Evidence for Large Direct *CP* Violation in $B^{\pm} \to \rho(770)^0 K^{\pm}$ from Analysis of Three-Body Charmless $B^{\pm} \to K^{\pm}\pi^{\pm}\pi^{\pm}$ Decays

A. Garmash,[30] K. Abe,[6] K. Abe,[40] I. Adachi,[6] H. Aihara,[42] Y. Asano,[46] T. Aushev,[9] T. Aziz,[38] S. Bahinipati,[4] A. M. Bakich,[37] M. Barbero,[5] I. Bedny,[1] U. Bitenc,[10] I. Bizjak,[10] A. Bondar,[1] A. Bozek,[23] M. Bračko,[6,16,10] J. Brodzicka,[23] T. E. Browder,[5] P. Chang,[22] Y. Chao,[22] A. Chen,[20] K.-F. Chen,[22] W. T. Chen,[20] B. G. Cheon,[3] R. Chistov,[9] Y. Choi,[36] Y. K. Choi,[36] A. Chuvikov,[30] J. Dalseno,[17] M. Danilov,[9] M. Dash,[47] J. Dragic,[6] A. Drutskoy,[4] S. Eidelman,[1] D. Epifanov,[1] S. Fratina,[10] N. Gabyshev,[1] T. Gershon,[6] A. Go,[20] G. Gokhroo,[38] B. Golob,[15,10] A. Gorišek,[10] H. C. Ha,[12] T. Hara,[27] Y. Hasegawa,[35] N. C. Hastings,[42] K. Hayasaka,[18] H. Hayashii,[19] M. Hazumi,[6] T. Hokuue,[18] Y. Hoshi,[40] S. Hou,[20] W.-S. Hou,[22] Y. B. Hsiung,[22] T. Iijima,[18] A. Imoto,[19] K. Inami,[18] A. Ishikawa,[6] R. Itoh,[6] M. Iwasaki,[42] Y. Iwasaki,[6] P. Kapusta,[23] N. Katayama,[6] H. Kawai,[2] T. Kawasaki,[24] H. R. Khan,[43] H. Kichimi,[6] S. K. Kim,[34] S. M. Kim,[36] K. Kinoshita,[4] S. Korpar,[16,10] P. Križan,[15,10] P. Krokovny,[1] R. Kulasiri,[4] C. C. Kuo,[20] A. Kuzmin,[1] Y.-J. Kwon,[48] S. E. Lee,[34] T. Lesiak,[23] A. Limosani,[6] S.-W. Lin,[22] D. Liventsev,[9] F. Mandl,[8] D. Marlow,[30] T. Matsumoto,[44] A. Matyja,[23] W. Mitaroff,[8] K. Miyabayashi,[19] H. Miyake,[27] H. Miyata,[24] Y. Miyazaki,[18] T. Nagamine,[41] E. Nakano,[26] M. Nakao,[6] Z. Natkaniec,[23] S. Nishida,[6] O. Nitoh,[45] S. Noguchi,[19] T. Ohshima,[18] T. Okabe,[18] S. Okuno,[11] S. L. Olsen,[5] H. Ozaki,[6] C. W. Park,[36] H. Park,[13] K. S. Park,[36] L. S. Peak,[37] R. Pestotnik,[10] L. E. Piilonen,[47] M. Rozanska,[23] Y. Sakai,[6] N. Satoyama,[35] T. Schietinger,[14] O. Schneider,[14] J. Schümann,[22] C. Schwanda,[8] A. J. Schwartz,[4] R. Seidl,[31] M. E. Sevior,[17] H. Shibuya,[39] B. Shwartz,[1] J. B. Singh,[28] A. Somov,[4] R. Stamen,[6] S. Stanič,[25] M. Starič,[10] T. Sumiyoshi,[44] S. Suzuki,[32] S. Y. Suzuki,[6] F. Takasaki,[6] K. Tamai,[6] N. Tamura,[24] M. Tanaka,[6] G. N. Taylor,[17] Y. Teramoto,[26] X. C. Tian,[29] K. Trabelsi,[5] T. Tsuboyama,[6] T. Tsukamoto,[6] S. Uehara,[6] T. Uglov,[9] S. Uno,[6] P. Urquijo,[17] G. Varner,[5] K. E. Varvell,[37] S. Villa,[14] C. H. Wang,[21] M.-Z. Wang,[22] Y. Watanabe,[43] E. Won,[12] Q. L. Xie,[7] A. Yamaguchi,[41] M. Yamauchi,[6] Heyoung Yang,[34] L. M. Zhang,[33] Z. P. Zhang,[33] V. Zhilich,[1] and D. Zürcher[14]

