ELSEVIER
SCIENCE DIRECT
PHYSICS LETTERS B
Physics Letters B 595 (2004) 318–322
www.elsevier.com/locate/physletb

Direct CP violation in $B^{\mp} \to \pi^{\mp}\omega$, $\pi^{\mp}\rho^0$, $\pi^0\rho^{\mp}$, and in $\overline{B^0}(B^0) \to \pi^{\mp}\rho^{\pm}$ with an enhanced branching ratio for $\pi^0\rho^0$

Saul Barshay [a], Georg Kreyerhoff [a], Lalit M. Sehgal [b]

[a] III. Physikalisches Institut, RWTH Aachen, D-52056 Aachen, Germany
[b] Institut für theoretische Physik, RWTH Aachen, D-52056 Aachen, Germany

Received 7 May 2004; accepted 15 June 2004

Available online 23 June 2004

Editor: H. Georgi

Abstract

We present a novel dynamics for generating sizable CP-violating asymmetries in the decays of charged $B^{\mp} \to \pi^{\mp}\omega, \pi^{\mp}\rho^0, \pi^0\rho^{\mp}$, and in $\overline{B^0}(B^0) \to \pi^{\mp}\rho^{\pm}$. The dynamics for the necessary final-state interactions involves the mixing of G-parity eigenstates of the system $(\overline{D}^*D, D^*\overline{D})$ with the $G = \pm 1$ states of $\pi\omega$ and $\pi\rho$, respectively. The dynamical effect is enhanced by the empirically large branching ratio for decays to $(\overline{D}^*D, D^*\overline{D})$. A correlated result is a markedly enhanced branching ratio for $\overline{B^0}(B^0) \to \pi^0\rho^0$, which has now been observed in two experiments.

Direct CP violation in the decays of charged and neutral B mesons is the central theme in current experiments [1–3] at the two B-meson factories. Today, some forty years after the discovery of indirect CP violation in the two-pion decay of K_L^0 [4], direct CP violation has been established only in the matrix elements for the two-pion decays of the neutral K system [5]. It is yet to be established in decays of a charged particle. Recently, one experiment [1] has given results which indicate a sizable CP-violating asymmetry in the decays $B^{\mp} \to \pi^{\mp}\eta$, as predicted by theoretical estimates in 1991 [6], and also in the decays $B^{\mp} \to K^{\mp}\eta$ [7]. Further, one experiment [2] has given a large direct CP violation in $\overline{B^0}(B^0) \to \pi^-\pi^+$ [8]. This group has now given an indication [3] of a sizable asymmetry in $B^{\mp} \to \pi^{\mp}\omega$. All of these decays have similar, low branching ratios measured to be in the range of $(2–7) \times 10^{-6}$. In order to have direct CP violation observable, there must be (strong) interactions among particles in the final states [6]. It is physically clear that if there exists a decay channel with an empirically large branching ratio (i.e., a large decay amplitude) which has the same, conserved strong-interaction quantum numbers as the final hadron state, then decay into this channel followed by even a small mixing with the final state, will produce the essential strong-interaction, imaginary contribution to the amplitude, which will be sizable [8]. When the large decay amplitude involves a term in the CKM matrix with a different weak phase from the term relevant to

E-mail addresses: barshay@kreyerhoff.de (S. Barshay), georg@kreyerhoff.de (G. Kreyerhoff).

