CP Violation and the Search for New Physics *

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Abstract

We present an overview of CP violation in the Standard Model and Beyond, describing various possible sources of CP violation and how to search for them.

1 Introduction

It is well known that CP violation can be introduced in the Standard Model (SM) with three or more generations, provided one allows for complex Yukawa couplings. For a long time the only experimental evidence for CP violation came from the Kaon sector. Recently, one has had experimental evidence for CP violation also in the B sector. Yet, CP violation continues being one of the least experimentally constrained aspects of the SM. Since the breaking of CP is closely related to one of the least theoretically understood sectors of the SM, namely the Higgs sector and the generation of fermion masses and mixings, it is clear that the study of CP violation, both theoretically and experimentally, is likely to play a major rôle in the future development of Particle Physics.

1.1 Experimental evidence for CP violation

The following three independent CP observables have been measured [1]:

(i) Kaon sector:

\[
|\epsilon_k| = (2.28 \pm 0.02) \times 10^{-3} \\
\epsilon'/\epsilon = (1.72 \pm 0.18) \times 10^{-3}
\]

\[ (1) \]

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(ii) B sector

\[ \sin(2\beta) = 0.75 \pm 0.09 \text{(stat.)} \pm 0.04 \text{(syst.)} \quad \text{BaBar} \quad (2) \]

\[ \sin(2\beta) = 0.99 \pm 0.15 \quad \text{Belle} \quad (3) \]

(iii) Baryon Asymmetry of the Universe (BAU)

\[ n_B / n_\gamma = (1.5 - 6.3) \times 10^{-10} \quad (4) \]

The results (i), (ii) are in agreement with the Standard Model (SM) and its Kobayashi-Maskawa (KM) mechanism of CP violation. On the other hand, it is by now established that the strength of CP violation in the SM is not sufficient to generate the observed BAU [4].

1.2 The Strong CP problem

An essential feature of 'tHooft’s solution of the $U(1)$ problem is the fact that the QCD Lagrangian has to include a term:

\[ L_\theta = \theta_{QCD} \frac{g^2}{32\pi^2} F_{\mu\nu} \tilde{F}_{\mu\nu} \quad (5) \]

where \( \tilde{F}_{\mu\nu} \equiv (1/2)\epsilon_{\mu\nu\rho\sigma} F_{\rho\sigma} \) and \( \theta_{QCD} \) is a free parameter. The inclusion of this term is crucial for the solution of the $U(1)$ problem, but it leads to another difficulty, due to the fact that \( L_\theta \), violates P, T and CP, while conserving C. In the SM, the quark mass matrices \( M_u, M_d \) are generated through spontaneous symmetry breaking of the $SU(2) \times U(1)$ gauge symmetry and they are, in general, arbitrary complex matrices which are diagonalized by a bi-unitary transformation acting on left-handed and right-handed fields. These transformations include in particular the chiral transformation necessary to make \( M_u, M_d \) diagonal, real which induces a contribution to \( \theta_{QCD} \):

\[ \theta_{QCD} \rightarrow \bar{\theta} \equiv \theta_{QCD} + \theta_{QFD} \quad (6) \]

where

\[ \theta_{QFD} = \arg \det(M_u M_d) \quad (7) \]

As a result, \( \bar{\theta} \) is the physical parameter which measures the strength of CP violation in non-perturbative QCD, leading in particular to an electric dipole moment (EDM) for the neutron. In chiral perturbation theory, the following result has been obtained for the neutron EDM

\[ D_n = (3.6 \times 10^{-16} \bar{\theta}) \ ecm \quad (8) \]

The experimental bound on \( D_n \) implies the following bound on \( \bar{\theta} \):

\[ \bar{\theta} < 10^{-10} \quad (9) \]

Why should a dimensionless free parameter like \( \bar{\theta} \), be so small? This is the so-called strong CP problem. Various solutions to the strong CP problem have been put forward, including the following:
(i) \( m_u = 0 \) solution

This would be the simplest solution. If the up quark were exactly massless, then \( \bar{\theta} \) could be set to zero by making a chiral transformation of the up quark field. The difficulty with this solution stems from the fact that it has been shown by Gasser and Leutwyler \(^6\) that the up quark mass does not vanish. It is worth pointing out that a different point of view has been expressed by other authors \(^8\).

