Results for $\phi_1$ and $\phi_2$ from Belle

Pit Vanhoefer  
Max-Plank-Institut für Physik  
Föringer Ring 6  
München 80805 GERMANY

We present a summary of measurements sensitive to the CKM angles $\phi_1$ and $\phi_2$, performed by the Belle experiment using the final data sample of $772 \times 10^6 B\bar{B}$ pairs at the $\Upsilon(4S)$ resonance produced at the KEK asymmetric $e^+e^-$ collider. We discuss $CP$ asymmetries from the decays $B^0 \to c\bar{c}K^0$, $D(\ast^+)D^{(\ast)-}$ which are sensitive to $\phi_1$ and from $B \to \pi^+\pi^-$, $a_1 \pm \pi^\mp$ being sensitive to $\phi_2$. Furthermore the measurement of the branching fraction of $B^0 \to \rho^0\rho^0$ decays and fraction of longitudinal polarization in this decay is presented and used to constrain $\phi_2$ with an isospin analysis in the $B \to \rho\rho$ system.

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1 Introduction

One major precision test of the Standard Model (SM) is to validate the Cabibbo-Kobayashi-Maskawa (CKM) mechanism for violation of the combined charge-parity (CP) symmetry \[1, 2\]. This is one of the main purposes of the Belle experiment at KEK which has significantly contributed proving the CKM scheme and constraining the unitarity triangle for $B$ decays to its current precision. Any deviation from unitarity would be a clear hint for physics beyond the SM. These proceedings give a summary of the experimental status of measurements of the CKM angles $\phi_1$ and $\phi_2$ defined from the CKM matrix elements as $\phi_1 \equiv \pi - \arg(-V_{td}V_{tb}^*/(V_{cd}V_{cb}^*))$ and $\phi_2 \equiv \arg(-V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)$.

The CKM angles can be determined by measuring the time-dependent asymmetry between $B_0$ and $\bar{B}^0$ decays into a common CP eigenstate \[3\]. In the decay sequence, $\Upsilon(4S) \to B_{CP}B_{Tag} \to f_{CP}f_{Tag}$, where one of the $B$ mesons decays into a CP eigenstate $f_{CP}$ at a time $t_{CP}$ and the other decays into a flavour specific final state $f_{Tag}$ at a time $t_{Tag}$, the time-dependent decay rate is given by

$$P(\Delta t, q) = e^{-|\Delta t|/\tau_{B_0}} \left[ 1 + q(A_{CP} \cos \Delta m_d \Delta t + S_{CP} \sin \Delta m_d \Delta t) \right],$$ (1)

where $\Delta t \equiv t_{CP} - t_{Tag}$, $\Delta m_d$ is the mass difference between the mass eigenstates $B_H$ and $B_L$ and $q = +1(-1)$ for $B_{Tag} = B^0(\bar{B})$. The CP asymmetry is given by

$$\frac{N(B \to f_{CP}) - N(B \to \bar{f}_{CP})}{N(B \to f_{CP}) + N(B \to \bar{f}_{CP})},$$ (2)

where $N(B(\bar{B}) \to f_{CP})$ is the number of events of a $B(\bar{B})$ decaying to $f_{CP}$, the asymmetry can be time-dependent. The parameters $A_{CP}$ and $S_{CP}$ describe direct and mixing-induced CP violation, respectively \[4\]. All measurements presented here are based on Belle’s final data set of $772 \times 10^6$ BB pairs.

2 The Angle $\phi_1$

First-order (tree) weak processes proceeding via $b \to c$ quark transitions such as $B^0 \to (c\bar{c})K^0$, $D^{(*)+}D^{(*)-}$, are directly sensitive to the angle $\phi_1$, which is the CKM angle currently measured with the smallest experimental uncertainty.

2.1 The Decay Channels $B^0 \to (c\bar{c})K^0$

The decays $B^0 \to (c\bar{c})K^0$, including the so-called ‘golden channel’ $B^0 \to J/\psi K_S^0$, provide a theoretically and experimentally very clean environment to extract $\phi_1$.