0370-2693
doi:10.1016/j.physletb.2004.06.062

the direct decay into the final state, then the necessary conditions for observing an asymmetry are met [6]. This dynamical mechanism explains [8] the large, direct CP violation observed in $\overline{B^0}(B^0) \to \pi^+\pi^-$ [2]. In a correlated way, the same dynamics predicts an enhanced branching ratio for $\overline{B^0}(B^0) \to \pi^0\pi^0$, as is observed [9,10]. Mixing with the isospin-zero state of the $\pi\pi$ system occurs from the isospin-zero state of $D\overline{D}$. The D^+D^- decay mode has a branching ratio now known to be large, $\sim 2.5 \times 10^{-4}$ [11]. In addition to the above-mentioned possible asymmetry in $\pi^\mp\omega$ [3], recent results from the other experiment [12], allow for significant asymmetries with a definite pattern of signs in $B^\mp \to \pi^\mp\rho^0$ and $\pi^0\rho^\mp$. In this Letter, we show how sizable asymmetries can occur in $\pi^\mp\omega$, $\pi^\mp\rho^0$, $\pi^0\rho^\mp$, due to small, strong-interaction mixings with states of $\overline{D}^*D$ and $D^*\overline{D}$. It is also known that neutral B decay to $D^{*\mp}D^\pm$ has a large branching ratio, $\sim 8.8 \times 10^{-4}$ [13]. In this analysis, we use an idea put forward some time ago [14], concerning the presence in charged B decays of two distinct, strong-interaction eigenstates of the charged systems ($\overline{D}^*D$, $D^*\overline{D}$), with different G-parities, $G = \pm 1$, which are the G-parities of the charged $\pi\omega$ and $\pi\rho$ systems, respectively. A further striking consequence of the final-state mixing is a marked enhancement of the branching ratio for $\overline{B^0}(B^0) \to \pi^0\rho^0$, like that for $\pi^0\pi^0$ [8].

The following states have $G = \pm 1$, respectively [14]. Both charged states have isospin $I = 1$, and the same spin-parity (0^-)

$$\begin{aligned} (\overline{D}^*D)_+ &= \frac{1}{\sqrt{2}}\left(D^{*-}D^0 + D^{*0}D^-\right), \\ &\quad G = +1, \qquad I = 1, \\ (\overline{D}^*D)_- &= \frac{1}{\sqrt{2}}\left(D^{*-}D^0 - D^{*0}D^-\right), \\ &\quad G = -1, \qquad I = 1. \end{aligned} \tag{1}$$

When mixing of the $G = +1$ state with the state of $\pi^-\omega$ occurs, the physical decay amplitudes A including final-state interactions, are given in terms of the "bare" decay amplitudes $\tilde{A}$, by

$$\begin{pmatrix} A_{\pi^-\omega} \\ A_{(\overline{D}^*D)_+} \end{pmatrix} = \begin{pmatrix} \cos\theta_+ & i\sin\theta_+ \\ i\sin\theta_+ & \cos\theta_+ \end{pmatrix} \begin{pmatrix} \tilde{A}_{\pi^-\omega} \\ \tilde{A}_{(\overline{D}^*D)_+} \end{pmatrix}. \tag{2}$$

The matrix parameterized by the mixing angle θ_+, is simply the square root of the S-matrix with neglect of phase factors associated with elastic scattering [8]. The latter were found to have little effect upon calculated asymmetries in $\overline{B^0}(B^0) \to \pi\pi$ (as is illustrated in Table 1 and Fig. 1 of Ref. [8]). The states of the charged $\pi\rho$ system with isospin $I = 1, 2$ are

$$\left.\begin{aligned} (\pi\rho)_1 &= \tfrac{1}{\sqrt{2}}\left(\pi^0\rho^- - \pi^-\rho^0\right), \\ &\quad I = 1, \\ (\pi\rho)_2 &= \tfrac{1}{\sqrt{2}}\left(\pi^0\rho^- + \pi^-\rho^0\right), \\ &\quad I = 2 \end{aligned}\right\} \quad G = -1. \tag{3}$$

The $I = 1$ state mixes with the $G = -1$ state $(\overline{D}^*D)_-$ given in Eq. (1), leading to physical decay amplitudes given in terms of an angle θ_- and bare decay amplitudes by

$$\begin{pmatrix} A_{(\pi\rho)_1} \\ A_{(\overline{D}^*D)_-} \end{pmatrix} = \begin{pmatrix} \cos\theta_- & i\sin\theta_- \\ i\sin\theta_- & \cos\theta_- \end{pmatrix} \begin{pmatrix} \tilde{A}_{(\pi\rho)_1} \\ \tilde{A}_{(\overline{D}^*D)_-} \end{pmatrix}. \tag{4}$$

