CP Violation and B Physics

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Introduction

All predictions of the standard model (SM) of particle physics have been confirmed – there is no doubt that it is correct. However, for a variety of reasons – hierarchy problem, large number of parameters, many unanswered questions, etc. – it is believed that there must be physics beyond the SM. The search for this new physics (NP) is the focus of virtually all work (experimental and theoretical) in particle physics today.

CP violation (C is charge conjugation, P is parity) is necessary to explain the lack of antimatter in the universe (i.e., the baryon-antibaryon asymmetry). CPV has been observed at low energies, and there is a SM explanation. However, this cannot also explain the CPV in the early universe. That is, there must be a new source of CPV.

Experiments are looking for CP-violating signals in disagreement with the SM, i.e., evidence for NP. In this talk I focus on CPV in the B system. I review the signals of NP, the results (to date) of searches for this NP, and future methods to search for NP in B decays.

CP Violation

Weak interactions: the W couples only to the left-handed (right-handed) components of fermions (antifermions). That is, the coupling to e_L^- differs from that to $e_R^- \Longrightarrow$ violation of P. Similarly, the coupling to e_L^- differs from that to $e_L^+ \Longrightarrow$ violation of C. But the couplings to e_L^- and e_R^+ are equal $\Longrightarrow$ CP conserved.

Kaons: 2 states seen:

$$\begin{aligned} K_S : &\qquad \tau_S \sim 10^{-10}\ \mathrm{sec}\ , \\ K_L : &\qquad \tau_L \sim 10^{-7}\ \mathrm{sec}\ . \end{aligned}$$

Decays:

$$\begin{aligned} K_S \to \pi\pi &\qquad CP = +\ , \\ K_L \to \pi\pi\pi &\qquad CP = -\ . \end{aligned}$$

Thus, K_S has CP $+$, K_L has CP $-$, and CP is conserved.

However, 1964: the decay $K_L \to 2\pi$ was observed. Small branching ratio ($\simeq 10^{-3}$), but shows that CP is violated.

$\Longrightarrow$ Define

$$K_1 \equiv \frac{1}{\sqrt{2}}\left[K^0 + \bar{K}^0\right] \quad (CP = +) ,$$
$$K_2 \equiv \frac{1}{\sqrt{2}}\left[K^0 - \bar{K}^0\right] \quad (CP = -) .$$

Physical states are linear combinations of CP $+$ et CP $-$:

$$K_S \equiv \frac{1}{1+|\epsilon|^2}\left[K_1 - \epsilon K_2\right] ,$$
$$K_L \equiv \frac{1}{1+|\epsilon|^2}\left[K_2 + \epsilon K_1\right] ,$$

with $|\epsilon| = 2.26 \times 10^{-3}$.

Theory: (1) no weak interactions: K^0 and $\bar{K}^0$ are stable. They are eigenstates of H with the same mass:

$$H = \begin{pmatrix} m_0 & 0 \\ 0 & m_0 \end{pmatrix} .$$

(2) Turn on weak interactions: K^0 and $\bar{K}^0$ can now decay $\Longrightarrow$ they are not eigenstates of H. Thus, $\exists$ K^0–$\bar{K}^0$ mixing. If CP is conserved:

$$H = \begin{pmatrix} m_0 & \Delta \\ \Delta & m_0 \end{pmatrix} .$$

Eigenstates: K_1 et K_2 (eigenstates of CP).

(3) Add CP violation:

$$H = \begin{pmatrix} m_0 & \Delta \\ \Delta^* & m_0 \end{pmatrix} \quad , \qquad \frac{1+\epsilon}{1-\epsilon} = \sqrt{\frac{\Delta}{\Delta^*}} .$$

Note: if Δ is real, $\epsilon = 0$ (CP conserved). Thus, CP violation is due to *phases* in the weak interactions.