*There exists an alternate notation where $C_{CP} = -A_{CP}$. 
Since possible additional contributions to the leading order tree diagram, see Fig. 1a), are negligible or even carry the same weak phase [4], the measured CP asymmetry $S_{CP} = \eta_{CP} \sin(2\phi_1)$ reveals an unpolluted value of $\phi_1$, with the decay channel’s CP eigenvalue $\eta_{CP}$. The combined measurement of CP violation in the golden channel and $B^0 \to \psi(2S)K^0_S$, $B^0 \to \chi_c K^0_S$, and $B^0 \to J/\psi K^0_L$ provide currently the world’s most precise value of $\sin(2\phi_1) = 0.667 \pm 0.023$ (stat) ± 0.012 (syst) [5], as shown in Fig. 1. No direct CP violation was observed, $A_{CP} = 0.006 \pm 0.016$ (stat) ± 0.012 (syst), as predicted by the SM [6].

2.2 The Decays Channels $B^0 \to D^{(*)+}D^{(*)-}$

The decays $B^0 \to D^{(*)+}D^{(*)-}$ are also sensitive to $\phi_1$, however additional contributions from loop (penguin) processes make a pollution of the measured observables possible. Hence also direct CP violation can occur. Compared to the previous Belle measurement, the updated result of $B^0 \to D^+D^-$ decays benefits from a better continuum suppression due to the use of neural-networks. The CP asymmetries obtained are $S_{CP} = 1.06^{+0.21}_{-0.11}$ (stat) ± 0.08 (syst) and $A_{CP} = 0.43 \pm 0.16$ (stat) ± 0.05 (syst) [7] and are in good agreement with the results from Babar [8]. The pseudo-scalar to vector scalar decay $B^0 \to D^{\pm}D^{\mp}$ is a decay into a non CP-eigenstate. One therefore has to consider four flavor charge combinations and the time-dependent decay rate in Eq. 1 has to be expanded to five $CP$ parameters [9, 10]. The indirect $CP$ asymmetry
obtained is $S_{CP} = -0.78 \pm 0.15$ (stat) $\pm 0.05$ (syst), no direct $CP$ violation has been observed \[7\]. $B^0 \to D^{*+}D^{*-}$ is a pseudo-scalar to vector vector decay and therefore composed of $CP$ even and odd components. An angular analysis in the transversity basis is performed to separate the different $CP$ states. The fraction of $CP$-odd states is found to be $R_{\perp} = 0.138 \pm 0.024$ (stat) $\pm 0.006$ (syst) and a first observation of mixing-induced $CP$ violation has been reported; $S_{CP} = -0.79 \pm 0.13$ (stat) $\pm 0.03$ (syst), $A_{CP} = 0.15 \pm 0.08$ (stat) $\pm 0.04$ (syst) \[11\]. The $\Delta t$ distributions and $CP$ asymmetries for each mode are shown in Fig. 2.

![Figure 2: $\Delta t$ distributions for each flavour tag and the $CP$ asymmetries, each with the fit result on top. a) $B^0 \to D^+D^-$, b) $B^0 \to D^{*\pm}D^{\mp}$ and c) $B^0 \to D^{*+}D^{*-}$.

### 3 $\phi_2$

Decays proceeding via $b \to uud$ quark transitions such as $B^0 \to \pi\pi$, $\rho\pi$, $\rho\rho$ and $a_1(1260)\pi$, are directly sensitive to $\phi_2$. At tree level we expect $A_{CP} = 0$ and $S_{CP} = \sin 2\phi_2$. Again, possible penguin contributions can give rise of direct $CP$ violation, $A_{CP} \neq 0$ and also pollute the measurement of $\phi_2$, $S_{CP} = \sqrt{1 - A_{CP}^2 \sin(2\phi_2^{eff})}$ where the observed $\phi_2^{eff} \equiv \phi_2 - \Delta \phi_2$ is shifted by $\Delta \phi_2$ due to different weak phases from additional non-leading contributions.

Despite this, it is possible to determine $\Delta \phi_2$ in $B^0 \to h^+h^-$ with an $SU(2)$ isospin analysis by considering the set of three $B \to hh$ decays where the $hh$s are either two pions or two longitudinally polarized $\rho$s, related via isospin symmetry \[12\]. The $B \to hh$ amplitudes obey the triangle relations,

$$A_{+0} = \frac{1}{\sqrt{2}} A_{+-} + A_{00}, \quad \overline{A}_{-0} = \frac{1}{\sqrt{2}} \overline{A}_{+-} + \overline{A}_{00}. \quad (3)$$

Isospin arguments demonstrate that $B^+ \to h^+h^0$ is a pure first-order mode in the limit of neglecting electroweak penguins, thus these triangles share the same base, $A_{+0} =$
\[ A_0, \Delta \phi_2 \] can then be determined from the difference between the two triangles. This method has an inherent 8-fold discrete ambiguity in the determination of \( \phi_2 \).

