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CP violation in B decays at Belle

Anton POLUEKTOV[*][†]
The University of Warwick, UK
Budker Institute of Nuclear Physics, Novosibirsk, Russia
E-mail: `A.O.Poluektov@warwick.ac.uk`

This report is devoted to the updated measurement of the direct CP violation parameter ϕ_3 performed by Belle collaboration using a Dalitz plot analysis of the $K_S^0\pi^+\pi^-$ decay of the neutral D meson produced in $B^\pm \to D^{(*)}K^\pm$ decays. The analysis uses three decays: $B^+ \to DK^+$, and $B^+ \to D^*K^+$ with $D^* \to D\pi^0$ and $D^* \to D\gamma$, as well as the corresponding charge-conjugate modes. From a combined maximum likelihood fit to these modes, we obtain $\phi_3 = 78.4^{\circ}{}^{+10.8^\circ}_{-11.6^\circ} \pm 3.6^\circ(\mathrm{syst}) \pm 8.9^\circ(\mathrm{model})$. The significance of *CP* violation ($\phi_3 \neq 0$) in our measurement is $(1 - 5\times 10^{-4})$, or 3.5 standard deviations.

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[*] Speaker.

[†] On behalf of Belle collaboration

Measurements of the Unitarity Triangle parameters allow to search for New Physics effects at low energies. Most of such measurements are currently performed at B factories by BaBar and Belle experiments. This report is devoted to the recent developments of Belle collaboration in measuring the angle ϕ_3. This parameter is the least-well constrained by direct measurements while the theoretical uncertainties are expected to be small, so the new results are of particular interest.

Various methods for preforming a ϕ_3 measurement in $B \to DK$ decays have been proposed[1, 2]; the most sensitive technique relies on three-body D decays [3, 4] such as $K_S^0\pi^+\pi^-$. The weak parts of the amplitudes that contribute to the decay $B^+ \to DK^+$ are given by $V_{cb}^*V_{us} \sim A\lambda^3$ for $\overline{D}{}^0K^+$ final state and $V_{ub}^*V_{cs} \sim A\lambda^3(\rho + i\eta)$ for D^0K^+; the two amplitudes interfere as the D^0 and $\overline{D}{}^0$ decay into the same final state $K_S^0\pi^+\pi^-$. Assuming no CP asymmetry in D decay, the amplitude of the D decay from $B^\pm \to DK^\pm$ as a function of Dalitz variables $m_+^2 = m_{K_S^0\pi^+}^2$ and $m_-^2 = m_{K_S^0\pi^-}^2$ is

$$M_\pm = f(m_\pm^2, m_\mp^2) + re^{\pm i\phi_3 + i\delta} f(m_\mp^2, m_\pm^2), \tag{1}$$

where $f(m_+^2, m_-^2)$ is the amplitude of the $\overline{D}{}^0 \to K_S^0\pi^+\pi^-$ decay, r is the ratio of the magnitudes of the two interfering amplitudes, and δ is the strong phase difference between them. The $\overline{D}{}^0 \to K_S^0\pi^+\pi^-$ decay amplitude f can be determined from a large sample of flavor-tagged $\overline{D}{}^0 \to K_S^0\pi^+\pi^-$ decays produced in continuum e^+e^- annihilation. Simultaneous fit of B^+ and B^- data allows to obtain the values of r, ϕ_3 and δ. Refer to [3] and [5] for a detailed description of the technique.

Excited states of neutral D and K mesons can also be used, although the values of δ and r can differ for these decays. The results for $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ with $D^* \to D\pi^0$ using the data sample of 605 fb^{-1} were already reported by Belle [6]. Here we report the results using the decay $B^\pm \to D^*K^\pm$ with $D^* \to D\gamma$ and the combined ϕ_3 measurement with the three modes. The mode $D^* \to D\gamma$ has the same parameters as $B^\pm \to D^*K^\pm$ with $D^* \to D\pi^0$, except that due to the opposite parities of the $D\gamma$ and $D\pi^0$ states, the strong phases differ by 180° [7]. This provides an additional cross-check and allows us to reduce the systematic uncertainties in the combined measurement.

The selection of B candidates is based on the CM energy difference $\Delta E = \sum E_i - E_{\text{beam}}$ and the beam-constrained B mass $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - (\sum \vec{p}_i)^2}$, where E_{beam} is the CM beam energy, E_i and $\vec{p}_i$ are the CM energies and momenta of the B candidate decay products. We select events with $M_{\text{bc}} > 5.2$ GeV/c^2 and $|\Delta E| < 0.15$ MeV for the analysis. The requirement on the invariant mass of the neutral D candidate is $|M_{K_S^0\pi^+\pi^-} - M_{D^0}| < 11$ MeV/c^2. To select $B^+ \to D^*K^+$, $D^* \to D\pi^0$ events we require the mass difference ΔM of D^* and D to satisfy $140\ \text{MeV}/c^2 < \Delta M < 144\ \text{MeV}/c^2$. In the case of $B^+ \to D^*K^+$ with $D^* \to D\gamma$, γ is required to have an energy $E_\gamma > 100$ MeV, and the mass difference $\Delta M < 152\ \text{MeV}/c^2$. In the Dalitz plot fit, we use two event shape variables to better separate signal and $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ background events: the cosine of the angle θ_{thr} between the thrust axis of the B daughters and that of the rest of the event, and a Fisher discriminant [8] $\mathscr{F}$ composed of the B production angle, the angle of the B thrust axis relative to the beam and nine parameters representing the momentum flow in the event relative to the B thrust axis.

