CP violation in B meson decays

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CP violation in neutral B meson decays has been observed confirming the prediction of the Kobayashi-Maskawa model where introduction of six quarks naturally induces CP violation in the weak interaction. The measurements of CP asymmetry in B meson decays were made at the newly constructed Asymmetric B factories, which consist of high luminosity, energy-asymmetric e+e- colliders (KEKB and PEP-II) and detectors (Belle and BaBar). The results are in good agreement and are consistent with other experimental results within the framework of the Standard Model.

1. INTRODUCTION

CP violation is one of the most fundamental mysteries of the universe. The first experimental evidence for CP violation was observed in the decay of the neutral kaon system in 1964 [1] and was not suggested by theory. In 1973, when only three quarks were known, Kobayashi and Maskawa (KM) introduced a six quarks hypothesis in order to naturally accommodate CP violation to the theory of weak interaction [2]. The subsequent discovery of the c, b and t quarks strongly suggested the validity of the KM model for CP violation. In 1980, Sanda, Carter and Bigi pointed out that the KM model contains the possibilities of sizable CP violation in certain decay modes of neutral B mesons [3]. The subsequent measurement of the lifetimes of B mesons and observation of large $B^0\bar{B}^0$ mixing indicated that the measurements of CP violation in B decays would provide important tests of the KM model.

In contrast to the theoretical progress, CP violation was not observed experimentally in any system other than the neutral kaon system during the twentieth century. In 2001, however, two international collaborations, BaBar and Belle groups, announced the observation of CP violation in neutral B meson decays [4,5].

This article is a brief review of theoretical background, experimental methods and the recent results on the CP violation measurement in B meson decays from the Belle and BaBar groups.

1.1. Kobayashi-Maskawa model

In the Standard Model, the quark mass eigenstates are not the same as the weak eigenstates, and the matrix relating these states for six quarks was given by Kobayashi and Maskawa [2]. Conventionally, the mixing is expressed in terms of the $3\times3$ unitary
Cabibbo-Kobayashi-Maskawa (CKM) matrix, as shown below:

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} = \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix},
\]

and the CKM matrix elements must contain at least an irreducible complex phase. Generally, the complex phase is assigned to the furthest off-diagonal matrix elements, \( V_{ub} \) and \( V_{td} \).

The Lagrangian for weak decays of quarks and its \( CP \) conjugate are expressed as:

\[
-L = (g_W/\sqrt{2}) \sum_{j,k} N \left[ \bar{u}_{jL} \gamma^{\mu} V_{jk} d_{kL} W_{j\mu}^+ + \bar{d}_{kL} \gamma^{\mu} V_{jk}^* u_{jL} W_{k\mu}^- \right]
\]

\[
-L^{CP} = (g_W/\sqrt{2}) \sum_{j,k} N \left[ \bar{d}_{kL} \gamma^{\mu} V_{jk}^* u_{jL} W_{k\mu}^- + \bar{u}_{jL} \gamma^{\mu} V_{jk} d_{kL} W_{j\mu}^+ \right],
\]

where \( V_{jk} \) are the CKM matrix elements. If some of CKM matrix elements are complex, then these Lagrangians are not the same, and \( CP \) violation appears naturally.

Unitarity of the CKM matrix gives the following relation involving \( V_{ub} \) and \( V_{td} \):

\[
V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0.
\]

The three terms form a closed triangle in the complex plane, call the ‘unitarity triangle’. The three internal angles are defined as,

\[
\phi_1 = \pi - \arg \left( \frac{V_{ub}}{V_{cd}} \right) = \beta,
\]

\[
\phi_2 = \arg \left( \frac{V_{ud}}{V_{cd}} \right) = \alpha,
\]

\[
\phi_3 = \arg \left( \frac{V_{ub}}{V_{ud}} \right) = \gamma.
\]

Two naming conventions for these angles are commonly used in the literature, but I mainly use \( \phi_1 \) notation in this article. If there is no \( CP \) violation, then the internal angle \( \phi_1 \) must be zero. Therefore the observation of non-zero values for \( \phi_1 \) directly indicate the existence of \( CP \) violation in \( B \) meson decays within the framework of the KM model.

