

## Contents

**Preface** *XIII*

**Acknowledgments** *XVII*

**Glossary** *XIX*

|          |                                                  |
|----------|--------------------------------------------------|
| <b>1</b> | <b>Higgs</b> <i>1</i>                            |
| 1.1      | Introduction <i>1</i>                            |
| 1.2      | Higgs Interactions <i>2</i>                      |
| 1.2.1    | Standard Model <i>2</i>                          |
| 1.2.2    | Lagrangian After Symmetry Breaking <i>5</i>      |
| 1.2.3    | Decay Modes <i>6</i>                             |
| 1.3      | Mass <i>9</i>                                    |
| 1.3.1    | Predictions from EW Data <i>9</i>                |
| 1.3.2    | Vacuum stability <i>10</i>                       |
| 1.3.3    | Theoretical Upper Limit <i>12</i>                |
| 1.4      | Little and Big Hierarchy Problem <i>16</i>       |
| 1.5      | Higgs in the Supersymmetry <i>19</i>             |
| 1.5.1    | Two Higgs Doublets <i>19</i>                     |
| 1.5.2    | Coupling Strengths of MSSM Higgs <i>22</i>       |
| 1.5.3    | Mass Spectrum of MSSM Higgs <i>24</i>            |
| 1.6      | Is the Higgs Elementary? <i>28</i>               |
| 1.6.1    | Technicolor Model <i>29</i>                      |
| 1.6.2    | Little Higgs Model <i>31</i>                     |
| 1.7      | Production and Detection of Higgs <i>38</i>      |
| 1.7.1    | Higgsstrahlung $e^-e^+ \rightarrow hZ$ <i>39</i> |
| 1.7.2    | W Boson Fusion <i>39</i>                         |
| 1.7.3    | Productions at the Hadron Collider <i>43</i>     |
| 1.7.4    | Signals at LHC <i>46</i>                         |
| 1.7.5    | Higgs Detection Methods <i>48</i>                |
| 1.7.6    | Discovery of Higgs <i>51</i>                     |
| 1.7.7    | SM Higgs? <i>52</i>                              |

|          |                                      |            |
|----------|--------------------------------------|------------|
| 1.7.8    | MSSM Higgs and Future Prospect       | 55         |
| 1.8      | Summary                              | 58         |
| <b>2</b> | <b>Neutrino</b>                      | <b>61</b>  |
| 2.1      | Introduction                         | 61         |
| 2.2      | Neutrino Mass                        | 62         |
| 2.2.1    | Mass Matrix                          | 65         |
| 2.2.2    | Left-Right Symmetric Model           | 69         |
| 2.3      | Electromagnetic Interaction          | 70         |
| 2.4      | Neutrino Mixing                      | 73         |
| 2.5      | Neutrino Oscillation                 | 76         |
| 2.5.1    | Two-Flavor Oscillation               | 76         |
| 2.5.2    | Atmospheric Neutrino                 | 79         |
| 2.5.3    | Accelerator Experiments              | 82         |
| 2.6      | Underground Detectors                | 87         |
| 2.7      | Solar Neutrino                       | 93         |
| 2.7.1    | The Solar Puzzle                     | 93         |
| 2.7.2    | Matter Oscillation                   | 100        |
| 2.7.3    | Reactor Experiment                   | 111        |
| 2.8      | Three-Flavor Oscillation             | 114        |
| 2.8.1    | PMNS Matrix                          | 114        |
| 2.8.2    | Summary of Experimental Data         | 120        |
| 2.8.3    | CP Violation and Mass Hierarchy      | 121        |
| 2.8.4    | Future Prospects                     | 124        |
| 2.9      | Double Beta Decay                    | 126        |
| 2.9.1    | The Effective Majorana Mass          | 128        |
| 2.9.2    | Current Status                       | 129        |
| 2.9.3    | To Design an Experiment              | 131        |
| 2.9.4    | Experimental Apparatus               | 133        |
| 2.10     | Supernova Neutrino                   | 136        |
| 2.10.1   | Stellar Evolution                    | 138        |
| 2.10.2   | Feedback to Particle Physics         | 150        |
| <b>3</b> | <b>Grand Unified Theories</b>        | <b>155</b> |
| 3.1      | Introduction                         | 155        |
| 3.2      | Why GUTs?                            | 155        |
| 3.2.1    | Weinberg Angle in GUTs               | 157        |
| 3.2.2    | Quantization of the Electric Charge  | 157        |
| 3.2.3    | Triangle Anomaly                     | 158        |
| 3.3      | $SU(5)$                              | 160        |
| 3.3.1    | Fermion Representation               | 161        |
| 3.3.2    | Representation of the Gauge Particle | 164        |
| 3.3.3    | Symmetry Breakdown                   | 168        |
| 3.3.4    | Predictions                          | 170        |
| 3.4      | $SO(10)$                             | 174        |

