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Excerpt
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Part I

Basics of CP violation

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Prologue

All animals are equal.
But some animals are
more equal than others!
G. Orwell, Animal Farm

The sciences in general and physics in particular are full of fascinating phenomena; this is why they have attracted intense human interest early on and have kept it ever since. Yet even so we feel that the question to which degree nature is invariant under time reversal and **CP** transformations is so fundamental that it richly deserves its own comprehensive monograph. Two lines of reasoning – different, though not unrelated to each other – lead us to this conclusion. The first relies on multi-layered considerations, the second is based on a property inferred for the whole universe.

- The first line of reasoning centres on the important role symmetries have always played in physics. It has been recognized only last century, though, how central and crucial this role actually is, and this insight forms one of the lasting legacies of modern physics to human perception of nature and thus to human culture. The connection between continuous symmetries – like translational and rotational invariance – and conserved quantities – momentum and angular momentum for these examples – has been formulated through Noether's theorems. The pioneering work of Wigner and others revealed how atomic and nuclear spectra that appeared at first sight to be quite complicated could be understood through an analysis of underlying symmetry groups, even when they hold only in an approximate sense. This line of reasoning was successfully applied to nuclear and elementary particle physics through the introduction of isospin symmetry $SU(2)$, which was later generalized to $SU(3)$ symmetry in particle physics.

A completely new chapter has been opened through the introduction of *local* gauge theories. In particular Yang–Mills theories were introduced as a formal extrapolation of abelian gauge theories like QED. It was realized only considerably later that the gauge principle plays an essential role in constructing fully relativistic quantum theories that are both non-trivial and renormalizable. Furthermore, it was understood that symmetry breaking can be realized in two different modes, namely *manifestly* and *spontaneously*.

Similarly, *discrete* symmetries have formed an important part of our understanding of the physical world around us – as in crystallography and chemistry. The weight of such considerations is emphasized further with the imposition of permutation symmetries in quantum theory as expressed through Bose–Einstein and Fermi–Dirac statistics. Embedding discrete symmetries into local gauge theories has led to intriguing consequences; among them is the emergence of anomalies, which will be discussed in later chapters.

The primary subject of this book will be discrete symmetries which are of general and fundamental relevance for physics:

- parity **P** – reflecting the space coordinate $\vec{x}$ into $-\vec{x}$;
- charge conjugation **C** – transforming a particle into its antiparticle;
- the combined transformation of **CP**;
- time reversal **T** – changing the time coordinate t into $-t$; it thus amounts to reversal of motion.

We have learnt that nature is largely, but not completely, invariant under these transformations. Although these insights were at first less than eagerly accepted by our community, they form an essential element of what is called the Standard Model (SM) of high energy physics. Yet the story is far from over. For the SM contains 20-odd parameters; those actually exhibit a rather intriguing pattern that cannot be accidental. They must be shaped by some unknown New Physics, and we consider it very likely that a comprehensive analysis of how these discrete symmetries are implemented in nature will reveal the intervention of New Physics.

Furthermore we believe that time reversal, **T**, and the combined transformation of **CP** occupy a very unique place in the pantheon of symmetries. The fact that their violation has been observed in nature has consequences the importance of which cannot be overestimated. Once it was realized that **P** and **C** are violated – and actually violated maximally – it was noted with considerable relief that **CP** was apparently still conserved. For it had been suggested that microscopic **T** invariance follows from Mach's principle; because of **CPT** invariance that holds so naturally in quantum field theories, **CP** violation could not occur without **T** violation.

There is a subtle point about time reversal that is to be understood. **T** can be viewed as reversal of motion. The notion that the laws of nature might be invariant under such a transformation seems absurd at first sight. When watching a filmed sequence of events we can usually tell with *great confidence* whether the film is being played forward or backward. For example, a house of cards will collapse into a disordered pile rather than rise out from such a pile by itself. However this disparity can be understood by realizing that while both sequences are in principle equally possible – as demanded by microscopic **T** invariance – the second one is so unlikely to occur for a macroscopic system as to make it practically impossible. That is why the expression 'with great confidence' was used above. We will address this point in more detail later on.

It came as a great shock that microscopic **T** invariance is violated in nature, that 'nature makes a difference between past and future' even on the most fundamental level. We might feel that such a statement is sensationalist rather than scientific; yet there is indeed something very special about a violation of the invariance under **T** or **CP**. We offer the following observations in support of our view. Elucidating them will be one of the central themes of our book. They might carry little meaning for the reader at this point; yet we expect this to have changed after she or he has finished the book.

