Results on CP Violation from Belle

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Abstract. I describe the recent measurement of the CP violating parameter $\sin 2\phi_1 = (0.99 \pm 0.14 \pm 0.05)$ from the Belle experiment at KEK.

INTRODUCTION

In 1973, Kobayashi and Maskawa (KM) first proposed a model where CP violation is incorporated as an irreducible complex phase in the weak-interaction quark mixing matrix \cite{1}. The idea was remarkable and daring because it required the existence of six quarks at a time when only the $u$, $d$ and $s$ quarks were known to exist. The subsequent discoveries of the $c$, $b$ and $t$ quarks, and the compatibility of the model with the CP violation observed in the neutral kaon system led to the incorporation of the KM mechanism into the Standard Model, even though it had not been conclusively tested experimentally.

In 1981, Sanda, Bigi and Carter pointed out that a consequence of the KM model was that large CP violating asymmetries could occur in certain decay modes of the $B$ mesons\cite{2}. These asymmetries may occur when a neutral $B$ meson decays to a CP eigenstate. In this case the amplitude for the direct decay interferes with that for the process where the $B$ meson first mixes to a $B$ meson that then decays to the CP eigenstate.

The unitarity of the CKM matrix implies that the existence of three measurable phases. In the “Nihongo” convention, these are denoted

$$
\phi_1 \equiv \arg \left( -\frac{V_{td}^* V_{tb}}{V_{td}^* V_{tb}} \right), \quad \phi_2 \equiv \arg \left( -\frac{V_{ud}^* V_{ub}}{V_{ud}^* V_{ub}} \right), \quad \phi_3 \equiv \arg \left( -\frac{V_{cd}^* V_{cb}}{V_{cd}^* V_{cb}} \right).
$$

while at SLAC these angles are usually referred to as $\beta$, $\alpha$ and $\gamma$, respectively.

A non-zero value of $\phi_{CP}$ results in the time dependent asymmetry

$$
A_f = \frac{R(B^0 \to f_{CP}) - R(\bar{B}^0 \to f_{CP})}{R(B^0 \to f_{CP}) + R(\bar{B}^0 \to f_{CP})} = \xi_f \sin 2\phi_{CP} \cdot \sin(\Delta m \cdot (t_2 \pm t_1)),
$$

where $\xi_f$ is the CP eigenvalue ($\pm 1$), $\Delta m$ denotes the mass difference between the two $B^0$ mass eigenstates and $t_1$ and $t_2$ are the proper time for the tagged-$B$ and CP eigenstate decays, respectively. The $+$ sign corresponds to the case where the $B^0$ and $\bar{B}^0$ are in an even L orbital angular momentum state, the $-$ sign obtains for odd L states such as the $\Upsilon(4S)$. A determination of $A_f$ thus provides a measurement of $\sin 2\phi_{CP}$.

We note that due to the restrictions of quantum mechanics, time integrated asymmetries at the $\Upsilon(4S)$ resonance (which corresponds to the $-$ sign in the above equation) are identically zero. Therefore, one must make time dependent measurements. Since the
pairs of B mesons are produced nearly at rest in the usual arrangement at threshold, the \(\Upsilon(4S)\) center of mass frame must be boosted. This is accomplished by the use of beams with asymmetric energies. For example at KEK-B, \(\beta\gamma \sim 0.43\), and as a result the typical \(B\) meson decay length is dilated from \(20\mu\text{m}\) to about \(200\mu\text{m}\), which is measurable with double-sided silicon strip vertex detectors close to the interaction point.

The measurement therefore requires:

- a large sample of reconstructed \(B \rightarrow (c\bar{c})K^0\) eigenstate decays;
- a determination of the flavor of the accompanying \(B\) (“tagging”);
- a measurement of \(\Delta z\), the vertex separation between the \(CP\) eigenstate and flavor tag decays; and
- a fit to the flavor-tagged vertex distribution to extract \(\sin^2\phi_1\).