|          |                                        |            |
|----------|----------------------------------------|------------|
| 3.4.1    | Left–Right Symmetric World             | 174        |
| 3.4.2    | New Gauge Bosons $Z'$ and $W'$         | 175        |
| 3.5      | Hierarchy Problem                      | 182        |
| 3.6      | SUSY GUT                               | 185        |
| <b>4</b> | <b>Supersymmetry I: Basics</b>         | <b>189</b> |
| 4.1      | Introduction                           | 189        |
| 4.1.1    | Toy Model                              | 190        |
| 4.1.2    | Field Theoretical Operators            | 191        |
| 4.2      | Two-Component Formalism                | 193        |
| 4.2.1    | Majorana Fields                        | 193        |
| 4.2.2    | SUSY Operators                         | 198        |
| 4.2.3    | Superspace                             | 200        |
| 4.3      | Chiral Superfield                      | 203        |
| 4.3.1    | Products of Chiral Superfields         | 206        |
| 4.4      | Vector Superfields                     | 206        |
| 4.4.1    | Field Strength                         | 209        |
| 4.5      | Action                                 | 210        |
| 4.5.1    | SUSY Invariant Action                  | 210        |
| 4.5.2    | Kinetic Energy of Chiral Superfield    | 212        |
| 4.5.3    | Superpotential                         | 213        |
| 4.5.4    | Lagrangian of the Chiral Fields        | 215        |
| 4.5.5    | Kinetic Energy of Vector Field         | 216        |
| 4.6      | Gauge Interaction                      | 217        |
| 4.6.1    | Global $U(1)$ Transformation           | 217        |
| 4.6.2    | Local $U(1)$ Transformation            | 217        |
| 4.6.3    | Non-Abelian Interaction                | 219        |
| 4.7      | Summary of SUSY Lagrangian             | 220        |
| 4.8      | Spontaneous Symmetry Breaking          | 221        |
| 4.8.1    | $D$ -Term Breaking                     | 222        |
| 4.8.2    | $F$ -Term Breaking                     | 223        |
| <b>5</b> | <b>Supersymmetry II: Phenomenology</b> | <b>225</b> |
| 5.1      | Introduction                           | 225        |
| 5.2      | Minimum Supersymmetric Standard Model  | 226        |
| 5.2.1    | Particle Spectrum                      | 226        |
| 5.2.2    | Interactions                           | 229        |
| 5.2.3    | Constraints                            | 230        |
| 5.2.4    | SUSY Breaking                          | 231        |
| 5.2.5    | Higgs Potential                        | 232        |
| 5.3      | Minimum SUGRA                          | 235        |
| 5.3.1    | Soft- SUSY Breaking                    | 235        |
| 5.3.2    | Mass Formula                           | 237        |
| 5.3.3    | $\mu$ Problem                          | 241        |
| 5.4      | GMSB                                   | 241        |

|          |                                           |            |
|----------|-------------------------------------------|------------|
| 5.4.1    | Messenger Particles                       | 242        |
| 5.4.2    | Mass Formula                              | 242        |
| 5.4.3    | Features of GMSB                          | 244        |
| 5.5      | AMSB and Extra Dimension                  | 245        |
| 5.6      | Summary of Mass Spectra                   | 247        |
| 5.7      | Searches for Sparticles                   | 248        |
| 5.7.1    | Production Mechanism                      | 249        |
| 5.7.2    | Sleptons                                  | 250        |
| 5.7.3    | Charginos and Neutralinos                 | 253        |
| 5.7.4    | LSP                                       | 255        |
| 5.7.5    | Gluino and Squarks                        | 255        |
| 5.7.6    | Stop                                      | 260        |
| 5.7.7    | R-hadrons                                 | 261        |
| 5.7.8    | Gravitino                                 | 262        |
| 5.8      | Current Status                            | 263        |
| <b>6</b> | <b>Extra Dimension</b>                    | <b>267</b> |
| 6.1      | Introduction                              | 267        |
| 6.2      | KK Tower                                  | 270        |
| 6.2.1    | Effective Coupling Strength in 4D         | 272        |
| 6.3      | Chiral Fermions                           | 273        |
| 6.3.1    | Orbifold $S^1/Z_2$                        | 275        |
| 6.3.2    | Mass Generation and Localization          | 278        |
| 6.3.3    | Hierarchy                                 | 282        |
| 6.3.4    | Split Fermion Scenario                    | 285        |
| 6.4      | Gauge Field in ED                         | 287        |
| 6.4.1    | Action in 4D                              | 287        |
| 6.4.2    | Coupling Strength                         | 288        |
| 6.4.3    | Gauge–Higgs Unification                   | 289        |
| 6.5      | Gravitational Field                       | 292        |
| 6.5.1    | Decomposition of the Gravitational Fields | 294        |
| 6.6      | Warped Extra Dimension                    | 296        |
| 6.6.1    | Anti-de Sitter Space $AdS_5$              | 296        |
| 6.6.2    | RS1 Scenario                              | 299        |
| 6.6.3    | RS2 scenario                              | 300        |
| 6.6.4    | Gravitons in the RS Model                 | 302        |
| 6.6.5    | Signals for Warped ED                     | 305        |
| 6.7      | Universal Extra Dimension (UED)           | 308        |
| 6.7.1    | General Features                          | 308        |
| 6.7.2    | Selection Rules                           | 308        |
| 6.7.3    | Constraints                               | 311        |
| 6.7.4    | Signals for UED                           | 312        |
| 6.8      | Searches for Generic ED                   | 313        |
| 6.8.1    | Astrophysical Constraints on ADD Models   | 314        |
| 6.8.2    | Collider Experiments on ADD Models        | 316        |