SM Explanation of CP Violation

Weak interactions:

$$\begin{pmatrix} \bar{u}^0 & \bar{c}^0 & \bar{t}^0 \end{pmatrix} \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \begin{pmatrix} d^0 \\ s^0 \\ b^0 \end{pmatrix} W ~,$$

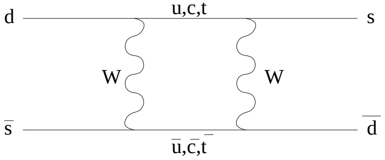
where the q^0 are the states that are involved in the weak interactions. But they are not the physical states (like $\{K^0, \bar{K}^0\}$ and $\{K_S, K_L\}$). In fact, the physical states u, c, t are linear combinations of u^0, c^0, t^0, and similarly for d, s, b and d^0, s^0, b^0.

This implies that $\exists$ transitions between all quarks with $Q_{em} = \frac{2}{3}$ $(u,~c,~t)$ and those with $Q_{em} = -\frac{1}{3}$ $(d,~s,~b)$. These couplings are parametrized by the Cabibbo-Kobayashi-Maskawa (CKM) matrix:

$$\begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} W ~, \qquad V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} ~.$$

V_{CKM} is unitary, and is parametrized by 3 angles (real) and one phase (complex). Point: with 3 generations, the weak interactions automatically include a phase. This phase is responsible for CP violation in the kaon system.

K^0–$\bar{K}^0$ mixing is automatically produced in the SM (box diagrams):



The K^0–$\bar{K}^0$ mixing amplitude is complex $\Longrightarrow$ $\epsilon \neq 0$.

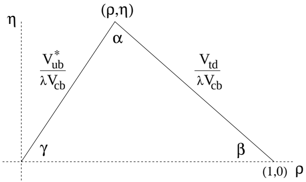
Based on the experimental data, only the corner elements have large phases:

$$V_{CKM} \simeq \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & V_{ts} & V_{tb} \end{pmatrix} .$$

The 1^{st} and 3^{rd} columns are orthogonal:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 = |V_{ud}||V_{ub}|e^{i\beta} + |V_{cd}||V_{cb}| + |V_{td}||V_{tb}|e^{-i\gamma} .$$

This is a triangular relation in the complex plane: the *unitarity triangle*:



Angles α, β and γ all proportional to η, nonzero values imply CP violation. We have $\alpha + \beta + \gamma = \pi$.

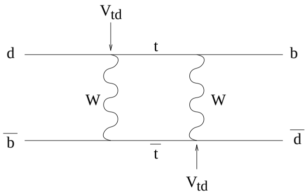
Test SM explanation: measure α, β and γ independently.

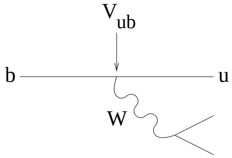
- Do we find that $\alpha + \beta + \gamma = \pi$?
- Are their values consistent with other measurements (e.g., sides of unitarity triangle)?
- Are all other CP-violating effects small?

$\mathbf{B_d^0}$, $\mathbf{\bar{B}_d^0}$ and $\mathbf{B^\pm}$

α, β, γ can all be measured without hadronic uncertainty in B decays.

- $|A(B \to f)|^2 \neq |A(\bar{B} \to \bar{f})|^2 \Longrightarrow$ CP violation: must have at least 2 contributing amplitudes with a relative weak phase.
- Due to B^0–$\bar{B}^0$ mixing, a particle "born" as a B^0 will become, in time, a combination of B^0 and $\bar{B}^0$: $B^0(t)$. The $B^0(t)$ can decay as a B^0 or $\bar{B}^0$. If both B^0 and $\bar{B}^0$ can decay to f, one can have interference between $B^0 \to f$ and $\bar{B}^0 \to f$, leading to CP violation.
- B decays include the two phases in the corner elements of V_{CKM}. β is found in B_d^0–$\overline{B_d^0}$ mixing, and γ appears in the transition $b \to u$:





$\Longrightarrow$ all angles of the unitarity triangle can be measured in B decays; various final states f can be used:

- α: $B_d^0(t) \to \pi\pi$, $\rho\pi$, $\rho\rho$, etc.
- β: $B_d^0(t) \to J/\psi K_S$, ϕK_S, etc.
- γ: $B \to DK$, etc.