(Belle Collaboration)

[1]*Budker Institute of Nuclear Physics, Novosibirsk*
[2]*Chiba University, Chiba*
[3]*Chonnam National University, Kwangju*
[4]*University of Cincinnati, Cincinnati, Ohio 45221*
[5]*University of Hawaii, Honolulu, Hawaii 96822*
[6]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[7]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[8]*Institute of High Energy Physics, Vienna*
[9]*Institute for Theoretical and Experimental Physics, Moscow*
[10]*J. Stefan Institute, Ljubljana*
[11]*Kanagawa University, Yokohama*
[12]*Korea University, Seoul*
[13]*Kyungpook National University, Taegu*
[14]*Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne*
[15]*University of Ljubljana, Ljubljana*
[16]*University of Maribor, Maribor*
[17]*University of Melbourne, Victoria*
[18]*Nagoya University, Nagoya*
[19]*Nara Women's University, Nara*
[20]*National Central University, Chung-li*
[21]*National United University, Miao Li*
[22]*Department of Physics, National Taiwan University, Taipei*
[23]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[24]*Niigata University, Niigata*
[25]*Nova Gorica Polytechnic, Nova Gorica*
[26]*Osaka City University, Osaka*
[27]*Osaka University, Osaka*
[28]*Panjab University, Chandigarh*
[29]*Peking University, Beijing*
[30]*Princeton University, Princeton, New Jersey 08544*

0031-9007/06/96(25)/251803(6)

[31]RIKEN BNL Research Center, Upton, New York 11973
[32]Saga University, Saga
[33]University of Science and Technology of China, Hefei
[34]Seoul National University, Seoul
[35]Shinshu University, Nagano
[36]Sungkyunkwan University, Suwon
[37]University of Sydney, Sydney, New South Wales
[38]Tata Institute of Fundamental Research, Bombay
[39]Toho University, Funabashi
[40]Tohoku Gakuin University, Tagajo
[41]Tohoku University, Sendai
[42]Department of Physics, University of Tokyo, Tokyo
[43]Tokyo Institute of Technology, Tokyo
[44]Tokyo Metropolitan University, Tokyo
[45]Tokyo University of Agriculture and Technology, Tokyo
[46]University of Tsukuba, Tsukuba
[47]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[48]Yonsei University, Seoul

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We report results on a Dalitz analysis of three-body charmless $B^\pm \to K^\pm\pi^\pm\pi^\mp$ decay including searches for direct CP violation. We report the first observation of the decay $B^\pm \to f_2(1270)K^\pm$ with a statistical significance above 6σ. We also observe first evidence for large direct CP violation in the $B^\pm \to \rho(770)^0K^\pm$ channel. The results are obtained with a data sample that contains 386×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

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Decays of B mesons to three-body charmless hadronic final states provide new possibilities for CP violation searches. In decays to two-body final states ($B\to K\pi$, $\pi\pi$, etc.) direct CP violation can be observed as a difference in B and $\bar{B}$ decay rates. In decays to three-body final states that are often dominated by quasi-two-body channels, direct CP violation can also manifest itself as a difference in relative phase between two quasi-two-body amplitudes that can be measured via amplitude (Dalitz) analysis. So far direct CP violation has been observed only in decays of neutral K mesons [1] and recently in neutral B meson decays [2]. However, large direct CP violation is expected in charged B decays to some quasi-two-body charmless hadronic modes [3].

