

Method for flavor tagging in neutral B meson decays

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A method is proposed for tagging the flavor of neutral B mesons in the study of CP -violating decay asymmetries. The method makes use of a possible difference in interactions in $B\pi$ or $B^*\pi$ systems with isospins $\frac{1}{2}$ and $\frac{3}{2}$, and would be particularly clean if the $I=\frac{1}{2}$ systems can be detected as “ B^{**} ” resonances.

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I. INTRODUCTION

So far, CP violation has been seen only in decays of neutral kaons. The leading contender for the description of this effect, a nontrivial phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1], makes specific predictions for CP -violating asymmetries in decays of mesons containing a b quark. These asymmetries are particularly easily interpreted in decays of neutral B mesons to CP eigenstates such as $J/\psi K_S$ [2]. In this manner, uncertainties associated with unknown final-state interactions can be circumvented. However, the identification of the flavor of the initial B has proved to be nontrivial. Methods proposed up to now rely on the production of a B or \bar{B} in association with a particle of the opposite b -flavored quantum number, whose decay serves to tag the flavor of the neutral B of interest.

In the present article, we describe a method of tagging the flavor of a neutral B meson which makes use of the (strong) interaction of the decaying b or \bar{b} quark with other quarks before the time of decay. The method is expected to be successful if there is a clearly identifiable difference between low-mass pion- B interactions in channels with isospin $\frac{1}{2}$ and those with isospin $\frac{3}{2}$. Such a difference would exist, for instance, if there is a well-defined region of positive-parity pion- B resonances in the mass range below 5.8 GeV.

The presence of a π^+ in a low-mass combination with a neutral B meson is then circumstantial evidence that the B meson is a B^0 , and not a \bar{B}^0 . We show here how to convert such circumstantial evidence to a quantitative measurement.

A method similar to the one we propose, making use of the decay chain $D^{*\pm} \rightarrow (\bar{D})^0 \pi^\pm$, has been in use for some time for tagging the flavor of neutral D mesons [3]. In the case of B mesons, there is not enough energy for the B^* (the 3S_1 state of a b quark and a light antiquark) to decay to the B (the 1S_0 state) and a pion. The B^* always

decays to a B and a photon of about 46 MeV. However, it is highly likely that there exists a region of positive-parity $J=0, 1$, and 2 resonances corresponding to the P -wave levels of a b quark and a light (\bar{u} or \bar{d}) antiquark which decay to $B\pi$ and/or $B^*\pi$. As a result, one can identify (on a statistical basis) the flavor of a neutral B meson by making use of its correlation with an appropriately chosen charged pion.

Since production of positive-parity charmed meson (“ D^{**} ”) resonances appears to account for about 20 or 30% of D meson production in the e^+e^- continuum [3,4], the corresponding production of “ B^{**} ” resonances at higher e^+e^- energies, and perhaps at hadron colliders as well, is likely to be non-negligible.

A general description of the tagging method is given in Sec. II. One must measure decays of a neutral B^0 or \bar{B}^0 to states of definite flavor in order to calibrate production rates. The fact that neutral B^0 and \bar{B}^0 mesons mix with one another introduces some unavoidable dilution of the statistical power of this method.

A simplified approach to tagging, described in Sec. III, is applicable to charge-symmetric production processes such as $\bar{p}p$ and e^+e^- reactions. In this case, the measured asymmetry is related to the desired quantity by a dilution factor common to all measured asymmetries, which cancels if one takes their *ratio* for two different final states. Such ratios have been shown to provide useful information about the fundamental CKM parameters [5].

A special circumstance allows one to calibrate neutral B production using decays of charged B mesons. When the initial state has zero isospin, processes involving neutral and charged B mesons can be related to one another by means of a simple isospin reflection. This case is described in Sec. IV.

The method yields useful results only when there are nontrivial correlations between the charged pion and the decaying B . The most promising example of such correlations occurs when the charged pion and the B are decay

products of P -wave $b\bar{u}$ and $b\bar{d}$ resonances (or their charge conjugates). We describe the expected behavior of such resonances in Sec. V, and mention kinematic circumstances which require one to know the properties of these resonances rather precisely. A more general picture under which such correlations are expected, based on quark fragmentation, is also described.

We conclude in Sec. VI.

