CP asymmetries in charmless baryonic decays of charged B mesons

Gad Eilam*
Department of Physics, University of California, Los Angeles, California 90024

Michael Gronau
Department of Physics, Technion, Haifa, Israel

Jonathan L. Rosner
Department of Physics and Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

(Received 9 August 1988)

The CP asymmetry in charmless inclusive hadronic decays of charged B mesons is calculated in the three-generation Kobayashi-Maskawa model. Asymmetries are found favoring the decays of B^+ over B^- which may be as large as 3% and 5% for strangeness zero and one final states, respectively. It is suggested that asymmetries at this level or larger may be observable in the decay modes $B^\pm \to p\bar{p}\pi^\pm$ and $B^\pm \to p\bar{p}K^\pm$.

CP violation in charged B decays may be manifested by the observation of partial rate asymmetries between corresponding charge-conjugate final states in B^- and B^+ decays.[1,2] Such asymmetries require the existence of two different decay mechanisms for a given final state. The two mechanisms must have different CP-violating weak phases as well as different final-state strong-interaction phases, or some other phases which are invariant under charge conjugation. Charmless hadronic B decays have all these necessary ingredients.

The ARGUS Collaboration[3] has recently reported the first charged-B decay mode to a charmless final state, with branching ratio

$$B(B^\pm \to p\bar{p}\pi^\pm) = (5.2\pm1.4\pm1.9)\times10^{-4} \; . \tag{1}$$

While the CLEO Collaboration[4] does not confirm the ARGUS observation, setting an upper limit of about 2 parts in 10^{-4} for this branching ratio, the two experiments are compatible with one another if $B(B^\pm \to p\bar{p}\pi^\pm) \simeq (1-2)\times10^{-4}$. A question of immediate interest is the expected CP asymmetry in this and similar baryonic modes.

The purpose of this paper is to calculate the CP asymmetry in inclusive charmless hadronic $B^\pm$ decays in the standard Kobayashi-Maskawa[5] (KM) three-generation model, and to discuss its implication in decay modes of the type $p\bar{p}\pi$ and $p\bar{p}K$.

The inclusive CP asymmetry was first studied in Ref. 1. This work was carried out prior to measurements of the b-quark weak mixings. We shall present new estimates based on the present status of the weak mixing matrix.[6] We then estimate rates and asymmetries both in semi-inclusive baryonic modes and in exclusive final states, with the help of considerations such as those presented in Ref. 7. An independent estimate of inclusive CP asymmetries for charged-B-meson charmless decays has appeared recently while the present work was being completed.[8] The exclusive modes discussed in Ref. 8 do not include baryons, and conclusions somewhat more pessimistic than ours are reached regarding the observability of CP asymmetries in exclusive modes.

To set the stage, let us recall recent estimates of the charmless inclusive rates of the two interfering mechanisms.

In the strangeness-one channel, the loop-induced (so-called "penguin") inclusive $b \to s$ branching ratio is at the level of $1-2\,\%$ (Refs. 9 and 10) depending somewhat on the unknown t-quark mass. In fact, we shall be concerned with the rate for $b \to s +$ [nonstrange light $q\bar{q}$ pair(s)], which will be estimated using results of Ref. 10 to be somewhat smaller. This dominant mechanism is to be compared with the smaller tree-level $b \to u\bar{u}s$ decay, for which the expected branching ratio is about 4% $|V_{ub}/V_{cb}|^2$. The limits[3,6,7] $0.07 < |V_{ub}/V_{cb}| < 0.2$ yield branching ratios in the range $0.02-0.2\,\%$.

The opposite situation occurs in strangeness zero final states. Here the tree-level $b \to u\bar{u}d$ decay is the dominant one with an inclusive branching ratio of 4% $|V_{ub}/0.2V_{cb}|^2$. The corresponding loop-induced rate may be as large as 0.4% (Refs. 11 and 12) though a smaller rate cannot be excluded on the basis of present information on the quark mixing matrix.

These estimates indicate that in both strange and nonstrange charmless final states of B decays, one may encounter the interesting situation of having two interfering mechanisms with comparable amplitudes. Substantial CP asymmetries can then arise.

