CP VIOLATION

Why didn’t the matter in our Universe annihilate with antimatter immediately after its creation? The study of CP violation may help to answer this fundamental question. Reflecting the explosion of new results over the last decade, this second edition has been substantially expanded. From basic principles to the front-line of research, this account presents the information and theoretical tools necessary to understand this phenomenon.

Charge conjugation, parity and time reversal are introduced, before describing the Kobayashi–Maskawa (KM) theory for CP violation and examining our understanding of CP violation in kaon decays. Following chapters reveal how the discovery of B mesons provided a new laboratory to study CP violation with KM theory predicting large asymmetries, and discuss how these predictions have been confirmed since the first edition of this book. This led to M. Kobayashi and T. Maskawa receiving the 2008 Nobel Prize for Physics. Later chapters describe the search for a new theory of nature’s fundamental dynamics. The observation of neutrino oscillations provides opportunities to reveal CP violation in the lepton sector, which might drive baryogenesis in a Big Bang Universe. The importance of close links with experiment is stressed, and numerous problems are included. This book is suitable for researchers in high energy, atomic and nuclear physics and in the history and philosophy of science.

IKAROS BIGI was born in Munich, Germany. Following undergraduate and postgraduate studies at the Universities of Munich, Oxford and Stanford, he has taught and researched at the Max-Planck Institute for Physics, CERN, RWTH Aachen, UCLA, the University of Oregon, SLAC and the University of Notre Dame. He is a former scholarship student of the Maximilian Foundation and Scholarship Foundation of the German People and has been appointed both a Heisenberg Fellow and a Max-Kade Fellow.

ICHIRO SANDA was born in Tokyo, and at the age of 14 accompanied his father who was transferred to the United States on business. After a bachelor’s degree in physics from the University of Illinois and a Ph.D. from Princeton University, he taught and researched at Columbia University, Fermilab and Rockefeller University. In 1992, after 34 years in the US, he went to Japan as a Professor of physics at Nagoya University. He is now the Chairman of the physics department at Kanagawa University. He is
a winner of the 10th Inoue Prize (1993) and the 43rd Nishina Memorial Prize (1997). Both prizes have been awarded for his work in CP violation, and on $B$ physics.

Since 1980 the authors have written 14 papers together. In their first paper they explained the special role for CP violation played by certain $B$ meson decays; among them was the channel $B \to \psi K_S$, where the first CP asymmetry outside $K$ decays was established in 2001. In 2004 they were jointly awarded the J. J. Sakurai Prize by the American Physical Society ‘for pioneering theoretical insights that pointed the way to the very fruitful experimental study of CP violation in $B$ decays, and for continuing contributions to the field of CP and heavy flavor physics’.
CAMBRIDGE MONOGRAPHS ON
PARTICLE PHYSICS
NUCLEAR PHYSICS AND COSMOLOGY 28

General Editors: T. Ericson, P. V. Landshoff

1. K. Winter (ed.): Neutrino Physics
2. J. F. Donoghue, E. Golowich and B. R. Holstein: Dynamics of the Standard Model
3. E. Leader and E. Predazzi: An Introduction to Gauge Theories and Modern Particle Physics, Volume 1: Electroweak Interactions, the 'New Particles' and the Parton Model
4. E. Leader and E. Predazzi: An Introduction to Gauge Theories and Modern Particle Physics, Volume 2: CP-Violation, QCD and Hard Processes
5. C. Grupen: Particle Detectors
6. H. Grosse and A. Martin: Particle Physics and the Schrödinger Equation
7. B. Anderson: The Lund Model
9. I. I. Bigi and A. I. Sanda: CP Violation
10. A. V. Manohar and M. B. Wise: Heavy Quark Physics
12. D. Green: The Physics of Particle Detectors
15. E. Leader: Spin in Particle Physics
16. J. D. Walecka: Electron Scattering for Nuclear and Nucleon Scattering
17. S. Narison: QCD as a Theory of Hadrons
18. J. F. Letessier and J. Rafelski: Hadrons and Quark-Gluon Plasma
19. A. Donnachie, H. G. Dosch, P. V. Landshoff and O. Nachtmann: Pomeron Physics and QCD
20. A. Hoffmann: The Physics of Synchrotron Radiation
21. J. B. Kogut and M. A. Stephanov: The Phases of Quantum Chromodynamics
22. D. Green: High PT Physics at Hadron Colliders
24. D. M. Brink and R. A. Broglia: Nuclear Superfluidity
25. F. E. Close, A. Donnachie and G. Shaw: Electromagnetic Interactions and Hadronic Structure
27. V. Gribov: Strong Interactions of Hadrons at High Energies
CP VIOLATION