The background composition for $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ with $D^* \to D\pi^0$ is obtained from a two-dimensional unbinned maximum likelihood fit in the variables M_{bc} and ΔE (see [6] for details). The number of events in the signal box ($M_{\text{bc}} > 5.27$ GeV/c^2, $|\Delta E| < 30$ MeV, $|\cos\theta_{\text{thr}}| < 0.8$, $\mathscr{F} > -0.7$) for $B^\pm \to DK^\pm$ mode is 756 with the signal purity of 70%. For $B^\pm \to D^*K^\pm$ mode with $D^* \to D\pi^0$, the number of events in the signal box is 149, the signal purity is 80%.

Table 1: Results of the signal fits in parameters (x,y). The first error is statistical, the second is experimental systematic error. Model uncertainty is not included.

Parameter	$B^+ \to DK^+$	$B^+ \to D^*K^+$, $D^* \to D\pi^0$	$B^+ \to D^*K^+$, $D^* \to D\gamma$
x_-	$+0.105 \pm 0.047 \pm 0.011$	$+0.024 \pm 0.140 \pm 0.018$	$+0.144 \pm 0.208 \pm 0.025$
y_-	$+0.177 \pm 0.060 \pm 0.018$	$-0.243 \pm 0.137 \pm 0.022$	$+0.196 \pm 0.215 \pm 0.037$
x_+	$-0.107 \pm 0.043 \pm 0.011$	$+0.133 \pm 0.083 \pm 0.018$	$-0.006 \pm 0.147 \pm 0.025$
y_+	$-0.067 \pm 0.059 \pm 0.018$	$+0.130 \pm 0.120 \pm 0.022$	$-0.190 \pm 0.177 \pm 0.037$

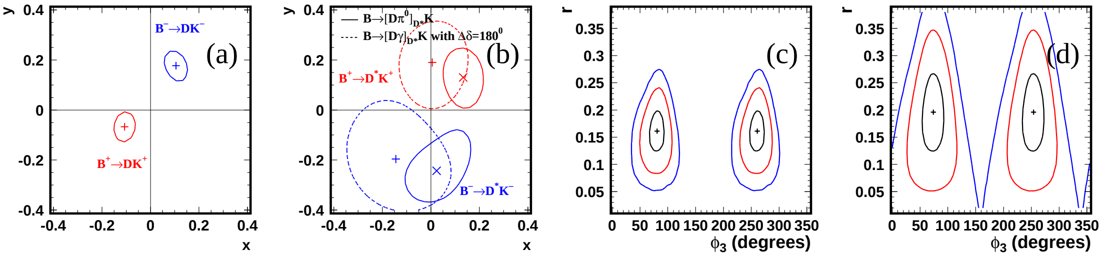

Figure 1: One standard deviation regions for the parameters $x = r\cos(\pm\phi_3 + \delta)$ and $y = r\sin(\pm\phi_3 + \delta)$ for $B^+ \to DK^+$ (a), and $B^+ \to D^*K^+$ (b) samples, separately for B^- and B^+ data. For the $B^\pm \to D^*K^\pm, D^* \to D\gamma$ mode (dashed line in (b)) the $x_\pm$ and $y_\pm$ sign is swapped to account for the relative strong phase difference of 180° wrt $B^\pm \to D^*K^\pm$, $D^* \to D\pi^0$ sample (solid line). Projections of one, two and three standard deviation regions for the $B^+ \to DK^+$ (c) and $B^+ \to D^*K^+$ (d) mode onto the (r, ϕ_3) planes.

Due to larger number of background sources for $B^\pm \to D^*K^\pm$ sample with $D^* \to D\gamma$, their fractions are obtained from an unbinned fit of the distribution of variables $M_{\rm bc}$, ΔE, $\cos\theta_{\rm thr}$, and $\mathscr{F}$. The background includes continuum and $B\overline{B}$ components; the latter is subdivided into events with combinatorial D^0 (studied using a generic MC sample), and those with real D^0 mesons (for which a dedicated MC simulation is performed). The relative fractions of $B\overline{B}$ backgrounds with real D^0 except for $B^\pm \to D^*\pi^\pm$ and $B^\pm \to DK^\pm$ are fixed given their PDG branching ratios and MC efficiencies. The number of experimental events in the signal box is 141, the signal purity is 42%.

