Dalitz Analysis of $B \rightarrow Khh$ Decays at Belle

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We report results on the Dalitz analysis of three-body charmless $B^+ \rightarrow K^+\pi^+\pi^-$, $B^0 \rightarrow K^0\pi^+\pi^-$ and $B^+ \rightarrow K^+K^+K^-$ decays including searches for direct CP violation in the $B^+ \rightarrow K^+\pi^+\pi^-$ mode. Branching fractions for a number of quasi-two-body intermediate states are reported. We also observe evidence with 3.9σ significance for a large direct CP violation in $B^\pm \rightarrow \rho(770)^0K^\pm$ channel. This is the first evidence for CP violation in a charged meson decay. The results are obtained using a Dalitz analysis technique with a large data sample of $B\bar{B}$ pairs collected with the Belle detector operating at the KEKB asymmetric energy $e^+e^-$ collider.

Keywords: charmless $B$ decays, CP violation

I. INTRODUCTION

Decays of $B$ mesons to three-body charmless hadronic final states provide a rich laboratory for studying $B$ meson decay dynamics and provide new possibilities for CP violation searches. In decays to two-body final states ($B \rightarrow K\pi$, $\pi\pi$, etc.) direct CP violation can only be observed as a difference in $B$ and $\bar{B}$ decay rates. In decays to three-body final states dominated by quasi-two-body channels, direct CP violation can also manifest itself as a difference in relative phases between two quasi-two-body channels. Large direct CP violation is expected in charged $B$ decays to some quasi-two-body charmless hadronic modes $^1$.

II. APPARATUS, DATA SAMPLE & EVENT SELECTION

The Dalitz analysis of $B^+ \rightarrow K^+\pi^+\pi^-$ and $B^+ \rightarrow K^+K^+K^-$ decays is performed with a 140 fb$^{-1}$ data sample; for a Dalitz analysis of the $B^0 \rightarrow K^0\pi^+\pi^-$ decay and for CP violation searches in the decay $B^+ \rightarrow K^+\pi^+\pi^-$, we use a data sample of 357 fb$^{-1}$. The data are collected with the Belle detector $^2$ operating at the KEKB asymmetric-energy $e^+e^-$ collider with a center-of-mass (c.m.) energy at the $\Upsilon(4S)$ resonance.

We identify $B$ candidates using two almost independent kinematic variables: $\Delta E = (\sum_i \sqrt{c^2p_i^2 + c^4m_i^2}) - E^*_{\text{beam}}$ and $M_{bc} = \frac{1}{2} \sqrt{E^*_{\text{beam}}^2 - c^2(\sum_i p_i)^2}$, where the summation is over all particles from a $B$ candidate; $p_i$ and $m_i$ are their c.m. three-momenta and masses, respectively. The dominant background to studied processes is due to $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$ and $c$ quarks) continuum events. This background is suppressed using variables that characterize the event topology. A detailed description of the continuum suppression technique can be found in Ref. $^3$ and references therein. From a MC study we find the dominant background
originating from other $B$ decays that peaks in the signal region is due to $B \to Dh$, where $h$ stands for a charged pion or kaon and due to $B \to J/\psi(2S)|\mu^+\mu^-|K$ decays, where muons are misidentified as pions. We veto these backgrounds by applying requirements on the invariant mass of the appropriate two-particle combination. The most significant background from charmless $B$ decays to $B \to K\pi\pi$ channels originates from $B \to \eta'[\gamma\pi^+\pi^-]K$, from $B^+ \to \pi^+\pi^+\pi^-$, where one of the two same charge pions is misidentified as a kaon, and from $B \to K\pi$ processes. These backgrounds cannot be removed and are taken into account when fitting the data. We find no charmless $B$ decay modes that produce a significant background to the $K^+K^+K^-$ final state. The $\Delta E$ distributions for $K^+\pi^+\pi^-$, $K_0^0\pi^+\pi^-$ and $K^+K^+K^-$ candidates that pass all the selection requirements are shown in Fig. 1.