2001: Belle and BaBar mesure $\sin 2\beta$ in $B_d^0(t) \to J/\psi K_S$. This is the first observation of CP violation outside the kaon system!

Latest values for the angles:

$$\alpha = \left(85.4^{+4.0}_{-3.9}\right)^\circ \ , \ \ \beta = \left(21.38^{+0.79}_{-0.77}\right)^\circ \ , \ \ \gamma = \left(68.0^{+8.0}_{-8.5}\right)^\circ \ .$$

Note: $\alpha + \beta + \gamma \simeq 180^\circ$. So this test does not reveal the presence of NP.

However, $\exists$ other tests. E.g., the SM predicts that
$A_{CP}(B_d^0(t) \to J/\psi K_S) = A_{CP}(B_d^0(t) \to \phi K_S) = \sin 2\beta$.

2003:

$$\begin{aligned} \text{BaBar}: \quad & A_{CP}(B_d^0(t) \to J/\psi K_S) = 0.76 \pm 0.07 \ , \\ & A_{CP}(B_d^0(t) \to \phi K_S) = -0.18 \pm 0.51 \pm 0.07 \ , \\ \text{Belle}: \quad & A_{CP}(B_d^0(t) \to J/\psi K_S) = 0.71 \pm 0.09 \ , \\ & A_{CP}(B_d^0(t) \to \phi K_S) = -0.73 \pm 0.64 \pm 0.22 \ . \end{aligned}$$

$\Longrightarrow$ NP!?

Unfortunately, 2012:

$$\begin{aligned} \text{BaBar}: \quad & A_{CP}(B_d^0(t) \to J/\psi K_S) = 0.657 \pm 0.036 \pm 0.012 \ , \\ & A_{CP}(B_d^0(t) \to \phi K_S) = 0.66 \pm 0.17 \pm 0.07 \ , \\ \text{Belle}: \quad & A_{CP}(B_d^0(t) \to J/\psi K_S) = 0.670 \pm 0.029 \pm 0.013 \ , \\ & A_{CP}(B_d^0(t) \to \phi K_S) = 0.90^{+0.09}_{-0.19} \ . \end{aligned}$$

No NP.

In $B \to V_1 V_2$ (V_i are spin-1 vector mesons), $\exists$ "triple product" (TP) observable $\vec{p} \cdot (\varepsilon_1 \times \varepsilon_1)$, where $\vec{p}$ is a final-state momentum in the rest frame of B and ε_i is the spin of V_i. The TP is odd under T (time reversal) $\Longrightarrow$ odd under CP (CPT theorem). Nonzero asymmetry between TP's in $B \to V_1 V_2$ and $\bar{B} \to \bar{V}_1 \bar{V}_2$ is signal of CP violation. SM predicts that all TP's $\simeq 0$ (A. Datta and D.L., Int. J. Mod. Phys. A **19**, 2505 (2004)).

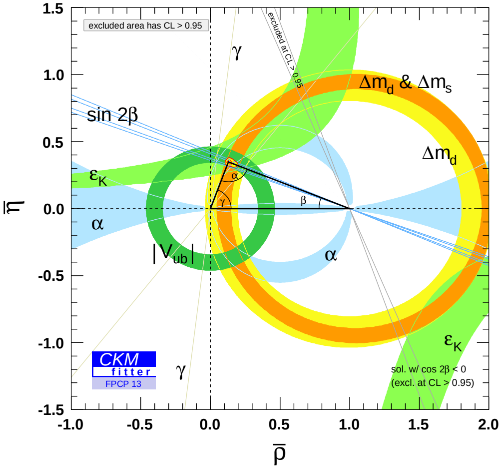
2004: BaBar measures nonzero TP asymmetry in $B_d^0 \to \phi K^{*0}$:

$$A_T^0 = +0.11 \pm 0.05 \pm 0.01 \ .$$

Signal only 1.7σ, but still...