II. GENERAL TAGGING METHOD

The method we propose relies upon the detection of neutral B mesons with identified flavor (B^0 or \bar{B}^0) in conjunction with a pion of positive or negative charge nearby in phase space, and the detection of a CP eigenstate f as a B^0 or \bar{B}^0 decay product (we do not know which, *a priori*) in conjunction with a similar pion. We begin by discussing the states of identified flavor.

A B^0 or \bar{B}^0 may be accompanied by a charged pion nearby in rapidity (equivalently, in a state of low effective mass with the B^0 or \bar{B}^0). We propose that a $B^0 = b\bar{d}$ is more likely to be accompanied by a $\pi^+ = d\bar{u}$, while a $\bar{B}^0 = b\bar{d}$ is more likely to be accompanied by a $\pi^- = d\bar{u}$. This may be seen either from a simple picture of fragmentation, or from the likely existence of positive-parity resonances in the pion- B or pion- B^* systems. Such resonances are expected to have isospin $\frac{1}{2}$. We shall discuss them more extensively in Sec. V. There we shall specify more precisely how the accompanying pion is to be chosen.

We define the relative rates of production of B^0 and \bar{B}^0 mesons in low-mass combinations with charged pions to be

$$\begin{aligned} N(\bar{B}^0\pi^-) &\equiv P_1, & N(\bar{B}^0\pi^+) &\equiv P_2, \\ N(B^0\pi^+) &\equiv P_3, & N(B^0\pi^-) &\equiv P_4. \end{aligned} \quad (1)$$

The first and third channels are ‘‘nonexotic,’’ and are the ones in which we might see some resonant enhancement. The second and fourth channels are purely $I = \frac{3}{2}$, and no such enhancement is expected. Hence we anticipate that $P_1 > P_2$ and $P_3 > P_4$. In the limit of complete resonance dominance, we would have $P_2 = P_4 = 0$.

Let us denote a flavored state which we know to have come from a B^0 by T (for ‘‘tag’’) and the corresponding state for a \bar{B}^0 by \bar{T} . Examples of states T include $D^-\pi^+$ and $J/\psi K^{*0}$, where the K^{*0} is seen to decay to $K^+\pi^-$. (We are using the usual convention in which a B^0 meson contains a \bar{b} quark.) We can measure four separate correlations of states T or \bar{T} with charged pions. These measurements serve to normalize the production of B^0 and \bar{B}^0 in combination with the pion of either charge. We assume that the decay rates of B^0 to T and \bar{B}^0 to \bar{T} are equal. For the $D^-\pi^+$ and $J/\psi K^{*0}$ final states, this is true in the standard picture of CP violation [6], where a single amplitude dominates the decay. The assumption can, of course, be directly verified.

Because of B^0 - \bar{B}^0 mixing, an initial B^0 has relative probabilities $(1-\chi_d)$ and χ_d of decaying to the states T and \bar{T} , respectively. The parameter χ_d is related to the mass mixing parameter $x_d \equiv (\Delta m/\Gamma)_d = 0.71 \pm 0.14$ [7]

for neutral B mesons by

$$\chi_d = x_d^2 / (2 + 2x_d^2) = 0.17 \pm 0.04. \quad (2)$$

The relative numbers of $T\pi$ states of various types are then given by

$$N(\bar{T}\pi^-) = (1-\chi_d)P_1 + \chi_d P_4, \quad (3)$$

$$N(\bar{T}\pi^+) = (1-\chi_d)P_2 + \chi_d P_3, \quad (4)$$

$$N(T\pi^+) = (1-\chi_d)P_3 + \chi_d P_2, \quad (5)$$

$$N(T\pi^-) = (1-\chi_d)P_4 + \chi_d P_1, \quad (6)$$

where we have omitted an overall branching ratio. These equations can be solved pairwise for the P_i , since χ_d is very far from $\frac{1}{2}$. For example, we have

$$P_1 = [1 - 2\chi_d]^{-1} [(1-\chi_d)N(\bar{T}\pi^-) - \chi_d N(T\pi^-)], \quad (7)$$

$$P_4 = [1 - 2\chi_d]^{-1} [(1-\chi_d)N(T\pi^-) - \chi_d N(\bar{T}\pi^-)], \quad (8)$$

with similar expressions for P_2 and P_3 but with $\pi^- \rightarrow \pi^+$. The error on χ_d itself is expected to decrease in the future, but some amplification of the experimental errors in $N(T\pi^\pm)$ and $N(\bar{T}\pi^\pm)$ will nonetheless occur in the course of inverting the relations (3)–(6) to obtain the P_i .