III. DALITZ ANALYSIS RESULTS

For the amplitude analysis we select events in the $B$ signal region defined as an ellipse around the $M_{bc}$ and $\Delta E$ mean values: $\left(\frac{M_{bc}-M_B}{7.5 \text{ MeV}/c^2}\right)^2 + \left(\frac{\Delta E}{40 \text{ MeV}}\right)^2 < 1$. We find that $B^+ \to K^+\pi^+\pi^-$ signal is well described by a coherent sum of the $K^*(892)^0\pi^+$, $K_0^*(1430)^0\pi^+$, $\rho(770)^0K^+$, $f_0(980)K^+$, $f_X(1300)K^+$, $\chi_{c0}K^+$ quasi-two-body channels and a non-resonant component. The channel $f_X(1300)K^+$ (with mass and width of $f_X(1300)$ to be determined from the fit) is added to account for an excess of signal events visible in $M(\pi^+\pi^-)$ spectrum near $1.3 \text{ GeV}/c^2$. Results of the best fit are shown in Figs. 2 (a,b). The mass and width of the $f_X(1300)$ state obtained from the fit are consistent with those for the $f_0(1370)$, however more data are required for more definite conclusion. To test for the contribution of other possible quasi-two-body intermediate states such as $K^*(1410)^0\pi^+$, $K^*(1680)^0\pi^+$, $K_2^0(1430)^0\pi^+$ or $f_2(1270)K^+$, we include an additional amplitude for each of these channels in the decay amplitude one by one and repeat the fit to data. None of these channels have a statistically significant signal. Branching fraction and upper limit results are summarized in Table II. For more details see Ref. [4].

In the fit to $K_2^0\pi^+\pi^-$ events we use decay amplitude $\mathcal{M}$ similar to those constructed in
the analysis of $B^+ \to K^+ \pi^+ \pi^-$ decay. The masses and widths of all resonances are fixed at either their world average values from PDG or at values determined from the analysis of $B^+ \to K^+ \pi^+ \pi^-$ decay (for $f_0(980)$ and $f_X(1300)$). Since in this analysis we do not distinguish between $B$ or $\bar{B}$ decays the signal PDF is a non-coherent sum $S(K_S^0 \pi^+ \pi^-) = |\mathcal{M}(K_S^0 \pi^+ \pi^-)|^2 + |\mathcal{M}(K_S^0 \pi^- \pi^+)|^2$. Results of the best fit are shown in Figs. 2 (d-f). All plots demonstrate good agreement between data and the fit. Branching fraction results are

TABLE I: Summary of branching fraction results. The first quoted error is statistical, the second is systematic and the third is the model error.

