Dalitz plot analysis of $B \to DDK$ decays

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We present Dalitz plot analyses for the decays of $B$ mesons to $D^-D^0K^+$ and $D^0\bar{D}^0K^+$. [Charge conjugate reactions are implicitly assumed throughout.] We report the observation of the $D_{s1}^*(2700)^+$ resonance in these two channels and obtain measurements of the mass $M(D_{s1}^*(2700)^+) = 2699^{+14}_{-7}$ MeV/$c^2$ and of the width $\Gamma(D_{s1}^*(2700)^+) = 127^{+24}_{-19}$ MeV, including statistical and systematic uncertainties. In addition, we observe an enhancement in the $D^0K^+$ invariant mass around 2350–2500 MeV/$c^2$ in both decays $B^0 \to D^-D^0K^+$ and $B^+ \to D^0\bar{D}^0K^+$, which we are not able to interpret. The results are based on 429 $fb^{-1}$ of data containing $471 \times 10^6 B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the BABAR detector at the SLAC National Accelerator Laboratory.

PRESENTED AT

The 7th International Workshop on Charm Physics
(CHARM 2015)
Detroit, MI, 18-22 May, 2015

Work supported by the U.S. Department of Energy.
1 Introduction

We analyze $B$ decays to $DDK$ final states via Dalitz plots in order to measure the mass and width of the $D_{sJ}^*(2700)^+$. This is the first time that Dalitz plot analyses have been performed for $B \rightarrow DDK$ decays.

The data analyzed here were recorded by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ storage ring operating at the SLAC National Accelerator Laboratory. This analysis uses the complete BABAR data sample collected at the $\Upsilon(4S)$ resonance corresponding to an integrated luminosity of 429 fb$^{-1}$ [1]. The BABAR detector is described in detail elsewhere [2]. Our Monte Carlo simulation uses EVTGEN [3] to model the kinematics of $B$ mesons and JETSET [4] to model continuum processes, $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$). The BABAR detector and its response to particle interactions are modeled using the GEANT4 [5] simulation package.

2 Data set and selection

The selection and reconstruction of $B^0 \rightarrow D^-D^0K^+$ and $B^+ \rightarrow \bar{D}^0D^0K^+$, along with 20 other $B \rightarrow \bar{D}^{(*)}D^{(*)}K$ modes, is described in Ref. [6]. We reconstruct $D$ mesons in the modes $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^0$, and $D^+ \rightarrow K^-\pi^+\pi^0$. For the mode $B^+ \rightarrow \bar{D}^0D^0K^+$, at least one of the $D^0$ mesons is required to decay to $K^-\pi^+$. We use the beam-energy-substituted mass ($m_{ES}$) and $\Delta E$, the difference between the reconstructed energy of the $B$ candidate and the beam energy in the $e^+e^-$ center-of-mass frame to assist in identifying signal and in case of multiple candidates per event we use the latter to make a selection. Finally, we keep only events with $|\Delta E| < 10-14$ MeV depending on the $D$ final state [6].

We fit the $m_{ES}$ distributions, as described in detail in Ref. [6] to obtain signal yields; however, since there are 22 $B \rightarrow \bar{D}^{(*)}D^{(*)}K$ modes that can cross-feed each other an iterative procedure is employed to obtain 635 $\pm$ 47 and 901 $\pm$ 54 signal events for $B^0 \rightarrow D^-D^0K^+$ and $B^+ \rightarrow \bar{D}^0D^0K^+$, respectively [6]. For the Dalitz analyses we use the $5.275 < m_{ES} < 5.284$ GeV/c$^2$ region to obtain a total of 1470 events with a signal purity of $(38.6 \pm 2.8 \pm 2.1)$% for $B^0 \rightarrow D^-D^0K^+$ and 1894 events with a signal purity of $(41.6 \pm 2.5 \pm 3.1)$% for $B^+ \rightarrow \bar{D}^0D^0K^+$, where the first uncertainties are statistical and the second systematic.

3 Dalitz plot analyses

We use an isobar model formalism to perform the Dalitz plot analysis [7]. The formalism is well-known and we merely note here that the dynamical amplitude, a Breit-Wigner form, contains a multiplicative factor $F_r$ which is the Blatt-Weisskopf damping factor for the resonance. [8]
We extract the complex amplitudes present in the data (from their moduli $\rho_i$ and phases $\phi_i$), and the mass and width of the $D_{s1}^*(2700)^+$ resonance using an unbinned maximum likelihood fit where the minimized negative twice-log-likelihood is called $F$ and the $D_{s1}^*(2700)^+$ resonance is the reference amplitude. We compare fits using $\Delta F \equiv F - F_{\text{nominal}}$.