Now let a state which was produced as B^0 at time $t=0$ decay to a CP eigenstate f with probability D_f , while a state which was \bar{B}^0 at $t=0$ decays to f with probability \bar{D}_f . We are interested in the (time-integrated) asymmetry [6]

$$A(f) \equiv \frac{\Gamma(B_{t=0}^0 \rightarrow f) - \Gamma(\bar{B}_{t=0}^0 \rightarrow f)}{\Gamma(B_{t=0}^0 \rightarrow f) + \Gamma(\bar{B}_{t=0}^0 \rightarrow f)} = \frac{D_f - \bar{D}_f}{D_f + \bar{D}_f}. \quad (9)$$

For the final state $f = J/\psi K_S$, it has been shown that the asymmetry $A(f)$ measures the angle β of the unitarity triangle (a fundamental parameter of the CKM matrix) to a very good approximation [8] (for notation see, e.g., Ref. [5]):

$$A(J/\psi K_S) = -\frac{x_d}{1+x_d^2} \sin 2\beta, \quad (10)$$

since a single amplitude contributes to each decay $B^0 \rightarrow J/\psi K^0$ and $\bar{B}^0 \rightarrow J/\psi \bar{K}^0$. There are some questions [8] as to whether the same is true for the $\pi^+\pi^-$ final state, but in the simplest case one has

$$A(\pi^+\pi^-) = -\frac{x_d}{1+x_d^2} \sin 2\alpha, \quad (11)$$

where α is another angle in the unitarity triangle.

Now we measure the numbers of CP eigenstates f in conjunction with charged pions, always taking the same mass range for $f\pi^\pm$ as we took for the decays to states of identified flavor. Let the numbers of final states $f\pi^\pm$ (where the charged pion is that referred to above) be denoted by $N_{f\pm}$. Then the number of $f\pi^\pm$ states will be

$$N_{f+} \equiv N(f\pi^+) = P_3 D_f + P_2 \bar{D}_f, \quad (12)$$

$$N_{f-} \equiv N(f\pi^-) = P_4 D_f + P_1 \bar{D}_f. \quad (13)$$

As long as $P_1P_3 - P_2P_4 \neq 0$, we can invert Eqs. (12) and (13) to find

$$D_f = (P_1N_{f+} - P_2N_{f-}) / (P_1P_3 - P_2P_4), \quad (14)$$

$$\bar{D}_f = (P_3N_{f-} - P_4N_{f+}) / (P_1P_3 - P_2P_4). \quad (15)$$

Since it is likely that $P_1 > P_2$ and $P_3 > P_4$, we expect to be able to perform this operation. Its validity depends on the existence of nontrivial correlations between charged

pions and neutral B mesons. These correlations can be searched for experimentally.

The asymmetry $A(f) = (D_f - \bar{D}_f) / (D_f + \bar{D}_f)$ is then

$$A(f) = \frac{(P_1 + P_4)N_{f+} - (P_3 + P_2)N_{f-}}{(P_1 - P_4)N_{f+} + (P_3 - P_2)N_{f-}}. \quad (16)$$

An explicit form in terms of ‘‘tagging’’ final states comes from solving Eqs. (3)–(6):

$$(1 + x_d^2)A(f) = \frac{[N(\bar{T}\pi^-) + N(T\pi^-)]N_{f+} - [N(T\pi^+) + N(\bar{T}\pi^+)]N_{f-}}{[N(\bar{T}\pi^-) - N(T\pi^-)]N_{f+} + [N(T\pi^+) - N(\bar{T}\pi^+)]N_{f-}}. \quad (17)$$

This is our central result.

III. CHARGE-SYMMETRIC PRODUCTION

Let us consider a production process such as $p\bar{p}$ or e^+e^- annihilation, in which the cross sections for production of B^0 and \bar{B}^0 states should be equal. In the $p\bar{p}$ case this follows from the charge-conjugation invariance of the strong interactions. In electron-positron annihilation the production of a b quark is always accompanied by production of a \bar{b} quark, and the subsequent fragmentation into hadrons conserves charge symmetry.