| Mode | $\mathcal{B}(B^+ \to R h^+) \times \mathcal{B}(R \to h^+ h^-) \times 10^6$ | $\mathcal{B}(B^+ \to R h^+) \times 10^6$ |
|-------|-------------------------------------------------|-------------------------------------------------|
| $K^+ \pi^+ \pi^-$ charmless total | - | 46.6 ± 2.1 ± 4.3 |
| $K^*(892)^0 [K^+ \pi^-] \pi^+$ | 6.55 ± 0.60 ± 0.60±0.38±0.57 | 9.83 ± 0.90 ± 0.90±0.57±0.86 |
| $K_0^*(1430)^0 [K^+ \pi^-] \pi^+$ | 27.9 ± 1.8 ± 2.6±5.4 | 45.0 ± 2.9 ± 6.2±8.7 |
| $K^*(1410)^0 [K^+ \pi^-] \pi^+$ | < 2.0 | - |
| $K^*(1680)^0 [K^+ \pi^-] \pi^+$ | < 3.1 | - |
| $K_2^*(1430)^0 [K^+ \pi^-] \pi^+$ | < 2.3 | - |
| $\rho(770)^0 [\pi^+ \pi^-] K^+$ | 4.78 ± 0.75 ± 0.44±0.91±0.87 | 4.78 ± 0.75 ± 0.44±0.91±0.87 |
| $f_0(980)[\pi^+ \pi^-] K^+$ | 7.55 ± 1.24 ± 0.69±1.48±0.96 | - |
| $f_2(1270)[\pi^+ \pi^-] K^+$ | < 1.3 | - |
| Non-resonant | - | 17.3 ± 1.7 ± 1.6±17.1 |
| $K_0^0 \pi^+ \pi^-$ charmless | - | 47.5 ± 2.4 ± 3.7 |
| $K^*(892)^0 [K^0 \pi^-] \pi^-$ | 5.61 ± 0.72 ± 0.43±0.43±0.20 | 8.42 ± 1.08 ± 0.65±0.43±0.43 |
| $K_0^*(1430)^0 [K^0 \pi^-] \pi^-$ | 30.8 ± 2.4 ± 2.4±3.0±3.0 | 49.7 ± 3.8 ± 3.8±1.2±4.8 |
| $K^*(1410)^0 [K^0 \pi^-] \pi^+$ | < 3.8 | - |
| $K^*(1680)^0 [K^0 \pi^-] \pi^+$ | < 2.6 | - |
| $K_2^*(1430)^0 [K^0 \pi^-] \pi^+$ | < 2.1 | - |
| $\rho(770)^0 [\pi^+ \pi^-] K^0$ | 6.13 ± 0.95 ± 0.47±1.00±1.00 | 6.13 ± 0.95 ± 0.47±1.00±1.00 |
| $f_0(980)[\pi^+ \pi^-] K^0$ | 7.60 ± 1.66 ± 0.59±0.48±0.67 | - |
| $f_2(1270)[\pi^+ \pi^-] K^0$ | < 1.4 | - |
| Non-resonant | - | 19.9 ± 2.5 ± 1.5±0.7±1.2 |
| $K^+ K^- K^-$ charmless total | - | 30.6 ± 1.2 ± 2.3 |
| $\phi[K^+ K^-] K^+$ | 4.72 ± 0.45 ± 0.35±0.39±0.22 | 9.60 ± 0.92 ± 0.71±0.78±0.46 |
| $\phi(1680)[K^+ K^-] K^+$ | < 0.8 | - |
| $f_0(980)[K^+ K^-] K^+$ | < 2.9 | - |
| $f_2(1525)[K^+ K^-] K^+$ | < 4.9 | - |
| $\alpha_2(1320)[K^+ K^-] K^+$ | < 1.1 | - |
| Non-resonant | - | 24.0 ± 1.5 ± 1.8±1.9±5.7 |
| $\chi_{oo}[\pi^+ \pi^-] K^+$ | 1.37 ± 0.28 ± 0.12±0.34±0.35 | - |
| $\chi_{oo}[K^+ K^-] K^+$ | 0.86 ± 0.26 ± 0.06±0.20±0.05 | - |
| $\chi_{oo} K^+$ combined | - | 196 ± 35 ± 33±197 ±26 |
| $\chi_{oo}[\pi^+ \pi^-] K^0$ | < 0.56 | - |
FIG. 2: Results of the fit to events in the $B$ signal region for the (a,b) $K^+\pi^+\pi^-$, (c) $K^+K^+K^-$, and (d,e,f) $K_S^0\pi^+\pi^-$ final state. Points with error bars are data, the open histogram is the fit result and hatched histogram is the background component.

summarized in Table I. For more details see Ref. [5].

We find that the $K^\pm K^\mp K^-$ signal is well described by an amplitude that is a coherent sum of the $\phi K^+$, $f_X(1500)K^+$, $\chi_{c0}K^+$ quasi-two-body channels and a non-resonant component, where the $f_X(1500)K^+$ (with mass and width of $f_X(1500)$ to be determined from the fit) channel is added to describe the excess of signal events visible in $K^+K^-$ mass spectrum near 1.5 GeV/$c^2$. As there are two identical kaons in the final state, the decay amplitude is symmetrized with respect to interchange of two kaons of the same charge $S(K^+K^+K^-) = |\mathcal{M}(K^+_1K^+_2K^-) + \mathcal{M}(K^+_2K^+_1K^-)|^2$. Results of the fit are shown in Fig.2(c) and summarized in Table I. For more details see Ref. [4].

IV. SEARCH FOR DIRECT CP VIOLATION IN $B^\pm \rightarrow K^\pm \pi^\mp \pi^\mp$

For $CP$ violation studies the amplitude for each quasi-two-body channel is modified from $ae^{i\delta}$ to $ae^{i\delta}(1 \pm be^{i\varphi})$, where the plus (minus) sign corresponds to $B^+$ ($B^-$) decay. With such a parameterization, the charge asymmetry, $A_{CP}$, for a particular quasi-two-body $B \rightarrow f$ channel can be calculated as

$$A_{CP}(f) = \frac{N^- - N^+}{N^- + N^+} = -\frac{2b \cos \varphi}{1 + b^2}.$$  

Results of the fit are given in Table II. The statistical significance of the asymmetry quoted in Table II is calculated as $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$, where $\mathcal{L}_{\text{max}}$ and $\mathcal{L}_0$ denote the maximum
TABLE II: Results of the best fit to $K^\pm\pi^\pm\pi^\mp$ events in the $B$ signal region. The first quoted error is statistical and the second is the model dependent uncertainty. The quoted significance is statistical only.

