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Review

The Physics of the B Factories

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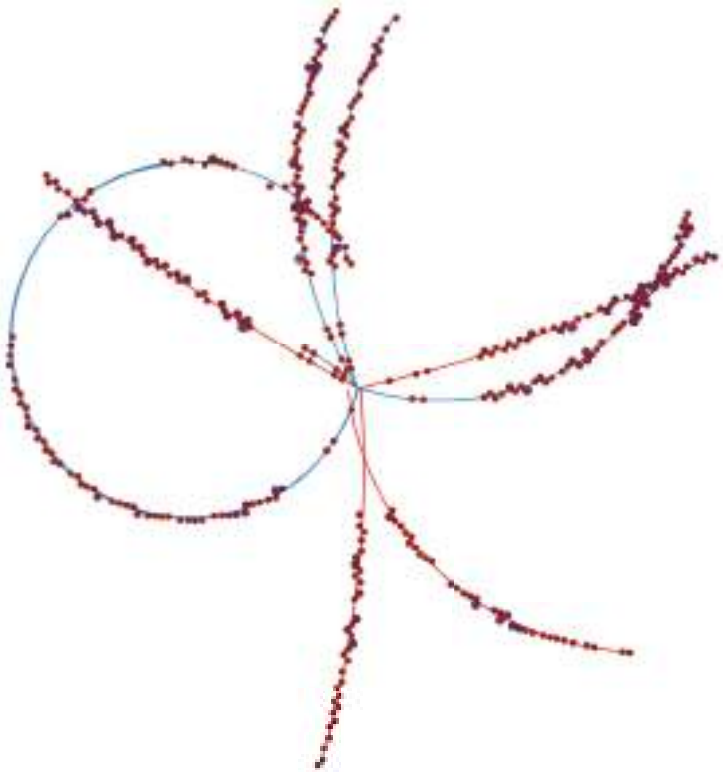

Foreword

"The Physics of the B Factories" describes a decade long effort of physicists in the quest for the precise determination of asymmetry — broken symmetry — between particles and anti-particles. We now recognize that the matter we see around us is the residue — one part in a billion — of the matter and antimatter that existed in the early universe, most of which annihilated into the cosmic background radiation that bathes us. But the question remains: how did the baryonic matter-antimatter asymmetry arise? This book describes the work done by some 1000 physicists and engineers from around the globe on two experimental facilities built to test our understanding of this phenomenon, one at the SLAC National Accelerator Laboratory in California, USA, and a second at the KEK Laboratory, Tsukuba, Japan, and what we have learned from them in broadening our understanding of nature.

Why is our universe dominated by the matter of which we are made rather than equal parts of matter and antimatter? This question has puzzled physicists for decades. However, this was not the question we addressed when we wrote the paper on CP violation in 1972. Our question was whether we can explain the CP violation observed in the K meson decay within the framework of the renormalizable gauge theory. At that time, Sakharov's seminal paper was already published, but it did not attract our attention. If we were aware of the paper, we would have been misled into seeking a model satisfying Sakharov's conditions and our paper might not have appeared.

In our paper, we discussed that we need new particles in order to accommodate CP violation into the renormalizable electroweak theory, and proposed the six-quark scheme as one of the possible ways introducing new particles. We thought that the six-quark scheme is very interesting, but it was just a possibility. The situation changed when the tau-lepton was found and it was followed by the discovery of the Upsilon particle. The existence of the third generation became reality. However, it was still uncertain whether the mixing of the six quarks is a real origin of the observed CP violation. Theoretical calculation of CP asymmetries in the neutral K meson system contains uncertainty from strong interaction effects. What settled this problem were the B Factories built at SLAC and KEK.

These B Factories are extraordinary in many ways. In order to fulfill the requirements of special experiments, the beam energies of the colliding electron and positron are asymmetric, and the luminosity is unprecedentedly high. It is also remarkable that severe competition between the two laboratories boosted their performance. One of us (M. Kobayashi) has been watching the development at KEK very closely as the director of the Institute of Particle and Nuclear Studies of KEK for a period of time. As witnesses, we appreciate the amazing achievement of those who participated in these projects at both laboratories.

The B Factories have contributed a great deal to our understanding of particle physics, as documented in this book. In particular, thanks to the high luminosity far exceeding the design value, experimental groups measured mixing angles precisely and verified that the dominant source of CP violation observed in the laboratory experiments is flavor mixing among the three generations of quarks. Obviously we owe our Nobel Prize to this result.

Now we are awaiting the operation of the next-generation Super B Factories. In spite of its great success, the Standard Model is not an ultimate theory. For example, it is not thought to be possible for the matter dominance of the universe to be explained by the Standard Model. This means that there will still be unknown particles and unknown interactions. We have a lot of theoretical speculations but experimental means are rather limited. There are great expectations for the Super B Factories to reveal a clue to the world beyond the Standard Model.