In the present case we have $P_1 = P_3$ and $P_2 = P_4$, and a simpler result

$$A_{\text{obs}}(f) \equiv \frac{N_{f+} - N_{f-}}{N_{f+} + N_{f-}} = \frac{P_1 - P_2}{P_1 + P_2} A(f) \quad (18)$$

follows from Eq. (16). The first factor corrects for the dilution of the observed effect as a result of the tagging process. In order that it be nonzero, we require only that $P_1 \neq P_2$. As we have mentioned, $P_1 > P_2$ is most likely for appropriately chosen pions, and $P_2 = 0$ in the limit that the interaction in the $I = \frac{1}{2}$ channel is dominant. In terms of ‘‘tagging’’ final states, one may write

$$\left[1 + x_d^2\right] A(f) = \left[\frac{N(\bar{T}\pi^-) + N(\bar{T}\pi^+)}{N(\bar{T}\pi^-) - N(\bar{T}\pi^+)} \right] A_{\text{obs}}(f) \quad (19)$$

for the case of charge-symmetric production.

Note added in proof. The decay rates of B^0 to the tagging final state T and \bar{B}^0 to \bar{T} may not be equal if CP is violated. However, these rates cancel in the ratios of Eq. (4) to Eq. (3) and Eq. (6) to Eq. (5). When $P_3 = P_1$ and $P_4 = P_2$, these ratios can be solved for P_2/P_1 as long as $\chi_d < \frac{1}{2}$. The ratio P_2/P_1 should be the same for the two cases as a result of C invariance of the strong interactions. It can then be used in Eq. (18) to relate the observed asymmetry to the physical asymmetry. Equation (19) is valid in this case in spite of CP violation in $B^0 \rightarrow T$.

Since the required number of events to see an observed asymmetry A_{obs} at the level of S standard deviations is $(S/A_{\text{obs}})^2$ [6], this number is proportional to a factor $(P_1 + P_2)^2 / (P_1 - P_2)^2 > 1$. This factor is to be compared with ones involved in tagging via the associated B , which typically involve a branching ratio to a leptonic or other

final state. There, it is the inverse branching ratio which governs the required number of events.

Even if the dilution factor is unknown, it cancels out if we study two *different* final states f and f' :

$$\frac{N_{f+} - N_{f-}}{N_{f+} + N_{f-}} \bigg/ \frac{N_{f'+} - N_{f'-}}{N_{f'+} + N_{f'-}} = A(f) / A(f'). \quad (20)$$

The ratio of decay asymmetries for the final states $\pi^+\pi^-$ and $J/\psi K_S$, for example, provides interesting information on the parameters in the Cabibbo-Kobayashi-Maskawa matrix, if the reservations expressed in Ref. [8] can be dealt with [9]. In that case, we have just

$$A(\pi^+\pi^-) / A(J/\psi K_S) = \sin 2\alpha / \sin 2\beta, \quad (21)$$

leading to simple geometric constraints on the unitarity triangle [5].

IV. ISOSCALAR PRODUCTION

A. Cases of isoscalar production

We shall be able to make use of isospin reflection symmetry whenever the initial state leading to a $B\pi$ resonance has isospin zero. Cases in which this can occur include the following.

(1) *The reaction $e^-e^+ \rightarrow b\bar{b}$.* If the current (acting through a virtual photon or virtual Z^0) produces the $b\bar{b}$ pair directly, that pair is of course produced with zero isospin. The subsequent fragmentation to hadrons also conserves isospin.

(2) *Hadronic collisions involving projectiles with $I=0$,* such as deuterium-deuterium, carbon-carbon, oxygen-oxygen, or $^{40}\text{Ca}-^{40}\text{Ca}$ collisions.

(3) *Production of the $b\bar{b}$ state and its fragmentation products (including the pions in the $B\pi$ resonances) from an initial gluonic state,* as occurs in any perturbative QCD description of hadronic $b\bar{b}$ production. This condition can be violated if the pions do not come from fragmentation of the b quarks.