As pointed out in Ref. 1, the CP asymmetry follows primarily from the CP-odd interference of the intrinsically real tree-level ("spectator") b-quark decay and the complex loop-induced ("penguin") $b \to d(s)$ decay (see Fig. 1 in Ref. 1). We have calculated this interference in analytic form (the CP-even interference was calculated in Ref. 12). The dominant contribution[13] comes from the interference of the absorptive part of the physical of $c\bar{c}$ quark pair in the penguin diagram with the intrinsically real tree-level diagram.

To illustrate the origin of the CP asymmetry, we write the relevant amplitudes contributing to decays to nonstrange hadrons as

$$A(b \to u\bar{u}d) = [A_T + (A_{Pu}^R + iA_{Pu}^I)]V_{ub}V_{ud}^* + (A_{Pc}^R + iA_{Pc}^I)V_{cb}V_{cd}^* + A_{Pt}^R V_{tb}V_{td}^* . \quad (2)$$

Here A_T is the (intrinsically real) tree amplitude, while A_{Pi}^R and A_{Pi}^I are the real and imaginary parts of the penguin amplitude with quark $i=u,c,t$ in an internal loop. The amplitude for the charge-conjugate process contains complex-conjugated Kobayashi-Maskawa (KM) factors, but the phases of the penguin amplitudes remain the same. The asymmetry A_0 (the subscript will denote strangeness) for $du\bar{u}$ final states is then

$$A_0 \equiv \frac{|A(b \to du\bar{u})|^2 - |A(\bar{b} \to \bar{d}\bar{u}u)|^2}{|A(b \to du\bar{u})|^2 + |A(\bar{b} \to \bar{d}\bar{u}u)|^2} \simeq \mathrm{Re}(\rho_A \rho_{\mathrm{KM}}^{(0)}) - \mathrm{Re}(\rho_A \rho_{\mathrm{KM}}^{(0)*}) , \quad (3)$$

where we have defined

$$\rho_A \equiv \frac{A_{Pc}^R + iA_{Pc}^I}{A_T} , \quad (4)$$

$$\rho_{\mathrm{KM}}^{(0)} \equiv \frac{V_{cb}V_{cd}^*}{V_{ub}V_{ud}^*} , \quad (5)$$

and the result $|\rho_A \rho_{\mathrm{KM}}^{(0)}| \ll 1$ has been anticipated in obtaining the second line of Eq. (3). Defining[14,15]

$$\phi \equiv \arg \left[\frac{V_{cb}V_{cd}^*}{V_{ub}V_{ud}^*} \right] , \quad (6)$$

we find[13]

$$A_0 \simeq -2\,\mathrm{Im}\rho_A \sin\phi \left| \frac{V_{cb}V_{cd}}{V_{ub}V_{ud}} \right| . \quad (7)$$

Here

$$\mathrm{Im}\rho_A = A_{Pc}^I / A_T = A_T^* A_{Pc}^I / |A_T|^2 . \quad (8)$$

Equation (7) makes it clear that the sign of the asymmetry is uniquely predicted in terms of KM phases and kinematic factors associated with tree and penguin amplitudes. Here we have suppressed an integration over final-state variables which must be performed in Eqs. (3) and (8).

The penguin amplitude also leads to the final states $dd\bar{d}$, $ds\bar{s}$, and dgg. However, since there are no tree contributions to these final states, they do not contribute to the numerator of Eq. (3). Their contribution to the denominator is small since the tree amplitude is expected to be the dominant process for nonstrange final states.

An explicit calculation in which integration is performed over kinematic variables of the final state leads to

$$A_0 = \frac{\Gamma(b \to du\bar{u}) - \Gamma(\bar{b} \to \bar{d}\bar{u}u)}{\Gamma(b \to du\bar{u}) + \Gamma(\bar{b} \to \bar{d}\bar{u}u)} \simeq -\frac{16}{27}\alpha_s \frac{|V_{cb}V_{cd}|}{|V_{ub}|} I\left[\left[\frac{2m_c}{m_b}\right]^2\right] \sin\phi , \quad (9)$$

where I is related to the numerator of Eq. (8) and is given by

$$I(\xi) \equiv \int_\xi^1 dx (1-x)^2(1+2x) \left[1 - \frac{\xi}{x}\right]^{1/2} \left[1 + \frac{\xi}{2x}\right] . \quad (10)$$