The KEKB high luminosity double storage ring facility was commissioned with remarkable speed starting in late 1998. This accelerator facility allows us to satisfy the first requirement. By the summer of 2001, \(29.1\,\text{fb}^{-1}\) was integrated on the \(\Upsilon(4S)\). This data sample was used for the \(\sin^2\phi_1\) measurement and corresponds to 31.3 million \(B\bar{B}\) pairs. KEKB uses a \(\pm 11\,\text{mrad}\) crossing angle to separate the incoming and outgoing beams and minimize parasitic collisions. So far no special limitations associated with the crossing angle have been observed (e.g. synchrobetatron oscillations). KEKB now routinely achieves peak instantaneous luminosities above \(5 \times 10^{33}/\text{cm}^2/\text{sec}\) with acceptable experimental backgrounds and trigger rates in the Belle detector. The beam currents are still far below the design values and therefore there is room for further improvements in luminosity. Much larger data samples are expected in the near future.

The Belle detector has good lepton identification and high efficiency for both charged and neutral particles. It allows the \(CP\) eigenstate decays to be efficiently reconstructed. Belle is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), a mosaic of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to identify muons and \(K_L\)’s (KLM). The detector is described in detail elsewhere \([3]\). Examples of its performance are given in the following section.

The Belle experiment starting physics data taking in 1999. In the summer of 2001, Belle (together with BABAR) announced the observation of the first statistically significant signals for \(CP\) violation outside of the kaon system. In this report I will describe some of the details of the measurement.

**SIN 2\(\phi_1\) MEASUREMENT**

We reconstruct \(B^0\) decays to the following \(CP\) eigenstates \([5]\): \(J/\psi K_S, \psi(2S)K_S, \chi_{c1}K_S, \eta_cK_S\) for \(\xi_f = -1\) and \(J/\psi K_L\) for \(\xi_f = +1\). We also use \(B^0 \rightarrow J/\psi K^{*0}\) decays where \(K^{*0} \rightarrow K_S\pi^0\). Here the final state is a mixture of even and odd \(CP\), depending on the relative orbital angular momentum of the \(J/\psi\) and \(K^{*0}\). The \(CP\) content is determined from a fit to the full angular distribution of all \(J/\psi K^*\) decay modes other than \(K^{*0} \rightarrow \)


$K_S \pi^0$. We find that the final state is primarily $\xi_f = +1$; the $\xi_f = -1$ fraction is $0.19 \pm 0.04(\text{stat}) \pm 0.04(\text{syst})$ [9].

$J/\psi$ and $\psi(2S)$ mesons are reconstructed via their decays to $\ell^+\ell^-$ ($\ell = \mu, e$). The $\psi(2S)$ is also reconstructed via $J/\psi \pi^+\pi^-$, and the $\chi_{c1}$ via $J/\psi \gamma$. The $\eta_c$ is detected in the $K^+K^-\pi^0$ and $K_S K^-\pi^+$ modes. For the $J/\psi K_S$ mode, we use $K_S \to \pi^+\pi^-$ and $\pi^0\pi^0$ decays; for other modes we only use $K_S \to \pi^+\pi^-$. The $J/\psi$ and $\psi(2S)$ $\to \mu^+\mu^-$ candidates are reconstructed from oppositely charged track pairs where at least one track is positively identified as a muon by the KLM system and the other is either positively identified as a muon or has an ECL energy deposit consistent with that of a minimum ionizing particle. For $e^+e^-$ decays, we use oppositely charged track pairs where at least one track is a well identified electron and the other track satisfies minimal $dE/dx$ and $E/p$ requirements. For dielectrons, we correct for final state radiation or bremsstrahlung and recover additional $\psi$ candidates by including the four-momentum of every photon detected within 0.05 radians of the original $e^+$ or $e^-$ direction in the $e^+e^-$ invariant mass calculation. Candidate $K_S \to \pi^+\pi^-$ decays are oppositely charged track pairs that have an invariant mass between 482 and 514 MeV/$c^2$, which corresponds to $\pm 3\sigma$ around the $K_S$ mass peak.

