Measurement of the Cabibbo-Kobayashi-Maskawa angle $\gamma$ in $B^{\mp} \to D^{(*)}K^{\mp}$ decays with a Dalitz analysis of $D \to K_S^{0}\pi^{-}\pi^{+}$

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K. Yamamoto,44
We report on a measurement of the Cabibbo-Kobayashi-Maskawa CP-violating phase $\gamma$ through a Dalitz analysis of neutral $D$ decays to $K^0_S \pi^- \pi^+$ in the processes $B^+ \rightarrow D^{(*)0} K^+$, $D^* \rightarrow D\pi^0, D\gamma$. Using a sample of 227 million $B\bar{B}$ pairs collected by the BABAR detector, we measure the amplitude ratios $r_B = 0.12 \pm 0.08 \pm 0.03 \pm 0.04$ and $r_B^* = 0.17 \pm 0.10 \pm 0.03 \pm 0.03$, the relative strong phases $\delta_B = (104 \pm 45 \pm 17 \pm 16) \gamma$ and $\delta_B^* = (-64 \pm 41 \pm 14 \pm 15) \gamma$ between the amplitudes $A(B^- \rightarrow D^{(*)0} K^-)$ and $A(B^+ \rightarrow D^{(*)0} K^+)$, and $\gamma = (70 \pm 31 \pm 10 \pm 11 \gamma)$. The first error is statistical, the second is the experimental systematic uncertainty and the third reflects the Dalitz model uncertainty. The results for the strong and weak phases have a two-fold ambiguity.

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The reconstruction efficiencies (purities in the signal region $m_{BS} > 5.272$ GeV/$c^2$) are 18% (63%), 5.9% (86%), 8.1% (52%) for the $B^\to D^0K^-$, $B^\to D^{*0}(\bar{D}^0\pi^0)K^-$, and $B^\to D^{*0}(\bar{D}^0\gamma)K^-$ decay modes, respectively. The cross-feed among the different samples is negligible.

The $D^0$ decay amplitude is determined from an unbinned maximum-likelihood Dalitz fit to a high-purity region of data (Fig. 2). We use the isobar formalism described in Ref. [13] to express $A_D$ as a sum of two-body decay-matrix elements (subscript $r$) and a non-resonant (subscript NR) contribution,

$$A_D(m_2^2, m_4^2) = \sum_r a_r e^{i\phi_r} A_r(m_2^2, m_4^2) + a_{NR} e^{i\phi_{NR}},$$

where each term is parameterized with an amplitude $a_r$ and a phase $\phi_r$. The function $A_r(m_2^2, m_4^2)$ is the Lorentz-invariant expression for the matrix element of a $D^0$ meson decaying into $K^{0}\pi^-\pi^+$ through an intermediate resonance $r$, parameterized as a function of the position in the Dalitz plane.

Table I summarizes the values of $a_r$ and $\phi_r$ obtained using a model consisting of 16 two-body elements comprising 13 distinct resonances and accounting for efficiency variations across the Dalitz plane and the small background contribution. For $r = \rho(770), \rho(1450)$ we use the functional form suggested in Ref. [14], while the remaining resonances are parameterized by a spin-dependent relativistic Breit-Wigner distribution. For intermediate states with a $K^*$, the regions of interference between DCS and CA decays are particularly sensitive to $\gamma$, and we include the DCS component when a significant contribution is expected. In addition, we find that the inclusion of the scalar $\pi\pi$ resonances $\sigma$ and $\sigma'$ significantly improves the quality of the fit [15]. Since the two $\sigma$ resonances are not well established and are only introduced to improve the description of our data, the uncertainty on their existence is considered in the systematic errors. We estimate the goodness of fit through a two-dimensional $\chi^2$ test and obtain $\chi^2 = 3824$ for 3054 − 32 degrees of freedom.

We simultaneously fit the $B^\to D^{*0}K^-$ samples using an unbinned extended maximum-likelihood fit to extract the $CP$-violating parameters along with...
the signal and background yields. Three different background components are considered: continuum events, $B^+ \to \bar{D}^{(*)0}\pi^-$ and $\Upsilon(4S) \to B\bar{B}$ (other than $B^+ \to \bar{D}^{(*)0}\pi^+$) decays. In addition to $m_{ES}$, the fit uses $\Delta E$ and a Fisher discriminant [12] to distinguish signal from $B^+ \to \bar{D}^{(*)0}\pi^-$ and continuum background, respectively.