We neglect the small contribution of the color-magnetic form factor, which may be enhanced, however, by QCD corrections.[10–12] The integral $I(\xi)$ is very sensitive to the value of $\xi \equiv (2m_c/m_b)^2$. We use constituent-quark masses[16] $m_c = 1.66$ GeV/c^2, $m_b = 5.0 \pm 0.3$ GeV/c^2 (the actual error allowed in Ref. 16 on $m_b - m_c$ is only about ± 50 MeV/c^2), and we obtain $\xi = 0.44^{+0.06}_{-0.05}$, $I(\xi) \simeq 0.077 \pm 0.024$. With $\alpha_s(m_b) = 0.19$ (see Ref. 17), we then find [taking $|V_{cd}| \simeq |V_{us}| = 0.22$ and the central value of $I(\xi)$]

$$1\% < -A_0/\sin\phi = 1.9\times 10^{-3} |V_{cb}/V_{ub}| < 3\% . \quad (11)$$

For decays into final states with a single strange hadron, the penguin amplitude provides the dominant contribution. Here we must be concerned with the $b \to sd\bar{d}$ amplitude, which contributes to the total inclusive rate for

$$b \to s + [\text{nonstrange light } q\bar{q} \text{ pair(s)}] \quad (12)$$

but not to the asymmetry. We shall estimate on the basis of the calculation in Ref. 10 for $b \to sq\bar{q}$ and $b \to sgg$ that the rate for Eq. (12) is about $\frac{5}{6}$ of the inclusive $b \to s$ rate. We then find the asymmetry A_1 for a single strange particle in the final state to be

$$A_1 \equiv \frac{\Gamma(b \to s\bar{u}u, sd\bar{d}, sgg) - \Gamma(\bar{b} \to \bar{s}u\bar{u}, \bar{s}d\bar{d}, \bar{s}gg)}{\Gamma(b \to s\bar{u}u, sd\bar{d}, sgg) + \Gamma(\bar{b} \to \bar{s}u\bar{u}, \bar{s}d\bar{d}, \bar{s}gg)} \simeq -\frac{48\pi^2}{5\alpha_s} \frac{|V_{us}V_{ub}|}{|V_{cb}|} \frac{I \sin\phi}{F(m_c, m_t)} . \quad (13)$$

The function $F(m_c, m_t)$, obtained from Ref. 18, has the following approximate forms for the respective ranges of m_t:

$$F(m_c, m_t) \simeq \begin{cases} \ln^2(m_t^2/m_c^2), & m_t^2 \ll m_W^2 , \\ \ln^2(m_W^2/m_c^2), & m_t^2 \gtrsim m_W^2 . \end{cases} \quad (14)$$

For the range[19] $40 < m_t < 200$ GeV/c^2 the actual values of F are smaller by about 10% and we find

$$1\% < -A_1/\sin\phi = (0.19 \pm 0.04) |V_{ub}/V_{cb}| < 5\% , \quad (15)$$

where the uncertainty in the numerical coefficient reflects the unknown t-quark mass.

Equations (11) and (15) show that quite sizable asymmetries, up to a few percent, are expected in both strangeness zero and one inclusive channels for large values of the CP phase ϕ. Note that A_0 and A_1 depend on $|V_{ub}/V_{cb}|$ in inverse forms.

At present the CP phase ϕ is badly determined. From studies of CP violation in the neutral K system and from B-$\bar{B}$ mixing, one infers[20] that ϕ may take almost any value aside from those near 0 or π. For small values of m_t (45–50 GeV/c^2) one finds $125° < \phi < 150°$, with $|V_{ub}/V_{cb}|$ required to be close to its present upper limit. For larger m_t, the restrictions on ϕ and $|V_{ub}/V_{cb}|$ become weaker. Finally, for $m_t = 200$ GeV/c^2, any value within the bounds $20° < \phi < 170°$, $0.07 < |V_{ub}/V_{cb}| < 0.2$ is allowed [the recent CLEO result[4] weakens the lower bound on $|V_{ub}/V_{cb}|$ further to approximately 0.04; the upper bound in Eq. (11) is then increased, while the lower bound in Eq. (15) is decreased accordingly].

One may optimistically hope that ϕ is not too far from 90°, so that asymmetries as large as a few percent may be obtained in inclusive charmless decays.