B. Isospin relations

When isospin reflection $I_3 \rightarrow -I_3$ is a good symmetry, one has the following relations between final states involving B 's and associated pions:

$$N(B^-\pi^+) = N(\bar{B}^0\pi^-) = P_1, \quad N(B^-\pi^-) = N(\bar{B}^0\pi^+) = P_2, \quad (22)$$

$$N(B^+\pi^-) = N(B^0\pi^+) = P_3, \quad N(B^+\pi^+) = N(B^0\pi^-) = P_4, \quad (23)$$

where we have used the definitions of Sec. II. One must be careful that isospin splittings between charged and neutral B^{**} resonances are not so large as to cause measurable effects, but this appears highly unlikely. The situation is quite different in the case of the decays $D^* \rightarrow D\pi$, where some channels are actually closed as a result of such splittings.

The result of Sec. II for decay asymmetries now may be transcribed directly. Expressed in terms of ratios of measured numbers of events, it is

$$A(f) = \frac{N_{f+}[N(B^-\pi^+) + N(B^+\pi^+)] - N_{f-}[N(B^+\pi^-) + N(B^-\pi^-)]}{N_{f+}[N(B^-\pi^+) - N(B^+\pi^+)] + N_{f-}[N(B^+\pi^-) - N(B^-\pi^-)]}. \quad (24)$$

One needs nontrivial B -pion correlations which differ in exotic ($I = \frac{3}{2}$) and nonexotic channels in order for the relation to be useful.

As in Sec. III, the assumption of a charge-symmetric production process allows the above relation to be expressed in terms of the product of a dilution factor, now given in terms of charged B rates, and an observed asymmetry. Explicitly, we have

$$A(f) = \frac{N(B^-\pi^+) + N(B^+\pi^+)}{N(B^-\pi^+) - N(B^+\pi^+)} \cdot \frac{N_{f+} - N_{f-}}{N_{f+} + N_{f-}}. \quad (25)$$

This is the case in e^+e^- annihilation.

V. CORRELATIONS OF B MESONS AND PIONS

A. Resonance spins and decay channels

A b quark and a light antiquark can form P -wave positive-parity resonances with $J=0, 1$, and 2 . The $J=0$ and $J=2$ states are pure spin triplets, while two physical $J=1$ states are expected to be linear combinations of spin-singlet and spin-triplet states with definite values of light-quark total angular momentum (spin + orbital angular momentum) [10,11]. The allowed decay channels are

$$\begin{aligned} B(J=0) &\rightarrow B\pi, & B(J=1) &\rightarrow B^*\pi, \\ B(J=2) &\rightarrow B\pi, & B^*\pi. \end{aligned} \quad (26)$$

Detection of the soft photon emitted in B^* decay could help identify the P -wave states with maximum efficiency.

B. Mass estimates:

Extrapolation from charmed mesons

In the limit of heavy-quark symmetry [11], the energy required to excite a light antiquark bound to a heavy quark should be independent of the mass of the heavy quark. Accordingly, we shall use the masses of the observed P -wave charmed mesons to estimate those of the corresponding excited B mesons.

There are candidates for P -wave charmed mesons at 2420 and 2460 MeV [4]. It is likely that the state at 2420 MeV corresponds to one or both of the expected $J=1$ levels, since it decays only to $D^*\pi$. The state at 2460 MeV probably corresponds to the $J=2$ level, since it is seen to decay both to $D\pi$ and to $D^*\pi$.

We will not know the fine-structure splitting in the P -

wave charmed meson multiplet until all four states have been identified. However, it is likely that the spin-averaged mass $\bar{M}_P(D)$ of the P -wave charmed mesons lies at or below that of the $J=1$ candidate at 2420 MeV. We estimate the mass difference associated with a P -wave excitation by comparing this value with the spin-averaged mass of S -wave charmed mesons:

$$\bar{M}_S(D) \equiv [3M(D^*) + M(D)]/4 = 1973 \text{ MeV}, \quad (27)$$

where we have used averages over isospin splittings. Consequently, we estimate that

$$\bar{M}_P(D) - \bar{M}_S(D) \lesssim 450 \text{ MeV}. \quad (28)$$

To reduce the uncertainty on this number, it would be very helpful to detect the $J=0$ state, decaying only to $D\pi$.