1.2. \( CP \) asymmetry in neutral \( B \) meson decays

The internal angles of the unitarity triangle are closely related to the decay of neutral \( B \) meson system. As in the neutral kaon system, the mixing between \( B^0 \) and \( \bar{B}^0 \) causes the time evolution of an initially pure \( B^0 \) (or \( \bar{B}^0 \)) state into a \( B^0(t) \) (or \( \bar{B}^0(t) \)) state which is an admixture of \( B^0 \) and \( \bar{B}^0 \) states at proper time \( t \). Suppose \( B^0(t) \) and \( \bar{B}^0(t) \) decay into \( CP \) eigenstate \( f_{CP} \), the decay rates at proper time \( t \) is:

\[
\Gamma(B^0(t) \to f_{CP}) = |A|^2 e^{-\Gamma t} \left[ \frac{1 + |\lambda_f|^2}{2} \cos(\Delta M t) - \frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) \right]
\]

\[
\Gamma(\bar{B}^0(t) \to f_{CP}) = |A|^2 e^{-\Gamma t} \left[ \frac{1 + |\lambda_f|^2}{2} - \frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) + \text{Im} \lambda_f \sin(\Delta M t) \right]
\]
where $A$, $\bar{A}$ and $\lambda_f$ are defined as

$$A = \langle f_{CP} | H | B^0 \rangle, \quad \bar{A} = \langle f_{CP} | H | B^0 \rangle, \quad \lambda_f = \frac{q \bar{A}}{p A}$$

Here, $p$ and $q$ are the parameters for mixing $CP$ violation of neutral $B$ mesons, and $\Delta M$ denotes the mass difference between the two mass eigenstates of neutral $B$ mesons. A time dependent $CP$ violating asymmetry $A_{CP}$ is then given by

$$A_{CP}(t) = \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

$$= \frac{2 \text{Im} \lambda_f}{1 + |\lambda_f|^2} \sin(\Delta M t) - \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \cos(\Delta M t)$$

$$= S_f \sin(\Delta M t) + A_f \cos(\Delta M t) \quad (8)$$

The standard model predicts

$$q = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}} = \exp(-2i\phi_{\text{mixing}}). \quad (9)$$

If only one amplitude (or two with the same weak phase) contributes to $A$ and $\bar{A}$ then $|\bar{A}/A| = 1$, which is equivalent to $|\lambda_f| = 1$, and the relationship between the measured asymmetry and KM phase is cleanly predicted by

$$A_{CP}(t) = \text{Im} \lambda_f \sin(\Delta M t) = -\xi_f \sin 2(\phi_{\text{mixing}} + \phi_{\text{decay}}) \sin(\Delta M t) \quad (10)$$

Here we define $\bar{A}/A = \xi_f \exp(-2i\phi_{\text{decay}})$, where $\xi_f = \pm1$ is the $CP$ eigenvalue of the state $f_{CP}$. Note that the combination $\phi_{\text{mixing}} + \phi_{\text{decay}}$ is parameterization independent. This is the $CP$ violation due to the interference between decays with and without $B^0\bar{B}^0$ mixing.

Note that the asymmetry vanishes when it is integrated over time. Therefore the measurement of the time difference of the neutral $B$ meson decays is essential to the observation of this mixing enhanced $CP$ violation. This is the motivation for the construction of a new type of asymmetric energy $e^+e^-$ collider, which is described in the next section.

2. EXPERIMENTAL APPARATUS

In order to measure the $CP$ asymmetry in neutral $B$ meson decays, the experimental apparatus must 1) produce a lot of $B$ mesons, 2) find $CP$ eigenstate decays, 3) identify $B$ meson flavors and 4) measure the decay time difference. The $\Upsilon(4S)$ is the best source of $B^0\bar{B}^0$ pairs. However, in the rest frame of $\Upsilon(4S)$, the mean flight length of $B$ mesons is only about 25 $\mu m$, which is too short to be detected with present detector technology in a collider experiment. To solve the problem, a new idea was proposed. By making the energies of colliding beams asymmetric, the whole system is Lorentz boosted, and the decay lengths of $B$ mesons are dilated and become measurable with our present experimental devices [6].
New B factories, called 'Asymmetric B Factories', are proposed and constructed. They consist of high-luminosity, energy-asymmetric $e^+e^-$ colliders (KEKB at KEK and PEP-II at SLAC) equipped with high quality 4π detectors (Belle at KEKB and BaBar at PEP-II). The energies of KEKB (PEP-II) are 8.0 (9.0) GeV for electrons and 3.5 (3.1) GeV for positrons. The Lorentz boost factors ($\beta\gamma$) are 0.43 and 0.56 for KEKB and PEP-II, respectively. Both colliders have broken luminosity records and KEKB has achieved the world record of luminosity, $8 \times 10^{33}$ cm$^{-2}$ sec$^{-1}$, which is about one order of magnitude higher than that of CESR which was the first type of Symmetric B Factory.