We now turn to estimates of the *CP* asymmetry in exclusive *B* decays. Here, a twofold difficulty enters. First, the overlap in kinematics[21] and isospin may be different from that for free quarks and may be hard to estimate. As in D^0 and D^+ decays, certain matrix elements may enhance some isospin amplitudes relative to others. Second, final-state interaction phases can be generated by the rescattering of the outgoing hadrons. One has some evidence for this effect, for example, in $D \to \bar{K}\pi$ decays.[22] These phases, which are hard to determine,[23] will in general affect the *CP*-odd asymmetry.

To elucidate this last difficulty let us denote the tree-level and penguin four-fermion operators by $O_{\rm tr}$ and $O_{\rm pen} = O^c_{\rm pen} + O^t_{\rm pen}$ (separated into the *c*- and *t*-quark terms), respectively. These operators contain phases due to KM elements, which are complex-conjugated for charge-conjugate processes. In addition, the matrix elements of these operators will in general pick up different final-state-interaction phases, $\delta_{\rm tr}$ and $\delta_{\rm pen}$, due to their different isospin structure. Thus the decay amplitude of $B^- = b\bar{u}$ to a final state f will be given by

$$A(B^- \to f) = \langle f | O_{\rm tr} | B^- \rangle e^{i\delta_{\rm tr}} + (e^{i\theta_{c\bar{c}}} \langle f | O^c_{\rm pen} | B^- \rangle + \langle f | O^t_{\rm pen} | B^- \rangle) e^{i\delta_{\rm pen}} . \quad (16)$$

Here $\theta_{c\bar{c}}$ is the phase associated with the fact that the *c*-quark penguin graph contributes both real and imaginary parts for gluon momentum transfers above $c\bar{c}$ threshold. The phases $\delta_{\rm tr}$, $\theta_{c\bar{c}}$, and $\delta_{\rm pen}$ are all invariant under charge conjugation. The matrix elements may consist of sums of various isospin and angular momentum amplitudes, with different final-state phases for each. The *CP* asymmetry, which depends on the generally unknown phase difference $\delta_{\rm tr} - \delta_{\rm pen}$, may average out to a smaller value when kinematic and isospin sums are taken.

In order to bypass these difficulties when studying decay modes of the type $B^- \to p\bar{p}\pi^-$ and $B^- \to p\bar{p}K^-$ one may make some simplifying assumptions. Let us consider the semi-inclusive decays $B^- \to N\bar{N}$ + (any number of pions) and $B^- \to \Lambda(\Sigma)\bar{N}$ or $N\bar{N}K$ + (any number of pions), where baryons from charm decay are excluded. These processes may be described by a free quark decay followed by the fragmentation of the outgoing quarks into the observed baryon [N or Λ (Σ)]. Two quarks already emerge from the weak vertex. It is reasonable to assume that these pick up a third quark from the vacuum to form the baryon.[24] One may expect this semi-inclusive process to occur with approximately equal rates in the tree-level and penguin diagrams, which have similar kinematics.

One may further assume that the fractions of baryonic decays in $S = 0$ and 1 charmless hadronic final states are each about equal to that for charmed baryons in charmed hadronic final states. This last fraction has been measured to be about 10% of the total hadronic rate.[25] We shall assume that this same fraction represents the charmless semi-inclusive baryonic rates, so that

$$B(B^- \to N\bar{N} + n\pi) \simeq \begin{cases} 0.4\% |V_{ub}/0.2V_{cb}|^2 \ \text{(tree level)} , & \text{(17a)} \\ (1-4)\times 10^{-4} \ \text{(penguin)} , & \text{(17b)} \end{cases}$$

$$B(B^- \to [\Lambda(\Sigma)\bar{N} \text{ or } N\bar{N}K] + n\pi) \simeq \begin{cases} (0.1-0.2)\% \ \text{(penguin)} , & \text{(18a)} \\ 2\times 10^{-4} |V_{ub}/0.2V_{cb}|^2 \ \text{(tree level)} . & \text{(18b)} \end{cases}$$