The spin-averaged mass of S -wave B mesons is

$$\bar{M}_S(B) \equiv [3M(B^*) + M(B)]/4 = 5315 \text{ MeV}. \quad (29)$$

If $\bar{M}_P(B) - \bar{M}_S(B) \lesssim 450 \text{ MeV}$ as suggested by the corresponding value for charmed mesons, we expect a region of P -wave $B\pi$ or $B^*\pi$ resonances lying below 5.8 GeV.

The detection of a photon from the decay $B^* \rightarrow B\gamma$ may be difficult, since the photon will only have 46 MeV in the B^* center of mass. If a resonance of mass 5.8 GeV or less decays to a B^* meson and a pion, and the photon in the decay of the B^* meson is not detected, the resulting $B\pi$ system will also have an effective mass less than 5.8 GeV, but should still be confined to a rather narrow mass interval since the photon is so soft.

The fine-structure splittings in heavy-quark–light-quark systems are characterized by two distinct scales [10,11]. First, the light quark and the orbital angular momentum are coupled up to a total angular momentum $J_{\text{light}} = \frac{1}{2}$ or $\frac{3}{2}$. The mass difference associated with $J_{\text{light}} = \frac{1}{2}$ or $\frac{3}{2}$ will not change when we go from D to B mesons. It could be considerable; we do not know, since we have only seen two states [$D(2420)$ and $D(2460)$] so far. Second, J_{light} couples to the spin of the heavy quark. When $J_{\text{light}} = \frac{1}{2}$, we get states of total spin $J=0, 1$, while when $J_{\text{light}} = \frac{3}{2}$ we get $J=1, 2$. The splitting of the two states with a given J_{light} should behave as the inverse of the heavy-quark mass. If the $D(2420)$ and $D(2460)$ are both states of $J_{\text{light}} = \frac{3}{2}$, for example, their B meson analogues may be closer together in mass. This proximity could be an advantage in reducing backgrounds.

C. Isospin considerations

Let us henceforth ignore the soft photon which may be emitted in B^* decay, and speak of resonances in the $B\pi$ system as standing for both $B\pi$ and $B^*\pi$. These resonances should occur only in $I = \frac{1}{2}$ (“nonexotic”) and not in $I = \frac{3}{2}$ (“exotic”) channels. Similar behavior is noted for resonances involving strange particles. Nonexotic mesonic channels correspond to states which can be formed of a quark and an antiquark, while exotic mesons require at least two quarks and two antiquarks. No exotic mesons have been observed up to now.

We expect resonances in the channels $B^-\pi^+$, $\bar{B}^0\pi^-$, $B^+\pi^-$, and $B^0\pi^+$, but not in the channels $B^-\pi^-$, $\bar{B}^0\pi^+$, $B^+\pi^+$, or $B^0\pi^-$. All channels with a neutral pion should contain resonances, but with strength one-half of that in the isospin-related channels involving charged pions.

It is most likely that accidental exotic combinations of a pion and a B can be avoided when the fragments of the corresponding antiparticle are far away in rapidity. Thus, the method we propose may not be particularly useful for production of a $b\bar{b}$ pair near threshold. The reaction $e^-e^+ \rightarrow Z^0 \rightarrow b\bar{b}$ would seem to be ideal for present purposes, if sufficient statistics can be obtained. The program we propose includes measurements which will *check* whether nonexotic and exotic $B\pi$ combinations show a different mass spectrum.

D. Fragmentation of b and \bar{b} quarks

Another argument in favor of nontrivial correlations between pions and B mesons, at least when the $B-\pi$ system is of low effective mass, may be presented in the language of quark fragmentation. At the same time, this argument exposes a source of potential dilution of the correlation.

Let us consider a b quark to fragment to a $\bar{B}^0 = b\bar{d}$ meson. Somewhere not far from the B^0 in phase space there should then exist a d quark, which is the partner of the $\bar{d}d$ pair which has been produced in the fragmentation process. This d quark is more likely to give rise to a π^- than to a π^+ . However, its probability for generating a π^+ in a low-mass combination with the \bar{B}^0 is nonzero. For example, the d quark could fragment to a ρ^0 meson, which then decays to $\pi^+\pi^-$.

For such reasons, the detection of correlations between pions and B mesons may require experimental study rather than mere theoretical speculation. There may be particularly favorable regions of phase space which we have not anticipated for which the difference between nonexotic and exotic $B\pi$ channels is most pronounced.

