

# Contents

|          |                                                                                 |           |
|----------|---------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                                             | <b>1</b>  |
| <b>2</b> | <b>Relativistic Quantum Mechanics and Fields</b>                                | <b>7</b>  |
| 2.1      | The Dirac Equation                                                              | 7         |
| 2.2      | Solutions for Free Particles                                                    | 8         |
| 2.3      | Relativistic Free-Field Theories                                                | 11        |
| 2.3.1    | Real Scalar Field                                                               | 12        |
| 2.3.2    | Vector Field                                                                    | 13        |
| 2.3.3    | Electromagnetic Field                                                           | 13        |
| 2.3.4    | Spinor Dirac Field                                                              | 14        |
| 2.3.5    | Real Scalar Field with Quartic Self-Interaction                                 | 14        |
| 2.4      | The Dirac Equation in a Central Potential                                       | 20        |
| <b>3</b> | <b>Basic Features of the Meson Theory<br/>of Nucleon–Nucleon Interactions</b>   | <b>25</b> |
| 3.1      | One-Boson Exchange Potentials in Configuration Space                            | 25        |
| 3.2      | One-Boson Exchange Potentials in Momentum Space                                 | 32        |
| <b>4</b> | <b>The Relativistic Mean-Field Approximation<br/>for Nuclear Structure</b>      | <b>39</b> |
| 4.1      | General Characteristics of the Relativistic Framework                           | 39        |
| 4.1.1    | Large Scalar and Vector Fields                                                  | 39        |
| 4.1.2    | Spin–Orbit Force                                                                | 40        |
| 4.1.3    | Saturation                                                                      | 40        |
| 4.2      | Relativistic Mean-Field Approximation for Finite Nuclei                         | 48        |
| 4.3      | Relation of the RMF Model<br>to the Skyrme–Hartree–Fock Approach                | 52        |
| 4.4      | Renormalization of the Kinetic Energy<br>to Obtain Saturation in Nuclear Matter | 62        |
| 4.5      | Relativistic Mean-Field Approximation<br>for Deformed Nuclei                    | 64        |
| 4.6      | Optimal Parameter Sets<br>for the Relativistic Mean-Field Model                 | 67        |

|          |                                                                                   |     |
|----------|-----------------------------------------------------------------------------------|-----|
| <b>5</b> | <b>Electromagnetic Interactions of Nucleons<br/>in the Relativistic Framework</b> | 75  |
| 5.1      | The Vector Dominance Model<br>and the Nuclear Coulomb Potential                   | 75  |
| 5.1.1    | Results of Calculations                                                           | 80  |
| 5.2      | Nuclear Magnetic Moments in the Relativistic Approach                             | 82  |
| <b>6</b> | <b>The Relativistic Approach to Nucleon–Nucleus Scattering</b>                    | 89  |
| 6.1      | Energy Dependence of the Real Part<br>of the Optical Potential                    | 89  |
| 6.2      | Coulomb–Nuclear Interference Effects<br>in Nucleon–Nucleus Scattering             | 92  |
| 6.3      | Relativistic Impulse Approximation                                                | 94  |
| 6.4      | $\bar{p}$ –Nucleus Scattering                                                     | 96  |
| <b>7</b> | <b>Pion Dynamics and Chiral Symmetry</b>                                          | 99  |
| 7.1      | Pionic Excitations in Nuclear Matter                                              | 99  |
| 7.2      | Equations of Motion for a Pion Field<br>in a Nuclear Medium                       | 101 |
| 7.3      | Pionic Polarization in Infinite Nuclear Matter                                    | 104 |
| 7.4      | Contribution of the $\Delta_{33}$ Resonance<br>to the Pion Polarization Operator  | 107 |
| 7.5      | Basic Equations of the Linear $\sigma$ and $\sigma$ – $\omega$ Models             | 113 |
| 7.6      | Chiral $\sigma$ – $\omega$ Model for Finite Nuclei                                | 122 |
| 7.7      | Effective Gauge-Invariant Nuclear Lagrangian                                      | 125 |
| 7.8      | Mean-Field Results for Nuclear Matter and Finite Nuclei                           | 130 |
| <b>8</b> | <b>The Relativistic Hartree–Fock Approach</b>                                     | 137 |
| 8.1      | The Relativistic Hartree–Fock Lagrangian                                          | 137 |
| 8.2      | The Relativistic Hartree–Fock Approach<br>for Symmetric Nuclear Matter            | 141 |
| 8.3      | The Relativistic Hartree–Fock Approach for Finite Nuclei                          | 146 |
| 8.4      | Determination of Parameters and Numerical Results                                 | 148 |
| 8.5      | The Relativistic Hartree–Fock Approach<br>with Meson Self-Coupling Terms          | 154 |
| 8.6      | Spin–Orbit Interaction                                                            | 160 |
| 8.7      | Pseudospin as a Relativistic Symmetry                                             | 165 |
| <b>9</b> | <b>Brueckner–Hartree–Fock Methods for Nuclear Matter<br/>and Finite Nuclei</b>    | 173 |
| 9.1      | The Brueckner–Hartree–Fock Approach                                               | 173 |
| 9.2      | The Brueckner–Bethe–Goldstone Method<br>for Internucleon Correlations             | 175 |
| 9.3      | $\Delta$ -Isobar for Nuclear Interactions and Nuclear Structure                   | 182 |