To reconstruct $\chi_{c1} K_S$ decays, we select $\chi_{c1} \to J/\psi \gamma$ decays, rejecting $\gamma$'s that are consistent with $\pi^0 \to \gamma\gamma$ decays, and impose the requirement $385 < M_{\ell\ell} - M_{\ell\ell} < 430.5$ MeV/$c^2$. For $\eta_c$ decays, we distinguish kaons from pions using a combination of CDC $dE/dx$ measurements and information from the TOF and ACC systems. Candidate $\eta_c \to K^+K^-\pi^0$ ($K_S K^-\pi^+$) decays are selected with a $KK\pi$ mass requirement that takes into account the natural width of the $\eta_c$. For $J/\psi K^{*0}$ ($K_S \pi^0$) decays, we use $K_S \pi^0$ combinations that have an invariant mass within 75 MeV/$c^2$ of the nominal $K^*$ mass. We reduce background from low-momentum $\pi^0$'s by requiring $\cos\theta_K > 0.8$, where $\theta_K$ is the angle between the $K_S$ momentum vector and the $K^{*0}$ flight direction calculated in the $K^{*0}$ rest frame.

FIGURE 1. The beam-energy constrained mass distribution for all decay modes combined other than $J/\psi K_L$. The shaded area is the estimated background. The signal region is the range 5.27 - 5.29 GeV/$c^2$. 


Reconstructed $B$ meson decays are identified using the beam-constrained mass $M_{\text{beam}} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B - E_{\text{beam}}$, where $E_{\text{beam}}$ is the cms beam energy, and $p_B$ and $E_B$ are the $B$ candidate three-momentum and energy calculated in the cms.

Figure 1 shows the combined $M_{bc}$ distribution for all channels other than $J/\psi K_L$ after a mode-dependent requirement on $\Delta E$. The $B$ meson signal region is defined as $5.270 < M_{bc} < 5.290$ GeV/$c^2$. Table 1 lists the numbers of observed candidates ($N_{\text{ev}}$) and the background ($N_{\text{bkgd}}$) determined by extrapolating the rate from the $\Delta E$ vs. $M_{bc}$ sideband region into the signal region. About 65% of the exclusive CP signal events (44% of the full CP sample) are reconstructed in the $B^0 \rightarrow \psi K_S$, $K_S \rightarrow \pi^+\pi^-$ mode.

Candidate $B^0 \rightarrow J/\psi K_L$ decays are selected by requiring ECL and/or KLM hit patterns that are consistent with the presence of a shower induced by a neutral hadron. $K_L$ candidates with ECL information only are treated separately from the $K_L$ candidates with KLM hits. The centroid of the shower is required to be within a 45° cone centered on the $K_L$ direction that is inferred from two-body decay kinematics and the measured four-momentum of the $J/\psi$. To reduce the background we cut on a likelihood ratio that depends on the $J/\psi$ cms momentum, the angle between the $K_L$ and its nearest-neighbor charged track, the charged track multiplicity of the event, the extent to which the event is consistent with a $B^+ \rightarrow J/\psi K^{*+}(K_L\pi^+)$ hypothesis, and the polar angle with respect to the z direction of the reconstructed $B^0$ meson in the cms. In addition, events that were reconstructed as $B^0 \rightarrow J/\psi K_S$, $J/\psi K^{*0}(K^+\pi^-, K_S\pi^0)$, $B^+ \rightarrow J/\psi K^+$, or $J/\psi K^{*+}(K^+\pi^0, K_S\pi^\pm)$ decays are removed. Finally, $K_L$ clusters with positions that match photons from reconstructed $\pi^0$'s are also rejected.