The $\pi\rho$ amplitude with $I = 2$ has no mixing; it is given by the bare amplitudes

$$A_{(\pi\rho)_2} = \tilde{A}_{(\pi\rho)_2}. \tag{5}$$

Solving Eqs. (2)–(5), we obtain three complex, physical decay amplitudes in terms of two parameters θ_+, θ_-. Since our numerical results are for $|\theta_\pm| \ll 1$, we simplify the formulae with $\cos\theta_\pm \sim 1$

$$\begin{aligned} A_{\pi^-\omega} &= \tilde{A}_{\pi^-\omega} + i\frac{\sin\theta_+}{\sqrt{2}}\left(\tilde{A}_{D^{*-}D^0} + \tilde{A}_{D^{*0}D^-}\right), \\ A_{\pi^0\rho^-} &= \tilde{A}_{\pi^0\rho^-} + i\frac{\sin\theta_-}{2}\left(\tilde{A}_{D^{*-}D^0} - \tilde{A}_{D^{*0}D^-}\right), \\ A_{\pi^-\rho^0} &= \tilde{A}_{\pi^-\rho^0} - i\frac{\sin\theta_-}{2}\left(\tilde{A}_{D^{*-}D^0} - \tilde{A}_{D^{*0}D^-}\right). \end{aligned} \tag{6}$$

In order to show the correlated results for different asymmetries, with no parameters other than the final-state mixings, we use, as we have done in our work on $\overline{B^0}(B^0) \to \pi\pi$ [8], bare amplitudes given by the Bauer–Stech–Wirbel phenomenological model [15]. This model is useful as a first approximation for parameterizing and correlating branching ratios [16,17]:

$$\begin{aligned} \tilde{A}_{\pi^-\omega} &\cong \frac{N\lambda_u}{\sqrt{2}}\left(r'a_1 + ra_2\right), \\ \tilde{A}_{\pi^-\rho^0} &\cong \frac{N\lambda_u}{\sqrt{2}}\left(r'a_1 + ra_2\right), \\ \tilde{A}_{\pi^0\rho^-} &\cong \frac{N\lambda_u}{\sqrt{2}}\left(ra_1 + r'a_2\right) \end{aligned} \tag{7}$$

Table 1
The flavor-averaged branching ratio $\mathrm{Br}(\overline{B}/B)$ in units of 10^{-6}, and the asymmetry A_{CP} [3,19], as calculated from the amplitudes in Eqs. (6), (10), (14). The first columns under Br and A_{CP} have $\theta_+ = \theta_- = \theta = 0$; The second columns $\theta_+ = 0.025$, $\theta_- = 0.25$, $\theta = -0.09$. The numbers under $N_\omega = 0.6$ are for $N \to N_\omega$ in the $\pi\omega$ bare amplitudes in Eqs. (7), (11). We have not listed data for $\pi^-\rho^+$ and $\pi^+\rho^-$ separately. These numbers involve correlated data parameters. The separation is not given explicitly in Refs. [19,21]. See p. 10 of Ref. [20] for separate asymmetries from the data. These do follow the distinctive pattern of those calculated in this Letter and listed above, with $A_{\mathrm{CP}}(\pi^-\rho^+) \sim -0.62 \pm 0.27 < A_{\mathrm{CP}}(\pi^+\rho^-) \sim -0.11 \pm 0.17$

	$\mathrm{Br}(\overline{B}/B)$			A_{CP}			Data			Ref. [17]
	$\theta_i = 0$	$\theta_i \neq 0$	$N_\omega = 0.6$	$\theta_i = 0$	$\theta_i \neq 0$	$N_\omega = 0.6$	$\mathrm{Br}(\overline{B}/B)$	A_{CP}	Refs.	A_{CP}
$\pi^-\omega$	8.8	9.3	6.1	0	+0.40	+0.49	$5.7^{+1.4}_{-1.3} \pm 0.6$	$+0.50^{+0.25}_{-0.21} \pm 0.02$	[3]	−0.02
							$5.5 \pm 0.9 \pm 0.5$	$+0.03 \pm 0.16 \pm 0.03$	[1]	
$\pi^-\rho^0$	8.8	9.1		0	−0.32		$9.5 \pm 1.1 \pm 0.8$	$-0.19 \pm 0.11 \pm 0.02$	[12]	+0.04
$\pi^0\rho^-$	11.2	11.5		0	+0.28		$10.9 \pm 1.9 \pm 1.9$	$+0.24 \pm 0.16 \pm 0.06$	[12]	−0.04
							$13.8 \pm 2.4^{+1.5}_{-1.6}$	$+0.06 \pm 0.19 \pm 0.04$	[23]	
$\pi^0\omega$	0.45×10^{-2}	0.27	0.27	0	+0.22	+0.18	< 1.9		[3]	
$\pi^\mp\rho^\pm$	27.8	30.4		0	−0.13		$22.6 \pm 1.8 \pm 2.2$	$-0.18 \pm 0.08 \pm 0.03$	[19,20]	
								$-0.114 \pm 0.062 \pm 0.027$	[21]	
$\pi^-\rho^+$	11.4	13.6		0	−0.63					+0.006
$\pi^+\rho^-$	16.4	16.8		0	−0.28					−0.015
$\pi^0\rho^0$	0.55	1.71		0	+0.81		$1.4 \pm 0.6 \pm 0.3$		[12]	−0.16
							$5.1 \pm 1.6 \pm 0.8$		[23]	