4 The Decay \( B \to \pi \pi \)

Preliminary results of the \( CP \) parameters in this pseudo-scalar to scalar scalar decay yield \( S_{CP} = -0.636 \pm 0.082 \) (stat) \( \pm 0.027 \) (syst) and \( A_{CP} = 0.328 \pm 0.061 \) (stat) \( \pm 0.027 \) (syst). The \( \Delta t \) distributions and the resulting \( CP \) asymmetry are shown in Fig. 3 a). Belle excludes the range \( \phi_2 \not\in [23.8^\circ, 66.8^\circ] \) at the 1\( \sigma \) level by performing an isospin analysis to remove the penguin contribution, see Fig. 3 b). The amount of direct \( CP \) violation was found to be smaller compared to the previous measurement at Belle [13]. The previous result was confirmed with the previous data set of \( 535 \times 10^6 \) \( B\bar{B} \) pairs. The updated \( CP \) asymmetries are in better agreement with other experiments [14].

Figure 3: a) \( \Delta t \) distribution for each flavour tag and the fit result on top and the resulting \( CP \) asymmetry for \( B^0 \to \pi^+\pi^- \). Mixing-induced \( CP \) violation can be clearly seen in the asymmetry plots and the height difference in the \( \Delta t \) projection indicates direct \( CP \) violation. b) scan of \( \phi_2 \) from an isospin analysis in the \( B \to \pi\pi \) system, the dashed line corresponds to the one \( \sigma \) level.
5 The Decay $B^0 \rightarrow \rho^0 \rho^0$

The presence of multiple, largely unknown backgrounds with the same four charged pions final state as $B^0 \rightarrow \rho^0 \rho^0$ make this rare decay quite difficult to isolate. Interference between the various $4\pi$ modes need to be considered. Having a decay into two vector particles, an angular analysis has to be performed, similar to the decay $B^0 \rightarrow D^+ D^-$. As for $B^0 \rightarrow \rho^+ \rho^- [15, 16, 17]$, the decay $B \rightarrow \rho \rho$ is naively expected to be polarized dominantly longitudinally. However, color-suppressed $B$ decays into light vectors are especially difficult to predict [18]. Besides updating to the full data set, a helicity angle $\cos \Theta_H$ for each $\rho^0$ is added to the fit. The angles, defined in the helicity basis, are powerful in separating the different backgrounds and allow one to measure the fraction $f_L$ of longitudinal (purely $CP$-even) polarization in $B \rightarrow \rho \rho$ decays. As a preliminary result, Belle obtains $\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0) = (1.02 \pm 0.30 \text{ (stat)} \pm 0.22 \text{ (syst)}) \times 10^{-6}$ with a fraction of longitudinal polarization, $f_L = 0.21_{-0.22}^{+0.18} \text{ (stat)} \pm 0.11 \text{ (syst)}$. Having a significance of 2.9 standard deviations, an upper limit of $\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0) < 1.5 \times 10^{-6}$ at the 90% CL is provided [19]. Since this mode is currently statistically (and systematically) limited and is found to decay dominantly into transversally polarized $\rho^0$'s ($CP$-even and odd), a measurement of the $CP$ asymmetries has not been performed. However, the size of the amplitude of the decays into longitudinally polarized $\rho^0$s from this measurement has been used in an isospin analysis together with world averages of $B^0 \rightarrow \rho^+ \rho^-$ and $B^+ \rightarrow \rho^+ \rho^0$ decays [20] (longitudinal polarization only). The resulting constraint consistent with the SM value is $\phi_2 = (91.0 \pm 7.2)^\circ$. The relatively small amplitude of $B^0 \rightarrow \rho^0 \rho^0$ makes the isospin analysis in the $B \rightarrow \rho \rho$ less ambiguous. In addition, Belle reported the first evidence of $B^0 \rightarrow f_0 \rho^0$ decays with a significance of 3.0 $\sigma$; $\mathcal{B}(B^0 \rightarrow f_0 \rho^0) = (0.86 \pm 0.27 \text{ (stat)} \pm 0.15 \text{ (syst)}) \times 10^{-6}$. Distributions of the difference of energy of the reconstructed signal $B$ to the beam energy, $\Delta E$ and one of the helicty angles, each with the fit result on top, are shown in Fig. 4 together with the $\phi_2$ scan from the isospin analysis.