Figure 2 shows the $p_B^{\text{cms}}$ distribution, calculated with the $B^0 \rightarrow J/\psi K_L$ two-body decay hypothesis. The histograms are the results of a fit to the signal and background distributions. The shapes are derived from the Belle GEANT based Monte Carlo (MC) simulation. However, the normalization and peak position of the signal are allowed to vary. There are 397 entries in the $0.2 \leq p_B^{\text{cms}} \leq 0.45$ GeV/c signal region with KLM clusters. There are 172 entries in the range $0.2 \leq p_B^{\text{cms}} \leq 0.40$ GeV/c with clusters in the ECL only. The fit finds a total of $346 \pm 29 J/\psi K_L$ signal events, and a signal purity

| Mode | $N_{\text{ev}}$ | $N_{\text{bkgd}}$ |
|------|----------------|-----------------|
| $J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$ | 457 | 11.9 |
| $J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$ | 76 | 9.4 |
| $\psi(2\ell)(\ell^+\ell^-)K_S(\pi^+\pi^-)$ | 39 | 1.2 |
| $\psi(2\ell)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$ | 46 | 2.1 |
| $\chi_c(1)(J/\psi\gamma)K_S(\pi^+\pi^-)$ | 24 | 2.4 |
| $\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$ | 23 | 11.3 |
| $\eta_c(K_SK^+\pi^-)K_S(\pi^+\pi^-)$ | 41 | 13.6 |
| $J/\psi K^{*0}(K_S\pi^0)$ | 41 | 6.7 |

**Table 1.** The numbers of observed events ($N_{\text{ev}}$) and the estimated background ($N_{\text{bkgd}}$) in the signal region for each $f_{CP}$ mode.
of 61%. Thus, about 33% of the signal in the full CP eigenstate sample is reconstructed in the $B^0 \rightarrow \psi K_L$ mode.

![Figure 2](image)

**FIGURE 2.** The $p_{c.m.}^B$ distribution for $B^0 \rightarrow J/\psi K_L$ candidates with the results of the fit. The solid line is the signal plus background; the shaded area is background only. The signal region for KLM (ECL-only) clusters is $0.2 \leq p_{c.m.}^B \leq 0.45(0.40)$ GeV/c.

To identify the flavor of the accompanying $B$ meson, leptons, kaons, $\Lambda$’s, charged slow pions from $D^* \rightarrow D^0 \pi^+$ decays, and energetic pions from two-body $B$ decay (e.g. $B^0 \rightarrow D^{*+} \pi^+$) are used. A likelihood based method, described in detail below, is used to combine information from the different categories and to take into account their correlations. The figure of merit for flavor tagging performance is the effective efficiency, $\epsilon_{eff}$, which is $\epsilon(1 - 2w^2)$ summed over all tagging categories. This method gives $\epsilon_{eff} = 0.270 \pm 0.008^{+0.006}_{-0.009}$.

A Monte Carlo simulation is used to determine a table for a category-dependent variable that indicates whether a particle originates from a $B^0$ or $\bar{B}^0$. The values of this variable range from $-1$ for a reliably identified $\bar{B}^0$ to $+1$ for a reliably identified $B^0$ and depend on the tagging particle’s charge, cm momentum, polar angle, particle-identification probability, as well as other kinematic and event shape quantities. For lepton tags, the missing momentum and recoil momentum are included in the likelihood determination. For slow pion tags, the angle between the pion and the thrust axis of the non-$f_{CP}$ tracks is used. Charged kaon tags accompanied by $K_S$ mesons, which have additional strange quark content and a lower tagging value, are treated as a separate tagging category.

The results from the separate, particle-level categories are then combined in a second stage that takes correlations for the case of multiple particle-level tags into account. This second stage determines two event-level parameters, $q$ and $r$. The first, $q$, has the discrete values $q = +1$ when the tagged $B$ meson is more likely to be a $B^0$ and $-1$ when it is more likely to be a $\bar{B}^0$. The parameter $r$ is an event-by-event flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. The value of $r$ is used only to sort data into six intervals of flavor purity; the wrong-tag probabilities that are used in the final CP fit are determined from data.
TABLE 2. The event fractions ($f_l$) and incorrect flavor assignment probabilities ($w_l$) for each $r$ interval. The errors include both statistical and systematic uncertainties.