| Channel                  | $b$       | $\varphi$, ($^\circ$) | $A_{CP}$, (%) | Significance, ($\sigma$) |
|--------------------------|-----------|------------------------|---------------|--------------------------|
| $K^* (892)\pi^\pm$       | 0.078 $\pm$ 0.033 $^{+0.012}_{-0.003}$ | $-18 \pm 44$ $^{+5}_{-13}$ | $-14.9 \pm 6.4$ $^{+0.8}_{-0.8}$ | 2.6 |
| $K_0 (1430)\pi^\pm$      | 0.069 $\pm$ 0.031 $^{+0.010}_{-0.008}$ | $-123 \pm 16$ $^{+4}_{-5}$ | $+7.6 \pm 3.8$ $^{+2.0}_{-0.9}$ | 2.7 |
| $\rho (770)^0 K^\pm$     | 0.28 $\pm$ 0.11 $^{+0.07}_{-0.05}$    | $-125 \pm 32$ $^{+10}_{-85}$ | $+30 \pm 11$ $^{+11}_{-4}$ | 3.9 |
| $f_0 (980) K^\pm$        | 0.30 $\pm$ 0.19 $^{+0.10}_{-0.04}$    | $-82 \pm 8$ $^{+2}_{-2}$ | $-7.7 \pm 6.5$ $^{+4.1}_{-1.6}$ | 1.6 |
| $f_2 (1270) K^\pm$       | 0.37 $\pm$ 0.17 $^{+0.04}_{-0.07}$    | $-24 \pm 29$ $^{+14}_{-20}$ | $-59 \pm 22$ $^{+3}_{-0}$ | 2.7 |
| $\chi_{c0} K^\pm$       | 0.15 $\pm$ 0.35 $^{+0.08}_{-0.07}$    | $-77 \pm 94$ $^{+64}_{-11}$ | $-6.5 \pm 19$ $^{+2.9}_{-1.4}$ | 0.7 |

likelihood with the best fit and with the asymmetry fixed at zero, respectively. Systematic uncertainty for $A_{CP}$ results in Table II is 3%. The only channel where the statistical significance of the asymmetry exceeds the 3$\sigma$ level is $B^\pm \to \rho (770)^0 K^\pm$, where we find a 3.9$\sigma$ effect. Figures 3(a,b) show the $M(\pi^\pm\pi^\mp)$ distributions for the $\rho (770)^0 - f_0 (980)$ mass region separately for $B^-$ and $B^+$ events. The effect is more apparent when $M(\pi^\pm\pi^\mp)$ spectra for the two helicity angle regions shown in Figs. 3(c-f) are compared. Results on the $A_{CP}$ measurement are summarized in Table II. To cross check the asymmetry observed in $B^\pm \to \rho (770)^0 K^\pm$ we make an independent fit to $B^-$ and $B^+$ subsamples. We also confirm the significance of the asymmetry observed in $B^\pm \to \rho (770)^0 K^\pm$ channels with MC pseudo-experiments. For

FIG. 3: $\pi^+\pi^-$ mass spectra for $B^-$ (top row) and $B^+$ (bottom row) events for different helicity regions: (a,b) no helicity cuts; (c,d) $\cos \theta_H^{\pi\pi} < 0$; (e,f) $\cos \theta_H^{\pi\pi} > 0$; Points with error bars are data, the open histogram is the fit result and the hatched histogram is the background component.
more details see Ref. [6]. The large value of $A_{CP}$ measured in $B^{\pm} \rightarrow \rho(770)^0 K^{\pm}$ is in agreement with a recent update by BaBar [7] and some theoretical predictions [1]. The statistical significance of the asymmetry varies from $3.7\sigma$ to $4\sigma$ depending on the model used to fit the data. This is the first evidence for $CP$ violation in the decay of a charged meson.

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