Status of CP Violation

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Abstract

The Standard Model parametrization of CP violation is described. Tests of this parametrization using the observed heavy flavour decays and implications for New physics are discussed.

Key words: CP violation, B mesons, New Physics

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1. A bit of history

With the announcement of the 2008 Nobel prize in Physics, there has been a lot of excitement among the community working on CP violation (CPV). In 1972, Kobayashi and Maskawa had proposed that CPV could be incorporated as a single phase in the three generation quark mixing matrix. With only three quarks \((u,d,s)\) known at that time, it had been a bold step. CPV had been discovered in 1964, as a tiny effect in the decays of \(K\) mesons by Cronin and Fitch. CPV has an important role to play in the matter-antimatter asymmetry of the universe. It is believed that the Universe was born with equal amounts of matter and antimatter, but since we only see matter around us, it implies that matter and antimatter behave differently. In 1967, Sakharov gave the famous three conditions for generating a baryon number asymmetry in the universe:

- Baryon number violation, to allow the antibaryons to disappear while baryons survive.
- CPV, since the decay rates of baryons and antibaryons must differ.
- Departure from thermal equilibrium, to ensure that the created asymmetry is not washed away.

Ten years after Sakharov laid down the above stated conditions, the bound state of the \(b\) quark, the Upsilon was observed. In 1984, Bigi and Sanda showed that in the Kobayashi and Maskawa (KM) picture, the CP violating effects would be observable in the \(B\) system if, the \(B\) has a long lifetime and if, the neutral \(B\) mixing is large. In 1987, large \(B^0 - \bar{B}^0\) mixing was indeed observed by ARGUS at DESY. In 1999, the B factories started operation with the detectors, Babar at SLAC and Belle at KEK. In the
same year, direct CPV was clearly confirmed in Kaon decays. The year 2001 saw the observation of large CPV using the golden mode $B \rightarrow J/\psi K_s$ at both Belle and Babar. This provided the first and unambiguous verification of the complex phase in the KM proposal. In the years that followed, results from Belle and Babar provided additional supporting evidence for the KM scheme.

2. CP Violation in the Standard Model

In the Standard model (SM), CPV arises from the complex Yukawa couplings. The Yukawa interactions generate the mass terms. The product of unitary matrices that diagonalize the mass matrices is the Cabibbo-Kobayashi-Maskawa (CKM) matrix and it relates the weak eigenstates to the mass eigenstates,

$$
\begin{pmatrix}
d' \\
s' \\
b'
\end{pmatrix} = V_{\text{CKM}} \begin{pmatrix}
d \\
s \\
b
\end{pmatrix} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \begin{pmatrix}
d \\
s \\
b
\end{pmatrix}.
$$

The elements of the CKM matrix describe the charged current couplings. The matrix has to be unitary by construction. The orthonormality relation obtained by using the first and third columns of $V_{\text{CKM}}$ is a simple complex relation,

$$
\alpha = \arg \left( -\frac{V_{ub}^* V_{td}}{V_{ub}^* V_{td}} \right), \quad \beta = \arg \left( -\frac{V_{cb}^* V_{td}}{V_{cb}^* V_{td}} \right) \quad \text{and} \quad \gamma = \arg \left( -\frac{V_{ub}^* V_{td}}{V_{ub}^* V_{td}} \right).
$$

The CKM has a hierarchical structure, in the Wolfenstein representation it has the form

$$
V_{\text{CKM}} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda + \frac{A^2 \lambda^2}{2} [1 - 2(\rho + i\eta)] & 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} (1 + 4A^2) & A\lambda^2 \\
A\lambda^3 [1 - (1 - \frac{\lambda^2}{2})(\rho + i\eta)] & -A\lambda^2 + \frac{A^2 \lambda^4}{2} [1 - 2(\rho + i\eta)] & 1 - \frac{A^2 \lambda^4}{2} + O(\lambda^6)
\end{pmatrix} + O(\lambda^6)
$$

Nonzero values of the phases ($\eta \neq 0$) imply CPV. A huge effort has been made at the $B$ factories and now also at the Tevatron to measure the weak phases.