The fit to a single Dalitz distribution with free parameters $x_\pm = r_\pm\cos(\pm\phi_3 + \delta)$ and $y_\pm = r_\pm\sin(\pm\phi_3 + \delta)$ ("$+$" and "$-$" correspond to B^+ and B^- decays, respectively) is performed by the unbinned maximum likelihood technique, using variables m_+^2, m_-^2, $M_{\rm bc}$, ΔE, $\cos\theta_{\rm thr}$ and $\mathscr{F}$. The distributions of each of the background components are assumed to be factorized as products of a Dalitz plot distribution (m_+^2, m_-^2), and distributions in $(M_{\rm bc}, \Delta E)$, and $(\cos\theta_{\rm thr}, \mathscr{F})$. The results of the data fits in the variables $x_\pm$ and $y_\pm$ are shown in Fig. 1 (a) and (b) and listed in Table 1.

Confidence intervals in r, ϕ_3 and δ are obtained from the $(x_\pm, y_\pm)$ values using a frequentist technique. The procedure is identical to that in our previous analysis [5]. Figures 1 (c) and (d) show the projections of the three-dimensional confidence regions onto the (r, ϕ_3) plane for $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ modes. In the results for the $B^\pm \to D^*K^\pm$ mode, we combine both $D^* \to D\pi^0$ and $D^* \to D\gamma$ final states, taking into account the relative strong phase of 180° between them. The values of the parameters are $\phi_3 = 80.8^{\circ}{}^{+13.1^\circ}_{-14.8^\circ} \pm 5.0^\circ \pm 8.9^\circ$, $r = 0.161^{+0.040}_{-0.038} \pm 0.011^{+0.050}_{-0.010}$, $\delta = 137.4^{\circ}{}^{+13.0^\circ}_{-15.7^\circ} \pm 4.0^\circ \pm 22.9^\circ$ for the $B^\pm \to DK^\pm$ mode, and $\phi_3 = 73.9^{\circ}{}^{+18.9^\circ}_{-20.2^\circ} \pm 4.2^\circ \pm 8.9^\circ$, $r = 0.196^{+0.073}_{-0.072} \pm 0.013^{+0.062}_{-0.012}$, $\delta = 341.7^{\circ}{}^{+18.6^\circ}_{-20.9^\circ} \pm 3.2^\circ \pm 22.9^\circ$ for the $B^\pm \to D^*K^\pm$ mode. The first error is statistical, the second is experimental systematic, and the third is the model uncertainty.

Experimental systematic errors come from uncertainty in the knowledge of the distributions used in the fit (*i.e.* Dalitz plot distributions of the backgrounds, and the $(M_{\rm bc},\Delta E)$ and $(\cos\theta_{\rm thr},\mathscr{F})$ distributions of the backgrounds and signal), fractions of background components, and the efficiency distribution across the phase space. The model used for the $\overline{D}^0\to K^0_S\pi^+\pi^-$ decay amplitude is one of the main sources of error in the analysis. The current measurement uses the same model variations as in the previous analysis [6] giving $\Delta\phi_3=8.9^\circ$ as a model uncertainty estimate. The statistical precision of the ϕ_3 measurement is already comparable to the estimated model uncertainty. However, it is possible to eliminate this uncertainty using the constraints on the $\overline{D}^0\to K^0_S\pi^+\pi^-$ decay amplitude obtained by CLEO in the analysis of $\psi(3770)\to D^0\overline{D}^0$ decays [9, 10].

The two event samples, $B^+\to DK^+$ and $B^+\to D^*K^+$, are combined in order to improve the sensitivity to ϕ_3. The confidence levels for the combination of two modes are obtained using the frequentist technique based on the parameters PDFs for the individual modes. From the combination of all modes, we obtain the value $\phi_3=78.4^\circ{}^{+10.8^\circ}_{-11.6^\circ}(\mathrm{stat})\pm3.6^\circ(\mathrm{syst})\pm8.9^\circ(\mathrm{model})$ (the solution with $0<\phi_3<180^\circ$). We also obtain values of the amplitude ratios $r_{DK}=0.160^{+0.040}_{-0.038}(\mathrm{stat})\pm 0.011(\mathrm{syst})^{+0.050}_{-0.010}(\mathrm{model})$. and $r_{D^*K}=0.196^{+0.072}_{-0.069}(\mathrm{stat})\pm0.012(\mathrm{syst})^{+0.062}_{-0.012}(\mathrm{model})$. With the systematic and model errors taken into account, the *CP* violation significance is estimated to be $(1-5\times10^{-4})$, or 3.5 standard deviations. The results agree with the measurements performed by BaBar collaboration using the same technique [11].

In summary, we report results of a measurement of the unitarity triangle angle ϕ_3 with a method based on Dalitz plot analysis of $\overline{D}^0\to K^0_S\pi^+\pi^-$ decay in the process $B^+\to D^{(*)}K^+$ using a 605 fb^{-1} of data collected by the Belle detector. Compared to previously reported measurement, the precision was improved by adding the sample with D^* decaying to $D\gamma$ state. The significance of *CP* violation for the combined measurement is $(1-5\times10^{-4})$, or 3.5 standard deviations.

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