(ii) Peccei-Quinn solution

Peccei and Quinn have pointed out \(^9\) that if there is a global chiral symmetry \( U(1)^{\text{PQ}} \) under which both the quarks and the Higgs multiplets transform trivially, the \( \bar{\theta} \) parameter becomes a dynamical variable which can be set to zero. It was pointed out by Weinberg and Wilczek \(^10\) that since \( U(1)^{\text{PQ}} \) is a global continuous symmetry which is spontaneously broken by the vacuum, there is a Goldstone boson, named axion, which acquires mass through instanton effects. The original axion has been immediately ruled out by experiment and so far, none of the its variants have been discovered. The Peccei-Quinn suggestion is clearly one of the most elegant solutions to the strong CP problem. Its main drawback, is the fact that axions have not been experimentally discovered yet.

(iii) Solutions with calculable and naturally small \( \bar{\theta} \)

In this class of solutions, one imposes CP (or P) invariance at the Lagrangian level and chooses a Higgs potential so that CP (or P) is spontaneously broken. The CP (or P) invariance of the Lagrangian requires \( \theta_{\text{QCD}} = 0 \). If appropriate symmetries are added to the Lagrangian so that \( \theta_{\text{QED}} \) vanishes at tree level, then \( \bar{\theta} \) equals zero at tree level and receives small, calculable contributions in higher orders. A specially attractive scenario in this class of theories is the one proposed by Barr and Nelson \(^11\), which can be implemented in the context of Grand Unified Theories or in the framework of \( SU(2) \times U(1) \) \(^12\).

2 Motivation for New Physics contributions to CP Violation

Although the SM and its KM mechanism of CP violation is in agreement with all the data in the Kaon and B sectors, there is motivation to consider New Physics contributions to CP violation, namely:

(i) The fact that the strength of CP violation in the SM is not sufficient to generate the observed BAU provides a strong motivation to consider new sources of CP violation, beyond the KM mechanism. Whether the new sources of CP violation needed to generate the correct BAU will be “visible” at low energies (e.g. through the study of CP asymmetries in B-decays), is an open question. It depends very much on the origin of these new sources of CP violation. If
these new contributions to CP breaking arise, for example, from low-energy
supersymmetry or due to the presence of Z-mediated flavour-changing neutral
currents [13], then it is likely that they will manifest themselves as deviations
from the SM predictions for CP asymmetries in B-decays. However one may
generate the correct BAU through a completely different mechanism like, for
example, baryogenesis through leptogenesis [14]. In this framework, a lepton
asymmetry is initially generated by the decay of right-handed neutrinos and it
is then converted into a baryon asymmetry by \((B + L)\) - violating sphaleron
processes. In this case, the relevant sources of CP violation have to do with
the coupling of right-handed neutrinos [15] and therefore the predictions of the SM
for CP asymmetries in B-decays will not be affected.

(ii) Almost all extensions of the SM include new sources of CP violation.
For example, in supersymmetric extensions of the SM, there is a large number
of new phases which may play a rôlè in CP asymmetries in the B system [16]
as well as through their contribution to various EDMS.

3 CP violation in gauge theories

There are two ways of introducing CP violation in gauge theories [17]:

- **At the Lagrangian level:**
  In this case, the Lagragian is such that there is no transformation that may
  be physically interpreted as a CP transformation, under which the Lagrangian
  is invariant. The minimal model of this class is the 3 generation Standard
  Model with complex Yukawa couplings, where the Kobayashi-Maskawa (KM)
  mechanism takes place.

- **Spontaneous CP violation:**
  Two conditions have to be satisfied in order to achieve spontaneous CP
  violation:
(i) There is a transformation that may be physically interpreted as CP, under which the Lagrangian is invariant.

(ii) There is no transformation that may be physically interpreted as CP, under which both the Lagrangian and the vacuum are invariant.