| $l$ | $r$       | $f_l$   | $w_l$   |
|-----|-----------|---------|---------|
| 1   | 0.000 − 0.250 | 0.405   | 0.465^{+0.010}_{-0.009} |
| 2   | 0.250 − 0.500 | 0.149   | 0.352^{+0.015}_{-0.014} |
| 3   | 0.500 − 0.625 | 0.081   | 0.243^{+0.021}_{-0.036} |
| 4   | 0.625 − 0.750 | 0.099   | 0.176^{+0.022}_{-0.017} |
| 5   | 0.750 − 0.875 | 0.123   | 0.110^{+0.014}_{-0.011} |
| 6   | 0.875 − 1.000 | 0.140   | 0.041^{+0.010}_{-0.010} |

FIGURE 3. $\Delta t$ distributions for the events with $q_{\xi_f} = +1$ (solid points) and $q_{\xi_f} = -1$ (open points). The results of the global fit (with $\sin^2 \phi_1 = 0.99$) are shown as solid and dashed curves, respectively.

To avoid dependence on the MC, the probabilities of an incorrect flavor assignment, $w_l$ ($l = 1, 6$), are determined directly from the data for six $r$ intervals using exclusively reconstructed, self-tagged $B^0 \rightarrow D^{(*)} \ell^+ \nu, D^{(*)} - \pi^+, D^{(*)} - \rho^+$ and $J/\psi K^{*0}(K^+ \pi^-)$ decays. The $b$-flavor of the accompanying $B$ meson is assigned according to the flavor-tagging algorithm described above. The exclusive decay and tag vertices are reconstructed using the same vertexing algorithm that is used in the $CP$ fit. The values of $w_l$ are obtained from the amplitudes of the time-dependent $B^0\overline{B}^0$ mixing oscillations: $(N_{OF} - N_{SF})/(N_{OF} + N_{SF}) = (1 - 2w_l) \cos(\Delta m_d \Delta t)$. Here $N_{OF}$ and $N_{SF}$ are the numbers of opposite flavor and same flavor events. The value of $\Delta m_d$ is fixed at the world average [8]. Table 2 lists the resulting $w_l$ values together with the fraction of the events ($f_l$) in each $r$ interval.

The $f_{CP}$ vertex is determined using lepton tracks from $J/\psi$ or $\psi(2S)$ decays, or prompt tracks from $\eta_c$ decays. The $f_{tag}$ vertex is determined from well reconstructed tracks not assigned to $f_{CP}$. Tracks that form a $K_S$ are not used. The tracks used for vertexing must have at least one three dimensional point with consistent hits in $r-\phi$ plus at least one additional $z$ hit. Each vertex position is required to be consistent with the interaction point profile smeared in the $r-\phi$ plane by the $B$ meson decay length. We use an iterative
between the two distributions; this demonstrates visually that fit takes into account the effects of background, vertex resolutions and incorrect tagging. The maximum likelihood fit to the time distributions of the tagged and vertexed events. The resolution (rms) for $\Delta z$ from $q = 1$. Figure 3 shows the observed $\Delta t$ vs. $M$ for $B^0 \rightarrow \psi K$ decays where some $\xi_f$ values. For $B^0 \rightarrow \psi K_{L}$, a study using events in the $\Delta E$ vs. $M_{bc}$ sideband regions shows that the $f_{c}$ component is negligible. For these modes we use $\tau_{bkg}(\Delta t) = \delta(\Delta t)$. In the case of $B^0 \rightarrow \psi K_{L}$, the background is dominated by $B \rightarrow \psi X$ decays where some final states are $CP$ eigenstates. We estimate the fractions of the background components with and without a true $K_{L}$ cluster by fitting the $p_{\text{cm}}^{\text{em}}$ distribution to the expected shapes determined from MC. We also use the MC to determine the fraction of events with definite $CP$ content within each component. The result is a background that is 71% from non-$CP$ modes with $\tau_{bkg} = \tau_{B}$. For the $CP$-mode backgrounds, we use the signal pdf given above with the appropriate $\xi_f$ values. For $\psi K^{*}(K_{L} \pi^{0})$, which is 13% of the background, we use the $\xi_f = -1$ content determined from the full $\psi K^{*}$ sample. The