The initial values of the parameters are randomized and we perform 250 such fits to ensure stable convergence to a global minimum. Both the efficiency and the background are parameterized by binned values and we perform a 2-dimensional interpolation to obtain values at desired locations on the plot.

The Dalitz plots for $B^0 \to D^- D^0 K^+$ and $B^+ \to D^0 D^0 K^+$ are shown in Fig. 2. The known amplitudes that could give a contribution in the Dalitz plot for both modes are nonresonant events, the $D_{s1}^*(2700)^+$ meson, and the $D_{s2}^*(2573)^+$ meson, which can decay to $D^0 K^+$, but has not been observed in $B \to D^{(*)}DK$ decays. The $D_{sJ}^*(2860)^+$ state is not included in the nominal fit. For the mode $B^+ \to D^0 D^0 K^+$, the additional
contributions from charmonium states included in the fit are the $\psi(3770)$ meson, and the $\psi(4160)$ meson.

In the following fits, the masses and widths of these resonances are fixed to their world averages \[9\], except for the $D^*_{s1}(2700)^+$ where the parameters are free to vary. The spin of this resonance is assumed to be 1. Preliminary fits with the components mentioned above fail to give satisfactory $\chi^2/n_{dof}$. Also, the low mass region between 2350 and 2500 MeV/c\(^2\) is not well described, especially for $B^+ \rightarrow \overline{D}^0 D^0 K^+$. After verifying that this enhancement is due to signal and not background or a cross-feed reflection, using two methods to subtract background, we proceed to fit it using an ad-hoc function that exponentially falls with $m^2(D^0 K^+)$. We call these our nominal fits. Since this region does not overlap significantly with the $D^*_{s1}(2700)^+$ region of interest, we are content to ascribe a systematic error to this effect. [We tried a low mass resonance but it only marginally improves the nominal fit.] The nominal fit for $B^0 \rightarrow D^- D^0 K^+$ returns $\chi^2/n_{dof} = 56/45$ and the nominal fit for $B^+ \rightarrow \overline{D}^0 D^0 K^+$ gives $\chi^2/n_{dof} = 86/48$. These fits are presented in Figures 4, 5, and 6. The high value of the $\chi^2/n_{dof}$ can be partly explained by differences in the data and fit densities in the $\psi(3770)$ region.

We consider several sources of systematic uncertainties in the fit parameters such as the moduli, the phases, the fit fractions, and the mass and width of the $D^*_{s1}(2700)^+$; the combined result of this investigation is reported as the second error below.

### 4 Results

The results for the Dalitz plot analysis of the modes $B^0 \rightarrow D^- D^0 K^+$ and $B^+ \rightarrow \overline{D}^0 D^0 K^+$ are presented in Tables 1 and 2. This is the first time the $D^*_{s1}(2700)^+$ is
observed in the decay $B^0 \to D^- D^0 K^+$. An excess at low $D^0 K^+$ invariant mass is evident but we have been unable to determine its origin.

Using the Dalitz fit fractions and the total branching fractions measured in a previous publication \[6\] with the exact same data sample we obtain the results presented in Table 3.

We list results for the mass and width of the $D_{s1}^+(2700)$ meson in Table 4. Combining modes we obtain

$$M(D_{s1}^+(2700)) = 2699^{+14}_{-7} \text{ MeV}/c^2,$$

$$\Gamma(D_{s1}^+(2700)) = 127^{+24}_{-19} \text{ MeV},$$

compatible with the world averages. Repeating our fits with the $J = 0$ and $J = 2$ hypotheses (see results in Table 5) we conclude that $J = 1$ is strongly favored; further
Figure 6: Projections of the Dalitz plot on $M(DK)$ axis for the data (dots) and for the result of the nominal fit (total histogram) for the modes $B^0 \to D^- D^0 K^+$ (left) and $B^+ \to \overline{D}^0 D^0 K^+$ (right).

Table 1: Results from the Dalitz plot fit (moduli, phases, and fractions) for $B^0 \to D^- D^0 K^+$. The different contributions are listed: the $D^{*}_{s1}(2700)^+$ and $D^{*}_{s2}(2573)^+$ resonances, the nonresonant amplitude and the low-mass excess described by an exponential. The first uncertainties are statistical and the second systematic.

| Contribution | Modulus  | Phase (°) | Fraction (%) |
|--------------|----------|-----------|--------------|
| $D^{*}_{s1}(2700)^+$ | 1.00     | 0         | 66.7 ± 7.8+3.5−3.8 |
| $D^{*}_{s2}(2573)^+$ | 0.031 ± 0.008 ± 0.002 | 277 ± 17+6−9 | 3.2 ± 1.6+0.3−0.4 |
| Nonresonant   | 1.33 ± 0.63+0.46−0.35 | 287 ± 21+10−15 | 10.9 ± 6.6+7.0−4.3 |
| Exponential   | 6.94 ± 1.83+0.82−0.43 | 269 ± 33+17−15 | 9.9 ± 2.9+3.0−3.3 |

assuming parity conservation in the resonant decays we deduce that the $D^{*}_{s1}(2700)^+$ has $J^P = 1^−$.