The minimal model of this class is the Lee model, with two Higgs doublets and with flavour changing neutral currents in the Higgs sector. We will discuss this model in subsection 3.2.

3.1 CP violation in the Standard Model

In the SM the Yukawa couplings are in general $n_g \times n_g$ complex matrices in flavour space, with $n_g$ denoting the number of fermion generations. Upon spontaneous symmetry breaking of the $SU(2) \times U(1)$ gauge symmetry, these couplings lead to complex quark mass matrices $M_u, M_d$ for the up and down quarks, respectively. These mass matrices are diagonalized by bi-unitary transformations:

\[ U^u_L M_u U^u_R = D_u \equiv \text{diag.}(m_u, m_c, m_t) \]  
\[ U^d_L M_d U^d_R = D_d \equiv \text{diag.}(m_d, m_s, m_b) \]

In the mass eigenstate basis, the charged currents can then be written as:

\[ \mathcal{L}_W = \frac{g}{\sqrt{2}} \bar{u}_L V_{CKM} \gamma^\mu d_L W^\mu + h.c. \]  

with $V_{CKM} = U^u_L U^d_R$. The mass terms are:

\[ \mathcal{L}_{\text{mass}} = m_u \bar{u}_u + m_c \bar{c}_c + m_t \bar{t}_t + m_d \bar{d}_d + m_s \bar{s}_s + m_b \bar{b}_b. \]  

One has the freedom to rephase the quark fields:

\[ u_\alpha \rightarrow u'_\alpha = e^{-i\phi_\alpha} u_\alpha \]  
\[ d_k \rightarrow d'_k = e^{-i\psi_k} d_k \]

Under the above rephasing, the mass terms remain invariant, while $V_{CKM}$ transforms as:

\[ V_{\alpha k} \rightarrow V'_{\alpha k} = e^{i(\psi_k - \phi_\alpha)} V_{\alpha k} \]

where we have dropped the suffix $CKM$.

It is obvious that only rephasing invariant quantities have physical meaning. The simplest rephasing invariant functions of $V_{\alpha k}$ are moduli and invariant quartets:

\[ |V_{\alpha k}|^2, \quad Q_{\alpha i \beta j} = V_{\alpha i} V_{\beta j} V_{\alpha j}^* V_{\beta i}^* \]

Assuming a non-degenerate quark mass spectrum, the most general CP transformation for the quark fields which leaves the Lagrangian invariant, is:

\[ CP u_\alpha(t, \vec{r})(CP)^\dagger = e^{i \xi k} \gamma^0 C \bar{u}_\alpha^T(t, -\vec{r}) \]  
\[ CP d_k(t, \vec{r})(CP)^\dagger = e^{i \xi k} \gamma^0 C \bar{d}_k^T(t, -\vec{r}) \]
It can be readily verified that CP invariance constrains all rephasing invariant functions of $V$ to be real. In particular, CP invariance implies that $\text{Im} Q_{\alpha i\beta j} = 0$. For two generations there is only one quartet and unitarity constrains its imaginary part to vanish. Indeed

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* = 0 \quad (20)$$

implies

$$V_{us}^* V_{cs} V_{cd} + |V_{as}|^2 V_{cs}^2 = 0 \quad (21)$$

and thus:

$$\text{Im}(V_{ud}V_{cs}^* V_{cd}) = 0 \quad (22)$$

For three or more generations, unitarity does not constrain $\text{Im} Q_{\alpha i\beta j}$ to vanish and therefore CP violation can arise. This is the KM mechanism. Unitarity of $V_{CKM}$ plays a major role in restricting the strength of CP violation in the SM and it implies a series of relations which can be used to test the SM, with the potential of uncovering New Physics. Let us consider orthogonality of the first two rows of $V_{CKM}$:

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad (23)$$

Multiplying both sides of Eq. (23) by $V_{us}^* V_{cs}$, and taking imaginary parts, one obtains:

$$\text{Im}(V_{ud}V_{cs}^* V_{cd}) = \text{Im}(V_{us}V_{cb}^* V_{ub}) \quad (24)$$