By 2007, hint of NP has gone away. Both Belle and BaBar measure TP asymmetries in $B_d^0 \to \phi K^{*0}$ consistent with 0.

Combine angles and sides. Are they consistent?



Constraints on the unitarity triangle from measurements of α, β and γ, K^0–$\bar{K}^0$, B_d^0–$\overline{B_d^0}$ and B_s^0–$\overline{B_s^0}$ mixing, and $|V_{ub}|$. Quite consistent; not much room for NP.

Taken from the CKM-fitter web site.

So, do all B-decay measurements agree with the SM? No!

There are 4 $B \to \pi K$ decays: $B^+ \to \pi^+ K^0$, $B^+ \to \pi^0 K^+$; $B_d^0 \to \pi^- K^+$, $B_d^0 \to \pi^0 K^0$. The 4 amplitudes are related by isospin:

$$A(B^+ \to \pi^+ K^0) + \sqrt{2} A(B^+ \to \pi^0 K^+) \\ = A(B_d^0 \to \pi^- K^+) + \sqrt{2} A(B_d^0 \to \pi^0 K^0) \ .$$

They are described by 8 unknown theoretical parameters.

There are 10 experimental observables: 8 branching ratios (B and $\bar{B}$), 1 mixing-induced CP-violating asymmetry, and the weak phase γ – all have been measured. More observables than unknowns $\Longrightarrow$ can do a fit.

Find: $\chi^2/d.o.f. = 3.2/2$. Corresponds to a disagreement with the SM at the level of 1-2σ. Not statistically significant. But in addition, the best-fit values of some of the unknowns are at odds with theory. Not a definitive signal of NP, but still problematic. Known as the "$B \to \pi K$ puzzle."

$B \to K^*(\to \bar{K}^0\pi)\mu^+\mu^-$: with 4 particles in the final state, the angular distribution is complicated, and there are many observables. These include the leptonic forward-backward asymmetry A_{FB}, the differential branching ratio, K^* spin-dependent asymmetries, etc. (CP conserving), and various TPs (CP violating). Many of these have been measured by LHCb (dedicated B-physics experiment at the LHC, CERN).

In S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D **88**, 074002 (2013), an optimized set of observables is used, with a limited sensitivity to hadronic inputs (form factors). It is found that there is a discrepancy with the SM of between 3.5σ and 4.2σ, depending on which observables are included.

Strong hint of NP – will have to keep an eye on this.

$B \to D^{(*)}\tau\nu_\tau$: measure two ratios

$$R(D) = \frac{\Gamma(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\Gamma(\bar{B} \to D\ell^-\bar{\nu}_\ell)} \ , \qquad R(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\Gamma(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)} \ ,$$

where $\ell = e$ or μ. (CP-conserving process.)

SM predicts $R(D) = 0.297 \pm 0.017$ and $R(D^*) = 0.252 \pm 0.003$.

BaBar finds $R(D) = 0.440 \pm 0.072$ and $R(D^*) = 0.332 \pm 0.030$. Combined deviation: 3.4σ above SM. Belle does not quote average R values. However, a 'private average' given by A. Bozek of Belle (presented at FPCP2013), leads to a combined BaBar + Belle deviation of 4.8σ.

Strong hint of NP. Charged Higgs? Leptoquarks?

$\mathbf{B_s^0}$ and $\mathbf{\bar{B}_s^0}$

$B_s^0 \to \mu^+\mu^-$: in SM, branching ratio predicted to be $(3.35 \pm 0.32) \times 10^{-9}$. (CP-conserving process.)

2011: CDF Collaboration (Fermilab) reports

$$B(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8} \ .$$

Hint of NP.

2012: Unfortunately, LHCb does not confirm this:

$$B(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9} \ .$$

No NP.

2010: DØ (Tevatron, Fermilab) measured the CP-violating asymmetry

$$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} ~,$$

where $N_b^{\pm\pm}$ is the number of $b\bar{b} \to \mu^\pm \mu^\pm X$ events. This measurement disagrees with the SM at the level of 3.9σ.