At this point it is useful to introduce a simple mnemonic for the smallest number of events needed to display an asymmetry, given two interfering processes with sufficiently different amplitudes. Let the processes for b decay have amplitudes A_1 and $A_2 e^{i\delta_f}$, where δ_f is the relative final-state phase, and assume $|A_2| \ll |A_1|$. Then

$$A = \frac{\Gamma(b \to f) - \Gamma(\bar{b} \to \bar{f})}{\Gamma(b \to f) + \Gamma(\bar{b} \to \bar{f})} \simeq -2 \left| \frac{A_2}{A_1} \right| \sin\delta_{\rm KM} \sin\delta_f , \quad (19)$$

where $\delta_{\rm KM} = \arg(A_2/A_2)$. The number $N_{\rm ev}$ of $b \to f$ and $\bar{b} \to \bar{f}$ events needed to see an asymmetry of N standard deviations is approximately

$$N_{\rm ev} = N^2/A^2 \simeq \frac{N^2 |A_1/A_2|^2}{4\sin^2\delta_{\rm KM} \sin^2\delta_f} = \frac{N^2 B_1/B_2}{4\sin^2\delta_{\rm KM}\sin^2\delta_f} , \quad (20)$$

where B_1 is the branching ratio for the more frequent processes [e.g., (17a) or (18a) in the example above] and B_2 is the branching ratio for the less frequent process [e.g., (17b) or (18b) in the above example.] Then the *total* number of $B + \bar{B}$ decays needed is approximately

$$N_{\rm tot} = N_{\rm ev}/B_1 = N^2 (4B_2 \sin^2\delta_{\rm KM} \sin^2\delta_f)^{-1} . \quad (21)$$

The required number of events is governed by the branching ratio for the rarer process, and to this approximation the branching ratio for the more frequent process does not appear.

Let us apply this rule to the charmless semi-inclusive baryonic decays of B mesons, whose expected branching ratios are indicated in Eqs. (17) and (18). Notice that the rarer processes in Eqs. (17) and (18) each have branching ratios of the order of 10^{-4}. Then for a signal of N standard deviations, we need to observe a total of $\sim 10^4 N^2 (4\sin^2\delta_{\rm KM}\sin^2\delta_f)^{-1} B^- + B^+$ decays.

For the processes (17) and (18), $\sin^2\delta_{\rm KM} = \sin^2\phi$, where

ϕ is the angle defined in Eq. (6). The value of $\sin^2\delta_{KM}$ then can be as large as 1 or as small as about $\frac{1}{30}$. The phase δ_f can be estimated crudely on the basis of the c-loop contribution to the penguin graph discussed earlier. This should be considered to be merely an educated guess, since the relative phase between the direct and penguin amplitudes may be affected by the baryon-antibaryon spin structure already at the semi-inclusive level. In reality the sign and magnitude of δ_f may differ from our free-quark estimate. Comparing the imaginary part [Eq. (10)] and the real part of the corresponding overlap integral of the penguin and tree contributions, one finds

$$\tan\theta_{c\bar{c}} \simeq \frac{\pi I}{\ln[\min(m_t, m_W)/m_c]} \approx 0.06 \text{ for } m_t \gtrsim m_W . \quad (22)$$

Equation (22) is a good approximation for the $b \to s$ process, for which the dominant contribution comes from the c loop, with a small correction from the t loop. For the $b \to d$ process, which may have an equally large u-loop contribution, Eq. (22) is qualitatively good (to within a factor of 2) and becomes quantitatively correct in the limit that $|V_{ub}/0.2V_{cb}| \ll 1$. We thus estimate $\sin^2\delta_f \approx \frac{1}{250}$, with smaller values possible only if the estimate (17b) significantly exceeds its lower limit.

We now combine the results for δ_{KM} and δ_f with Eq. (21) and the estimate $B_2 \approx 10^{-4}$. We then find that

$$N_{tot} \geq [(5\times10^5)-(1.5\times10^7)]N^2 , \quad (23)$$

charged B decays are needed to observe an asymmetry at the N-standard-deviation level in charmless semi-inclusive baryonic modes.

It is possible that $\sin^2\delta_f$ could be considerably larger than our estimate if inclusive processes involving baryons in the final state are governed primarily by large values of q^2 (above $c\bar{c}$ threshold) (we expect this to be more likely, however, for the exclusive low-multiplicity processes discussed below). The phase δ_f associated with the c-loop penguin diagram (which, we have argued, provides a dominant contribution to the penguin amplitudes), is 19° at the top of the kinematic range for $m_t \gtrsim m_W$, so $\sin^2\delta_f$ can be as large as 0.1 (for $m_t \lesssim m_W$ the phase δ_f can be even larger).