|          |                                          |     |
|----------|------------------------------------------|-----|
| 6.8.3    | TeV <sup>-1</sup> Extra Dimension Model: | 322 |
| 6.9      | Black hole production                    | 325 |
| <b>7</b> | <b>Axion</b>                             | 329 |
| 7.1      | Soliton                                  | 329 |
| 7.1.1    | Kink                                     | 329 |
| 7.1.2    | Vortex                                   | 334 |
| 7.1.3    | Winding Number                           | 337 |
| 7.1.4    | Spacetime Where the Soliton Lives        | 339 |
| 7.1.5    | Instanton                                | 340 |
| 7.1.6    | $\theta$ Vacuum                          | 347 |
| 7.1.7    | Electroweak Vacua                        | 348 |
| 7.2      | Strong CP Problem                        | 350 |
| 7.2.1    | Anomaly                                  | 350 |
| 7.2.2    | Chiral Transformation and the Mass Term  | 353 |
| 7.2.3    | U(1) problem                             | 355 |
| 7.3      | Why Do We Need the Axion?                | 356 |
| 7.3.1    | PQ Symmetry and the Standard Axion       | 357 |
| 7.3.2    | Invisible Axion                          | 360 |
| 7.4      | Constraints on Invisible Axions          | 363 |
| 7.4.1    | Coolant of the Stellar Evolution         | 363 |
| 7.4.2    | Axion as the Dark Matter                 | 367 |
| 7.4.3    | Misalignment axion                       | 367 |
| 7.5      | Laboratory Axion Searches                | 370 |
| <b>8</b> | <b>Cosmology I: Big Bang Universe</b>    | 377 |
| 8.1      | Why Do We Study Cosmology?               | 377 |
| 8.2      | Cosmic Equation                          | 378 |
| 8.2.1    | Robertson–Walker Metric                  | 379 |
| 8.2.2    | Friedmann Equation                       | 382 |
| 8.3      | Expanding Universe                       | 385 |
| 8.3.1    | Redshift of Light                        | 385 |
| 8.3.2    | Redshift of Particles                    | 386 |
| 8.3.3    | Cosmic Parameters                        | 386 |
| 8.4      | Thermal Universe                         | 389 |
| 8.4.1    | Thermodynamics                           | 389 |
| 8.4.2    | Radiation and Matter Dominance           | 392 |
| 8.4.3    | Time versus Temperature                  | 393 |
| 8.4.4    | Overview of Thermal History              | 394 |
| 8.5      | Cosmic Distance, Horizon                 | 396 |
| 8.5.1    | Distance                                 | 396 |
| 8.5.2    | Horizon                                  | 399 |
| 8.6      | Genesis                                  | 400 |
| 8.6.1    | Matter Universe                          | 400 |
| 8.6.2    | Baryogenesis                             | 401 |