| Sample                           | $\sin 2\phi_1$         |
|---------------------------------|-------------------------|
| $f_{ug} = B^0 (q = +1)$         | 0.84 ± 0.21             |
| $f_{ug} = \bar{B}^0 (q = -1)$  | 1.11 ± 0.17             |
| $J/\psi K_{S}(\pi^{+}\pi^{-})$| 0.81 ± 0.20             |
| $J/\psi K_{S}(\pi^{+}\pi^{-})$| 1.00 ± 0.40             |
| $J/\psi K_{L}$                 | 1.31 ± 0.23             |
| $J/\psi K^{*0}(K_{S}\pi^{0})$ | 0.85 ± 1.45             |
| All                            | 0.99 ± 0.14             |

procedure: if the quality of the vertex fit is poor, the track that is the largest contributor to the $\chi^2$ is removed and the fit is repeated. The typical vertex-finding efficiency and vertex resolution (rms) for $z_{CP}$ ($z_{tag}$) are 92 (91)% and 75 (140) $\mu$m, respectively. Note that the resolution on the tag side includes a large additional contribution from charm decay. Once the tag and CP eigenstate vertices are reconstructed, the proper time is calculated from $\Delta z/\gamma \beta$. After vertexing there are 560 events with $q = +1$ flavor tags and 577 events with $q = -1$. Figure 3 shows the observed $\Delta t$ distributions for the $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points) event samples. In the raw data there is a clear asymmetry between the two distributions; this demonstrates visually that $CP$ symmetry is violated.

To extract the measured value of the $CP$ violating parameter, we perform an unbinned maximum likelihood fit to the time distributions of the tagged and vertexed events. The fit takes into account the effects of background, vertex resolutions and incorrect tagging.

For modes other than $J/\psi K^{*0}$ the pdf expected for the signal is

$$P_{\text{sig}}(\Delta t, q, w_l, \xi_f) = \frac{e^{-|\Delta t|/\tau_{bkg}}}{2\tau_{bkg}} \{1 - \xi_f q(1 - 2w_l) \sin 2\phi_1 \sin(\Delta m_d \Delta t)\} ,$$

where we fix $\tau_{bkg}$ and $\Delta m_d$ at their world average values [9]. For the $B^0 \rightarrow \psi K^{*0}$ mode a more complex fit to $\Delta t$ and the transversity angle[8] is used to take into account the two $CP$ eigenstates which contribute[9].

The pdf used for the background distribution is $P_{\text{bkg}}(\Delta t) = f_{\tau}e^{-|\Delta t|/\tau_{bkg}}/2\tau_{bkg} + (1 - f_{\tau})\delta(\Delta t)$, where $f_{\tau}$ is the fraction of the background component with an effective lifetime $\tau_{bkg}$ and $\delta$ is the Dirac delta function. For all $f_{CP}$ modes other than $J/\psi K_{L}$, a study using events in the $\Delta E$ vs. $M_{bc}$ sideband regions shows that the $f_{c}$ component is negligible. For these modes we use $P_{\text{bkg}}(\Delta t) = \delta(\Delta t)$. TABLE 3. The values of $\sin 2\phi_1$ for various subsamples (statistical errors only).

| Sample                           | $\sin 2\phi_1$         |
|---------------------------------|-------------------------|
| $f_{ug} = B^0 (q = +1)$         | 0.84 ± 0.21             |
| $f_{ug} = \bar{B}^0 (q = -1)$  | 1.11 ± 0.17             |
| $J/\psi K_{S}(\pi^{+}\pi^{-})$| 0.81 ± 0.20             |
| $J/\psi K_{S}(\pi^{+}\pi^{-})$| 1.00 ± 0.40             |
| $J/\psi K_{L}$                 | 1.31 ± 0.23             |
| $J/\psi K^{*0}(K_{S}\pi^{0})$ | 0.85 ± 1.45             |
| All                            | 0.99 ± 0.14             |
remaining backgrounds are $\xi_f = -1$ states (10%) including $\psi K_S$, and $\xi_f = +1$ states (5%) including $\psi(2S)K_L$, $\chi_c K_L$ and $\psi\pi^0$.