The log-likelihood is

$$\ln L = -\sum_c N_c + \sum_j \ln \left( \sum_c N_c \mathcal{P}_c(\xi_j) \mathcal{P}_c^{Dalitz}(\eta_j) \right),$$

where $\xi_j = (m_{ES}, \Delta E, F_j)$ and $\eta_j = (m_1^2, m_2^2, \gamma_j)$ characterize the event $j$. Here, $\mathcal{P}_c(\xi)$ and $\mathcal{P}_c^{Dalitz}(\eta)$ are the probability density functions (PDF’s), and $N_c$ is the event yield for signal or background component $c$. For signal events, $\mathcal{P}_c^{Dalitz}(\eta)$ is given by $|\mathcal{A}_c^\pm(\eta)|^2$ corrected for the efficiency variations. All PDF shape parameters used to describe signal, continuum and $B^+ \to \bar{D}^{(*)0}\pi^-$ components are determined directly from $B^+ \to \bar{D}^{(*)0}K^-$ and $B^+ \to \bar{D}^{(*)0}\pi^-$ signal, sideband regions, and off-peak data, and are fixed in the final fit for CP parameters and event yields. Only the $m_{ES}$, $\Delta E$ and Dalitz PDF’s for $B\bar{B}$ background events are determined from a detailed Monte Carlo simulation. $B^+ \to \bar{D}^{(*)0}\pi^-$ candidates have been selected using criteria similar to those applied for $B^+ \to \bar{D}^{(*)0}K^-$ but requiring the bachelor pion not to be consistent with the kaon hypothesis.

The CP fit yields $282 \pm 20$, $90 \pm 11$, and $44 \pm 8$ signal $\bar{D}^0K^-$, $\bar{D}^{(*)0}(D^0\pi^0)K^-$, and $D^{0*}(D^0\gamma)K^-$ candidates, respectively, consistent with expectations based on measured branching fractions and efficiencies estimated from Monte Carlo simulation. The results for the CP-violating parameters $z_{\pm}^{(*)} = (x_{\pm}^{(*)}, y_{\pm}^{(*)})$, where $x_{\pm}^{(*)}$ and $y_{\pm}^{(*)}$ are defined as the real and imaginary parts of the complex amplitude ratios $r_B^{(*)} e^{i(\delta_B^{(*)} \pm \gamma)}$, respectively, are summarized in Table II. Here, $r_B^{(*)}$ is the amplitude ratio between the amplitudes $b \to u$ and $b \to c$, separately for $B^+$ and $B^-$. The only non-zero statistical correlations involving the CP deviation parameters are for the pairs $z_+^+, z_+^-$, $z_-^+, z_-^-$, and $z_+^\pm$, which amount to $3\%$, $6\%$, $-17\%$, and $-27\%$, respectively. The $z_{\pm}^{(*)}$ variables are more suitable fit parameters than $r_B^{(*)}$, $\delta_B^{(*)}$ and $\gamma$ because they are better behaved near the origin, especially in lower-statistics samples. Figures 3(a,b) show the one- and two-standard deviation confidence-level contours (statistical only) in the $z^{(*)}$ planes for $\bar{D}^0K^-$ and $\bar{D}^{0*}K^-$, and separately for $B^-$ (thick and solid lines) and $B^+$ (thin and dotted lines). Projections in the $r_B^{(*)} \gamma$ planes of the five-dimensional one- (dark) and two- (light) standard deviation regions, for (c) $\bar{D}^0K^-$ and (d) $\bar{D}^{0*}K^-$. The large single contribution to the systematic uncertainties in the CP parameters comes from the choice of the Dalitz model used to describe the $D^0 \to K^0_\pi^\mp \pi^\mp$ decay amplitudes. To evaluate this uncertainty we use the nominal Dalitz model (Table I) to generate large samples of pseudo-experiments. We then compare experiment by experiment the values of $z_{\pm}^{(*)}$ obtained from fits using the nominal model and a set of alternative models. We find that removing different combinations of $K^*$ and $\rho$ resonances (with low fit fractions), or changing the functional form of the resonance shapes, has little effect on the total $\chi^2$ of the fit, or on the values of $z_{\pm}^{(*)}$. However, models where one or both of the $\sigma$ resonances are removed lead to a significant increase in the $\chi^2$ of the fit. We use the average variations of $z_{\pm}^{(*)}$ corresponding to this second set of alternative models as the systematic uncertainty due to imperfect knowledge of $A_D$.