with parameters $a_1 \cong 1$, $a_2 \cong 0.2$, $N \cong 0.75$, and the CKM factor $\lambda_u = 3.6 e^{-i\gamma} \times 10^{-3}$, with $\gamma \sim 60°$. The overall normalization factor N was determined from the branching ratio for $B^\mp \to \pi^\mp \pi^0$ [8]. The coefficients r and r' arise from ratios of decay constants and overlaps. In the notation of Ref. [17], they are given by $r = A_{\pi\rho}/A_{\pi\pi} \sim A_{\pi\omega}/A_{\pi\pi}$ and $r' = A_{\rho\pi}/A_{\pi\pi} \sim A_{\omega\pi}/A_{\pi\pi}$, and have the approximate values $r \sim 3/2$, $r' \sim 5/4$. These phenomenological parameters have at least 15% uncertainty. We shall see in Table 1, that these amplitudes produce an adequate first approximation to the empirically similar charged-particle branching ratios (as do also the related bare amplitudes for $\overline{B^0}(B^0) \to \pi^-\rho^+, \pi^+\rho^-$ decays discussed below). (The absolute square of an amplitude gives the branching ratio.) To obtain the bare amplitudes for the coherent states $(\overline{D}^* D)_\pm$, we use a branching ratio approximately the same as the empirical branching ratio [13] for neutral B decay to $D^{*\mp} D^\pm$ of $\sim 8.8 \times 10^{-4}$, and the ratio $|\tilde{A}_{D^{*0}D^-}/\tilde{A}_{D^{*-}D^0}| \sim 0.8$, estimated in Table 7 of Ref. [16].[1] This implies a ratio $|\tilde{A}_{(\overline{D}^* D)_-}/\tilde{A}_{(\overline{D}^* D)_+}| \sim 0.11$ for the two G-parity eigenstates, and allows us to write

$$\tilde{A}_{D^{*-}D^0} \cong 2.62 a_1 \lambda_c, \qquad \tilde{A}_{D^{*0}D^-} \cong 2.10 a_1 \lambda_c,$$

$$\tilde{A}_{(\overline{D}^* D)_+} \cong 4.72 \frac{a_1 \lambda_c}{\sqrt{2}}, \qquad \tilde{A}_{(\overline{D}^* D)_-} \cong 0.52 \frac{a_1 \lambda_c}{\sqrt{2}}. \quad (8)$$

The CKM factor $\lambda_c \cong -8.8 \times 10^{-3}$.

Before discussing the results in Table 1, we obtain the amplitude for an additional decay $\overline{B^0}(B^0) \to \pi^0\omega$, which follows from the same physics as we have described above. The state which mixes into $\pi^0\omega$, with θ_+, is

$$\frac{1}{2}\left\{\left(D^{*-}D^+ + D^{*+}D^-\right) - \left(\overline{D^{*0}} D^0 + D^{*0}\overline{D^0}\right)\right\} \quad (9)$$

with $I = 1$ and charge-conjugation $C = -1$, like $\pi^0\omega$. The physical decay amplitude is then

$$A_{\pi^0\omega} \cong \tilde{A}_{\pi^0\omega} + i\frac{\sin\theta_+}{2}\left(\tilde{A}_{D^{*-}D^+} + \tilde{A}_{D^{*+}D^-}\right), \quad (10)$$

where we have taken $\tilde{A}_{\overline{D^{*0}}D^0} \cong 0 \cong \tilde{A}_{D^{*0}\overline{D^0}}$ [15]. We use the approximate bare amplitude from the phenomenological model [15–17]

$$\tilde{A}_{\pi^0\omega} \cong \frac{N\lambda_u}{2}(r - r')a_2, \quad \text{and}$$

$$\tilde{A}_{(D^{*-}D^+)_{C=-1}} \cong -4.72 \frac{|\lambda_c|}{2} \quad (11)$$

from Eqs. (8), (9). From Eqs. (10), (11), one immediately observes the same general physical effect as occurred in our study [8] of $\overline{B^0}(B^0) \to \pi^0\pi^0$: although