The search for direct CP violation in the three-body charmless $B^\pm \to K^\pm\pi^\pm\pi^\mp$ decay described in this Letter is performed by applying a Dalitz analysis technique [4] to a data sample containing 386×10^6 $B\bar{B}$ pairs, collected with the Belle detector [5] operating at the KEKB asymmetric-energy e^+e^- collider [6] with a center-of-mass (c.m.) energy at the $\Upsilon(4S)$ resonance. These results supersede the results reported in Ref. [7].

Charged tracks are required to have momenta transverse to the beam greater than 0.1 GeV$/c$ and to be consistent with originating from the interaction region. For charged kaon identification we impose a requirement on a particle identification variable which has 86% efficiency and a 7% fake rate from misidentified pions as measured from data. Charged tracks that are positively identified as electrons or protons are excluded. B candidates are identified using two kinematic variables: the energy difference $\Delta E = (\sum_i\sqrt{c^2|\mathbf{p}_i|^2 + c^4m_i^2}) - E^*_{\rm beam}$, and the beam constrained mass $M_{\rm bc} = \frac{1}{c^2}\sqrt{E^{*2}_{\rm beam} - c^2|\sum_i\mathbf{p}_i|^2}$, where the summation is over all particles from a B candidate; $\mathbf{p}_i$ and m_i are their c.m. three-momenta and masses, respectively; $E^*_{\rm beam}$ is the beam energy in the c.m. frame. The signal $M_{\rm bc}$ resolution is mainly given by the beam energy spread, and amounts to 2.9 MeV$/c^2$. The signal ΔE shape is fitted by a sum of two Gaussian functions with a common mean. In fits to the experimental data, we fix the width (35 MeV) and the relative fraction (0.16) of the second Gaussian function to the values obtained from Monte Carlo (MC) simulation. The common mean of the two Gaussian functions and the width of the main Gaussian are allowed to float.

The dominant background is due to $e^+e^-\to q\bar{q}$ ($q = u$, d, s, and c quarks) continuum events. We reject about 98% of this background while retaining 36% of the signal using variables that characterize the event topology. For more details see Ref. [8] and references therein. From MC studies we find that the dominant backgrounds originating from other B decays that peak in the signal region are due to $B^+\to\bar{D}^0[K^+\pi^-]\pi^+$ and due to $B^+\to J/\psi[\mu^+\mu^-]K^+$ and $B^+\to\psi(2S)[\mu^+\mu^-]K^+$ decays, where muons are misidentified as pions. We veto these backgrounds by applying requirements on the invariant masses of the appropriate two-particle combinations [7]. The most significant backgrounds from charmless B decays originate from $B^+\to\eta'[\gamma\pi^+\pi^-]K^+$,

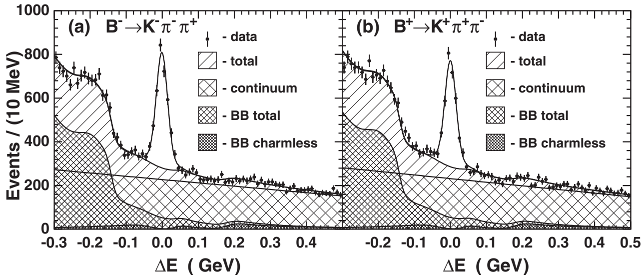

FIG. 1. ΔE distributions for (a) $B^- \to K^-\pi^-\pi^+$ and (b) $B^+ \to K^+\pi^+\pi^-$ events with $|M_{\rm bc} - M_B| < 7.5\ {\rm MeV}/c^2$. Points with error bars are data; the smooth curve is the fit result; the hatched areas are various background components.

$B^+ \to \pi^+\pi^+\pi^-$ where one of the two same-charge pions is misidentified as a kaon, and from $B^0 \to K^+\pi^-$ processes.