The present method appears to be a special case of a more general approach. The basic idea behind this generalization is the fact that the charge of the leading quark can propagate through and become visible in the jet containing the B meson. Such a jet-charge method has been employed in the identification of light quarks, for instance in Ref. [12]. First, this can result in a definite charge relation between the whole jet and the B flavor. Second, one might expect differences in the shape of properly chosen kinematical variables, now taking all

pion fragments of the jet into account. Such variables are, for example, the mass of the $B\pi$ system, or the momentum or transverse momentum of the pion in a suitable frame. In a manner equivalent to the calibration process described above, one can extract these distributions directly from the data and use them as input for a (multidimensional) fit or even a neural network analysis. We have described a method which places the most emphasis on the leading pion since those differences are expected to be most obvious for it.

E. Some kinematic considerations

Some simple examples show that it may not be trivial to reduce combinatorial backgrounds in establishing $B\pi$ correlations. These examples underscore the importance of a detailed understanding of resonances in the $B\pi$ and $B^*\pi$ systems.

Let us consider the effective mass of a $B\pi$ system in two reference frames: one in which the pion is at rest, and one in which the pion has 300 MeV of energy and is traveling transverse to the B .

In the first frame, the πB effective mass does not exceed the value of 5.8 GeV (our proposed upper limit for the lowest positive-parity resonances) until the B energy exceeds about 21 GeV. A B produced in e^+e^- annihilations at the Z^0 mass has an average energy of 30–35 GeV, but a hadronically produced B is unlikely to have such an energy with regard to any of its fragments since the hadronic production processes favor $b\bar{b}$ final states not far above threshold. The pions formed as a result of the filling of the rapidity gap between b and \bar{b} may be fairly soft with respect to *both* the b and the \bar{b} .

The second frame is probably a more realistic representation of a centrally produced pion in the $b\bar{b}$ center of mass in either a high-energy e^+e^- or hadronic collision. Here, the B energy corresponding to an effective $B\pi$ mass of 5.8 GeV is only about 9 GeV. Accordingly, accidental low-mass combinations of a B and a “wrong” pion are expected to be less frequent.

In order to solve the system of equations in Sec. II for D_f and \bar{D}_f , one must be able to see a difference between exotic and nonexotic channels. It may be necessary to make rather strict cuts on $B\pi$ systems such that they have a high probability of having originated in the lowest positive-parity resonances. Identification of the soft photon in B^* decay could help in making use of the specific masses of the $J=1$ resonances, and could also enhance the signal from the decay of the $J=2$ state, but may not be essential, since its omission would shift and broaden the $B\pi$ mass distribution only slightly.

VI. CONCLUSIONS

We have suggested a way to identify the flavor of a B^0 or \bar{B}^0 decaying to a CP eigenstate by means of a pion forming a low-mass combination with the neutral B meson. The most natural source of this combination is a band of positive-parity $J=0, 1,$ and 2 resonances lying somewhere below 5.8 GeV. If this band is rather narrow, the presence of a π^+ in this combination is circumstantial evidence in favor of the neutral B having been a B^0 , while

a π^- suggests an initial \bar{B}^0 .

We have not discussed a corresponding method for tagging B_s decays. Isospin forbids the decay $B_s^{**} \rightarrow B_s \pi$, while $B^{**} \rightarrow B_s K$ is likely to be kinematically forbidden. A method of tagging a B_s with an accompanying kaon in a jet has been suggested in Ref. [13].

We have proposed several means of converting ‘‘circumstantial evidence’’ to quantitative measurements which can be interpreted in terms of CP -violating asymmetries. The number of events required to observe a given asymmetry is proportional in certain simplified cases to a factor $(P_1 + P_2)^2 / (P_1 - P_2)^2$, where P_1 and P_2 are the relative probabilities for nonexotic and exotic low-mass $B\pi$ correlations. What is needed at present is an experimental study of the nature of these correlations in various production configurations, to see if they are strong enough to provide the needed information. The potential for tagging a neutral B via a particle nearby it

in phase space, rather than via the decay (e.g., to leptons) of an associated b -flavored hadron, has interesting implications for lepton identification and detector size in future experiments searching for CP violation in the B meson system.

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