Finally, our fits do not favor inclusion of the $D^{*}_{sJ}(2860)^+$ and $D^{*}_{sJ}(3040)^+$ resonances in the final states $B^0 \to D^- D^0 K^+$ and $B^+ \to \overline{D}^0 D^0 K^+$.

ACKNOWLEDGEMENTS

We would like to acknowledge the efforts of the BABAR collaboration.
Table 2: Results from the Dalitz plot fit (moduli, phases, and fractions) for $B^+ \to D^0 D^0 K^+$. The different contributions are listed: the $D^*_1(2700)^+$, $D^*_2(2573)^+$, $\psi(3770)$, and $\psi(4160)$ resonances, and the low-mass excess described by an exponential. The first uncertainties are statistical and the second systematic.

| Contribution     | Modulus | Phase (°) | Fraction (%) |
|------------------|---------|-----------|--------------|
| $D^*_1(2700)^+$  | 1.00    | 0         | 38.3 ± 5.0^{+0.8}_{-6.2} |
| $D^*_2(2573)^+$  | 0.021 ± 0.010^{+0.009}_{-0.003} | 267 ± 30^{+17}_{-13} | 0.6 ± 1.1^{+0.4}_{-0.2} |
| $\psi(3770)$     | 1.40 ± 0.21^{+0.20}_{-0.24} | 284 ± 22^{+26}_{-30} | 9.0 ± 3.1^{+0.4}_{-0.8} |
| $\psi(4160)$     | 0.78 ± 0.20^{+0.18}_{-0.14} | 188 ± 13^{+14}_{-17} | 6.4 ± 3.1^{+1.9}_{-2.4} |
| Exponential      | 16.15 ± 2.26^{+1.09}_{-1.74} | 308 ± 8^{+6}_{-5} | 44.5 ± 6.2^{+1.3}_{-2.1} |
| Sum              |         |           | 98.9 ± 9.2^{+2.5}_{-7.0} |

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Table 3: Summary of partial branching fractions. The first uncertainties are statistical and the second systematic. The notation $B^0 \to D^- D^*_s(2700)^+ [D^0 K^+]$ refers to $B^0 \to D^- D^*_s(2700)^+$ followed by $D^*_s(2700)^+ \to D^0 K^+$.

| Mode                          | $B \ (10^{-4})$   |
|-------------------------------|-------------------|
| $B^0 \to D^- D^*_s(2700)^+ [D^0 K^+]$ | 7.14 ± 0.96 ± 0.69 |
| $B^+ \to \bar{D}^0 D^*_s(2700)^+ [D^0 K^+]$ | 5.02 ± 0.71 ± 0.93 |
| $B^0 \to D^- D^*_s(2573)^+ [D^0 K^+]$ | 0.34 ± 0.17 ± 0.05 |
| $B^+ \to \bar{D}^0 D^*_s(2573)^+ [D^0 K^+]$ | 0.08 ± 0.14 ± 0.05 |
| $B^+ \to \psi(3770)K^+ [\bar{D}^0 D^0]$ | 1.18 ± 0.41 ± 0.15 |
| $B^+ \to \psi(4160)K^+ [\bar{D}^0 D^0]$ | 0.84 ± 0.41 ± 0.33 |

Table 4: Mass and width of the $D^*_s(2700)^+$ meson obtained from the Dalitz plot analyses of the modes $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$. The first uncertainties are statistical and the second systematic.

| Mode                          | Mass (MeV/$c^2$) | Width (MeV)   |
|-------------------------------|------------------|---------------|
| $B^0 \to D^- D^0 K^+$         | 2694 ± 8±13      | 145 ± 24±22   |
| $B^+ \to \bar{D}^0 D^0 K^+$   | 2707 ± 8±8       | 113 ± 21±20   |

Table 5: Value of $\Delta F$ and $\chi^2/n_{dof}$ for the hypotheses $J = 0, 1, 2$ for the two modes. The nominal fit is presented in bold characters.

| Mode                          | $J = 0$           | $J = 1$           | $J = 2$           |
|-------------------------------|-------------------|-------------------|-------------------|
|                               | $\Delta F$       | $\chi^2/n_{dof}$ | $\Delta F$       | $\chi^2/n_{dof}$ |
| $B^0 \to D^- D^0 K^+$         | 131               | 131/45            | 56/45             | 108               | 125/45             |
| $B^+ \to \bar{D}^0 D^0 K^+$   | 63                | 137/48            | 86/48             | 99                | 145/48             |