The ΔE distributions for $B^\pm \to K^\pm\pi^\pm\pi^\mp$ candidates that pass all the selection requirements are shown in Fig. 1. In the fit to the ΔE distribution we fix the shape of the $B\bar{B}$ background component from MC studies and let the normalization float. The shape of the $q\bar{q}$ background is parametrized by a linear function with the slope and normalization as free parameters of the fit. From these fits we find 2248 ± 79 (2038 ± 76) B^- (B^+) signal events; the width of the main signal Gaussian is 15.3 ± 0.5 MeV.

For the amplitude analysis we select events from the B signal region defined as an ellipse around the $M_{\rm bc}$ and ΔE mean values: $[\frac{M_{\rm bc}-M_B}{7.5\ {\rm MeV}/c^2}]^2 + [\frac{\Delta E}{40\ {\rm MeV}}]^2 < 1$. The total number of events in the signal region is 7757; the relative fraction of signal events is 0.512 ± 0.012. The distribution of background events is determined from analysis of events in the $M_{\rm bc}$-ΔE sideband region.

The analysis is performed by means of an unbinned maximum likelihood fit. The distribution of background events is parametrized by an empirical function with 11 parameters [7]. As found in Ref. [7], the three-body $B^+ \to K^+\pi^+\pi^-$ amplitude is well-described by a coherent sum of $K^*(892)^0\pi^+$, $K_0^*(1430)^0\pi^+$, $\rho(770)^0K^+$, $f_0(980)K^+$, $f_X(1300)K^+$, and $\chi_{c0}K^+$ quasi-two-body channels and a nonresonant amplitude. The $f_X(1300)K^+$ channel was introduced in order to describe an excess of signal events at $M(\pi^+\pi^-) \simeq 1.3\ {\rm GeV}/c^2$ [see Fig. 2(b)]. The best fit is achieved assuming $f_X(1300)$ is a scalar state; the mass and width determined from the fit (see below) are consistent with those for $f_0(1370)$ [9]. Each quasi-two-body amplitude includes a Breit-Wigner function, a B decay form-factor parametrized in a single-pole approximation, a Blatt-Weisskopf factor [10] for the intermediate resonance decay, and a function that describes angular correlations between final state particles. This is multiplied by a factor of $ae^{i\delta}$ that describes the relative magnitude and phase of the contribution. The nonresonant amplitude is parametrized by an empirical function $\mathcal{A}_{\rm nr}(K^+\pi^+\pi^-) = a_1^{\rm nr}e^{-\alpha s_{13}}e^{i\delta_1^{\rm nr}} + a_2^{\rm nr}e^{-\alpha s_{23}}e^{i\delta_2^{\rm nr}}$, where α, $a_i^{\rm nr}$ and $\delta_i^{\rm nr}$ are fit parameters, $s_{13} \equiv M^2(K^+\pi^-)$, and $s_{23} \equiv M^2(\pi^+\pi^-)$. In this analysis we modify the model by changing the parametrization of the $f_0(980)$ line shape from a Breit-Wigner function to a Flatté parametrization [11] and by adding two more channels: $\omega(782)K^+$ and $f_2(1270)K^+$. 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 the B^+ (B^-) decay. With such a parametrization the charge asymmetry, A_{CP}, for a particular quasi-two-body $B \to f$ channel is given by

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

It is worth noting that in this parametrization we assume zero relative phase between B^- and B^+ amplitudes.

First we fit the data with $b_i \equiv 0$ (no CP violation) and determine the parameters of the $f_X(1300)$ [($M = 1.449 \pm 0.013({\rm stat})\ {\rm GeV}/c^2$, $\Gamma = 0.126 \pm 0.025({\rm stat})\ {\rm GeV}/c^2$], $f_0(980)$ [$M = 0.950 \pm 0.009({\rm stat})\ {\rm GeV}/c^2$ and coupling constants $g_{\pi\pi} = 0.23 \pm 0.05({\rm stat})$ and $g_{KK} = 0.73 \pm 0.30({\rm stat})$], and the parameter of the nonresonant amplitude $\alpha = 0.195 \pm 0.018({\rm stat})$. We then fix these six parameters and repeat the fit to data with b and φ floating for all terms