Turning now to specific exclusive modes, such as $p\bar{p}\pi^-$ and $p\bar{p}K^-$, one may assume that these will appear in about $\frac{1}{10}$ and $\frac{1}{30}$ of all the corresponding $S=0$ and $S=1$ inclusive baryonic events. The first fraction describes reasonably well[7] the branching ratio of $B^- \to p\bar{p}\pi^-$ (assuming that the results of Refs. 3 and 4 are compatible with one another). For $|V_{ub}/V_{cb}|=0.15$, this branching ratio would be predicted to be about 2×10^{-4}. The second smaller fraction follows from the three times larger number of available $S=1$ three-body modes. Including a factor of 2 uncertainty in the estimates of these fractions we find

$$B(B^- \to p\bar{p}\pi^-) = \begin{cases} (3-6)\times10^{-4}|V_{ub}/0.2V_{cb}|^2 \text{ (tree level)}, & (24a)\\ (1-4)\times10^{-5} \text{ (penguin)}, & (24b)\end{cases}$$

$$B(B^- \to p\bar{p}K^-) = \begin{cases} (3-6)\times10^{-5} \text{ (penguin)}, & (25a)\\ (1.5-3)\times10^{-6} \text{ (tree level)}. & (25b)\end{cases}$$

In Eq. (25b) we have used our estimate of the average of results from Refs. 3 and 4, $B(B^\pm \to p\bar{p}\pi^\pm) \simeq (1-2)\times10^{-4}$, and multiplied it by a factor $|V_{us}|^2/3 \sim \frac{1}{60}$.

Taking the central values of Eq. (24) and (25), and assuming KM and final-state interaction phases ϕ and δ_f, respectively, one estimates according to Eq. (19) that

$$A(B^\pm \to p\bar{p}\pi^\pm) \equiv \frac{\Gamma(B^- \to p\bar{p}\pi^-) - \Gamma(B^+ \to p\bar{p}\pi^+)}{\Gamma(B^- \to p\bar{p}\pi^-) + \Gamma(B^+ \to p\bar{p}\pi^+)} = -0.7\sin\phi\sin\delta_f , \quad (26)$$

$$A(B^\pm \to p\bar{p}K^\pm) \equiv \frac{\Gamma(B^- \to p\bar{p}K^-) - \Gamma(B^+ \to p\bar{p}K^+)}{\Gamma(B^- \to p\bar{p}K^-) + \Gamma(B^+ \to p\bar{p}K^+)} = -0.5\sin\phi\sin\delta_f . \quad (27)$$

Choosing $B_2(p\bar{p}\pi^\pm)=(1-4)\times10^{-5}$ and $B_2(p\bar{p}K^\pm)=(1.5-3)\times10^{-6}$ in Eq. (21), with our educated guess of $\sin^2\delta_f \sim \frac{1}{250}$, we estimate that to observe an asymmetry signal of N standard deviations in $p\bar{p}\pi^\pm$ and $p\bar{p}K^\pm$ we would need to observe a total of at least $(2\times10^6, 2\times10^7)N^2/\sin^2\phi$ charged B decays.

We note that, as for semi-inclusive decays, the average q^2 which contributes to the final state affects our estimate of the final-state phase δ_f. For a low-multiplicity baryonic final state, in which the baryon and antibaryon appear to emerge nearly back to back,[3] it is quite likely that the q^2 value is near the top of its kinematic limit. As we have noted, $\sin^2\delta_f$ then can be as large as ≈ 0.1 if the penguin amplitude is dominated by the charmed-quark loop. This appears to be the case for $b \to s$, and also is true for $b \to d$ if $|V_{ub}/V_{cb}|$ is not too close to its present upper limit.

We have not addressed the very important question of hadronic final-state interactions in exclusive modes. For *two-body* B decays, in which all relative subenergies are large, one expects such final-state phases to be dominantly imaginary, corresponding to absorption. One might expect a similar regularity for three-body decays, in which case all final-state rescattering phases would be identical, and one would be left with the phase $\theta_{c\bar{c}}$ discussed previously.