I. I. BIGI

Physics Department, University of Notre Dame du Lac

A. I. SANDA

Physics Department, Kanagawa University
Dedicated to

Colette and Hiroko
# Contents

*Preface to the second edition*  page xvii  
*Preface to the first edition*  xix  

## Part I  Basics of CP violation  

### 1  Prologue  

### 2  Prelude: C, P and T in classical dynamics  

#### 2.1  Classical mechanics  

##### 2.1.1  Parity  

##### 2.1.2  Time reversal  

#### 2.2  Electrodynamics  

##### 2.2.1  Charge conjugation  

##### 2.2.2  Parity  

##### 2.2.3  Time reversal  

#### 2.3  Résumé  

Problems  

### 3  C, P and T in non-relativistic quantum mechanics  

#### 3.1  Parity  

#### 3.2  Charge conjugation  

#### 3.3  Time reversal  

#### 3.4  Kramers' degeneracy  

#### 3.5  Detailed balance  

#### 3.6  Electric dipole moments  

##### 3.6.1  The neutron EDM  

##### 3.6.2  Water molecules and atoms  

##### 3.6.3  Dumb-bells  

##### 3.6.4  Schiff's theorem  


Contents

3.7 Résumé 38
Problems 38

4 C, P and T in relativistic quantum theories 41
4.1 Notation 42
4.2 Spin-1 fields 43
4.3 Spin-0 fields 46
  4.3.1 Parity 46
  4.3.2 Charge conjugation 47
  4.3.3 Time reversal 47
4.4 Spin-1/2 fields 48
  4.4.1 Parity 49
  4.4.2 Charge conjugation 51
  4.4.3 Time reversal 52
4.5 CP and CPT transformations 53
4.6 Some consequences of the CPT theorem 56
4.7 ♠ Back to first quantization ♠ 58
4.8 ♠ Phase conventions for C and P ♠ 59
4.9 ♠ Internal symmetries ♠ 60
4.10 The role of final state interactions 62
  4.10.1 T invariance and Watson’s theorem 62
  4.10.2 Final state interactions and partial widths 64
  4.10.3 ♠ T symmetry and final state interactions ♠ 67
4.11 Résumé and outlook 69
Problems 70

5 The arrival of strange particles 73
5.1 The discovery of strange particles 73
5.2 The θ − τ puzzle 75
5.3 The ΔI = 1/2 rule 76
5.4 The existence of two different neutral kaons 77
5.5 CP invariant K^0 \rightarrow \bar{K}^0 oscillations 79
5.6 Regeneration – which is heavier: K_L or K_S? 83
5.7 The quiet before the storm 84
5.8 The discovery of CP violation 85
Problems 89

6 Quantum mechanics of neutral particles 90
6.1 The effective Hamiltonian 90
6.2 Constraints from CPT, CP and T 93
6.3 Spherical coordinates 93
6.4 ♠ On phase conventions ♠ 95
6.5 ♠ ΔM and ΔΓ ♠ 97
6.6 Master equations of time evolution 99
6.7 CP violation: classes (A), (B) and (C) 102
6.8 ♠ On the sign of the CP asymmetry ♠ 106
## Contents

6.9 What happens if you don’t observe the decay time? 107  
6.10 Regeneration 108  
6.11 The Bell–Steinberger inequality 110  
6.12 Résumé on $P^o - T^o$ oscillations 111  
Problems 113

### Part II Theory and experiments 115

7 The quest for CP violation in $K$ decays – a marathon 117  
7.1 The landscape 117  
7.2 $K_L \rightarrow \pi\pi$ decays 121  
7.2.1 Decay amplitudes 121  
7.2.2 Constraints on $A_2$ and $\bar{A}_2$ 124  
7.2.3 Relating $\epsilon$ to $M - \frac{1}{2}\Gamma$ 125  
7.2.4 The phase of $\epsilon$ 126  
7.3 Semileptonic decays 127  
7.4 $\blacklozenge P_L$ in $K \rightarrow \pi\mu\nu$ decays $\blacklozenge$ 129  
7.5 $\spadesuit K \rightarrow 3\pi$ $\spadesuit$ 133  
7.5.1 $K_S \rightarrow 3\pi^0$ 133  
7.5.2 $K_S \rightarrow \pi^+\pi^-\pi^0$ 133  
7.5.3 $K^\pm \rightarrow \pi^\pm \pi^+\pi^-$ 138  
7.6 $\spadesuit$ Hyperon decays $\spadesuit$ 138  
7.7 The bard’s song 141  
Problems 141