3. Why and how to measure the phases?

The KM mechanism for CPV is unique and predictive. Moreover, the CP phases can be measured through certain asymmetries which are free of hadronic uncertainties. Any inconsistencies if noted, would indicate physics beyond the SM or New Physics (NP). Since the baryon number density predicted by the KM mechanism is many orders of

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1 A few years ago, writing the elements of the matrix to $O(\lambda^3)$ would have been sufficient, but with increasing experimental precision and moreover since New Physics effects are expected to be tiny, we write the elements up to $O(\lambda^5)$. 

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magnitude below the observed value, we need new sources of CPV. Correlations among the many CPV observables in meson decays can possibly pinpoint the kind of NP or at least constrain its parameters. Phases can be observed only through interference terms in modes to which two (or more) different amplitudes with distinct phases contribute. The different ways in which the interference terms appear, result in the following categories of CPV:

(i) CPV in Mixing: If the mass eigenstates differ from the CP eigenstates, it leads to a relative phase between the dispersive and absorptive parts of the transition amplitude from the neutral meson, \( M^0 \) to its conjugate \( \bar{M}^0 \). For the neutral \( B \) it can be observed by measuring the semileptonic asymmetry,

\[
A_{\text{SL}}^{(q)} = \frac{\Gamma(B_q^0(t) \rightarrow l^- \nu l X) - \Gamma(\bar{B}_q^0(t) \rightarrow l^+ \nu l X)}{\Gamma(B_q^0(t) \rightarrow l^- \nu l X) + \Gamma(\bar{B}_q^0(t) \rightarrow l^+ \nu l X)} = \frac{|q/p|^4 - 1}{|q/p|^4 + 1},
\]

which will be nonzero if \( |q/p| \neq 1 \). Current measurements imply that \( A_{\text{SL}}^{(q)} \) is compatible with zero. In the K system, CPV in mixing had been seen,

\[
\frac{\Gamma(K^0 \rightarrow \pi^- l^+ \nu l) - \Gamma(K^0 \rightarrow \pi^+ l^- \nu l)}{\Gamma(K^0 \rightarrow \pi^- l^+ \nu l) + \Gamma(K^0 \rightarrow \pi^+ l^- \nu l)} = \frac{1-|q/p|^2}{1+|q/p|^2} = (3.32 \pm 0.06) \times 10^{-3},
\]

the measured value \( \boxed{1} \) is a weighted average of muon and electron measurements.

(ii) CPV in Decay (Direct): For a decay amplitude with two weak contributions, the amplitude and its conjugate have the form \( \boxed{2} \), \( A = A_1 e^{i\phi_1} e^{i\theta_1} + A_2 e^{i\phi_2} e^{i\theta_2} \), \( A = A_1 e^{-i\phi_1} e^{i\theta_1} + A_2 e^{-i\phi_2} e^{i\theta_2} \). The CP asymmetry is hence given by,

\[
A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{-2A_1 A_2 \sin(\Delta \phi) \sin(\Delta \theta)}{A_1^2 + A_2^2 + 2A_1 A_2 \cos(\Delta \phi) \cos(\Delta \theta)}.
\]

The asymmetry is non vanishing if \( \Delta \phi = \phi_2 - \phi_1 = 0 \) and \( \Delta \theta = \theta_2 - \theta_1 = 0 \). Direct CPV was clearly established in \( K \) decays with the accurate measurement of \( (\epsilon'/\epsilon) \) in the year 1999. In many \( B \) decay modes it has been measured to be significantly different from zero \( \boxed{2} \).

(iii) CPV due to interference between decays with and without mixing: Final states \( f \) into which both \( M^0 \) and \( \bar{M}^0 \) can decay, have two interfering paths provided by the direct decay of \( M^0 \rightarrow f \) and that of \( M^0 \rightarrow \bar{M}^0 \rightarrow f \). The time dependent decay rate of \( B^0 \rightarrow f \) thus has the form,

\[
\Gamma(B^0(t) \rightarrow f) = e^{-\Gamma t} \left[ \frac{|A|^2 + |\bar{A}|^2}{2} - \frac{|A|^2 - |\bar{A}|^2}{2} \cos(\Delta M t) - \text{Im} \left( \frac{q}{p} \frac{\bar{A}}{A} \right) \sin(\Delta M t) \right],
\]

while that for \( B_s \) and \( D \) decays is more complex, due to the width difference \( \Delta \Gamma \neq 0 \). In the golden mode \( B \rightarrow \psi K_s \), the decay amplitude is dominated by only one tree amplitude with a real CKM element, implying that \( \bar{A} = A \), the time dependent CP asymmetry has the simple form, \( a_{CP} = \sin(2\beta) \sin(\Delta M t) \) and is almost completely free of hadronic uncertainties (measures \( \beta \) cleanly up to \( \approx 1\% \)). Time dependent CP asymmetry has been measured in many other \( B \) decay modes, \( \pi \pi, \phi K_s \) etc.