The detectors BaBar [7] and Belle [8] have similar specifications. From innermost part are a silicon vertex detector, a central drift chamber, a particle identification system, an electromagnetic calorimeter consisting of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field, an iron flux-return located outside of the coil, instrumented with a detector for $K_L$ meson detection and muon identification. Both detectors have so far accumulated integrated luminosities about 90 fb$^{-1}$ by 2002.

3. DATA ANALYSES

In the experiment at asymmetric energy $e^+e^-$ collider, the time-dependent $CP$ asymmetries are measured as follows. An electron and positron with different energies collide to produce a $\Upsilon(4S)$, which immediately decays into a $P$-wave $B\bar{B}$ pair. The $B$ and $\bar{B}$ evolve coherently until one of them decays. When one of $B$ mesons decays into a flavor specific final state (tag-side), e.g., $B$, then the other must be $\bar{B}$ at that time. This is called flavor tagging. If one of $B$ mesons decay into a $CP$ eigenstate ($CP$-side) at $\Delta t$ after the flavor tagging, then we can measure time-dependent $CP$ asymmetries. The time interval $\Delta t$ is defined by

$$\Delta z \equiv z_{CP} - z_{tag} = \beta\gamma c \Delta t,$$

where $\Delta z$ is the distance between the two decay vertices along the beam direction and $\beta$ is the velocity of $B$ meson.

The analysis methods of Belle and Babar group are slightly different but essentially same. It may be worth noting that both groups adopted blind analysis strategies. The final results are hidden by adding some random numbers until the very final stage of the analyses. Once they open the results, they do not change the analysis methods at all to avoid human biases.

In this article, I describe Belle's analysis procedure, and refer to Babar's if necessary.

4. RESULTS

4.1. Measurement of $\sin 2\phi_1$

The decay mode: $B^0 \to J/\psi K_S^0 \to \ell^+\ell^-\pi^+\pi^-$ is a clean and most promising channel for the measurement of $\phi_1$, of the unitarity triangle, and is called the 'golden mode'. In the Standard Model, there are two classes of quark-level diagrams that contribute to hadronic $B$ decays, i.e., tree diagrams and penguin diagrams. Tree diagrams are those where the $W$ produces an additional quark-antiquark pair. Penguin diagrams are loop diagram where the $W$ reconnects to the same quark line. In the Golden Mode, since the dominant penguin diagram has the same weak phase as the tree diagram and the remaining term
is tiny, there is only one weak phase in the decay amplitude. Hence, in the asymmetry expression, all dependence on the amplitudes cancel out. To a good approximation,

$$\lambda_f \equiv \frac{q A}{p A} \approx \frac{V_{td}^* V_{td}}{V_{ts}^* V_{ts}} \frac{V_{cs}^* V_{cb}}{V_{cs}^* V_{cs}} \frac{V_{cd}^* V_{cd}}{V_{cs}^* V_{cs}} = -\exp(-2i\phi_1)$$

(12)

where the last factor arises from the $K^0\bar{K}^0$ mixing amplitude and appears because of the $K_S$ in the final state. The asymmetry $A_{CP}$ is then given by

$$A_{CP}(\Delta t) = -\xi_f \sin 2\phi_1 \sin(\Delta M \Delta t)$$

(13)

The same results can be obtained when $(\bar{c}\bar{c})K_{S,L}$ is chosen as the final state of the $B$ decay, where $(\bar{c}\bar{c})$ is one of the charmonium states. The decay modes used as $CP$ eigenstates are the following: $J/\psi K_S, \psi(2S)K_S, \chi_{c1}K_S, \eta_cK_S$ for $\xi_f = -1$ and $J/\psi K_L$ for $\xi_f = +1$.