8 The KM implementation of CP violation 143  
8.1 A bit of history 143  
8.2 The Standard Model 145  
8.2.1 QCD 146  
8.2.2 The Glashow–Salam–Weinberg model 147  
8.3 The KM ansatz 149  
8.3.1 The mass matrices 149  
8.3.2 Parameters of consequence 149  
8.3.3 Describing weak phases through unitarity triangles 151  
8.4 A tool kit 154  
8.4.1 The angles of the unitarity triangle 156  
8.5 The pundits’ judgement 157  
Problems 158

9 The theory of $K_L \rightarrow \pi\pi$ decays 160  
9.1 The $\Delta S = 1$ non-leptonic Lagrangian 160  
9.2 Evaluating matrix elements 164  
9.3 Chiral symmetry and vacuum saturation approximation 165  
9.4 $K \rightarrow \pi\pi$ decays 167
xii

Contents

9.5 ♠ Computation of $\epsilon'/\epsilon$ ♠ 168
  9.5.1 Determining matrix elements from data 169
  9.5.2 Numerical estimates 170
9.6 $\Delta S = 2$ amplitudes 172
  9.6.1 $\Delta M_K$ 174
  9.6.2 $\epsilon$ 175
9.7 ♠ SM expectations for $\langle P_\perp \rangle$ in $K_{13}$ decays ♠ 175
9.8 Résumé 176
Problems 177

10 Paradigmatic discoveries in $B$ physics 180
  10.1 The emerging beauty of $B$ hadrons 180
    10.1.1 The discovery of beauty 181
    10.1.2 The longevity of $B$ mesons 183
    10.1.3 The fluctuating identity of neutral $B$ mesons 185
    10.1.4 Another triumph for CKM dynamics 189
  10.2 What does the SM say about oscillations? 190
    10.2.1 Computation of $\Delta M$ 190
  10.3 ♠ On the sign of $\Delta M_B$ ♠ 192
  10.4 $\text{CP}$ violation in $B$ decays – like in $K$ decays, only different 193
  10.5 From sweatshops to beauty factories 197
    10.5.1 Disappointment at a symmetric machine 199
    10.5.2 A crazy idea 199
  10.6 First reward – $B_d \to \psi K_S$ 200
  10.7 The second reward – $B_d \to \pi^+ \pi^-$ 201
  10.8 More rewards – $B^0 \to K\pi$, $\eta' K_S$ 203
    10.8.1 $B \to K\pi$ 203
    10.8.2 $B_d \to \eta' K_S$ 205
  10.9 $\text{CPT}$ invariance vs. $T$ and $\text{CP}$ violation 206
  10.10 Reflections 207
    10.10.1 On the virtue of ‘over-designing’ 207
    10.10.2 The ‘unreasonable’ success of CKM theory 208
    10.10.3 Praising hadronization 209
    10.10.4 EPR correlations – a blessing in disguise 210
  10.11 Résumé 211
Problems 212

11 Let the drama unfold – $B$ $\text{CP}$ phenomenology 215
  11.1 Pollution from water fowls and others 215
  11.2 Determining $\phi_1$ 218
    11.2.1 How clean is $B_d \to \psi K_S$? 218
    11.2.2 ♠ Other ways to get at $\phi_1$ ♠ 219
Contents

11.3 Determining $\phi_2$ 222
11.3.1 Penguins in $B_d \to \pi \pi$ 222
11.3.2 Overcoming pollution 222
11.3.3 $B \to \pi \pi$ 223
11.3.4 $B \to \pi \rho, \rho \rho$ 224
11.4 Determining $\phi_3$ 225
11.4.1 Using doubly Cabibbo-suppressed decays 228
11.4.2 Dalitz plot analysis 228
11.5 Search for New Physics 229
11.5.1 Wrong-sign semileptonic decays: Class(B) 230
11.5.2 ♠ Theoretical estimate of $A_{SL}$ ♠ 230
11.5.3 What can oscillations tell us about New Physics? 235
11.5.4 $B_s \to \psi \phi, \psi \eta, D_s^+ D_s^-$: Class (C2) 236
11.5.5 $B_d \to \phi K_S, \eta K_S$: Class(C2) 238
11.5.6 $B_s \to K_S \rho^0$: Class (C1, C2) 238
11.5.7 $B_s \to D^\pm_s K^\mp$: Class (C1,C2) 240
11.6 Resumé 242
Problems 245