An analysis of this result, which included other measurements, concluded that new CP-violating physics could be present in B_d^0–$\overline{B_d^0}$ and/or B_s^0–$\overline{B_s^0}$ mixing, possibly up to the level of 40%.

2012: LHCb measured the phase of B_s^0–$\overline{B_s^0}$ mixing, β_s, in $B_s^0(t) \to J/\psi\phi$:

$$\beta_s = (-0.1 \pm 5.8~({\rm stat}) \pm 1.5~({\rm syst}))^\circ ~.$$

This is consistent with the SM, which predicts $\beta_s \simeq 0$. But the errors are still large enough that one can not rule out new physics.

The analysis of the DØ result was updated, taking into account the LHCb measurement. Conclusion: the SM is still disfavoured at the level of 2.4σ. One can eliminate the disagreement if there is new physics in B_d^0–$\overline{B_d^0}$ and/or B_s^0–$\overline{B_s^0}$ mixing, but now the effect cannot be too large.

2013: latest measurements of β_s by LHCb:

$$\begin{aligned} \beta_s(B_s^0(t) \to J/\psi\phi) &= (-2.0 \pm 2.6\ (\mathrm{stat}) \pm 0.3\ (\mathrm{syst}))^\circ\ , \\ \beta_s(B_s^0(t) \to J/\psi\pi^+\pi^-) &= (-0.3 \pm 2.0\ (\mathrm{stat}) \pm 0.3\ (\mathrm{syst}))^\circ\ . \end{aligned}$$

2013: LHCb has measured the two TPs in $B_s^0 \to \phi\phi$. They find

$$\begin{aligned} \mathcal{A}_u &= -0.055 \pm 0.036\ (\mathrm{stat}) \pm 0.018\ (\mathrm{syst})\ , \\ \mathcal{A}_v &= 0.010 \pm 0.036\ (\mathrm{stat}) \pm 0.018\ (\mathrm{syst})\ . \end{aligned}$$

No sign of NP.

Future: LHCb will measure the angular distribution of $B_s^0 \to K^{*0} \bar{K}^{*0}$. There are many CP-violating observables – direct CP asymmetries, TPs (B. Bhattacharya, A. Datta, M. Duraisamy and D.L., Phys. Rev. D **88**, 016007 (2013)). All are predicted to be $\simeq 0$ in the SM, so the observation of a nonzero value of any of them would be a signal of NP.

3-Body Decays

The standard way to obtain clean information about CKM phases is through the measurement of indirect CPV in $B^0/\bar{B}^0 \to f$. This requires that f be a CP eigenstate. Conventional wisdom: one cannot obtain such clean information from 3-body decays because final states such as $K_S\pi^+\pi^-$ are not CP eigenstates – the value of its CP depends on whether the relative $\pi^+\pi^-$ angular momentum is even (CP $+$) or odd (CP $-$).

And even if one could fix the CP sonehow, can only measure indirect CPV and get clean weak-phase information if decay is dominated by amplitudes with a single weak phase. But in general these decays receive significant contributions from amplitudes with a different weak phase. Need a way of dealing with this "pollution."

Recently it was shown that all of these difficulties can be overcome:

M. Imbeault, N. Rey-Le Lorier, D.L., Phys. Rev. D **84**, 034040 (2011), 034041 (2011);

N. Rey-Le Lorier, D.L., Phys. Rev. D **85**, 016010 (2012).

(1) Dalitz plots: in $B \to P_1 P_2 P_3$, one defines the three Mandelstam variables $s_{ij} \equiv (p_i + p_j)^2$, where p_i is the momentum of P_i. (The three s_{ij} are not independent, but obey $s_{12} + s_{13} + s_{23} = m_B^2 + m_1^2 + m_2^2 + m_3^2$.) The Dalitz plot is given in terms of two Mandelstam variables, say s_{12} and s_{13}. Key point: using an isobar analysis, one can reconstruct the full decay amplitude $\mathcal{M}(B \to P_1 P_2 P_3)(s_{12}, s_{13})$.

