zero Temperature;<br>Fermi Temperature      | 35       |
| 10.4.3 Equilibrium Properties at Low Temperatures                 | 37       |
| 10.5 Bose-Einstein Statistics                                     | 43       |
| 10.5.1 Examples of Boson Gases                                    | 43       |
| 10.5.2 Chemical Potentials of Boson Gases                         | 44       |
| Summary                                                           | 46       |
| Exercises                                                         | 46       |
| 10a Indistinguishable Particles<br>in a Harmonic Potential        | 46       |
| 10b Pauli Paramagnetism                                           | 51       |
| 10c Thermionic Effect                                             | 52       |
| 10d Metallic Film                                                 | 53       |
| 10e Neutron Stars                                                 | 54       |
| 10f Quantum Corrections to the Perfect Gas                        | 56       |
| 10g Spatial Correlations Due to Indistinguishability              | 56       |

|                                                                |     |
|----------------------------------------------------------------|-----|
| <b>11. Elements of Solid State Theory</b>                      | 59  |
| 11.1 Crystal Order                                             | 62  |
| 11.1.1 The Born-Oppenheimer Method                             | 62  |
| 11.1.2 Properties Related to the Crystal Structure             | 65  |
| 11.2 Single-Electron Levels in a Periodic Potential            | 68  |
| 11.2.1 Independent Electron Approximation                      | 68  |
| 11.2.2 Introduction to Band Theory                             | 73  |
| 11.2.3 Weak Binding Limit                                      | 79  |
| 11.2.4 Tight Binding Limit                                     | 83  |
| 11.2.5 Three-Dimensional Bands                                 | 86  |
| 11.3 Electrons in Metals, Insulators, and Semiconductors       | 90  |
| 11.3.1 Metals                                                  | 91  |
| 11.3.2 Insulators; Dynamics of Electrons and Holes             | 95  |
| 11.3.3 Microscopic Foundations<br>of Electrostatic Equilibrium | 107 |
| 11.3.4 Semiconductors                                          | 115 |
| 11.3.5 p-n Junctions, Photocell, Diode, and Transistor         | 122 |
| 11.4 Phonons                                                   | 129 |
| 11.4.1 Lattice Vibrations                                      | 130 |
| 11.4.2 Interpretation of a Mode as a Boson State               | 136 |
| 11.4.3 Specific Heats of Solids                                | 139 |
| 11.4.4 Thermal Equilibrium of a Vibrating String               | 143 |
| Summary                                                        | 153 |
| Exercises                                                      | 154 |
| 11a Point Defects in Crystals                                  | 154 |
| 11b Semiconductors in the Extrinsic<br>and Saturation Regimes  | 155 |
| 11c p-n Junction at Zero Temperature                           | 156 |
| 11d Einstein Model                                             | 158 |
| 11e Acoustic and Optical Phonons                               | 158 |
| 11f Ferromagnetism of Metals                                   | 159 |
| <b>12. Liquid Helium</b>                                       | 171 |
| 12.1 Peculiar Properties of Helium                             | 172 |
| 12.1.1 Phase Diagrams                                          | 172 |
| 12.1.2 Quantum Liquids                                         | 173 |
| 12.2 Helium Three                                              | 175 |
| 12.2.1 Equation of State                                       | 175 |
| 12.2.2 Thermal Properties                                      | 177 |
| 12.2.3 Solid-Liquid Transition                                 | 178 |
| 12.3 Helium Four and Bose Condensation                         | 179 |
| 12.3.1 Bose Condensation                                       | 179 |
| 12.3.2 Bose-Einstein Phase Transition                          | 183 |
| 12.3.3 Superfluidity and Superconductivity                     | 186 |
| Summary                                                        | 190 |

|                                                              |            |
|--------------------------------------------------------------|------------|
| Exercises                                                    | 191        |
| 12a Specific Heat of the Bose Gas                            | 191        |
| 12b Critical Fluctuations                                    | 192        |
| 12c Bose Condensation in a Canonical Ensemble                | 192        |
| 12d Rôle of the Interactions in the Bose Transition          | 195        |
| <b>13. Equilibrium and Transport of Radiation</b>            | <b>201</b> |
| 13.1 Quantizing the Electromagnetic Field                    | 202        |
| 13.1.1 Classical Modes in a Cavity                           | 202        |
| 13.1.2 Quantized Radiation Spectrum                          | 205        |
| 13.1.3 Field Operators                                       | 206        |