12 Rare $K$ and $B$ decays – almost perfect laboratories 248
12.1 Rare $K$ decays 248
12.1.1 $K_L \to \mu^+ \mu^-$ and $K^+ \to \pi^+ e^+ e^-$ 248
12.1.2 $K_L \to \pi^0 l^+ l^-$ 250
12.1.3 $K \to \pi \nu \bar{\nu}$ 251
12.1.4 ♠ $K \to \pi \pi \gamma$ (→) ♠ 254
12.2 Beauty decays 258
12.2.1 $B \to X_s \gamma$ 258
12.2.2 $B \to \mu^+ \mu^-$ 259
12.2.3 $B \to X + \nu \bar{\nu}$ 260
12.2.4 $B \to X_s + \mu^+ \mu^-$ 261
12.3 Résumé 262
Problems 263

13 ♠ CPT violation – could it be in $K$ and $B$ decays? ♠ 265
13.1 Equality of masses and lifetimes 266
13.2 Theoretical scenarios 267
13.3 CPT phenomenology for neutral kaons 268
13.3.1 Semileptonic decays 269
13.3.2 Asymmetries 270
13.3.3 Non-leptonic neutral $K$ decays 273
13.4 Harnessing EPR correlations 278
13.4.1 $\phi$ factory 279
13.4.2 Tests of CPT symmetry in $B$ decays 281
Contents

13.5 The moralist’s view 283

Problems 283

14 CP violation in charm decays – the dark horse 286
14.1 On the uniqueness of charm 286
14.2 $D^0 - \bar{D}^0$ oscillations 288
  14.2.1 Experimental evidence 288
  14.2.2 First résumé 291
  14.2.3 Theoretical expectations on $\Delta M_D$ & $\Delta \Gamma_D$ 291
  14.2.4 New Physics contributions to $\Delta M_D$ and $\Delta \Gamma_D$? 292
  14.2.5 ♠ Numerical predictions for $\Delta M_D$ and $\Delta \Gamma_D$ ♠ 293
14.3 CP violation 296
  14.3.1 Preliminaries 296
  14.3.2 CP asymmetries with out $D^0 - \bar{D}^0$ oscillations 298
  14.3.3 Oscillations – the new portal to CP violation 303
  14.3.4 Harnessing EPR correlations 309
14.4 Résumé and a call to action 312

Problems 313

15 The strong CP problem 314
15.1 The problem 314
15.2 Why $G \cdot \tilde{G}$ matters and $F \cdot \tilde{F}$ does not 315
15.3 ♠ The $U(1)_A$ problem ♠ 316
15.4 QCD and quark masses 318
15.5 The neutron electric dipole moment 319
15.6 Are there escape hatches? 321
  15.6.1 Soft CP violation 322
15.7 Peccei–Quinn symmetry 323
15.8 The dawn of axions – and their dusk? 326
  15.8.1 Visible axions 326
  15.8.2 Invisible axions 328
15.9 The pundits’ judgement 331

Problems 332

Part III Looking beyond the Standard Model 333

16 Quest for CP violation in the neutrino sector 335
16.1 Experiments 336
  16.1.1 Solar neutrinos 336
  16.1.2 Atmospheric neutrinos 340
  16.1.3 Man-made neutrinos 342
  16.1.4 Qualitative summary 343

© in this web service Cambridge University Press  www.cambridge.org
## Contents

16.2 Basics of neutrino oscillations 343  
16.2.1 Mass hierarchy 345  
16.2.2 Estimating $\theta_{13}$ and $\theta_{12}$ 346  
16.2.3 Atmospheric neutrinos 347  
16.3 Neutrino mixing parameters 347  
16.4 The MSW effect 349  
16.5 Neutrino masses 350  
16.6 Neutrino mixing with Majorana neutrinos 353  
16.7 Phases in the PMNS matrix 355  
16.8 CP and T violation in $\nu$ oscillations 356  
16.9 How to measure the Majorana phase? 358  
16.10 The bard’s song 359  
Problems 360  