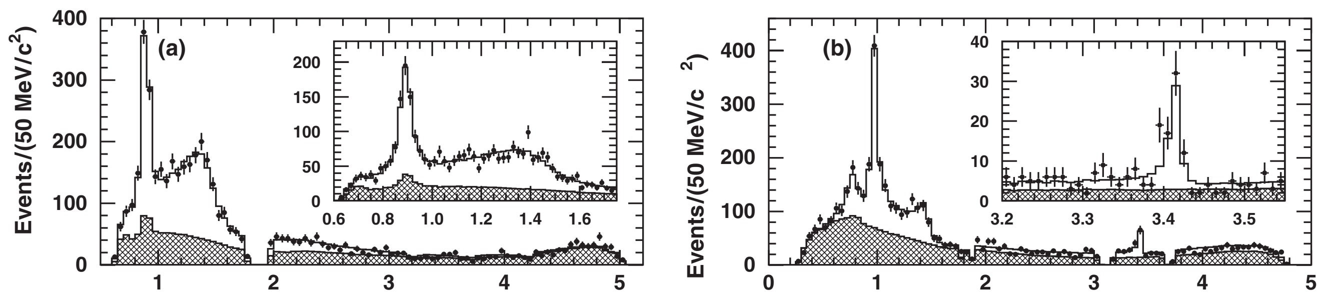

FIG. 2. Results of the fit to $K^\pm\pi^\pm\pi^\mp$ events in the B signal region: (a) $M(K^+\pi^-)$ distribution with $M(\pi^+\pi^-) > 1.5\ {\rm GeV}/c^2$; (b) $M(\pi^+\pi^-)$ distribution with $M(K^+\pi^-) > 1.5\ {\rm GeV}/c^2$. Points with error bars are data, the open histogram is the fit result and hatched histogram is the background component. Inset in (a) shows the $K^*(892) - K_0^*(1430)$ mass region in 20 ${\rm MeV}/c^2$ bins. Inset in (b) shows the χ_{c0} mass region in 10 ${\rm MeV}/c^2$ bins.

TABLE I. Results of the best fit to $K^{\pm}\pi^{\pm}\pi^{\mp}$ events. The first quoted error is statistical and the second is the model dependent uncertainty. The quoted asymmetry significance is statistical only and corresponds to 2 degrees of freedom.

Channel	Fraction (%)	δ (deg)	b	φ (deg)	Asymmetry significance (σ)
$K^*(892)\pi^{\pm}$	$13.0 \pm 0.8^{+0.5}_{-0.7}$	0 (fixed)	$0.078^{+0.040+0.012}_{-0.031-0.003}$	$-18 \pm 44^{+5}_{-13}$	2.6
$K_0^*(1430)\pi^{\pm}$	$65.5 \pm 1.5^{+2.2}_{-3.9}$	$55 \pm 4^{+1}_{-5}$	$0.069^{+0.032+0.010}_{-0.030-0.008}$	$-123 \pm 16^{+4}_{-5}$	2.7
$\rho(770)^0 K^{\pm}$	$7.85 \pm 0.93^{+0.64}_{-0.59}$	$-21 \pm 14^{+14}_{-19}$	$0.28^{+0.12+0.07}_{-0.09-0.09}$	$-125 \pm 32^{+10}_{-85}$	3.9
$\omega(782)K^{\pm}$	$0.15 \pm 0.12^{+0.03}_{-0.02}$	$100 \pm 31^{+38}_{-21}$	0 (fixed)	$\cdots$	$\cdots$
$f_0(980)K^{\pm}$	$17.7 \pm 1.6^{+1.1}_{-3.3}$	$67 \pm 11^{+10}_{-11}$	$0.30 \pm 0.19^{+0.05}_{-0.10}$	$-82 \pm 8^{+2}_{-2}$	1.6
$f_2(1270)K^{\pm}$	$1.52 \pm 0.35^{+0.22}_{-0.37}$	$140 \pm 11^{+18}_{-7}$	$0.37^{+0.19+0.11}_{-0.16-0.04}$	$-24 \pm 29^{+14}_{-20}$	2.7
$f_X(1300)K^{\pm}$	$4.14 \pm 0.81^{+0.31}_{-0.30}$	$-141 \pm 10^{+8}_{-9}$	$0.12 \pm 0.17^{+0.04}_{-0.07}$	$-77 \pm 56^{+88}_{-43}$	1.0
Nonresonant	$34.0 \pm 2.2^{+2.1}_{-1.8}$	$\delta_1^{\rm nr} = -11 \pm 5^{+3}_{-3}$	0 (fixed)	$\cdots$	$\cdots$
		$\delta_2^{\rm nr} = 185 \pm 20^{+62}_{-19}$			
$\chi_{c0}K^{\pm}$	$1.12 \pm 0.12^{+0.24}_{-0.08}$	$-118 \pm 24^{+37}_{-38}$	$0.15 \pm 0.35^{+0.08}_{-0.07}$	$-77 \pm 94^{+154}_{-11}$	0.7