– **CP** violation is more fundamental than **C** violation in the following sense: **C** violation as it was discovered can be described by saying that only left-handed neutrinos and right-handed anti-neutrinos interact. This, however, does not allow a genuine distinction of matter and anti-matter:[1] for their difference is expressed in terms of 'left' and 'right handed' which represents a convention – as long as **CP** is conserved! However once **CP** is violated – even if ever so slightly – then matter and antimatter can be distinguished in an absolute, convention-independent way. The practical realization of this general observation goes as follows: while the K_L meson can decay into a positron or an electron together with a pion of the opposite charge and a neutrino or anti-neutrino, it exhibits a slight preference for the mode $K_L \to e^+ \nu_e \pi^-$. The positron is then called an antilepton; matter and antimatter are thus distinguished by *nature* rather than by convention.
– Time reversal is described by an anti-unitary rather than a unitary operator, which introduces many intriguing subtleties. Among

[1] In our world the electron is defined as matter and the positron is defined as antimatter.

them is Kramer's degeneracy: from $\mathbf{T}^2 = \pm 1$ we deduce that two distinct classes of states can exist; those with $\mathbf{T}^2 = -1$ are interpreted as fermions, in contrast to bosons for which $\mathbf{T}^2 = 1$ holds.

- **CP** violation represents the most delicately broken symmetry observed so far in nature and provides us with a powerful phenomenological probe. Consider the historical precedent: the observation of $K_L \to \pi\pi$ in 1964 led to the prediction (in 1972) that a *third* family of quarks and leptons had to exist – before the existence of the final member of the *second* family, the charm quark, had been accepted. It took until 1995 before the top quark, the last member of the third family, had been discovered – with a mass about 400 times as much as the K_L meson!
- While **P** violation has not been understood in a profound way, it can unequivocably be embedded into the gauge sector through chiral couplings to the gauge bosons. Among other things, we can give a natural and meaningful definition of a 'maximal' violation of **P** or **C** invariance, namely that all interacting neutrinos [antineutrinos] are left-handed [right-handed]. Furthermore, the 'see-saw' mechanism provides us with an intriguing dynamical scenario invoking the restauration of **P** invariance at high energies to explain the smallness of neutrino masses. The situation is completely different for **CP** and **T** violation. In general it can enter through gauge or Yukawa interactions. In the Kobayashi–Maskawa (KM) ansatz it is implemented through complex Yukawa couplings; thus it is connected to the least understood part of the SM. The best that can be said is that the SM with three quark families allows for **CP** violation; yet the latter appears as a mere 'add-on'. We are not even able to give real meaning to the notion of 'maximal' **CP** violation.

• The second argument focuses on the observation that while the universe is almost empty, it is not completely empty and actually in a decidedly biased way so! To use a more traditional scientific language: for every trillion or so photons there is just a single baryon in the universe – apparently without any sight of an antibaryon that cannot be explained as the product of a primary collision between matter particles:

$$\text{today}: \quad N(\text{antibaryons}) \ll N(\text{baryons}) \ll N(\text{photons}) \qquad (1.1)$$

Of course we have no reason to complain about this state of affairs. Life could not have developed, we could not exist if nature had been more even-handed in its matter–antimatter distribution.

As first pointed out in a seminal paper by A. Sakharov, there are three essential elements in any attempt to understand the excess of

baryons over antibaryons in the universe as a dynamical quantity that can be *calculated* rather than merely *attributed to the initial conditions*:
(1) reactions that change baryon number have to occur;
(2) they cannot be constrained by **CP** invariance;
(3) they must proceed outside thermal equilibrium.
CP violation is thus one essential element in any attempt to achieve such an ambitious goal, and as it turns out, it is the one area that we can best subject to further experimental scrutiny.

In summary: understanding **CP** and **T** violation will bring with it both practical benefits and profound insights since it represents an essential and unalienable element in the fabric of nature's grand design, as sketched in Fig. 1.1. A second glance at this sketch shows that we are dealing with a highly interwoven as well as dense fabric, as is true for all high quality fabrics. To understand its structure, to exploit the inter-relationships among its elements and to interpret data, we obviously need a guiding principle (or two); the concept of symmetry in all its implementations can serve as such. We feel very strongly that progress towards understanding this tapestry can be made only through a feed-back between further dedicated and comprehensive experimental studies and theoretical analysis.

Synopsis

The aim of this book is to show that **T** and **CP** invariance and their violations are much more than exotic phenomena existing in their own little reservation. As indicated above (and discussed in more detail later on) these subjects are, despite their subtle appearance, intimately connected with nature's fundamental structure. Their proper treatment therefore requires a full understanding and usage of our most advanced theoretical tools, namely quantum mechanics and quantum field theory.[2] At the same time we will insist that close contact with experiment has to be maintained.