For these candidates, $B$ mesons are reconstructed by using the energy difference $\Delta E \equiv E_B - E_{\text{beam}}$ and beam-energy constrained mass $m_{bc} \equiv \sqrt{(E_{\text{beam}})^2 - (p_B)^2}$, where $E_{\text{beam}}$ is the beam energy in the center-of-mass system (cms) of the $\Upsilon(4S)$, and $E_B$ and $p_B$ are the cms energy and momentum of the reconstructed $B$ candidate, respectively.

Inclusive charged leptons, pions, kaons and $\Lambda$ baryons that are not associated with a reconstructed $CP$ eigenstate decay are used to identify the flavor of the accompanying $B$ meson. Flavor tagging is diluted by misidentification of the parent $B$ mesons (wrong tagging). In order to estimate the wrong-tag fraction, the Belle group, for example, adopted the following method. Based on the measured properties of charged tracks, two parameters, $q$ and $r$, are assigned to an event. The parameter $q$ is assigned $+1$ ($-1$) when the tag-side $B$ meson is likely to be a $B^0(\bar{B}^0)$, and $r$ is an event-by-event flavor tagging dilution factor determined by Monte Carlo, which ranges from $r = 0$ for no flavor tagging and $r = 1$ for unambiguous flavor tagging. It is used only to sort data into six intervals of $r$, according to estimated flavor purity. The wrong-tag fraction, $w_l(l = 1, 6)$, that are used in the final $CP$ fit are determined using time-dependent $B^0\bar{B}^0$ mixing oscillation:

$$\frac{N_{OF} - N_{SF}}{N_{OF} + N_{SF}} = (1 - 2w_l) \cos(\Delta M \Delta t),$$

(14)

where $N_{OF}$ and $N_{SF}$ are numbers of opposite and same flavor events. The effective tagging efficiency is determined to be $\epsilon_{eff} \equiv \sum_{l=1}^6 e_l(1 - 2w_l)^2 = 0.288 \pm 0.006$, where $e_l$ is the event fraction for each $r$ interval [11]. The error includes both statistical and systematic uncertainties. Babar group adopted somewhat different method from Belle' one, but they obtain a similar effective efficiency, $\epsilon_{eff} = 0.281 \pm 0.007$ [12].

The vertex position for the decay into the $CP$ eigenstate ($f_{CP}$) is reconstructed using leptons from $J/\psi$ decays or charged hadrons from the $\eta_c$ decay, and that for the decay into the flavor specific state ($f_{tag}$) is obtained with well-reconstructed tracks that are not assigned to $f_{CP}$. Each vertex position is required to be consistent with the interaction region profile. The proper time interval resolution function is formed by convolving the following components: the detector resolution, the shift in the tag-side vertex position due to secondary tracks originating from charmed particle decays, and smearing due to the kinematic approximation used to convert $\Delta z$ to $\Delta t$. Twelve resolution parameters are
Figure 1. The $\Delta t$ distributions for the events with $q_{f} = +1$ (solid circles) and $q_{f} = -1$ (open circles). The results of the global fit with $\sin 2\phi_1 = 0.719$ are shown as solid and dashed curves, respectively (Belle collaboration) [11].

determined from fits of data to the neutral and charged $B$ meson lifetimes. An average $\Delta t$ resolution is about 1.43 ps (rms) for Belle detector [9].

Figure 1 shows the observed $\Delta t$ distributions for the $q_{f} = +1$ (solid circles) and $q_{f} = -1$ (open circles) event samples from Belle group. The asymmetry between the two distributions clearly demonstrates the $CP$ violation. The $CP$ violation parameter $\sin 2\phi_1$ is determined from an unbinned maximum-likelihood fit to the observed $\Delta t$ distributions. The probability density function (PDF) expected for the signal distribution is given by

$$P_{\text{sig}}(\Delta t, q, w_1, \xi_f) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times [1 - q_{f} (1 - 2w_1) \sin 2\phi_1 \sin (\Delta M \Delta t)],$$

(15)

where the $B^0$ lifetime $\tau_{B^0}$ and mass difference $\Delta M$ are fixed at their world average values [10]. The PDF is convolved with the appropriate $\Delta t$ resolution functions to determine the likelihood for each event as a function of $\sin 2\phi_1$. The PDF for combinatorial background events is modeled as a sum of exponential and prompt components convolved with a sum of two Gaussians, which is regarded as a resolution function for the background. The only free parameter in the final fit is $\sin 2\phi_1$, which is determined by maximizing the likelihood functions.