[1] See also Table 13 in Ref. [15].

the all-neutral branching ratio is depressed in the bare amplitude by the small parameter a_2, and here also by destructive interference, an enhancement can occur due to the final-state interaction, where a system with a large decay amplitude $|\tilde{A}_{(D^{*-}D^+)_{C=-1}}|$ mixes into the $\pi^0\omega$ final state.

We calculate direct CP-violating asymmetries from $A_{\mathrm{CP}} = (|R|^2 - 1)/(|R|^2 + 1)$, where R is the ratio of an amplitude in Eqs. (6), (10) to the amplitude with $\lambda_u \to \lambda_u^*$, $\lambda_c \to \lambda_c^*$. In Table 1, we give representative asymmetries and branching ratios for the three charged decay modes and for $\pi^0\omega$, calculated from the amplitudes in Eqs. (6), (10) using small mixing angles $\theta_+ = +0.025$ and $\theta_- = +0.25$. (A single mixing of order 0.2 occurred in our work on $\overline{B^0}(B^0) \to \pi\pi$ [8].) We tabulate recent experimental results, from which it is clear that there are indications of possible sizable asymmetries with a definite pattern of signs. However, in contrast to this possibility which is given by our results using final-state interactions among specific systems of physical hadrons, there are representative results from recent calculations which neglect final-state interactions of this kind. In Table 1 we also list these asymmetry results [17,18] (for wide variations in these estimates, see the tabulations in Ref. [17]). Generally, the asymmetries in these calculations are small because of small strong-interaction phases.

There are striking distinctions in the $\pi\omega$ system, in particular. The mixing to $(\overline{D}^*D)_+$, even with the small mixing angle $\theta_+ = 0.025$, can result in a sizable asymmetry $A_{\mathrm{CP}}(\pi^\mp\omega) \sim +0.4$, in contrast to the very small ~ -0.02 in the last column of Table 1. The calculated branching ratio for $\pi^0\omega$ is about 5% of the branching ratio for $\pi^-\omega$, instead of the miniscule $\sim 0.1\%$ given in Table 9 of Ref. [17]. The elevated branching ratio is directly correlated with the possible sizable asymmetry in $\pi^\mp\omega$. Both effects arise from mixing with the $(\overline{D}^*D, D^*\overline{D})$ system. Since the $\pi^0\omega$ amplitude is dominated by the term from the strong-interaction mixing, the parameter for indirect CP violation [8], $S_{\pi^0\omega} \sim -\sin 2\beta \cong -0.7$ (for $2\beta \cong 45°$).

To complete the results which follow from this dynamics for final-state interactions, we give estimates for asymmetries and branching ratios in three more related decays $\overline{B^0}(B^0) \to \pi^-\rho^+, \pi^+\rho^-, \pi^0\rho^0$. Significant asymmetries may be present in the $\pi^\mp\rho^\pm$ modes [19–21]. In addition to the $I = 1, 2$ states, there is now an $I = 0$ state. The isospin states with $I_3 = 0$ are

$$
\begin{aligned}
(\pi\rho)_0 &= \frac{1}{\sqrt{3}}\left(\pi^-\rho^+ + \pi^+\rho^- - \pi^0\rho^0\right),\\
(\pi\rho)_1 &= \frac{1}{\sqrt{2}}\left(\pi^+\rho^- - \pi^-\rho^+\right),\\
(\pi\rho)_2 &= \frac{1}{\sqrt{6}}\left(\pi^-\rho^+ + \pi^+\rho^- + 2\rho^0\pi^0\right).
\end{aligned}
\tag{12}
$$