To pursue this goal our presentation will proceed as follows: first we will describe in considerable detail how **P**, **C** and **T** transformations are implemented in classical physics, and in theories with first and second quantization. Then we will briefly recapitulate how the study of strange particles initiated the observation of **P** non-invariance and led to the

[2] Even superstring theories might be called upon in the future to provide the substratum for the relevant field theory, as briefly mentioned in our discussion of CPT invariance and of New Physics scenarios.

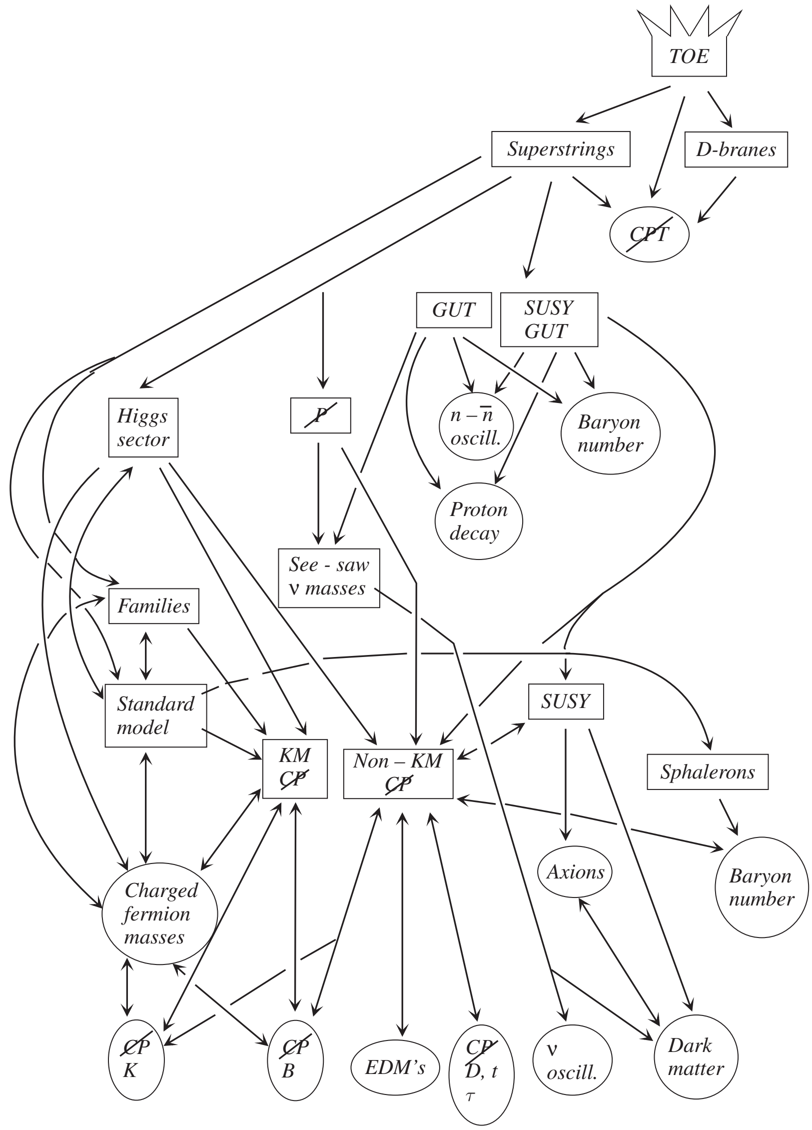

Figure 1.1 Nature's grand tapestry.

discovery of **CP** violation, before describing the phenomenology of the neutral kaon system in detail. After addressing other searches for **T** non-invariance in K decays and through electric dipole moments of neutrons and atoms, we introduce Kobayashi–Maskawa (KM) theory as the minimal implementation of **CP** violation in the SM of high energy physics, and apply it to the description of strange decays and electric dipole moments. We will emphasize how essential it is that a dedicated pursuit of searches for **CP** violation in light quark systems continue in the foreseeable future.

On the other hand, KM theory leads unequivocally to a 'paradigm of large **CP** asymmetries' in B decays. The rich phenomenology for beauty decays can be characterized by six points:

- some predictions enjoy high *parametric* reliability, in particular $B_d \to J/\psi K_S$ and $B_s \to J/\psi\eta$, $J/\psi\phi$;
- for others – as in $B_d \to \pi^+\pi^-$ – such reliability can be achieved through measuring related transitions;
- *parametric* reliability can be turned into *numerical* precision;
- there are many promising ways to search for indirect manifestations of 'New Physics', the most obvious ones being the analysis of $B_s \to J/\psi\eta$, $J/\psi\phi$, $D_s\bar{D}_s$, $\phi\phi$ and $B_d \to \phi K_S$, $\eta' K_S$;
- completion of such a program requires a long-term commitment;
- most importantly: *This KM paradigm has been verified experimentally even on the quantitative level!*

Even *before* this validation in B decays KM theory had exhibited attractive, or at least intriguing, aspects.

