In this paper we present fits to charmless hadronic B decay data from the BaBar, Belle and Cleo experiments using models by Beneke et al. and Ciuchini et al. When we include the data from pseudo-scalar vector decays (PV) the current experimental results favour the inclusions of a so-called "charming penguin" term. We also present fit results for the Unitary Triangle parameters and the CP violating asymmetries.

1 Introduction

A wealth of experimental data on hadronic charmless $B$ decays has become available from the BaBar and Belle experiments. In this paper we present an analysis, based upon QCD factorisation, of data on hadronic charmless $B$ decays. We also investigate the potential contribution to the decay amplitudes of $b$ quark annihilation and of so-called charming penguins. The data we attempt to fit includes pseudo-scalar ($\pi$ and $K$) and vector ($\rho$, $\omega$, $K^*$ and $\phi$) mesons. This is an extension of an earlier study.

The decay amplitude can be described by:

$$A(B \rightarrow M_1M_2) = \frac{G_f}{\sqrt{2}} \sum_{p=u,c} \sum_{i=1,10} \lambda_p a_i^p < M_1M_2|Q_i|B >_{\text{fact}}$$

with $\lambda_p$ the appropriate CKM matrix factor for the process. The coefficients $a_i$ can be written as: $a_i = a_{i,I} + a_{i,II}$.

The $a_{i,I}$ coefficients are similar to the ones of naive factorisation with vertex and penguin corrections included. We assume that all the light mesons have the same spatial wave function. As a consequence the $a_{i,I}$ coefficients are universal. The $a_{i,II}$ coefficients contain the hard spectator interactions. They contain an end-point divergence from the low energy contributions to the loop integrals, which is parametrised by the complex parameter $X_H$. The magnitude of $X_H$ is expected to be between 0 and 3.
B meson decay can also be initiated by the b quark annihilating with its partner. Contributions to the decay amplitude should be small, of order $\Lambda_{QCD}/M_B$, compared to the leading b quark decay. Because of the heavy b quark mass it is expected that perturbative QCD calculations will give a reliable estimate of the contributions of annihilation to the decay amplitude. Apart from the electroweak meson decay constants, $f_B$, $f_\pi$, $f_\rho$ etc, there is a low energy contribution coming from the loop integrals. This is parametrised by the complex parameter $X_A$.

Charming penguins originate from diagrams with a charm quark loop. According to Ciuchini et al. they can be enhanced. They behave similar to the $a_4$ coefficients in signs and Clebsch-Gordan coefficients and take the following form:

$$A_{b \rightarrow q} = \frac{G_F}{\sqrt{2}} [-V_{ub}^* V_{ub} (P_1 - P_{1GIM}^\text{GIM}) - V_{cq}^* V_{qb} P_1]$$

(2)

2 Fitting Method

We have attempted to fit the theoretical expressions for branching ratios with the available data as averaged by the Heavy Flavour Averaging Group. Measured branching ratios for seventeen channels are shown in Table 1. We take the measured branching ratios to be the mean of the $B$ and $\bar{B}$ decays. The CP asymmetries are not included in the fit. Their measurements are not always consistent between the experiments and the errors are large. Therefore we prefer to compare the measured results with the prediction from the fit.

For convenience we assign to each channel $(h_1 h_2)$ a number $\alpha$. The statistical and systematic errors have been combined into a single error $\sigma_\alpha$. The systematic errors are small in general and we ignore any correlation between the channels. We then write for a $\chi^2$ function

$$\chi^2(P_i) = \sum_\alpha [(\text{Br}_\alpha(P_i) - \text{Br}_\alpha(\text{exp})) / \sigma_\alpha]^2 + \text{additional constraints.}$$

(3)

$\text{Br}_\alpha(P_i)$ are the theoretical branching ratios in terms of ten parameters $P_i, i = 1, \ldots, 10$ which we take to be the three Wolfenstein CKM parameters $\{A, \rho, \eta\}$ and the seven soft QCD parameters $\{R_\pi, R^K_\chi, F_\pi, F_K, A_\rho, A_\omega, A_{K^*}\}$. For the fit to the charming penguin model we introduce four more terms: $P\text{GIM}_1$ and $P\text{GIM}_2$. In this case we fix $A$ to the world average on 0.82 and keep $R^K_\chi$ fixed at 1.0. The well known decay parameters $\{f_\pi, f_K, f_\rho, f_\omega, f_\phi, f_{K^*}\}$ are held at their mean values and the Wolfenstein CKM $\lambda$ parameter is taken to be $\lambda = 0.2205$. For the divergence parameters we take $|X_H| = |X_A| = 2$, which leads to reasonable values of e.g. sin$2\beta$. Additional terms were included in the $\chi^2$ to take into account experimental and theoretical constraints from outside the data on $B$ decay branching ratios. We search for a minimum of $\chi^2$ as a function of the $P_i$. We use the MINUIT program to minimise the $\chi^2$. The theoretical branching ratios and contributions of the individual channels to $\chi^2$ based on these best fit values are given in Table 1.

The values of the best fit parameters are shown in Table 2 together with our estimates of the errors. These errors are of course highly correlated. A plot of the error matrix ellipse for the Wolfenstein parameters $\rho$ and $\eta$ is shown in Fig. 1. For both models, the results in Table 2 for the best fit values of the various form factors lie within the spread of theoretical estimates. The $\chi^2$/dof is 34/16 for the BBNS fit and 16/12 for the charming penguins.