|           |                                          |            |
|-----------|------------------------------------------|------------|
| 8.6.3     | Leptogenesis                             | 404        |
| 8.6.4     | Neutrino Decoupling                      | 408        |
| 8.6.5     | Big Bang Nucleosynthesis                 | 410        |
| 8.7       | Last Scattering                          | 414        |
| 8.7.1     | Radiation–Matter Equality                | 414        |
| 8.7.2     | Recombination                            | 415        |
| 8.7.3     | Dark Age                                 | 417        |
| 8.8       | Inflation                                | 418        |
| 8.8.1     | Slow Rolling and Reheating               | 418        |
| 8.8.2     | Horizon Problem                          | 421        |
| 8.8.3     | Flatness Problem                         | 423        |
| 8.8.4     | Monopole Problem                         | 424        |
| <b>9</b>  | <b>Cosmology II: Structure Formation</b> | <b>425</b> |
| 9.1       | Galaxy Distribution                      | 425        |
| 9.1.1     | Introduction                             | 425        |
| 9.1.2     | Boltzmann Equation                       | 429        |
| 9.1.3     | Growth of the Fluctuation                | 434        |
| 9.1.4     | Dark Matter                              | 435        |
| 9.1.5     | Jeans Wavelength of the Neutrino         | 436        |
| 9.1.6     | Power Spectrum                           | 437        |
| 9.1.7     | Initial fluctuation                      | 444        |
| 9.1.8     | Effects of Neutrino Mass                 | 448        |
| 9.1.9     | Primordial Fluctuation                   | 448        |
| 9.2       | CMB Anisotropy                           | 454        |
| 9.2.1     | Overview                                 | 454        |
| 9.2.2     | Sachs–Wolfe Effect                       | 458        |
| 9.2.3     | Acoustic Oscillations                    | 459        |
| 9.2.4     | Doppler Effect                           | 462        |
| 9.2.5     | Silk Damping                             | 462        |
| 9.2.6     | Outcome of CMB Measurements              | 464        |
| 9.2.7     | Polarization                             | 467        |
| <b>10</b> | <b>Dark Matter</b>                       | <b>475</b> |
| 10.1      | Cosmic Budget                            | 475        |
| 10.2      | Evidences of Dark Matter                 | 475        |
| 10.2.1    | Rotation Curves of Spiral Galaxies       | 476        |
| 10.2.2    | Virial Mass of the Clusters              | 477        |
| 10.2.3    | X-ray Emitting Clusters                  | 478        |
| 10.2.4    | Gravitational Lens                       | 479        |
| 10.3      | Relics of the Big Bang                   | 489        |
| 10.3.1    | Freeze-Out                               | 489        |
| 10.3.2    | Hot Dark Matter                          | 490        |
| 10.3.3    | Cold Dark Matter                         | 491        |
| 10.3.4    | Candidates for the Dark Matter           | 493        |

|                   |                                           |            |
|-------------------|-------------------------------------------|------------|
| 10.4              | How to Detect?                            | 495        |
| 10.4.1            | Indirect methods                          | 495        |
| 10.4.2            | Production by Accelerators                | 497        |
| 10.4.3            | WIMPS Wind                                | 498        |
| 10.5              | Searches for DMs in the Halo              | 505        |
| 10.5.1            | General                                   | 505        |
| 10.5.2            | Bolometer                                 | 507        |
| 10.5.3            | Xe Detector                               | 508        |
| 10.5.4            | Current Status                            | 512        |
| <b>11</b>         | <b>Dark Energy</b>                        | <b>513</b> |
| 11.1              | Dark Energy                               | 513        |
| 11.1.1            | Accelerating Universe                     | 513        |
| 11.1.2            | Cosmic Age                                | 515        |
| 11.1.3            | $\Lambda$ CDM Model                       | 519        |
| 11.2              | Cosmological Constant                     | 520        |
| 11.3              | Quintessence model                        | 523        |
| 11.4              | Other Dark Energy Models                  | 532        |
| 11.5              | How to Investigate the Dark Energy?       | 533        |
| <b>Appendix A</b> | <b>Virial Theorem</b>                     | <b>543</b> |
| <b>Appendix B</b> | <b>Chandrasekhar Mass</b>                 | <b>545</b> |
| <b>Appendix C</b> | <b>Production of KK Gravitons</b>         | <b>549</b> |
| <b>Appendix D</b> | <b>Homotopy</b>                           | <b>551</b> |
| <b>Appendix E</b> | <b>General Relativity</b>                 | <b>559</b> |
| E.1               | Geodesic Equation                         | 559        |
| E.2               | Ricci Tensor and Scalar                   | 561        |
| E.3               | Gauge Degrees of Freedom                  | 561        |
| E.4               | Gravitational Waves                       | 563        |
| <b>Appendix F</b> | <b>Tensor Spherical Harmonic Function</b> | <b>565</b> |
| <b>Appendix G</b> | <b>Destiny of the Cosmos</b>              | <b>567</b> |
| <b>Appendix H</b> | <b>Answers to Some Problems</b>           | <b>571</b> |
|                   | <b>References</b>                         | <b>575</b> |
|                   | <b>Color Plates</b>                       | <b>597</b> |
|                   | <b>Index</b>                              | <b>617</b> |