Recently Barshay, Eich, and Sehgal[26] studied CP violation in $B^+ \to p\bar{p}\pi^\pm$ decays. They find the total CP asymmetry is about 0.07%, nearly 2 orders of magnitude below our estimate. Their calculation relies on the interference of the tree-level decay amplitude with the long-distance penguin contribution of the η_c intermediate state. This contribution is much smaller than that of the short-distance penguin amplitude we use, explaining the discrepancy between our results.

To summarize, we have discussed asymmetries in charmless decays of charged B mesons, in inclusive final states, semi-inclusive processes involving baryons, and exclusive final states such as $p\bar{p}\pi^{\pm}$ and $p\bar{p}K^{\pm}$. The usefulness of these last states will, of course, depend on whether the ARGUS signal[3] is eventually confirmed.[27] We stress that, as in any of the CP asymmetries involving interference of two processes with very different rates, the number of events required to observe the asymmetry is governed by the *rarer* decay process. It is then particularly important to verify experimentally the prediction of Refs. 11 and 12 that penguin $b \rightarrow d$ processes account for $(0.1-0.4)\%$ of all B meson decays. An alternative test of the importance of loop-dominated processes, on which our estimates are based, is an observation of the $p\bar{p}K$ mode at the level predicted here.

This work was supported in part by the U.S.-Israel Binational Science Foundation (BSF), Jerusalem, Israel, by the E.J. Bishop Research Fund, by the Technion VPR research fund, by the Fund for Promotion of Research at the Technion and by the U.S. Department of Energy under Grant No. DE-AC02-80ER-10587. We would also like to thank the University of California, Los Angeles (G.E.), the Aspen Center for Physics (M.G. and J.L.R.), and the Technion (J.L.R.) for hospitality during part of this work. J.L.R. would like to thank Bruce Winstein for a useful conversation.

*Permanent address: Department of Physics, Technion, Israel.

[1]Myron Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. **43**, 242 (1979).

[2]For recent works with further references, see Ling-Lie Chau and Hai-Yang Chen, Phys. Rev. Lett. **59**, 958 (1987); I. I. Bigi, V. A. Khoze, N. G. Uraltsev, and A. I. Sanda, in *CP Violations,* edited by C. Jarlskog (World Scientific, Singapore, in press).

[3]ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **209**, 119 (1988). For a preliminary result, see W. Schmidt-Parzefall, in *Proceedings of the 1987 International Symposium on Lepton and Photon Interactions at High Energies,* Hamburg, West Germany, 1987, edited by W. Bartel and R. Rückl [Nucl. Phys. B, Proc. Suppl. **3**, 257 (1987)].

[4]CLEO Collaboration, C. Bebek *et al.*, in Proceedings of the International Conference on High Energy Physics, 1988 (unpublished); Cornell University Report No. CLNS 88/862 (unpublished).

[5]M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[6]Sheldon Stone, in *CP Violations* (Ref. 2).

[7]Michael Gronau and Jonathan L. Rosner, Phys. Rev. D **37**, 688 (1988); Michael Gronau, in *Proceedings of the International Symposium on the Production and Decay of Heavy Flavors,* Stanford, California, 1987, edited by E. D. Bloom and A. Fridman [Ann. N. Y. Acad. Sci. **535**, (1988)].

[8]Jean-Marc Gérard and Wei-Shu Hou, Max-Planck-Institut Reports Nos. MPI-PAE/PTh 26/88, 1988 and MPI-PAE/PTh 56/88 (unpublished).

[9]Wei-Shu Hou, A. Soni, and Herbert Steger, Phys. Rev. Lett. **59**, 1521 (1987).

[10]Wei-Shu Hou, Nucl. Phys. **B308**, 561 (1988).

[11]G. Eilam and M. Gronau, Phys. Rev. Lett. **61**, 286 (1988).

[12]L. Łukaszuk, X. Y, Pham, and C. Vu Xuan, Phys. Lett. B **202**, 388 (1988).

[13]The CP-odd interference between the c- and t-quark loops is much smaller. See N. G. Deshpande, G. Eilam, A. Soni, and G. L. Kane, Phys. Rev. Lett. **57**, 1106 (1986). There is no CP-odd interference between the u-quark penguin amplitude and the tree-level amplitude, as a result of their identical weak mixing factors.