| 13.1.4 Photons                                               | 211        |
| 13.2 Equilibrium of Radiation in an Enclosure                | 215        |
| 13.2.1 Extensive Quantities                                  | 215        |
| 13.2.2 Planck's Law                                          | 218        |
| 13.3 Exchanges of Radiative Energy                           | 221        |
| 13.3.1 Black-Body Radiation                                  | 221        |
| 13.3.2 Absorption and Emission                               | 224        |
| 13.3.3 Kirchhoff's Law                                       | 227        |
| 13.3.4 Applications                                          | 229        |
| Summary                                                      | 233        |
| Exercises                                                    | 233        |
| 13a Pressure and Internal Energy                             | 233        |
| 13b Density of Photons in the 3K Radiation                   | 235        |
| 13c Neutrinos in Cosmology                                   | 235        |
| 13d Planetary Temperatures                                   | 237        |
| 13e Dewar Flasks                                             | 238        |
| 13f Greenhouse Effect                                        | 239        |
| <b>14. Non-Equilibrium Thermodynamics</b>                    | <b>241</b> |
| 14.1 Conservation Laws                                       | 243        |
| 14.1.1 The Problematics of Thermodynamics                    | 243        |
| 14.1.2 Different Kinds of Processes                          | 245        |
| 14.1.3 Relations Between Fluxes, Currents, and Densities     | 249        |
| 14.2 Response Coefficients                                   | 253        |
| 14.2.1 Local Equations of State                              | 253        |
| 14.2.2 Responses of the Fluxes to the Affinities             | 255        |
| 14.2.3 Some Common Transport Coefficients                    | 259        |
| 14.2.4 Curie's Principle and Onsager's Relations             | 261        |
| 14.2.5 Dissipation                                           | 265        |
| 14.2.6 Summary: Macroscopic Approach<br>to Dynamic Phenomena | 270        |
| 14.3 Microscopic Approach                                    | 273        |
| 14.3.1 Invariance and Conservation                           | 273        |
| 14.3.2 Microscopic Expression for the Fluxes in a Fluid      | 276        |

|            |                                                          |            |
|------------|----------------------------------------------------------|------------|
| 14.3.3     | Relevant Entropy                                         | 282        |
| 14.3.4     | Macroscopic, Microscopic<br>and Mesoscopic Descriptions  | 284        |
| 14.3.5     | The Projection Method                                    | 286        |
| 14.4       | Applications                                             | 290        |
| 14.4.1     | Particle and Heat Diffusion                              | 291        |
| 14.4.2     | Electrodynamics                                          | 293        |
| 14.4.3     | Thermoelectric Effects                                   | 297        |
| 14.4.4     | Local Equilibrium of a Fluid                             | 300        |
| 14.4.5     | Conservation Laws in a Fluid                             | 304        |
| 14.4.6     | Equations of Hydrodynamics                               | 308        |
|            | Summary                                                  | 317        |
|            | Exercises                                                | 318        |
| 14a        | Design of an Isotope Separation Plant                    | 318        |
| 14b        | Response to an External Perturbation                     | 321        |
| 14c        | Desorption                                               | 330        |
| <b>15.</b> | <b>Kinetic Equations</b>                                 | <b>331</b> |
| 15.1       | The Lorentz Model                                        | 333        |
| 15.1.1     | Gases with Scattering Centres                            | 333        |
| 15.1.2     | Successive Contractions of the Description               | 334        |
| 15.1.3     | Evolution of the Single-Particle Reduced Density         | 336        |
| 15.1.4     | Ballistic and Local Equilibrium Regimes                  | 340        |
| 15.1.5     | The Chapman-Enskog Method                                | 344        |
| 15.2       | Applications and Extensions                              | 349        |
| 15.2.1     | Diffusion and Conduction                                 | 349        |
| 15.2.2     | Semiconductors                                           | 353        |
| 15.2.3     | Metals                                                   | 357        |
| 15.2.4     | Thermalization of Electrons in a Conductor               | 364        |
| 15.2.5     | Neutron Physics                                          | 369        |
| 15.3       | The Boltzmann Equation                                   | 371        |
| 15.3.1     | The Boltzmann Collision Term                             | 371        |