|           |                                                                                           |            |
|-----------|-------------------------------------------------------------------------------------------|------------|
| 9.4       | Relativistic Extension of the BHF Theory<br>for Nuclear Matter .....                      | 187        |
| 9.5       | Finite Nuclei .....                                                                       | 194        |
| <b>10</b> | <b>Excited Nuclear States<br/>in the Relativistic RPA Method .....</b>                    | <b>201</b> |
| 10.1      | RRPA Method for Nuclear Matter and Finite Nuclei .....                                    | 201        |
| 10.2      | RRPA with Nonlinear Interactions for Giant Resonances ..                                  | 203        |
| 10.3      | Construction of the Meson Propagators .....                                               | 206        |
| 10.4      | Results for Collective States and Giant Resonances .....                                  | 208        |
| 10.5      | Cranked Relativistic Mean-Field Theory .....                                              | 216        |
| <b>11</b> | <b>The Equation of State of Nuclear Matter for Supernovas<br/>and Neutron Stars .....</b> | <b>219</b> |
| 11.1      | Thomas–Fermi Method for Nonuniform Matter .....                                           | 219        |
| 11.2      | Equation of State of Nuclear Matter .....                                                 | 223        |
| 11.3      | Neutron Star Matter and Neutron Star Profiles .....                                       | 232        |
| <b>12</b> | <b>Alternative Relativistic Models .....</b>                                              | <b>239</b> |
| 12.1      | Quark–Meson Coupling Models .....                                                         | 239        |
| 12.2      | The Relativistic Point-Coupling Model .....                                               | 246        |
| 12.3      | Scalar Derivative Coupling Models .....                                                   | 253        |
| <b>13</b> | <b>Some Recent Applications<br/>of Relativistic Nuclear Theory .....</b>                  | <b>261</b> |
| 13.1      | Mean Fields in Colliding Nuclear Matter .....                                             | 261        |
| 13.2      | Hartree–Fock–Bogoliubov Approximation .....                                               | 263        |
| 13.3      | Spin–Orbit Splitting for Single-Particle<br>and Single-Hole Energies .....                | 266        |
| 13.4      | The Anomalous Kink in the Isotope Shifts of Pb Nuclei ..                                  | 267        |
| 13.5      | Electroweak Interactions in Nuclei<br>in the Relativistic Framework .....                 | 268        |
| 13.6      | Hypernuclei in the Relativistic Framework .....                                           | 270        |
| 13.7      | Theoretical Analysis of $A(e, e'p)B$ Reactions .....                                      | 271        |
| 13.8      | Exclusive Pion Production in Nucleon–Nucleus Scattering ..                                | 272        |
| 13.9      | The Role of Relativity in Few-Body Systems .....                                          | 274        |
| 13.10     | Systematic Study of Even–Even Nuclei<br>up to the Drip Lines .....                        | 276        |
| 13.11     | Exotic Nuclei and Superheavy Nuclei .....                                                 | 279        |
| 13.12     | Dilepton Production by Bremsstrahlung of Meson Fields<br>in Nuclear Collisions .....      | 281        |
| 13.13     | (p, n) Spin Experiments and Relativity<br>in Nuclear Physics .....                        | 282        |
| 13.14     | Role of Currents ( $\omega$ and $\rho$ Fields) .....                                      | 284        |
| 13.15     | Fission Barriers .....                                                                    | 285        |
| 13.16     | Chiral Dynamics and Saturation of Nuclear Structure .....                                 | 286        |

|           |                                                                                  |     |
|-----------|----------------------------------------------------------------------------------|-----|
| <b>14</b> | <b>Summary and Outlook</b> .....                                                 | 289 |
| <b>A</b>  | <b>Appendices</b> .....                                                          | 293 |
| A.1       | Four-Dimensional Notation and the Dirac Matrices.....                            | 293 |
| A.2       | Properties of the Ground State of Nuclear Matter in the<br>Walecka Model .....   | 296 |
| A.3       | General Form of Local Dirac Equation.....                                        | 297 |
| A.4       | Equivalent Local Dirac Nuclear Models .....                                      | 299 |
| A.5       | Nucleon Effective Mass in the Nuclear Medium .....                               | 300 |
| A.6       | Radial Equations for the Upper and Lower Components<br>$G(r)$ and $F(r)$ .....   | 302 |
| A.7       | Boundary Conditions for Wave Functions and Meson<br>Potentials.....              | 304 |
| A.8       | Generalized Weinberg Transformation .....                                        | 305 |
| A.9       | Expansions of the Vertex Functions for Various Mesons ....                       | 306 |
| A.10      | Globally Chirally Invariant Lagrangian for the Model with<br>an Axial Meson..... | 307 |
| A.11      | Direct and Exchange Matrix Elements for the Two-Body<br>Spin–Orbit Force .....   | 309 |
| A.12      | Hartree–Fock Procedure for the Point-Coupling Model.....                         | 318 |
|           | <b>References</b> .....                                                          | 323 |
|           | <b>Index</b> .....                                                               | 347 |