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Preface

The inspiration for this book came from François le Diberder. During his term as spokesperson for *BABAR* he laid down a vision for the two B Factory detector collaborations, *BABAR* and Belle, to work together on a book that would describe the methodologies used and physics results obtained by those experiments. A key ideal emphasized from the outset was that this book should be written from a pedagogical perspective; it should be of interest to the student and expert alike. This vision was presented during a *BABAR* collaboration meeting on the island of Elba in May 2008 and a follow up Belle collaboration meeting at KEK, with visiting colleagues from the *BABAR* collaboration, and was embraced by the community. A number of workshops involving people from the theoretical community as well as the two collaborations were held on four continents over the following years. The resulting book, "The Physics of the B Factories", is a testament to the way that this concept captured the zeitgeist on both sides of the Pacific Ocean.

This book is divided into three parts, the first of which provides a brief description of the B Factories, including a short (though not exhaustive) historical perspective, as well as descriptions of the detectors, ancillary data acquisition systems and data (re)processing systems that were built by the two detector collaborations in the late 1990's. The second part of the book discusses tools and methods that are frequently used when analyzing the data collected. These range from details of low level reconstruction algorithms and abstract summaries of statistical methods to high level prescriptions used when evaluating systematic uncertainties on measurements of observables. The third part of the book is devoted to physics results. This includes sufficient theoretical discussion in order for the reader to understand the context of the work being described. We are indebted to our colleagues from the theoretical community who have helped us achieve our goal of explaining the physics of the B Factories in a broader context.

It should be noted that both B Factory experiments are still actively publishing results and as a result the work presented here is a snapshot of the output of the B Factories up to some point in time. Where appropriate, measurements from other experiments have been mentioned, however the focus of this book is on the output of the B Factories. As a result, any brief description of important work by others should be interpreted as a suggestion for further reading on a given topic.

Just as there are two B Factories, many of the observables studied or used in this book have a dual notation in the literature. While preparing this book we have placed the emphasis on the physics rather than trivialities such as convention. The most notable instance of this issue found here is that of the nomenclature used for the angles of the Unitarity Triangle. In order to retain a pedagogical approach we chose a method for selecting between the two notations that is symbolic of their equivalence from the perspective of physics. This choice was decided on the outcome of a coin flip.

It has been a privilege for us to work with our colleagues from the experimental and theoretical communities while compiling this book. The journey of preparing this tome has been as rewarding as being a part of the individual collaborations. This book has come into existence because of the efforts of the many people who have devoted their time and effort writing contributions found herein, and it belongs to the community who helped create it.

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Please note that this is the official version of *The Physics of the B Factories.* An auxiliary version of this book will be made available online, both on `arXiv` and the INSPIRE database, under the same entry as the official version of the book. The official version of the book uses the notation ϕ_1, ϕ_2, ϕ_3 for the angles of the Unitarity Triangle, and the auxiliary version uses the notation β, α, γ.

A note on conventions:

This book follows common practice in particle physics by using a relaxed system of natural units. The reduced Planck constant $\hbar$ is set to unity, and electromagnetic expressions include the fine structure constant α rather than dimensionful constants. Nevertheless, the units of energy (GeV, MeV, etc.) are distinguished from those of momentum (GeV/c, MeV/c) and mass (GeV/c^2, MeV/c^2); when length and time are explicitly mentioned, and especially in detector-related discussions, meters and seconds are used rather than the reciprocal of energy.

The treatment of charge conjugation depends on the context. Many analyses are motivated by possible differences between the behaviour of B^0 and $\overline{B}^0$: in such cases, samples of the two states are distinguished. When describing the method, however, if the text specifies reconstruction of $B^0 \to \pi^+ D^-$ with $D^- \to K^+\pi^-\pi^-$, it is usually implied that the equivalent procedure is followed for the charge conjugate mode $\overline{B}^0 \to \pi^- D^+$ with $D^+ \to K^-\pi^+\pi^+$. From time to time, explicit statements are made to resolve potential ambiguities.

Citations follow the author-year format, used in a flexible way. The most common form is surrounded by parentheses (Kobayashi and Maskawa, 1973). However, about 20% of cases incorporate the names of the authors into the grammar of the sentence, as when referring to the classic paper of Kobayashi and Maskawa (1973). Variant forms are used within the text of a parenthesis; all should be clear from the context.

The only unusual feature is the use of three bibliographies: one for *BABAR* papers (page 806), one for Belle papers (page 822), and one for other references (page 835). To avoid tedium, the "et al." is omitted for B Factory papers, citing only the first author of full *BABAR* Collaboration authorlists (Aubert, 2001e), and either the first member (Choi, 2011) or the whole of the first-authorship group (Mizuk, Danilov, 2006) for full Belle Collaboration authorlists. Long authorlists for "other" references are treated normally. The great majority of *BABAR* papers have either Aubert, del Amo Sanchez, or Lees as first author; most early Belle papers have Abe, but from 2002 onwards show great variety. Results are described as being from *BABAR* or Belle if the responsible experiment is not already apparent from the context. Occasionally, a *BABAR* paper and a Belle paper will be cited together, for example in a quoted average or in the body of a table. It should always be clear which bibliography is meant.

In such a long work, there is inevitably some variation in style and usage. As editors, we have endeavoured to keep this to a minimum.

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