The amplitude for a state with a given symmetry is then found by applying this symmetry to $\mathcal{M}(s_{12}, s_{13})$. In the following examples, we will want the fully-symmetric final state. The amplitude for this state, $\mathcal{M}_{\rm fs}$ ('fs' = 'fully symmetric'), is found by symmetrizing $\mathcal{M}(s_{12}, s_{13})$ under all permutations of 1,2,3.

(2) Diagrams: one first expresses the full amplitude in terms of diagrams. As in 2-body decays, one can remove the pollution due to additional decay amplitudes, and isolate the desired weak phase, by combining different decays related by a symmetry.

Application #1: the 5 decays $B_d^0 \to K^+\pi^0\pi^-$, $B_d^0 \to K^0\pi^+\pi^-$, $B^+ \to K^+\pi^+\pi^-$, $B_d^0 \to K^+K^0K^-$, and $B_d^0 \to K^0K^0\bar{K}^0$ are related by flavour SU(3). By combining information from their Dalitz plots (measured by BaBar), we can cleanly extract γ.

B. Bhattacharya, M. Imbeault and D.L., Phys. Lett. B **728**, 206 (2014).

Using a maximum likelihood fit, we find four preferred values for γ:

$$(31^{+2}_{-3})^\circ \quad , \quad (77 \pm 3)^\circ \quad , \quad (258^{+4}_{-3})^\circ \quad , \quad (315^{+3}_{-2})^\circ \ .$$

Three of these indicate new physics (is this a "$K\pi\pi$-$KK\bar{K}$ puzzle"?), but one solution – $(77 \pm 3)^\circ$ – is consistent with the standard model.

In all cases, the error is small, 2-4°. This is because the method applies to each point in the Dalitz plot, and we have averaged over all points. But note: we have not included the error due to correlations, and this could be important.

Application #2: LHCb has measured direct CP asymmetries in $B^+ \to K^+\pi^+\pi^-$, $B^+ \to K^+K^+K^-$, $B^+ \to K^+\pi^+K^-$ and $B^+ \to \pi^+\pi^+\pi^-$, with larger asymmetries observed in localized regions of the Dalitz plot. Problem: due to the requirement of strong phases, one cannot make clean predictions of direct CP asymmetries in the SM $\Longrightarrow$ cannot tell if the LHCb results suggest NP.

However, under SU(3), the SM predicts that

$$\begin{aligned} \sqrt{2}\mathcal{A}(B^+ \to K^+\pi^+\pi^-)_{\rm fs} &= \mathcal{A}(B^+ \to K^+K^+K^-)_{\rm fs} ~, \\ \sqrt{2}\mathcal{A}(B^+ \to K^+\pi^+K^-)_{\rm fs} &= \mathcal{A}(B^+ \to \pi^+\pi^+\pi^-)_{\rm fs} ~. \end{aligned}$$

LHCb has measured the Dalitz plots for these decays $\Longrightarrow$ these relations can be examined *now*, providing clean tests of the SM.

B. Bhattacharya, M. Gronau, M. Imbeault, D.L., J. Rosner, arXiv:1402.2909.

Conclusions

The purpose of measuring CP-violating observables in the B system is to test the SM explanation of CP violation, namely the CKM matrix. Now, we know that there must exist physics beyond the SM. As such, the real hope is that the study of CP violation in B decays will reveal the presence of this new physics. So far, this has not happened.

There have been a number of hints of NP that have gone away. And there are still some intriguing discrepancies with the predictions of the SM. We now know that any NP signals will be small. (This is consistent with the fact that no non-SM physics has been seen at the LHC.)

Flavor physics is complementary to collider physics – both direct and indirect signals of physics beyond the SM are necessary to identify it. For this reason, the search for NP in the B system continues. LHCb will continue to take data for some years. And soon Belle II will start running. Hopefully we will see some clear evidence for NP in B decays.