Comparing these results with the ones obtained by BaBar, we find good agreement in the branching fraction of $B^0 \rightarrow \rho^0 \rho^0$ decays, while there is a $2.1\sigma$ discrepancy in the fraction of longitudinal polarization; BaBar finds $f_L = 0.75_{-0.14}^{+0.11} \text{ (stat)} \pm 0.04 \text{ (syst)}$ [21]. Also the branching fraction of $B^0 \rightarrow f_0 \rho^0$ decays is significantly higher then the upper limit provided by BabBar; $\mathcal{B}(B^0 \rightarrow f_0 \rho^0) < 0.34 \times 10^{-6}$. Thus, further studies at higher statistics would be very interesting and hopefully will solve these tensions.
Figure 4: Distributions of a) $\Delta E$ and b) $\cos \Theta_H$ with the fit result on top. The shaded red area and the long dashed orange histogram are the $B^0 \to \rho^0 \rho^0$ and $f_0 \rho^0$ contributions, respectively. Furthermore, all four pion final states are shown in dashed cyan, the entire ($B\bar{B}$) background in dashed green (dark green) and the full PDF in blue. c) scan of $\phi_2$ from an isospin analysis in the $B \to \rho \rho$ system, the dashed line corresponds to the one $\sigma$ level.

6 The Decay $B^0 \to a_1(1260)^\pm \pi^\mp$

$B^0 \to a_1(1260)^\pm \pi^\mp$ is another decay with a four charged pion final state sensitive to $\phi_2$, but is similar to $B^0 \to D^{*\pm}D^\mp$, a decay into a non-$CP$ eigenstate. Belle reported the first evidence of mixing induced $CP$ violation in this mode with $3.1\sigma$; $S_{CP} = -0.51 \pm 0.14 \text{ (stat)} \pm (0.08) \text{ [22]}$. The amount of penguin pollution can in general be estimated by using $SU(3)$ symmetry [23] but would need more input data. Therefore a scan of an effective angle $\phi_2^{eff}$ has been presented, giving a fourfold solution for $\phi_2^{eff} \in [-25.5^\circ, -9.1^\circ], [34.7^\circ, 55.3^\circ]$ and $[99.1^\circ, 115.5^\circ]$, where the 2nd interval contains two overlapping solutions. The scan (c) is shown together with the $\Delta t$ distribution (a) and the $CP$ asymmetry (b) in Fig. 5.

Figure 5: a) projection of the fit result onto $\Delta t$ for $B^0 \to a_1(1260)^\pm \pi^\mp$. b) the resulting time-dependent $CP$ asymmetry. c) scan of $\phi_2^{eff}$ where the dashed line corresponds to the one $\sigma$ level.
7 Summary

We have presented recent measurements from Belle sensitive to the CKM phases $\phi_1$ and $\phi_2$ using the full data set. For $\phi_1$, Belle provides the currently most precise value, $\sin(2\phi_1) = 0.667 \pm 0.023 \text{ (stat)} \pm 0.012 \text{ (syst)}$, coming from $B^0 \to (\pi\pi)K^0$ decays. Furthermore Belle reported on $CP$ violation in $B \to D^{(*)+}D^{(*)-}$ decays, where mixing induced $CP$ violation in $B \to D^{*-}D^{*-}$ decays was observed for the first time.

Moreover, preliminary measurements of the $CP$ asymmetries in $B \to \pi^+\pi^-$ and the branching fraction of $B \to \rho^0\rho^0$, together with fraction of longitudinal polarized $\rho^0$s in this decay were presented. The data are used to constrain $\phi_2$ with an $SU(2)$ isospin analysis. Also, first evidence of mixing induced $CP$ violation in the decay $B^0 \to a_1(1260)+\pi^+$, together with a scan of an effective $\phi_2$ was presented. The current world averages of $\phi_1$ and $\phi_2$ as computed by the CKMfitter [24] (including the results presented) and UTfit [25] collaborations are $\phi_1 = (21.73^{+0.78}_{-0.74})^\circ$ and $\phi_2 = (88.5^{+4.7}_{-4.4})^\circ$ and $\phi_1 = (22.28\pm 0.92)^\circ$ and $\phi_2 = (89.1\pm 3.0)^\circ$, respectively. With BelleII being built and LHCb operating, the next generation of $B$ physics experiments are expected to further reduce the uncertainty of the CKM observables, e.g. the uncertainty of $\phi_2$ is expected to be reduced to $1^\circ - 2^\circ$ [26].

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