The $I = 0$ state with $C = -1$, can mix via a third angle θ, with the state

$$
\frac{1}{2}\left\{\left(D^{*-}D^+ + D^{*+}D^-\right) + \left(\overline{D^{*0}}D^0 + D^{*0}\overline{D^0}\right)\right\}.
\tag{13}
$$

Together with Eqs. (4), (5), one solves for the three additional physical decay amplitudes

$$
\begin{aligned}
A_{\pi^-\rho^+} &= \tilde{A}_{\pi^-\rho^+} - i\frac{\sin\theta_-}{2\sqrt{2}}\left(\tilde{A}_{D^{*-}D^+} - \tilde{A}_{D^{*+}D^-}\right)\\
&\quad + i\frac{\sin\theta}{2\sqrt{3}}\left(\tilde{A}_{D^{*-}D^+} + \tilde{A}_{D^{*+}D^-}\right),\\
A_{\pi^+\rho^-} &= \tilde{A}_{\pi^+\rho^-} + i\frac{\sin\theta_-}{2\sqrt{2}}\left(\tilde{A}_{D^{*-}D^+} - \tilde{A}_{D^{*+}D^-}\right)\\
&\quad + i\frac{\sin\theta}{2\sqrt{3}}\left(\tilde{A}_{D^{*-}D^+} + \tilde{A}_{D^{*+}D^-}\right),\\
A_{\pi^0\rho^0} &= \tilde{A}_{\pi^0\rho^0} - i\frac{\sin\theta}{2\sqrt{3}}\left(\tilde{A}_{D^{*-}D^+} + \tilde{A}_{D^{*+}D^-}\right).
\end{aligned}
\tag{14}
$$

As in Eqs. (7), (11), we use phenomenological, model amplitudes [16,17] as a first approximation

$$
\begin{aligned}
\tilde{A}_{\pi^-\rho^+} &\cong N\lambda_u r' a_1,\\
\tilde{A}_{\pi^+\rho^-} &\cong N\lambda_u r a_1,\\
\tilde{A}_{\pi^0\rho^0} &\cong \frac{N\lambda_u}{2}(r + r')a_2.
\end{aligned}
\tag{15}
$$

Note that the five complex, physical amplitudes in the $\pi\rho$ system satisfy a "pentagon" relationship [22] (as do the bare amplitudes, of course)

$$
\frac{A_{\pi^-\rho^+} + A_{\pi^+\rho^-}}{2} + A_{\pi^0\rho^0} = \frac{A_{\pi^-\rho^0} + A_{\pi^0\rho^-}}{\sqrt{2}}.
\tag{16}
$$

The additional asymmetries and branching ratios are given in Table 1, as calculated with $\theta = -0.09$. There is a suggestion in the recent data [19–21] on $\pi^-\rho^+$, $\pi^+\rho^-$ and $\pi^\mp\rho^\pm$ of significant asymmetries. Our results give this, in $\overline{B^0} \to \pi^-\rho^+$ in particular [20]. Our estimated asymmetry without flavor tagging $(\pi^\mp\rho^\pm)$

agrees with the data [21]. For comparison, the asymmetries indicated in the last column of Table 1 [17] are very small, as they must be when there is little strong interaction. The separate branching ratios for $\pi^-\rho^+$ and $\pi^+\rho^-$ come closer together as a consequence of the final-state interactions, in agreement with indications from the data [21]. Our estimated branching ratio for $\pi^0\rho^0$ is enhanced. Enhancement is observed in the data [12,23]. The size is essentially determined by the mixing θ with the coherent $C = -1$ $(\overline{D}^* D, D^* \overline{D})$ system which is produced with a large amplitude. Physically, this is the same dynamics that gives rise to the enhanced branching ratio of $\sim 2 \times 10^{-6}$ for $\overline{B^0}(B^0) \to \pi^0\pi^0$ [8]. The calculated parameter $S_{\pi^0\rho^0} \cong -0.56$; it differs from $-\sin(2\beta + 2\gamma) \cong -0.26$ because of the final-state interactions.

It is to be expected that $\overline{B^0}(B^0) \to \eta\omega$, will obtain a contribution from mixing with the same $(\overline{D}^* D, D^* \overline{D})$ system as $\pi^0\rho^0$, and thus will have a similar, enhanced branching ratio. This enhancement has just been observed in one experiment [24].