17 Possible corrections to the KM ansatz: right-handed currents and non-minimal Higgs dynamics 362  
17.1 Left–right symmetric models 363  
17.1.1 Basics 363  
17.1.2 The existing phenomenology in strange decays 367  
17.1.3 Electric dipole moments 372  
17.1.4 Prospects for CP asymmetries in beauty decays 373  
17.2 CP violation from Higgs dynamics 374  
17.2.1 A simple example 375  
17.2.2 Sources of CP violation 376  
17.2.3 CP phenomenology with heavy fermions 389  
17.3 The pundits’ résumé 391  
Problems 393  

18 CP violation without non-perturbative dynamics – top quarks and charged leptons 396  
18.1 Production and decay of top quarks 396  
18.1.1 $\sigma(t_{L}\bar{t}_{L})$ vs $\sigma(t_{R}\bar{t}_{R})$ 398  
18.1.2 Final state distributions in $e^{+}e^{-} \rightarrow t\bar{t}H^{0}$ 399  
18.2 On CP violation with leptons 400  
18.2.1 Positronium 401  
18.2.2 $\mu$ decays 402  
18.2.3 $\tau$ decays 403  
18.2.4 $\tau$ production 407  
18.3 Résumé on top and $\tau$ transitions 408  
Problems 410  

19 SUSY-providing shelter for Higgs dynamics 412  
19.1 The virtues of SUSY 413  
19.2 Low-energy SUSY 416  
19.2.1 The MSSM 417
19.3 Gateways for CP violation
19.3.1 A first glance at CP phases in MSSM 421
19.3.2 Squark mass matrices 422
19.3.3 Beyond MSSM 425
19.4 Confronting experiments 426
19.4.1 Electric dipole moments 426
19.4.2 SUSY contributions to $\Delta S \neq 0 \neq \Delta B$ transitions 428
19.4.3 Bounds on MI SUSY parameters 431
19.4.4 Can SUSY be generic? 432
19.5 The pundits’ résumé 433
Problems 434

20 Minimal flavour violation and extra dimensions 436
20.1 On minimal flavour violation 436
20.1.1 Defining, implementing and probing MFV 437
20.2 Extra (space) dimensions 440
20.3 The pundits’ call 443

21 Baryogenesis in the universe 444
21.1 The challenge 444
21.2 The ingredients 445
21.3 GUT baryogenesis 446
21.4 Electroweak baryogenesis 448
21.5 Leptogenesis driving baryogenesis 451
21.6 Wisdom – conventional and otherwise 452

Part IV Summary 455

22 Summary and perspectives 457
22.1 The cathedral builder’s paradigm 459
22.1.1 Present status and general expectations 460
22.1.2 A look back 461
22.2 Agenda for the future 462
22.3 Final words 463

References 465
Index 478
Although the preface to the first edition was written 10 years ago, we see no reason to take anything back from it. Instead we feel confirmed in both our general outlook and in many of our more specific predictions.

- The first direct manifestations of CP violation outside the $K^0 - \bar{K}^0$ complex have indeed been found in the decays of neutral $B$ mesons.
- There are already several modes where CP asymmetries have been established, and these were actually the expected ones.
- Their size is measured in units of 10%.
- $B_d - \bar{B}_d$ oscillations play an essential role in most cases.
- Last, but not least – the effects are in full agreement with the predictions of the theory of Kobayashi–Maskawa (KM).

The ‘battle for supremacy’ among theories for the observed CP violation that was still hanging in the balance at the end of the last millenium has been decided in favour of KM theory. Now the argument is over the issue of completeness, namely whether there are additional sources of CP violation. We know that the answer is most likely affirmative. For understanding the observed baryon number of the Universe as a dynamically generated quantity rather than an arbitrary initial condition requires CP violation (in the quark or lepton sector), and KM dynamics cannot fill this role. Probing CP invariance more precisely and comprehensively is called for also due to another reason and a most topical one. There are persuasive arguments for the observed electroweak symmetry breaking being driven or at least stabilized by New Physics characterized by the 1 TeV mass scale. Generic versions of such New Physics models should already have revealed themselves in flavour-changing neutral currents in $B$ transitions. This has not happened (yet), which has led to the suggestion that the anticipated ‘nearby’ New Physics must be of the minimal flavour violation variety. We find it much more likely that minimal flavour violation
Preface to the second edition

represents an approximate rather than an absolute rule, which will lead to observable deviations from standard model predictions, albeit on a numerically delicate level. Therefore we think it is mandatory to extend the high sensitivity programme of heavy flavour studies. Such considerations become timely with the LHC beginning to operate in 2008.