(A): It provides a natural gateway for **CP** violation to enter; no new degrees of freedom have to be postulated. Three complete quark families have been found experimentally. The SM then does *not automatically* conserve **CP**: it has enough structure to support the existence of a physical weak phase. It could still have turned out that this phase vanishes; yet within the SM context this would appear to be 'unnatural' – it would have to have a dynamical origin beyond the SM.

(B): It had accommodated the observed phenomenology – quite meagre in its positive signals *at that time* – within the experimental and theoretical uncertainties. It had made predictions borne out by the data, namely the elusiveness of direct **CP** violation and the tiny size of electric dipole moments. It had achieved this with some of the fundamental parameters – V_{td}, V_{ts} and m_t – observed to be of a numerical size that before (when the KM ansatz was conceived and for many years thereafter) would have appeared to be quite unreasonable.

Despite these intriguing features and the impressive validation in B decays we consider it quite unlikely that the KM ansatz could remain the final word on **CP** violation – far from it! We are willing to stake our reputation[3] on the prediction that dedicated and comprehensive studies of **CP** violation will reveal the presence of New Physics.

[3] Of course it is merely a theorists' reputation.

- The KM ansatz constitutes merely a *parametrization* of a profound phenomenon. The KM matrix actually reflects the mismatch in the alignment of the up-type and down-type quark mass matrices; its elements and thus also the origin of **CP** violation are, therefore, related to two of the central mysteries of the SM: why are there quark (and lepton) families and how do their masses get generated? Because of this connection it is not surprising that we cannot claim a true understanding of **CP** violation. On the other hand, without detailed knowledge of the physical elements of the KM matrix, we do not make full use of the information that nature is allowing us to acquire on the dynamics underlying the generation of fermion masses.
- What we already know about these matrix elements – mostly concerning their moduli – strongly suggests that some very specific dynamics was generating them. For the matrix, rather than being merely unitary, exhibits a very peculiar structure, as outlined before, that is quite unlikely to have come about by accident. The matrix thus contains information on New Physics – albeit in a highly coded form.
- Many extensions to the SM have been suggested to cure perceived, i.e. 'theoretical' ills of the SM. Now we have uncovered *experimental* evidence for the SM's incompleteness:
  (1) neutrinos do oscillate;
  (2) the SM has no candidate for Dark Matter;
  (3) the SM cannot drive baryogenesis.
  We do not even list the bizarre phenomenon referred to as Dark Energy.

CP studies represent highly sensitive probes for manifestations of such New Physics, and we must make the best use of it.

Beyond the pragmatic motivation to discuss other theories for **CP** breaking dynamics sketched above, there is an intellectual one as well. Those theories provide us with an opportunity to address general aspects of the way in which **CP** violation can be realized in nature.

(i) **CP** symmetry can be broken in a 'hard' way, i.e. through dimension-four operators in the Lagrangian, namely gauge couplings to fermions or Yukawa couplings. The KM ansatz is an implementation of the latter variant of such a scenario. For quark mass matrices are derived from the Yukawa couplings through the Higgs mechanism; since in the SM we introduce a single Higgs doublet field, we need the Yukawa couplings to exhibit an irreducible complex phase. This phase is then a free parameter and cannot be calculated.

(ii) **CP** invariance can be broken explicitly in a 'soft' manner, i.e. through operators of dimension below four. We will see that SUSY extensions provide for such scenarios which hold out the promise – or at least the hope – that the basic **CP** violating parameters could be understood dynamically.

(iii) **CP** symmetry is realized in a spontaneous fashion; this is also referred to – sloppily – as spontaneous **CP** violation: while the Lagrangian conserves **CP** (the gauge and Yukawa couplings can be made real), the ground state does not; the vacuum expectation value of neutral Higgs fields develop complex phases. Again, we entertain the hope that the relevant quantities can be derived from the dynamics – in principle, and some day. Models with an extended Higgs or gauge sector allow us to realize such scenarios.

We sketch various extensions of the KM implementation of **CP** violation – among them SUSY scenarios and extra (space) dimension models – and describe processes where realistically only the intervention of New Physics can produce observable **CP** asymmetries, namely in:

- the decays of charm hadrons and τ leptons;
- production and decay of the top quark;
- ν oscillations.

Finally, we address the most ambitious problem, namely baryogenesis in the Big Bang universe.