\( \phi_{1,2} \) and \( \delta_{1,2} \) are the weak and strong phases respectively.
4. Current Status and what it implies

Current data from $K$ and $B$ decays have been used by the UTfit collaboration [3] and the CKMfitter group [4] to perform a global fit in the $\bar{\rho} - \bar{\eta}$ plane, depicting the allowed region for the apex of the unitarity triangle. The resulting plots are shown in Fig. 1 and clearly show that all observations are consistent with each other. Fig. 2 shows the contributions from CP conserving and CP violating observables, again these are not only individually consistent but also with each other. Current observations hence imply that:

- $\eta$ is non vanishing, implying that the KM mechanism is working.
- There is consistency of results from $K$ mesons and $B$ mesons.
- Almost all CP violating observables (tree level and loop level) as well as measurements of rare decays and mixing parameters, are consistent with the KM mechanism. The CKM picture of SM seems to have been successful!
- CKM mechanism is the dominant mechanism for CP violation and flavor mixing.
- BUT, there is room for New Physics.

5. Hints of New Physics?

(i) The $\Delta A_{K\pi}$ puzzle: The CP asymmetry for $B^0 \to K^+\pi^-$ and for $B^+ \to K^+\pi^0$ is expected to be the same from isospin. However, the measured asymmetries [5] for these modes are: $A_{CP}(K^+\pi^-) = -0.098^{+0.012}_{-0.011}$ and $A_{CP}(K^+\pi^0) = 0.050 \pm 0.025$. The difference in these asymmetries, $\Delta A_{K\pi} = -0.147 \pm 0.028$, is non vanishing at 5.3$\sigma$. Note that the $B^0 \to K^+\pi^-$ mode gets contributions from Penguin and Tree diagrams, while the $B^+ \to K^+\pi^0$ mode can have additional colour suppressed and Electroweak penguin contributions (ignoring smaller contributions). There have been attempts to explain the discrepancy, through NP using fourth generation [6]. More recently [7], it has been indicated that the theory calculations are consistent, if sizable $\Lambda/m_b$ corrections are taken into account. Since, hadronic uncertainties are involved, predictions for CP violating asymmetries have large errors, so a firm conclusion cannot yet be made.

(ii) New Physics in $\Delta S$: For a final state $f$, the deviation of the time dependent CP asymmetry for $f$ from that of $\psi K_s$ mode, $\Delta S_f = -\eta_f S_f - S_{\psi K_s}$ is expected to be zero. While many modes are now consistent with this expectation, there are slight
deviations in some modes. While theory predictions are for small and positive deviations, experimental results yield negative deviations in some modes [8]. NP scenarios have been proposed to explain this discrepancy [9]. Although the effects now seem to be tiny, with small NP effects expected, we need to wait for improved statistical significance. In addition, there is a discrepancy in $S_{\psi K_s}$ versus $\beta$ measured from tree level measurements alone [10].

(iii) $\beta_s$ measurement at the Tevatron: CDF and D0 have performed a time dependent analysis of $B_s \rightarrow \psi \phi$, to get a correlated measurement of $(\beta_s, \Delta t)$. The Utfit combination of the Tevatron data gives a 2.9σ deviation [11] of $\phi_\beta$, from SM.

6. What kind of New Physics is possible?

In the Standard Model, there is no guiding flavour principle. The pattern of masses and mixing parameters is unexplained. It is unclear why there should be only three generations. The current baryon number density, $n_B/n_\gamma = (5.5 \pm 0.5) \times 10^{-10}$, reflects the baryon asymmetry induced by baryogenesis. New sources of CPV are required to generate this observed baryon asymmetry. Apart from these questions in the flavour sector, there are many other reasons which lead us to believe that the SM is a low energy effective theory of some fundamental theory. In particular, quadratic divergence in the SM Higgs mass, requires NP at around the TeV scale.