| 15.3.2     | Densities and Fluxes in a Gas                            | 377        |
| 15.3.3     | Transport Coefficients of a Gas                          | 381        |
| 15.3.4     | Gas Mixtures                                             | 388        |
| 15.3.5     | Brownian Motion                                          | 391        |
| 15.4       | Microscopic Reversibility vs Macroscopic Irreversibility | 395        |
| 15.4.1     | The Boltzmann Description                                | 395        |
| 15.4.2     | The $H$ -Theorem                                         | 398        |
| 15.4.3     | Irreversibility of the Boltzmann Equation                | 402        |
| 15.4.4     | Boltzmann and Thermodynamic Entropies                    | 408        |
| 15.4.5     | Spin Echoes                                              | 411        |
|            | Summary                                                  | 415        |
|            | Exercises                                                | 416        |
| 15a        | Diffusion in Solids; Doping                              | 416        |

|                                                            |                                                          |            |
|------------------------------------------------------------|----------------------------------------------------------|------------|
| 15b                                                        | Impedance in the Lorentz Model .....                     | 417        |
| 15c                                                        | Dynamics of a Lorentz Gas Particle .....                 | 419        |
| 15d                                                        | Hall Effect .....                                        | 421        |
| 15e                                                        | Absorption, Stimulated<br>and Spontaneous Emission ..... | 423        |
| 15f                                                        | Heat Transfer in Stars .....                             | 425        |
| <b>16.</b>                                                 | <b>Problems .....</b>                                    | <b>433</b> |
| 16.1                                                       | Paramagnetism of Spin Pairs .....                        | 434        |
| 16.2                                                       | Elasticity of a Polymer Chain .....                      | 436        |
| 16.3                                                       | Crystal Surfaces .....                                   | 437        |
| 16.4                                                       | Order in an Alloy .....                                  | 454        |
| 16.5                                                       | Ferroelectricity .....                                   | 456        |
| 16.6                                                       | Rotation of Molecules in a Gas .....                     | 460        |
| 16.7                                                       | Isotherms and Phase Transition of a Lattice Gas .....    | 463        |
| 16.8                                                       | Phase Diagram of Bromine .....                           | 480        |
| 16.9                                                       | White Dwarfs .....                                       | 488        |
| 16.10                                                      | Crystallization of a Stellar Plasma .....                | 499        |
| 16.11                                                      | Landau Diamagnetism .....                                | 503        |
| 16.12                                                      | Electron-Induced Phase Transitions in Crystals .....     | 508        |
| 16.13                                                      | Liquid-Solid Transition in Helium Three .....            | 516        |
| 16.14                                                      | Phonons and Rotons in Liquid Helium .....                | 521        |
| 16.15                                                      | Heat Losses Through Windows .....                        | 539        |
| 16.16                                                      | Incandescent Lamps .....                                 | 542        |
| 16.17                                                      | Neutron Physics in Nuclear Reactors .....                | 552        |
| 16.18                                                      | Electron Gas with a Variable Density .....               | 558        |
| 16.19                                                      | Snoek Effect and Martensitic Steels .....                | 563        |
| <b>Conclusion: The Impact of Statistical Physics .....</b> |                                                          | <b>571</b> |
| <b>Subject Index .....</b>                                 |                                                          | <b>577</b> |
| <b>Units and Physical Constants .....</b>                  |                                                          | <b>604</b> |
| <b>A Few Useful Formulae .....</b>                         |                                                          | <b>606</b> |