The last ingredient needed for the CP fit is the proper-time interval resolution, $R(\Delta t)$. This resolution function is parameterized by convolving a sum of two Gaussians (a main component due to the SVD vertex resolution and charmed meson lifetimes, plus a tail component caused by poorly reconstructed tracks) with a function that takes into account the cm motion of the $B$ mesons. The relative fraction of the main Gaussian is determined to be $0.97 \pm 0.02$ from a study of $B^0 \to D^{(*)-}\pi^+$, $D^{*-}\rho^+$, $D^{-}\pi^+$, $\psi K^{*0}$, $\psi K_S$ and $B^+ \to D^0\pi^+$, $\psi K^+$ events. The means ($\mu_{\text{main}}$, $\mu_{\text{tail}}$) and widths ($\sigma_{\text{main}}$, $\sigma_{\text{tail}}$) of the Gaussians are calculated event-by-event from the $f_{CP}$ and $f_{\text{tag}}$ vertex-fit error matrices and the $\chi^2$ values of the fit; typical values are $\mu_{\text{main}} = -0.24$ ps, $\mu_{\text{tail}} = 0.18$ ps and $\sigma_{\text{main}} = 1.49$ ps, $\sigma_{\text{tail}} = 3.85$ ps. An example of a fit for hadronic non-CP eigenstate using the resolution function modes is shown in Fig. 4. The fit agrees well with data out to 10 lifetimes on the logarithmic scale of the figure. As a consistency check, we obtain lifetimes for the neutral and charged $B$ mesons using the same vertexing procedure that is used for the CP fit. The results of the fit agree well with the world average $B^0$ lifetime value.[7]

The pdfs for signal and background are convolved with $R(\Delta t)$ to determine the likelihood value for each event as a function of $\sin 2\phi_1$:

$$L_i = \int \left\{ f_{\text{sig}} P_{\text{sig}}(\Delta t', q, w_l, \xi_f) R_{\text{sig}}(\Delta t - \Delta t') + (1 - f_{\text{sig}}) P_{\text{bkg}}(\Delta t') R_{\text{bkg}}(\Delta t - \Delta t') \right\} d\Delta t'$$

where $f_{\text{sig}}$ is the probability that the event is signal. The most probable $\sin 2\phi_1$ is the value that maximizes the likelihood function $L = \prod_i L_i$, where the product is over all events. (Note that the signal and background resolution functions are different.)
The result of the fit is
\[ \sin 2\phi_1 = 0.99 \pm 0.14 \text{(stat)} \pm 0.06 \text{(syst)}. \]

In Fig. 5(a) we show the asymmetries for the combined data sample that are obtained by applying the fit to the events in each \( \Delta t \) bin separately. The smooth curve is the result of the global unbinned fit. Figures 5(b) and (c) show the corresponding asymmetry displays for the \((c\bar{c})K_S (\xi_f = -1)\) and the \(J/\psi K_L (\xi_f = +1)\) modes separately. The observed asymmetries for the different \(CP\) states are indeed opposite, as expected. The curves are the results of unbinned fits applied separately to the two samples; the resultant \(\sin 2\phi_1\) values are \(0.84 \pm 0.17\text{(stat)}\) and \(1.31 \pm 0.23\text{(stat)}\), respectively.

The systematic error is dominated by uncertainties in the tails of the vertex distributions, which contribute 0.04. Other significant contributions come from uncertainties (a)
in \( w_l \) (0.03); (b) in the parameters of the resolution function (0.02); and (c) in the \( J/\psi K_L \) background fraction (0.02). The errors introduced by uncertainties in \( \Delta m_d \) and \( \tau_{B^0} \) are negligible.