The experimental systematic uncertainties include the errors on the $m_{ES}$, $\Delta E$, and $F$ PDF parameters for signal and background, the uncertainties in the knowledge of the Dalitz distribution of background events, the effi-

| TABLE II: CP-violating parameters $z_{\pm}^{(*)}$ obtained from the CP fit to the $B^+ \to \bar{D}^{(*)0}K^-$ samples. The first error is statistical, the second is the experimental systematic uncertainty and the third reflects the Dalitz model uncertainty. |
|-----------------|-----------------|-----------------|-----------------|
| $z_+^{(*)}$     | $y_+^{(*)}$     |
|-----------------|-----------------|-----------------|-----------------|
| $z_+^{(*)}$     | $0.08 \pm 0.07$ | $0.03 \pm 0.02$ | $0.06 \pm 0.09$ |
| $z_-^{(*)}$     | $-0.13 \pm 0.07$| $0.03 \pm 0.03$ | $0.02 \pm 0.08$ |
| $z_+^{(*)}$     | $-0.13 \pm 0.09$| $0.03 \pm 0.02$ | $-0.14 \pm 0.11$|
| $z_-^{(*)}$     | $0.14 \pm 0.09$ | $0.03 \pm 0.03$ | $0.01 \pm 0.12$ |
ciency variations across the Dalitz plane, and the uncertainty in the fraction of events with a real $D^0$ produced in a back-to-back configuration with a negatively-charged kaon. Less significant systematic uncertainties originate from the imprecise knowledge of the fraction of real $D^{0*}$s, the invariant mass resolution, and the statistical errors in the Dalitz amplitudes and phases from the fit to the tagged $D^0$ sample. The possible effect of CP violation in $B^- \rightarrow D^{(*)0}\pi^-$ decays and $B\bar{B}$ background was found to be negligible.

A frequentist (Neyman) construction of the confidence regions of $p \equiv (r_B, r_B^*, \delta_B, \delta_B^*, \gamma)$ based on the constraints on $z_k^{(*)}$ has been adopted [4]. Using a large number of pseudo-experiments corresponding to the nominal CP fit model but with many different values of the CP fit parameters, we construct an analytical (Gaussian) parameterization of the PDF of $z_k^{(*)}$ as a function of $p$. For a given $p$, the five-dimensional confidence level $C = 1 - \alpha$ is calculated by integrating over all points in the fit parameter space closer (larger PDF) to $p$ than the fitted data values. The one- (two-) standard deviation region of the $C$ parameters is defined as the set of $p$ values for which $\alpha$ is smaller than 3.7% (45.1%).

Figures 3(c,d) show the two-dimensional projections in the $r_B^{(*)}$ versus $\gamma$ planes, including systematic uncertainties, for $D^0K^-$ and $D^{0*}K^-$. The figures show that this Dalitz analysis has a two-fold ambiguity, $(\gamma, \delta_B^{(*)}) \rightarrow (\gamma + 180^\circ, \delta_B^{(*)} + 180^\circ)$. The significance of direct CP violation, obtained by evaluating $C$ for the most probable $\gamma, \delta_B^{(*)}$, corresponds to 1.6, 2.1, and 2.4 standard deviations, for $D^0K^-$ and $D^{0*}K^-$, and their combination, respectively. Similar results are obtained using a Bayesian technique with uniform a priori probability distributions for $r_B^{(*)}$, $\delta_B^{(*)}$, and $\gamma$.

In summary, we have measured the direct CP-violating parameters in $B^- \rightarrow D^{(*)0}K^-$ using a Dalitz analysis of $D^0 \rightarrow K^0_\pi^\pi^-\pi^+$ decays, obtaining $r_B = 0.12 \pm 0.08 \pm 0.03 \pm 0.04 \pm 0.02$, $r_B^* = 0.17 \pm 0.10 \pm 0.03 \pm 0.03$, $\delta_B = (104 \pm 45, 17, 16)\degree$, $\delta_B^* = (-64 \pm 41, -12, 15)\degree$, and $\gamma = (70 \pm 31, 12, 14)\degree [12\degree, 137\degree]$. The first error is statistical, the second is the experimental systematic uncertainty and the third reflects the Dalitz model uncertainty. The values inside square brackets indicate the two-standard deviation intervals. The results for $\gamma$ from $B^- \rightarrow D^0K^-$ and $B^- \rightarrow D^{0*}K^-$ alone are $(70 \pm 38)\degree$ and $(71 \pm 35)\degree$, respectively (statistical errors only). The constraint on $\gamma$ is consistent with that reported by the Belle Collaboration [8], which has a slightly better statistical precision since our $r_B^{(*)}$ constraint favors smaller values.

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