Similarly, one can prove that all $|\text{Im} Q|$ have the same value for any of the invariant quartets of the $3 \times 3$ $V_{CKM}$ matrix. This is a very special feature of the $3 \times 3$ unitary $V_{CKM}$ matrix, which would not hold true if, for example, there were four fermion generations. The quantity $|\text{Im} Q|$ can then be used as a measure of the strength of CP violation in the SM. Furthermore, $|\text{Im} Q|$ has a simple geometrical interpretation. To each of the six unitarity relations corresponding to orthogonality of rows and columns of $V_{CKM}$, one can associate a triangle in the complex plane, as in Fig.1. All the unitarity triangles have the same area, which is proportional to $|\text{Im} Q|$:

$$\text{Area} = \frac{1}{2} |\text{Im} Q| \quad (25)$$

Under rephasing of quark fields, the triangles rotate and thus the orientation of the unitarity triangles has no physical meaning. However the internal angles of the unitarity triangles are invariant under rephasing and do have physical meaning. Of special interest, is the triangle corresponding to orthogonality of the first and third columns of the $CKM$ matrix, represented in Fig.1. This triangle has the special feature of having all sides of comparable size. Furthermore, in the context of the $SM$, the internal angles of this triangle are related to various $CP$ asymmetries in B-meson decays. The angles $\alpha, \beta, \gamma$ are represented in Fig.1 and are defined by:

$$\alpha \equiv \text{arg}(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}) = \text{arg}(-Q_{ubtd}) \quad (26)$$
\[
\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{ub}V_{ub}^*}\right) = \arg(-Q_{bcd}) \quad (27)
\]

\[
\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = \arg(-Q_{bud}) \quad (28)
\]

One can derive necessary conditions for CP invariance in the SM, with an arbitrary number of generations, written in terms of weak-basis (WB) invariants.

These invariants have the advantage that they can be evaluated in any WB. An example of such a WB invariant condition for CP invariance is \[18\]:

\[
\text{tr}[H_u, H_d]^3 = 0 \quad (30)
\]

where \(H_u \equiv M_uM_u^\dagger\), \(H_d = M_dM_d^\dagger\). For two fermion generations Eq. \[30\] is automatically satisfied with arbitrary Hermitian matrices \(H_u, H_d\). This is, of course, to be expected since for the two generation SM, CP cannot be broken. For three generations, Eq. \[32\] is a necessary and sufficient condition for CP invariance.

This WB invariant can be evaluated in terms of quark masses and mixings:

\[
\text{tr}[H_u, H_d]^3 = 6i(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)(m_b^2-m_s^2)(m_b^2-m_d^2)(m_s^2-m_d^2)\text{Im}Q \quad (31)
\]

From Eq. \[31\] it follows that in order for CP violation to take place, no two quarks of a given charge can be degenerate. However, there is CP violation in the SM even in the limit where the mass of a given quark, for example \(m_u\), vanishes.

### 3.2 Spontaneous CP violation

An alternative way of introducing CP, T violation is having a Lagrangian which is CP and T invariant but a vacuum which breaks CP, T. In the SM, it is not possible to achieve spontaneous CP violation (SCPV). The minimal extension of the SM where SCPV can be obtained is the Lee model \[19\], where the gauge sector of the SM is not changed but in the Higgs sector, two scalar doublets are introduced. It has been shown that there is a range of parameters of the Higgs potential for which the minimum is at:

\[
<0|\Phi_1|0> = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}; \quad <0|\Phi_2|0> = \begin{pmatrix} 0 \\ v_2 e^{i\theta} \end{pmatrix} \quad (32)
\]

The minimum of Eq. \[32\] does conserve electric charge but it violates CP and T. At the time when Lee suggested this model, there were only two fermion generations, so CP breaking originated only in Higgs mediated interactions. In the case of three fermion generations, it can be readily verified that the relative phase \(\theta\) leads to CP violation both through neutral Higgs exchange and in charged weak interactions \[17\].
This can be shown by considering the Yukawa interactions:

\[ \mathcal{L}_Y = -\bar{Q}_L [\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2] d_R - \bar{Q}_L [\Gamma'_1 \Phi'_1 + \Gamma'_2 \Phi'_2] u_R + h.c. \]  

