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 Mazimilianeum 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'.

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CP VIOLATION

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Preface to the second edition

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 $K^0 - \overline{K}^0$ 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%.
- $B_d - \overline{B}_d$ 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 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.

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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.

- 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.