except $B^{\pm} \to \omega(782)K^{\pm}$ and the nonresonant amplitudes. Possible effects of these assumptions were studied, and are included in the final results as a part of the model uncertainty. Projections of the fit are shown in Fig. 2, and the results are summarized in Table I. We find that the statistical significance of the $B^{\pm} \to f_2(1270)K^{\pm}$ signal exceeds 6σ; this is the first observation of this decay mode. The significance of the $B^{\pm} \to \omega(782)K^{\pm}$ signal is 2.1σ. The statistical significance of these signals (and the asymmetries quoted in Table I) is calculated as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ and $\mathcal{L}_0$ denote the maximum likelihood with the nominal fit and with the corresponding amplitude (or asymmetry) fixed at zero, respectively. Note that the significance of the asymmetry is sensitive not only to $b_i \cos\varphi_i$, but also to $b_i \sin\varphi_i$, whereas A_{CP} is sensitive only to the former [Eq. (1)]. Therefore, the significance of the asymmetry should be interpreted as having 2 degrees of freedom. The only channel where the significance of the asymmetry exceeds the 3σ level is $B^{\pm} \to \rho(770)^0 K^{\pm}$. Figs. 3(a) and 3(b) show the $M(\pi^+\pi^-)$ distributions for the $\rho(770) - f_0(980)$ mass region separately for B^- and B^+ events. However, the interference term between $B \to \rho(770)K$ vector and $B \to f_0(980)K$ scalar amplitudes cancels out when making the $M(\pi^+\pi^-)$ projection for the entire range of the helicity angle $\theta_H^{\pi\pi}$ of the $\pi^+\pi^-$ system (the angle between the kaon and the pion of the opposite charge in the $\pi^+\pi^-$ rest frame). Thus only the difference in relative fractions can be observed from comparison of Figs. 3(a) and 3(b). The effect is more apparent in $M(\pi^+\pi^-)$ spectra for the two helicity angle regions $\cos\theta_H^{\pi\pi} < 0$ and $\cos\theta_H^{\pi\pi} > 0$ shown in Figs. 3(c), 3(d), 3(e), and 3(f). Here the difference in the interference terms for the B^- and B^+ decay amplitudes [due to different relative phases between the $B \to \rho(770)K$ and $B \to f_0(980)K$ amplitudes] can be distinguished as a difference in the shape of the $M(\pi^+\pi^-)$ spectra for B^- and B^+ decays. Results of the branching fraction and A_{CP} measurements are summarized in Table II, where for intermediate resonance fractions we use world average values [9]. The reconstruction efficiency is $22.4 \pm 0.2\%$, determined from signal MC simulation in which events are generated according to the matrix elements obtained from the best fit to data.