(33)

where \( Q_L \) denote the left handed quark doublets. The Yukawa couplings \( \Gamma_i, \Gamma'_i \) are real matrices, so that CP invariance holds at the Lagrangian level. Upon spontaneous gauge symmetry breaking, one obtains the following quark mass matrices:

\[
M_d = v_1 \Gamma_1 + v_2 \Gamma_2 e^{i\theta} \\
M_u = v_1 \Gamma'_1 + v_2 \Gamma'_2 e^{-i\theta}
\]

(34)

From Eqs. (34) one can compute \( H_u, H_d \) and verify that the WB invariant of Eq. (31) does not vanish in general, thus showing that in the Lee model with three fermion generations, CP is violated by charged weak interactions through the KM mechanism, in spite of the existence a single phase in the model, namely the phase \( \theta \). On the other hand, since quarks of a given charge receive mass from couplings to two different Higgs, there are flavour-changing neutral currents (FCNC) mediated by neutral Higgs. These couplings do lead to CP violation, as shown by Lee. In summary, in the Lee model with three fermion generations and two Higgs doublets, there are two sources of CP violation, the usual KM mechanism and Higgs exchange. The appearance of FCNC can be avoided by introducing extra discrete symmetries which constrain the Yukawa couplings in such a way that, for example, \( \Phi_1 \) only gives mass to down quarks while \( \Phi_2 \) only gives mass to the up quarks. In this case Higgs mediated neutral currents are naturally diagonal. However, the introduction of this discrete symmetry in the Lagrangian, forbids the presence of some terms in the Higgs potential in such a way that CP cannot be broken spontaneously \[21\]. One encounters a similar situation in the minimal supersymmetric standard model (MSSM), where CP cannot be spontaneously broken. In the context of minimal extensions of the SM, one can have natural flavour conservation (NFC) in the Higgs sector (i.e., absence of FCNC due to a symmetry rather than by fine tuning) and yet achieve spontaneous CP violation \[21\], by introducing a third Higgs doublet, which does not couple to quarks. In the context of supersymmetric extensions of the SM, spontaneous CP violation can be obtained in the next-to-minimal supersymmetric standard model (NMSSM) \[22\] with the introduction of a gauge singlet field. In both the above described schemes, the imposition of NFC in the Higgs sector, together with the requirement of spontaneous CP violation, leads to a real CKM matrix \[23\] and CP violation arises exclusively from physics beyond the SM. However, it should be emphasized that the above scenario of having a real CKM matrix is a very special case which results from the simultaneous requirement of spontaneous CP violation and NFC in the Higgs sector. When one considers extensions of the SM, the generic situation one encounters is having the coexistence of the KM mechanism with new sources of CP violation. As we have seen, this is the case of Lee's model, where besides the KM mechanism, one has a new source of CP violation, arising from Higgs exchange.
4 The Search for New Physics

Apart from its failure to account for the observed BAU, the SM and its KM mechanism of CP violation is in agreement with all the presently available experimental data. This agreement is an impressive success of the SM, which can be described in the following way. Let us adopt the standard parametrization of the CKM matrix, with three angles $\theta_1, \theta_2, \theta_3$ and one phase $\delta$ [1]. The three angles $\theta_1, \theta_2, \theta_3$ can be readily obtained from the knowledge of $|V_{us}|, |V_{ub}|, |V_{cb}|$ which can be extracted from Kaon and B-meson decays. Once these angles are fixed, one has to fit a large amount of data namely $\Delta M_B, \Delta M_{Bs}, \epsilon_k, \epsilon'/\epsilon$, and $a_{J/\psi K_s}$, with a single parameter $\delta$. In the near future, BaBar and Belle will have much more precise data on $a_{J/\psi K_s}$ and hopefully will measure other CP asymmetries leading to the determination of $\gamma$. In LHC, the measurement of $\Delta M_B$ will be possible [23], as well as a significant improvement on the precision of all other asymmetries. When all this data will become available, the SM and in particular its KM mechanism of CP violation will be subjected to a very stringent test, with the potential for discovering New Physics. In considering the effects of New Physics, it is useful to make the following reasonable assumptions:

(i) One assumes that the quark decay amplitudes $b \to c \bar{s}, b \to u \bar{d}$ as well as the semileptonic $b$ decays are dominated by the SM tree-level diagrams. This assumption is satisfied in most of the known extensions of the SM. In practice, this means that the extraction of $|V_{us}|, |V_{cb}|, |V_{ub}|$ from experimental data will continue being valid even in the presence of New Physics.

(ii) One allows for the possibility of having New Physics to $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixings. This is a reasonable assumption, because in the SM, $B - \bar{B}$ mixing receives contributions only at loop level and therefore New Physics can give additional contributions of comparable strength.

It is useful to parametrize the total contribution to the mixing as:

$$M_{12}^{(q)} = [M_{12}^{(q)}]_{SM} r_q^2 e^{i\phi_q}$$

where $q$ stands for $d, s$. From Eq. (35) it follows that $r_q \neq 1$ and or $\phi_q \neq 0$ signals the presence of New Physics. The main effect of the presence of New Physics contributions to $M_{12}^{(q)}$ is that the asymmetries $a_{J/\psi K_s}, a_{\pi+\pi-}$ will no longer measure the angles $\beta, \alpha$ but instead the following relation will apply:

$$a_{J/\psi K_s} = \sin(2\beta + \phi_q)$$
$$a_{\pi+\pi-} = \sin(2\alpha - \phi_q)$$

Due to the constraints of unitary of the CKM matrix, the SM flavour sector is quite constrained since various measurable quantities (which are in general independent) are related within the framework of the SM. Any deviation from these SM relations will signal the presence of New Physics. An example of such a relation is the Aleksan-London-Kayser [24] relation:

$$\sin \chi \simeq \frac{|V_{us}|^2 \sin \beta \sin \gamma}{|V_{ud}|^2 \sin(\gamma + \beta)}$$
with \( \chi \) defined by \( \chi \equiv \arg(-V_{cb}V_{ts}V_{cs}V_{tb}^*) \). The importance of Eq. (38) has been emphasized by Silva and Wolfenstein [25].

In a large class of models beyond the SM, in particular in the supersymmetric extension of the SM, the \( 3 \times 3 \) unitarity of \( V_{CKM} \) continues to hold. However, it should be emphasized that unitarity of \( V_{CKM} \) is an assumption which should be tested experimentally. Deviations of \( 3 \times 3 \) unitarity naturally arise in models with vector-like isosinglet quarks [26], i.e. quarks whose left-handed and right-handed components are both singlets under \( SU(2) \times U(1) \).

## 5 Conclusions

In the next few years crucial new data will be provided by the various B factories. With this new data, one will be able to test the flavour sector of the SM to a great level of accuracy. These experimental tests have the potential of discovering New Physics, specially if one takes into account that the SM is highly constrained. As we have emphasized, within the SM, a series of in principle independent measurable quantities are parametrized by a single parameter, namely the KM phase \( \delta \). Even in the event that no deviations from the SM predictions are found, future data on the various CP asymmetries as well as on \( B_s - \bar{B}_s \) mixing will still have a great impact, since they will lead to a precise determination of the \( V_{CKM} \) matrix, specially of its smallest elements, namely \( |V_{ub}|, |V_{td}| \). This will in turn have important implications for theories of flavour. In some of these theories, family symmetries are introduced which lead to calculability of \( V_{CKM} \) in terms of quark mass ratios. Some of these models differ from each other precisely in their predictions for \( |V_{ub}|, |V_{td}| \). Therefore, the measurement of these matrix elements within the SM will have the potential to select the correct theory of flavour.

In conclusion, the future data from B-factories will have a great impact on the physics of flavour and CP violation.

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