The results of the fit from Belle [11] and BaBar [12] are,

$$\sin 2\phi_1 = 0.719 \pm 0.074(\text{stat}) \pm 0.035(\text{syst}) : \text{Belle}$$

$$= 0.741 \pm 0.067(\text{stat}) \pm 0.033(\text{syst}) : \text{BaBar},$$

These results agree well and definitely confirm the existence of $CP$ violation in the $B$ meson system.

Figure 2 shows a comparison of the allowed region in the $\rho-\eta$ plane from the Belle $\sin 2\phi_1$ measurement with other experimental results. These results are in good agreement with the prediction of the Standard Model and indicate the validity of the Kobayashi-Maskawa scheme.
Figure 2. The comparison between sin 2\phi_1 measured by Belle group and other experimental results on the rescaled unitarity triangle [10].

4.2. CP violation in B^0 → π^+π^−

The decay B^0 → π^+π^- is a possible mode for the measurement of \phi_2. If only the tree diagram (b → u\bar{d}d) contributes, then,

\[
\lambda_f \approx \frac{V_{tb}V_{td}}{V_{tb}V_{td}^*} \cdot \frac{V_{ub}V_{ud}}{V_{ub}V_{ud}^*} = \exp (-2i (\phi_1 + \phi_3)) = \exp (-2i (\pi - \phi_2)) = \exp (2i\phi_2)
\]

(16)

and the time dependent CP asymmetry becomes simple,

\[
A_{CP}(\Delta t) = \sin 2\phi_2 \sin(\Delta M\Delta t).
\]

(17)

In this decay, however, the penguin diagrams (b → d\bar{u}u) cannot be neglected and the weak and strong phases of these diagrams are different, therefore the extraction of \phi_2 is not straightforward. Theoretically, the penguin contribution can be removed by means of an isospin analysis using the decays B^0 → π^+π^−, B^0 → π^0π^0 and B^± → π^±π^0 [13], but experimentally it is not easy to measure these decays with enough statistics.

On the other hand, the B^0 → π^+π^- decay provides an opportunity to observe direct CP violation if |\lambda_f| ≠ 1 or equivalent to |A/A| ≠ 1. The direct CP violation term has a cos(\Delta M\Delta t) time dependence in A_{CP}. The Belle group measured this decay mode using a 41.8 fb^-1 data sample, which contains 44.8 million B\bar{B} pairs [14]. The signal yield is extracted by fitting the ΔE distribution with a Gaussian π^+π^- signal function plus contributions from misidentified B^0 → K^+π^- events, three-body B-decays and continuum background. From the fit, they obtain 73.5 ± 13.8(stat) π^+π^- events, 28.4 ± 12.5(stat) K^+π^- events and 98.7 ± 7.0(stat) continuum events in the signal region. The K^+π^- contamination is consistent with the K → π misidentification probability measured independently. The contribution from three-body B-decays is negligible in the signal region.
Flavor tagging and vertexing follow the same procedure used for the $\sin 2\phi_1$ measurement. The $\Delta t$ resolution for the signal is obtained by convolving a sum of two Gaussians with a function that takes into account the cms motion of the $B$ mesons. The background resolution function, which is dominated by the continuum background, has the same functional form but the parameters are obtained from a side band region in $m_{bc}$ and $\Delta E$. Using these resolution functions, they perform a $B^0$ lifetime measurement that yields $\tau_{B^0} = 1.49 \pm 0.21$ (stat) ps for $B^0 \to \pi^+\pi^-$ candidates, which is consistent with the world average [10]. They determined the CP violation parameter by performing an unbinned maximum likelihood fit of a CP-violating PDF to the $\Delta t$ distributions (Figure 3).