[14]The combination $\rho_{\rm KM}^{(0)}$ defined in Eq. (5) is rephasing-invariant in the sense, for example, discussed by Isard Dunietz and Jonathan L. Rosner, Phys. Rev. D **34**, 1404 (1986).

[15]The angle ϕ is identical to the CP-violating weak phase in the convention first introduced by L. Maiani, Phys. Lett. **62B**, 183 (1976). One may then describe the quark mixing matrix in terms of $|V_{us}|$ $(\approx|V_{cd}|)$, $|V_{ub}|$, $|V_{cb}|$, and ϕ, $0<\phi<\pi$. See M. Gronau and J. Schechter, Phys. Rev. Lett. **54**, 385 (1985). In the convention of Lincoln Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983), ϕ is just equal to $\arg(V_{ub}{}^*)=\arctan(\eta/\rho)$.

[16]See, e.g., Jonathan L. Rosner, in *Techniques and Concepts of High Energy Physics,* edited by Thomas Ferbel (Plenum, New York, 1981), p. 1.

[17]Waikwok Kwong, Paul. B. Mackenzie, Rogerio Rosenfeld, and Jonathan L. Rosner, Phys. Rev. D **37**, 3210 (1988).

[18]T. Inami and C. S. Lim, Prog. Theor. Phys. **65**, 297 (1981); **65**, 1772(E) (1981); Nilendra G. Deshpande and Gad Eilam, Phys. Rev. D **26**, 2463 (1982).

[19]UA1 Collaboration, I. Wingerter, in *Looking Beyond the Z,* Topical Conference of the SLAC Summer Institute on Particle Physics, Stanford, California, 1987, edited by Eileen C. Brennan (SLAC, Stanford, CA, 1988); Ugo Amaldi *et al.*, Phys. Rev. D **36**, 1385 (1987); G. Costa *et al.*, Nucl. Phys. **B297**, 244 (1988).

[20]For a recent review with further references see G. Altarelli and P. Franzini, CERN Report No. TH.4914/87, 1987, presented at Symposium on Present Trends, Concepts and Instruments of Particle Physics, in honor of Marcello Conversi's 70th Birthday, Rome, Italy, 1987 (unpublished). (unpublished).

[21]We have in mind, for example, the momentum transfer $q^2=xm_b^2$ to the $u\bar{u}$ pair in $b\rightarrow s(d)u\bar{u}$, and the relative angular momenta of final-state particles.

[22]S. Kaptanoglu, Phys. Rev. D **18**, 1554 (1978); J. F. Donoghue and B. R. Holstein, *ibid.* **21**, 1334 (1980); H. J. Lipkin, Phys. Rev. Lett. **44**, 710 (1980); A. N. Kamal and E. D. Cooper, Z. Phys. C **8**, 67 (1981); A. N. Kamal, Stanford Linear Accelerator Center Reports Nos. SLAC-PUB-3443, 1984, and SLAC-PUB-3593, 1985 (unpublished); A. N. Kamal and M. D. Scadron, Phys. Rev. D **32**, 1164 (1985); Ling-Lie Chau and Hai-Yang Cheng, Phys. Rev. Lett. **56**, 1655 (1986); M. Bauer, B. Stech, and M. Wirbel, Z. Phys. C **34**, 103 (1987).

[23]I. Bigi and B. Stech, in *Proceedings of the Workshop on High Sensitivity Beauty Physics at Fermilab,* Batavia, Illinois, 1987, edited by A. J. Slaughter, N. Lockyer, and M. Schmidt (Fermilab, Batavia, IL, 1988), p. 239.

[24]I. I. Bigi, Phys. Lett. **106B**, 510 (1981).

[25]CLEO Collaboration, M. S. Alam *et al.*, Phys. Rev. Lett. **59**, 22 (1987); Schmidt-Parzefall, in *Proceedings of the 1987 Inter-*

national Symposium on Lepton and Photon Interactions at High Energies (Ref. 3).

[26]Saul Barshay, Eberhard Eich, and Lalit Sehgal, Phys. Lett. B **202**, 402 (1988).

[27]We should mention a recent estimate by V. L. Chernyak and I. R. Zhitnitsky, Novosibirsk Institute of Nuclear Physics Report No. 88–55, 1988 (unpublished), which predicts a much lower branching ratio for $B^- \to p\bar{p}\pi^-$ than observed by ARGUS (Ref. 3).