To assess how well any given fit represents the data, the Dalitz plot is subdivided into nonequal bins requiring that the number of events in each bin exceeds 25. A pseudo-χ^2 variable for the multinomial distribution is then calculated

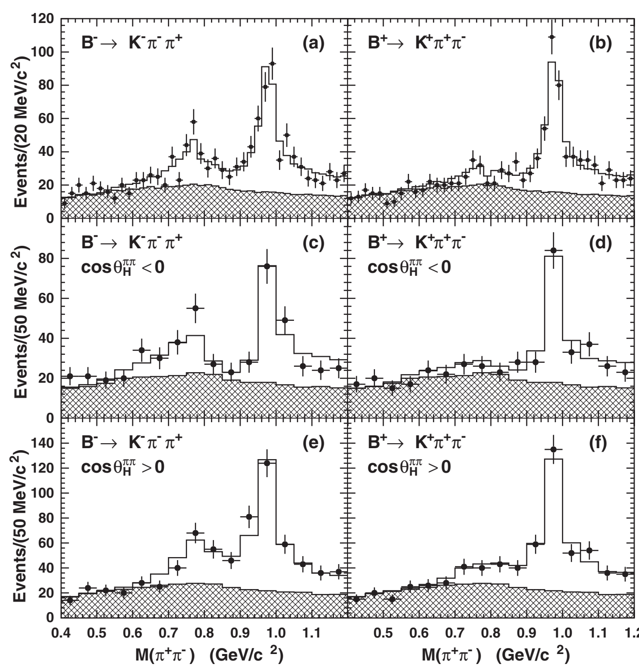

FIG. 3. $\pi^+\pi^-$ mass spectra for B^- (left column) and B^+ (right column) events for different helicity regions: (a), (b) no helicity cuts; (c), (d) $\cos\theta_H^{\pi\pi} < 0$; (e), (f) $\cos\theta_H^{\pi\pi} > 0$; Points with error bars are data, the open histogram is the fit result, and the hatched histogram is the background component.

TABLE II. Summary of branching fraction results. The first quoted error is statistical, the second is systematic and the third is the model uncertainty. Note that $B^+ \to \chi_{c0}K^+$ contribution is not included in the three-body charmless branching fraction.

Mode	$\mathcal{B}(B^\pm \to Rh^\pm \to K^\pm\pi^\pm\pi^\mp) \times 10^6$	$\mathcal{B}(B^\pm \to Rh^\pm) \times 10^6$	A_{CP} (%)
$K^\pm\pi^\pm\pi^\mp$ Charmless	$48.8 \pm 1.1 \pm 3.6$	$\cdots$	$+4.9 \pm 2.6 \pm 2.0$
$K^*(892)[K^\pm\pi^\mp]\pi^\pm$	$6.45 \pm 0.43 \pm 0.48^{+0.25}_{-0.35}$	$9.67 \pm 0.64 \pm 0.72^{+0.37}_{-0.52}$	$-14.9 \pm 6.4 \pm 2.0^{+0.8}_{-0.8}$
$K_0^*(1430)[K^\pm\pi^\mp]\pi^\pm$	$32.0 \pm 1.0 \pm 2.4^{+1.1}_{-1.9}$	$51.6 \pm 1.7 \pm 6.8^{+1.8}_{-3.1}$	$+7.6 \pm 3.8 \pm 2.0^{+2.0}_{-0.9}$
$\rho(770)^0[\pi^+\pi^-]K^\pm$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$	$+30 \pm 11 \pm 2.0^{+11}_{-4}$
$f_0(980)[\pi^+\pi^-]K^\pm$	$8.78 \pm 0.82 \pm 0.65^{+0.55}_{-1.64}$	$\cdots$	$-7.7 \pm 6.5 \pm 2.0^{+4.1}_{-1.6}$
$f_2(1270)[\pi^+\pi^-]K^\pm$	$0.75 \pm 0.17 \pm 0.06^{+0.11}_{-0.18}$	$1.33 \pm 0.30 \pm 0.11^{+0.20}_{-0.32}$	$-59 \pm 22 \pm 2.0^{+3}_{-3}$
Nonresonant	$\cdots$	$16.9 \pm 1.3 \pm 1.3^{+1.1}_{-0.9}$	$\cdots$
$\chi_{c0}[\pi^+\pi^-]K^\pm$	$0.56 \pm 0.06 \pm 0.04^{+0.12}_{-0.04}$	$112 \pm 12 \pm 18^{+24}_{-8}$	$-6.5 \pm 20 \pm 2.0^{+2.9}_{-1.4}$