The result of the fit to the 162 candidates (92 $B^0$ and 70 $\bar{B}^0$ tags) that remain after flavor tagging and vertex reconstruction is:

$$S_{\pi\pi} = -1.21^{+0.38}_{-0.27} \text{ (stat) } ^{+0.16}_{-0.13} \text{ (syst)};$$

$$A_{\pi\pi} = +0.94^{+0.22}_{-0.31} \text{ (stat) } \pm 0.09 \text{ (syst)}.$$

The result is 1.3σ away from the physical boundary $S_{\pi\pi}^2 + A_{\pi\pi}^2 = 1$, which is consistent with a statistical fluctuation.

They performed a number of cross checks. They examined the event yield and $\Delta t$ distributions for $B^0$- and $\bar{B}^0$-tagged events in the sideband region and find no significant asymmetry. They select $B^0 \to K^+\pi^-\nu$ candidates, which have the same topology as $B^0 \to \pi^+\pi^-$, by positively identifying charged kaons. The fitted result is:

$$S_{\pi\pi} = \ 0.15 \pm 0.24;$$

$$A_{\pi\pi} = 0.07 \pm 0.17.$$

which is consistent with null asymmetry as expected.

So far the result on the $B^0 \to \pi^+\pi^-$ measurement by Belle group seems reasonable and suggests the presence of direct CP violation in $B$ meson decays.

Contrary to that, however, Babar group reported a quite different result of the measurement of the same $B$ meson decays [15],

$$S_{\pi\pi} = \ 0.02 \pm 0.34 \text{ (stat) } \pm 0.05 \text{ (syst)};$$

$$C_{\pi\pi} = -0.30 \pm 0.25 \text{ (stat) } \pm 0.04 \text{ (syst)}.$$  

where $C_{\pi\pi} = -A_{\pi\pi}$ by definition. The BaBar result is consistent with null CP asymmetry in this decay.

The difference of these two results seems large but is within about 3σ, therefore a statistical fluctuation cannot be avoided at this stage. More statistics and detailed cross checks are needed to confirm the direct CP violation in $B^0 \to \pi^+\pi^-$ decay.

5. SUMMARY

After the discovery of CP violation in the $K$ meson system, no other CP violation has been seen until recently. Kobayashi and Maskawa introduced a model that explains CP violation in the weak interaction by introducing 6 quarks. Sanda and his collaborators pointed out that sizable CP violation in neutral $B$ meson decays is expected within
Figure 3. The $\Delta t$ distributions for the $B^0 \rightarrow \pi^+\pi^-$ candidates in the signal region: (a) candidates with $q = +1$, i.e. the tag side is identified as $B^0$; (b) candidates with $q = -1$; (c) $\pi^+\pi^-$ yields after background subtraction. The errors are statistical only and do not include the error of the subtracted background obtained by a fit. (d) the $CP$ asymmetry for $B^0 \rightarrow \pi^+\pi^-$ after background subtraction. (e) the $CP$ asymmetry for $B^0 \rightarrow \pi^+\pi^-$ sideband events. In Figs. (a) through (c), the curves show the results of the unbinned maximum likelihood fit. In Fig. (d), the solid curve shows the resultant $CP$ asymmetry, while the dashed (dotted) curve is the contribution from the cosine (sine) term.
the framework of the Kobayashi-Maskawa model. This theoretical work motivated the
construction of the asymmetric energy $e^+e^-$ colliders (KEKB and PEP-II) and the ac-
companying detectors (Belle and BaBar) designed to detect $CP$ violation in $B$ meson
decays.

The Belle and BaBar groups observed (2001) and confirmed (2002) the existence of $CP$
violation in the neutral $B$ meson system. The $CP$ violation parameter $\sin 2\phi_1 (= \sin 2\beta)$ is
definitely non-zero and lies in a region on the rescaled unitarity triangle, that is expected
by combining many other different experiments within the Standard Model. The first
step in the $B$ meson $CP$ violation program has been successfully completed with the
measurement of $\sin 2\phi_1$.

One of the next steps is a search for a different type of $CP$ violation, e.g., direct $CP$
v violation in $B$ meson decays. An indication of direct $CP$ violation in $B$ meson decay
has been reported by the Belle group from their measurement of $B^0 \rightarrow \pi^+\pi^-$, while the
BaBar group has reported a different result that is consistent with no $CP$ asymmetry.
More statistics and cross checks are needed to derive a decisive conclusion for direct $CP$
v violation at this stage.

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