Hence, we can extend the SM Lagrangian by higher dimension operators, suppressed by powers of the NP scale. Most rare decay modes are flavour changing neutral current (FCNC) processes that appear only at the loop level and are hence useful for NP searches. For example, consider the $\Delta F = 2$ processes of mixing involving the down type quark (D). In the SM, the Lagrangian has the form,

$$-\mathcal{L}_{\text{eff}} = \frac{C_0}{\Lambda_0^2} (V_{ti}^\dagger V_{ij}) [\bar{D}_{L \gamma \mu} D_{L}]^2,$$

where $C_0 \sim \mathcal{O}(1)$ and $\Lambda_0$ is the scale for loop suppressed SM processes. Assuming that the NP effective operator has the same Dirac structure as in the SM, we have

$$-\mathcal{L}_{\text{eff}}^{NP} = \frac{C_{NP}}{\Lambda_{NP}^2} [\bar{D}_{L \gamma \mu} D_{L}]^2$$

with coefficient, $C_{NP} \sim \mathcal{O}(1)$ and $\Lambda_{NP}$ of the order of the mass of the NP particle. The various measurements ($\Delta m_{B_s}, \Delta m_B, \Delta m_D, \Delta m_K, \epsilon_K$) of the $\Delta F = 2$ processes, imply that the NP scale must be above $10^2 - 10^4$ TeV, much larger than the weak scale. Thus, NP with generic flavour violation structure is excluded at the TeV scale. This is the New Physics Flavour puzzle [12].

It can be resolved by having Minimal Flavour violation(MFV). If the scale of NP has to be of TeV order, we need some principle to make the coefficients of FCNC’s small. In the SM, the global flavor symmetry group, $G_F = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$ is broken only by Yukawa couplings $Y_U$ and $Y_D$. In the MFV hypothesis, there is a unique source of breaking of $G_F$, operators that break $G_F$, must transform just as the Yukawa terms. It was formalized by D’Ambrosio et al [13], who suggested that the Yukawa couplings be promoted to spurions that transform under $G_F$ as, $Y_U \sim (3, 3, 1), Y_D \sim (3, 1, 3)$ (for the quark sector). MFV NP is also formally invariant under $G_F$, breaking coming only from insertions of spurion fields $Y_{U,D}$. Integrating out heavy fields (NP fields, Higgs, top, W and Z) leads to a low energy effective field theory invariant under $G_F$. Using the basis in which $Y_D = \lambda_D$ and $Y_U = V^\dagger \lambda_U$, where $\lambda_D$ and $\lambda_U$ are diagonal matrices proportional to quark masses and $V$ is the CKM matrix, insertions of $(Y_U Y_D^T)_{ij}$ will be of the order $\lambda_D^2 V_{ti}^* V_{tj}$, making this theory very predictive. In addition, if one imposes the constraint that the structure of low energy operators be the same as in SM
and only the Wilson coefficients of weak operators deviate from SM values, one gets the constrained MFV. This is clearly experimentally distinguishable, due to correlations between observables.

7. How do we look for New Physics?

In order to find NP, we need to make even more precise measurements of the CP violating phases. Measurement of Rare decays: $B_s \to µ^+µ^-$, $B \to τν$, $B \to K^*ℓ^+ℓ^-$, $B \to X_{s,d}ν \bar{ν}$, $B \to X_{s,d}γ$, $K \to πν \bar{ν}$, $µ \to eγ$ etc., have played an important role in constraining NP models and further precision measurements could pinpoint to NP (MFV or nonMFV) or at least narrow down the parameter space of various NP models. As an example, apart from the forward backward asymmetry being currently measured in $B \to K^*ℓ^+ℓ^-$ [5], a detailed angular analysis of this mode can be used to determine various other asymmetries [14]. Some of these asymmetries are CP violating and are expected to be negligible in the SM, a measured value would imply NP. In the $D$ system, within the SM CPV is negligible and an observation of CPV would be a clear signal of NP [15]. A technique to accurately determine all the mixing parameters, including the CP violating phase has been given in Ref. [16]. With higher statistics possible at LHCb and Super B factories, all such searches for NP should be feasible!

8. Conclusions

The Kobayashi Maskawa mechanism of CP violation has been well tested with the results from the B factories. However, to explain the baryon asymmetry, we expect new sources of CP violation. Search for new physics, requires precision measurements of the CP violating parameters. In conjunction with rare B and K decays, it could point to the kind of new physics present: SUSY, Extra Dimensions, Little Higgs ... We look forward to data from LHCb and Super B factories to achieve this goal.

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