as $\chi^2 = -2\sum_{i=1}^{N_{\rm bins}} n_i \ln(\frac{p_i}{n_i})$, where n_i is the number of events observed in the ith bin, and p_i is the number of predicted events from the fit. More details are given in Ref. [7]. The $\chi^2/N_{\rm bins}$ value of the fit to signal events is 182.5/141 (32 fit parameters) and 127.6/120 for the fit to background events.

The following sources of systematic error are found to be dominant in the determination of branching fractions: charged track reconstruction (3% in total); particle identification efficiency (4.5% in total); requirements on event shape variables (2.5%); signal yield determination from the ΔE fit (3.9%); model dependence (1%); number of produced $B\bar{B}$ pairs (1%). For the quasi-two-body channels additional sources are the uncertainty in parametrization of the background density function and the uncertainty in secondary branching fractions [2% for $f_2(1270)$, 11% for $K_0^*(1430)$ and 10.8% for χ_{c0} [9]]. Note that in the asymmetry calculation most of these systematic uncertainties cancel out. A few remaining sources are uncertain due to a possible asymmetry in background from charmless B decays (0.6%); the possible bias due to intrinsic detector asymmetry (1.6%); $B^\pm$ signal yields determination (1.1%).

To estimate model uncertainty in the branching fractions and A_{CP} for individual quasi-two-body channels, we vary the nominal model and repeat the fit to data. The following variations are performed separately: we add one additional channel which is either $K^*(1410)^0\pi^+$, $K^*(1680)^0\pi^+$, or $K_2^*(1430)^0\pi^+$; remove $\omega(782)K^+$ or $f_2(1270)K^+$ channel from the nominal model; fit the data assuming $f_X(1300)$ is a vector [$\rho(1450)$] or excluding this contribution; and use several alternative parametrizations of the nonresonant amplitude [7,12]. To cross-check the asymmetry observed in $B^\pm \to \rho(770)^0K^\pm$, we make an independent fit to B^- and B^+ subsamples. We also confirm the significance of the asymmetry observed in $B^\pm \to \rho(770)^0K^\pm$ channel with MC pseudoexperiments where events are distributed according to the matrix element determined from the fit to data. All the cross-checks give consistent results. Finally note that the second solution with a much smaller fraction of the $K^*(1430)\pi$ signal as found in Ref. [7] is confirmed in this analysis. However, comparisons with results on elastic K-π scattering [13] and with some theoretical considerations [14] favor the solution with a large $K^*(1430)\pi$ fraction. We find that values of CP parameters b and φ are almost solution independent; variation in their values is considered as a part of the model uncertainty.

In conclusion, we have performed an amplitude analysis of the three-body charmless $B^\pm \to K^\pm\pi^\pm\pi^\mp$ decay. The branching fractions for a number of quasi-two-body channels have been measured; we report the first observation of $B^+ \to f_2(1270)K^+$, a tensor-pseudoscalar decay. We also perform a search for direct CP violation in quasi-two-body intermediate states and find evidence for large direct CP violation in the decay $B^+ \to \rho(770)^0K^+$. This is consistent with recent results from *BABAR* Collaboration [12] and with some theoretical predictions [3]. The probability of observing an equal or larger asymmetry assuming there is no CP violation (p value) is 4.7×10^{-4}; the corresponding probability of fluctuation in A_{CP} value only is 2.7×10^{-3}. This is the first evidence for CP violation in the decay of a charged meson.

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