After we decided to write a second edition we realized how much updating and therefore work was needed. Yet our initial shock gave way to a better appreciation of how much progress has been achieved in the field of heavy flavour studies since the first edition. This in turn led to a sense of deep gratitude to our colleagues on the experimental as well as theoretical side who have made that exciting progress possible.

As indicated above, we see no reason to change the three main goals expressed for the first edition or the intended readership. On the other hand we have updated and even rearranged the material to reflect the greatly changed and expanded experimental and theoretical landscapes. The latter involves both ‘streamlining’ the previous discussion of theoretical models, since they are no longer viewed as alternatives to KM theory and emphasizing new directions in model building, in particular in the context of supersymmetry and models with extra (space) dimensions.

The first few years of the new millennium have seen discoveries in our field that by any measure were extraordinary. We are confident that even more profound progress will be made in the next two decades.

We want to thank D. Hefferman, S. Mishima, Y. Nakayama, T. Shindou, K. Ukai for bringing typos to our attention and W. Bernreuther, K. Kleinknecht and K. Schubert for pointers to the literature. One of us (I. B.) benefitted greatly from the unique environment at the Aspen Center of Physics while working on this book.

I. I. Bigi
ibigi@nd.edu

A. I. Sanda
sanda@kanagawa-u.ac.jp
Preface to the first edition

Some discoveries in the sciences profoundly change how we view nature. The discovery of parity violation in the weak interactions in 1956 certainly falls into this illustrious category. Yet it just started the shift to a new perspective; it was the discovery of CP violation in 1964 by Christenson, Cronin, Fitch and Turlay at Brookhaven National Lab – completely unexpected to almost all despite the experience of 8 years earlier – that established the new paradigm that even in the microscopic regime symmetries should not be assumed to hold a priori, but have to be subjected to determined experimental scrutiny.

It would seem that after the initial period of discoveries little progress has been achieved, since despite dedicated efforts CP violation has not been observed outside the decays of $K_L$ mesons, nor can we claim to have come to a real understanding of this fundamental phenomenon.

We have, however, ample reason to expect imminent dramatic changes. Firstly, direct CP violation has been observed in $K_L$ decays. Secondly, our phenomenological and theoretical descriptions have been refined to the point that we can predict with confidence that the known forces of nature will generate huge CP asymmetries, which could even be close to 100%, in the decays of so-called beauty mesons. Dedicated experiments are being set up to start taking data that would reveal such effects before the turn of the millennium. What they observe – or do not observe – will shape our knowledge of nature’s fundamental forces.

We consider it thus an opportune time to take stock, to represent CP invariance and its limitations in its full multi-layered complexity. In our presentation we pursue three goals.

- We want to provide a detailed frame of reference for properly evaluating the role of CP violation in fundamental physics and to prepare us for digesting the upcoming observations and discoveries.
Preface to the first edition

• We will show that an in-depth treatment of CP violation draws on most concepts and tools of particle physics. It thus serves as an unorthodox introduction to quantum field theories (and beyond).

• We want to communicate to the reader that the quest for understanding CP violation is more than just an important scholarly task. It represents a most exciting intellectual adventure of which we do not know the outcome. For this very purpose we provide historical perspectives from the last half century.

Accordingly our intended readership is manifold: we want

• to give (theoretical) guidance to the workers in the field;
• to provide an introduction for people who would like to become researchers in this field or at least educated observers;
• to present material which could serve as a supplementary text for courses on quantum field theory; and
• to allow people interested in the history and development of fundamental science to glean maybe some new insights.

We are not pretending our book makes easy reading. We hope, however, that the committed reader will find gratifying the way we start from the basics, give numerous homework problems as an integral part of the learning process and enrich – we think – the narrative with historical remarks. We actually believe that more than one reading will be necessary for a full understanding. To facilitate such an approach we designate sections which can be left out in a first reading by placing their title between the symbols ♠.

As theorists we cannot do full justice to experimental endeavours. Yet we try to communicate our conviction that physics is so wonderfully exciting exactly because it is an empirical science where theory and experiment play an interactive role.

We have benefitted greatly from interacting with many of our colleagues. In particular we would like to acknowledge Dr N. Uraltsev and Dr Z-Z. Xing for their advice and collaboration, Dr A. Garcia and Dr U. Sarid for their suggestions concerning the text. We also express our gratitude to Bernie and Theresa Vonderschmidt for their hospitality during the period in which part of the book was written.