Our present results on possible sizable asymmetries in certain charged-B decays are calculated using a physical-hadron approach to estimating final-state interactions, which has been successful [6,8]. There are present experimental indications that specific, charged-decay modes, $B^\mp \to \pi^\mp\omega$, $\pi^\mp\rho^0$, $\pi^0\rho^\mp$ [3,12], and $\overline{B^0}(B^0) \to \pi^-\rho^+, \pi^+\rho^-, \pi^\mp\rho^\pm$ [19–21], have significant asymmetries. We have given results for all of the asymmetries. For chosen small mixing angles, these results exhibit distinctive correlations in sign and in magnitude, which follow the pattern of the present data. Our positive results for these modes should encourage the experimenters to pursue these asymmetries, in the effort to finally establish CP violation in charged-particle decays. Directly correlated with the final-state interactions which give rise to asymmetries is the dynamical enhancement of decays: $\overline{B^0}(B^0) \to \pi^0\pi^0$, $\pi^0\rho^0$, $\pi^0\omega$. Striking enhancement of the $\pi^0\pi^0$ and $\pi^0\rho^0$ rates has appeared in the recent data [9,10,12,23].

References

[1] BaBar Collaboration, B. Aubert, et al., hep-ex/0311016.
[2] Belle Collaboration, K. Abe, et al., hep-ex/0401029.
[3] Belle Collaboration, C.H. Wang, et al., hep-ex/0403033.
[4] J.H. Christenson, J.W. Cronin, V.L. Fitch, R. Turlay, Phys. Rev. Lett. 13 (1964) 138.
[5] NA31 Collaboration, H. Burkhardt, et al., Phys. Lett. B 206 (1988) 168;
NA48 Collaboration, V. Fanti, et al., Phys. Lett. B 465 (1999) 335;
KTeV Collaboration, A. Alevi-Horati, et al., Phys. Rev. Lett. 38 (1999) 22.
[6] S. Barshay, D. Rein, L.M. Sehgal, Phys. Lett. B 259 (1991) 475.
[7] S. Barshay, G. Kreyerhoff, Phys. Lett. B 578 (2004) 330.
[8] S. Barshay, L.M. Sehgal, J. van Leusen, Phys. Lett. B 591 (2004) 97, hep-ph/0403049.
[9] BaBar Collaboration, B. Aubert, et al., Phys. Rev. Lett. 91 (2003) 241801.
[10] Belle Collaboration, S.H. Lee, et al., Phys. Rev. Lett. 91 (2003) 261801.
[11] Belle Collaboration, T. Browder, Talk at Lepton–Photon Symposium, Fermilab, Batavia, IL, August 2003.
[12] BaBar Collaboration, B. Aubert, et al., hep-ex/0311049.
[13] BaBar Collaboration, B. Aubert, et al., hep-ex/0303004.
[14] S. Barshay, L.M. Sehgal, Phys. Lett. B 185 (1987) 150.
[15] M. Bauer, B. Stech, M. Wirbel, Z. Phys. C 34 (1987) 103.
[16] M. Neubert, B. Stech, in: A.J. Buras, M. Lindner (Eds.), Heavy Flavours, second ed., World Scientific, Singapore, 1998, p. 294, hep-ph/9705292.
[17] M. Beneke, M. Neubert, hep-ph/0308039.
[18] See also similar small asymmetries tabulated in earlier work which neglects final-state interactions among physical hadrons, i.e., A. Ali, G. Kramer, C.-D. Lü, Phys. Rev. D 59 (1998) 014005.
[19] BaBar Collaboration, B. Aubert, et al., Phys. Rev. Lett. 91 (2003) 201802.
[20] BaBar Collaboration, M. Pivk, Talk at Moriond QCD, March 2003.
[21] BaBar Collaboration, L. Roos, Talk at Rencontres de Moriond, EW04, La Thuille, March 2004.
[22] H.J. Lipkin, Y. Nir, H.R. Quinn, A.E. Snyder, Phys. Rev. D 44 (1991) 1454.
[23] Belle Collaboration, F. Ronga, Talk at 18th Rencontres de Physique de la Vallée d'Aoste, March 2004.
[24] BaBar Collaboration, J. Smith, Talk at 39th Rencontres des Moriond, La Thuille, March 2004.