

## Table of Contents

|  |    |
|--|----|
| Introduction   | 1  |
| Acknowledgments  | 5  |
| Further Reading  | 5  |
| Thumbnail Sketches   | 6  |
| Equations  | 7  |
| 1 Preliminaries  | 8  |
| 1.1 Atoms, Nuclei and Particles                            | 8  |
| 1.2 Photons  | 15 |
| 1.3 Antiparticles  | 19 |
| 1.4 Mass and Energy  | 21 |
| 1.5 Events   | 24 |
| 1.6 Electron-Volts and Other Units                         | 30 |
| 1.7 Particle Names and the Greek Alphabet                  | 32 |
| 1.8 Scientific Notation                                    | 33 |
| 2 The Standard Model                                       | 35 |
| 2.1 Introduction   | 35 |
| 2.2 Conservation of Energy and Charge                      | 40 |
| 2.3 Quantum Numbers  | 43 |
| 2.4 Color  | 45 |
| 2.5 The Electron-Neutrino, Electron Number and<br>Crossing | 49 |
| 2.6 The First Family                                       | 53 |
| 2.7 Families and Forces                                    | 55 |

|      |  |     |
|------|--|-----|
| 2.8  | The Spin $\frac{1}{2}$ Particles                                       | 62  |
| 2.9  | The Spin 1 and 2 Particles   | 68  |
| 2.10 | Forces and Interactions  | 69  |
| 2.11 | Classification of Interactions   | 71  |
| 2.12 | Electromagnetic, Weak, Strong, Higgs and<br>Gravitational Interactions | 75  |
| 2.13 | Representing Interactions  | 77  |
| 2.14 | The Origin of Quantum Numbers  | 83  |
| 3    | Quantum Mechanics. Mixing  | 85  |
| 3.1  | Introduction   | 85  |
| 3.2  | The Two-Slit Experiment  | 88  |
| 3.3  | Amplitude and Probability  | 92  |
| 3.4  | Cabibbo and CKM Mixing   | 99  |
| 3.5  | Neutrino Mixing  | 108 |
| 3.6  | Particle Mixing  | 109 |
| 4    | Energy, Momentum and Mass-Shell  | 115 |
| 4.1  | Introduction   | 115 |
| 4.2  | Conservation Laws  | 118 |
| 4.3  | Relativity   | 126 |
| 4.4  | Relativistic Invariance  | 131 |
| 4.5  | The Relation $E = mc^2$  | 136 |
| 5    | Detection  | 140 |
| 5.1  | Introduction   | 140 |
| 5.2  | Photoelectric Effect   | 146 |
| 5.3  | Bubble Chambers  | 152 |
| 5.4  | Spark Chambers   | 157 |
| 5.5  | Proportional Wire Chambers   | 159 |
| 6    | Accelerators and Storage Rings   | 161 |
| 6.1  | Energy Bubbles   | 161 |
| 6.2  | Accelerators   | 165 |

|      |   |     |
|------|---|-----|
| 6.3  | Secondary Beams                                       | 178 |
| 6.4  | The Machine Builders                                  | 181 |
| 7    | The CERN Neutrino Experiment                          | 189 |
| 7.1  | Introduction  | 189 |
| 7.2  | Experimental Set-up                                   | 195 |
| 7.3  | Neutrino Physics                                      | 200 |
| 7.4  | The First Neutrino Experiments                        | 205 |
| 7.5  | Vector Bosons   | 208 |
| 7.6  | Missed Opportunities                                  | 213 |
| 7.7  | Epilogue  | 218 |
| 8    | The Particle Zoo                                      | 219 |
| 8.1  | Introduction  | 219 |
| 8.2  | Bound States  | 222 |
| 8.3  | The Structure of Quark Bound States                   | 225 |
| 8.4  | Spin of a Bound State                                 | 229 |
| 8.5  | Mesons  | 230 |
| 8.6  | Baryons   | 234 |
| 8.7  | Exotics   | 236 |
| 8.8  | Discovering Quarks                                    | 237 |
| 8.9  | Triplets versus Doublets and Lepton-Quark<br>Symmetry | 241 |
| 9    | Particle Theory                                       | 244 |
| 9.1  | Introduction  | 244 |
| 9.2  | Feynman Rules   | 246 |
| 9.3  | Infinities  | 255 |
| 9.4  | Perturbation Theory                                   | 258 |
| 9.5  | Renormalizability                                     | 264 |
| 9.6  | Weak Interactions                                     | 267 |
| 9.7  | Compton Scattering                                    | 270 |
| 9.8  | Neutral Vector Bosons                                 | 273 |
| 9.9  | Charmed Quarks  | 276 |
| 9.10 | The Higgs Particle                                    | 279 |

|      |                         |     |
|------|-------------------------|-----|
| 9.11 | General Higgs Couplings | 281 |
| 9.12 | Speculations            | 282 |
| 9.13 | $\rho$ -Parameter       | 283 |
| 10   | Finding the Higgs       | 285 |
| 11   | Quantum Chromodynamics  | 293 |
| 11.1 | Introduction            | 293 |
| 11.2 | Confinement             | 295 |
| 11.3 | Asymptotic Freedom      | 297 |
| 11.4 | Scaling                 | 300 |
| 12   | Epilogue                | 304 |
|      | Name Index              | 309 |
|      | Subject Index           | 317 |
|      | Photo Credits           | 337 |