A number of checks on the measurement were performed. Table 3 lists the results obtained by applying the same analysis to various subsamples. All values are statistically consistent with each other. The result is unchanged if we use the \( w_l \)'s determined separately for \( f_{\text{tag}} = B^0 \) and \( \bar{B}^0 \). Fitting to the non-CP eigenstate self-tagged modes \( B^0 \to D^{(*)-} \pi^+ \), \( D^+ \rho^+ \), \( J/\psi K^{*0}(K^+\pi^-) \) and \( D^{*-} \ell^+\nu \), where no asymmetry is expected, yields \( 0.05 \pm 0.04 \). The asymmetry distribution for this control sample is shown in Fig. 5(d).

A single consistent reconstruction and analysis procedure is used for all data samples. We verify that, as expected, the sin\(^2\phi_1\) values for the different run periods are consistent. With toy Monte Carlo studies we also verify that the analysis procedure and the errors in the analysis are well behaved when sin\(^2\phi_1\) is close to the physical boundary. As a further check, we used three independent CP fitting programs and two different algorithms for the \( f_{\text{tag}} \) vertexing and found no discrepancy.

Finally, we comment on the possibility of direct CP violation. The signal pdf for a neutral \( B \) meson decaying into a CP eigenstate can be expressed in the more general form

\[
P_{\text{sig}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \left\{ \frac{1 + |\lambda|^2}{2} + q(1 - 2 w_l) \right\} \left[ \xi_f \Im \lambda \sin(\Delta m_d \Delta t) - \frac{1 - |\lambda|^2}{2} \cos(\Delta m_d \Delta t) \right]
\]

where \( \lambda \) is a complex parameter that depends on both \( B^0\bar{B}^0 \) mixing and on the amplitudes for \( B^0 \) and \( \bar{B}^0 \) decay to a CP eigenstate. The presence of a cosine term (\( |\lambda| \neq 1 \)) indicates direct CP violation. For the primary analysis, we assumed \( |\lambda| = 1 \) which is the SM expectation. In order to test this assumption, we also performed a fit using the above expression with \( \Im \lambda = \text{“sin}\,2\phi_1\text{”} \) and \( |\lambda| \) as free parameters. We obtain \( |\lambda| = 1.03 \pm 0.09 \) and \( \Im \lambda = 0.99 \pm 0.14 \) for all CP modes combined, where the errors are statistical only. This result confirms the assumption used in our analysis.

**CONCLUSIONS**

In the summer of 2001, Belle (along with BABAR) presented its first significant measurement of the CP violating parameter sin\(^2\phi_1\). BELLE found

\[
\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06
\]

with a statistical significance of greater than six standard deviations\([10]\). This can be compared to the BABAR result of sin\(^2\phi_1 = 0.59 \pm 0.14 \pm 0.05\)[11]. The two results are based on data samples of comparable size (31 million and 32 million \( B\bar{B} \) pairs, respectively). The efficiencies and resolutions of the two experiments are also quite similar. However, although the weighted average of the two results agrees well with indirect determinations that assume the Standard Model, the two measurements themselves are
only marginally consistent. Larger data samples and additional more precise measurements will be required to fully reconcile these two results for $\sin 2\phi_1$. In parallel, a program for the measurement of the other angles, $\phi_2$ and $\phi_3$, has started.

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7. The measured $B$-lifetimes are: $\tau_{B^0} = 1.547 \pm 0.021$ ps and $\tau_{B^+} = 1.641 \pm 0.033$ ps (statistical errors only). These results are slightly different from recent Belle lifetime results due to the use of an improved resolution function.
8. $\theta_{tr}$ is defined as the angle between the $\ell^+$ direction in the $J/\psi$ rest frame and the $z$-axis, where the $x$-axis is defined as the direction of motion of the $J/\psi$ in the $\Upsilon(4S)$ rest frame. The $x$-$y$ plane is defined by the $K^*$ decay products in the $J/\psi$ rest frame.
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\[
\sin 2\phi_1 \cdot \sin(\Delta m_d \Delta t)
\]

(a) Combined

(b) \((\bar{c}c)K_S (\xi_f = -1)\)

(c) \(J/\psi K_L (\xi_f = +1)\)

(d) Non-CP sample

\[
\Delta t \text{ (ps)}
\]