3 Conclusions

The first conclusion would be that the factorisation approach works well. Most of the branching fractions in Table 1 are predicted correctly by both models. The fitted parameters in Table 2
look reasonable for both fits. The $\chi^2$ for the charming penguin fit is significantly better. This is due to the poor fit of BBNS for the decay modes with a $K^*$ meson. Also the experimental value for $\omega K^0$ is not easily accommodated within the BBNS model. Both models have a problem fitting the $\pi^0 K^0$ mode. Figure 1 shows the position of the apex of the Unitarity Triangle for both fits. The results agree with each other on the angle $\gamma$, but give a larger value than the fits from other measurements. The angle $\beta$ agrees well, although it has to be pointed out that for the BBNS the value of $\beta$ is sensitive to the choice for $X_A$.

Regarding the asymmetries it is too early to come to a conclusion. In many cases the experiments do not agree, in others the errors are so large that a meaningful discrimination is not possible. The asymmetries are in principle very sensitive to the different models and with improved statistics could become the final test of factorisation.

Table 1: Measured branching ratio $Br(exp)$, experimental error $\sigma$ (errors added in quadrature), theoretical branching ratio for best fit parameters and contribution to $\chi^2$ for various $B$ decay channels. Units are $10^{-6}$.

| Decay               | $Br(exp)$ | $\sigma$ | BBNS Br | $\chi^2$ | CP Br | $\chi^2$ |
|---------------------|----------|----------|---------|----------|-------|----------|
| $\pi^+ \pi^-$       | 4.8      | 0.5      | 5.1     | 0.3      | 4.9   | 0.1      |
| $\pi^0 \pi^-$       | 5.9      | 1.0      | 4.1     | 3.1      | 5.9   | 0.0      |
| $\rho^+ \pi^+$      | 25.4     | 4.2      | 24.6    | 0.1      | 22.8  | 0.4      |
| $\rho^0 \pi^-$      | 9.6      | 2.0      | 9.3     | 0.1      | 10.0  | 0.1      |
| $\omega \pi^-$      | 6.4      | 1.3      | 7.5     | 0.7      | 6.3   | 0.0      |
| $\pi^0 K^-$         | 12.7     | 1.2      | 13.1    | 0.1      | 12.9  | 0.0      |
| $\pi^- K^0$         | 18.0     | 1.7      | 19.9    | 1.3      | 19.6  | 0.9      |
| $\pi^- K^{*0}$      | 12.3     | 2.6      | 4.3     | 9.3      | 8.0   | 2.8      |
| $\omega K^-$        | 3.1      | 1.0      | 2.3     | 0.6      | 4.2   | 1.2      |
| $\phi K^-$          | 8.9      | 1.0      | 8.6     | 0.1      | 8.7   | 0.1      |
| $\phi K^{*-}$       | 10.7     | 2.6      | 10.2    | 0.0      | 11.4  | 0.1      |
| $\pi^- K^{*+}$      | 18.5     | 1.0      | 18.8    | 0.1      | 18.7  | 0.1      |
| $\pi^- K^{*0}$      | 12.0     | 6.6      | 4.6     | 3.6      | 8.2   | 1.7      |
| $\pi^0 K^0$         | 10.3     | 1.5      | 6.9     | 5.0      | 6.9   | 5.0      |
| $\omega K^0$        | 5.9      | 1.9      | 1.5     | 5.2      | 3.5   | 1.6      |
| $\phi K^0$          | 10.7     | 2.7      | 8.2     | 0.2      | 11.4  | 0.1      |
| $\phi K^{*0}$       | 8.8      | 1.3      | 9.6     | 0.3      | 8.3   | 0.2      |

Table 2: Best fit values and one-standard deviation errors for both methods. $F_{\pi,K}$ and $A_{\rho,\omega,K^*}$ are the transition form factors, $F_{B \rightarrow M}(0)$. $R_{\lambda,K}^\omega$ are the chiral enhancement factors, which are nominally power supressed, but in practice $O(1)$.

|        | $F_{\pi}$  | $F_K$   | $A_{\rho}$ | $A_{\omega}$ | $A_{K^*}$ |
|--------|------------|---------|------------|--------------|-----------|
| BBNS   | 0.243 ± 0.038 | 0.368 ± 0.031 | 0.326 ± 0.088 | 0.301 ± 0.086 | 0.314 ± 0.129 |
| CP     | 0.285 ± 0.017 | 0.382 ± 0.037 | 0.328 ± 0.052 | 0.316 ± 0.064 | 0.322 ± 0.111 |
| $R_{\lambda}^\omega$ | $R_{\lambda}^K$ | $A$ | $\bar{\rho}$ | $\bar{\eta}$ |
| BBNS   | 1.09 ± 0.24 | 1.19 ± 0.19 | 0.885 ± 0.061 | 0.026 ± 0.069 | 0.366 ± 0.073 |
| CP     | 1.0        | 1.0       | 0.82       | 0.006 ± 0.087 | 0.411 ± 0.039 |
| $P^I$  | arg($P^I$) | $P^{GIM}$ | arg($P^{GIM}$) |
| CP     | 0.059 ± 0.007 | 1.58 ± 0.10 | 0.33 ± 0.12 | 0.93 ± 0.21 |
Table 3: CP asymmetries from BaBar and Belle and fit predictions. Only statistical errors are included.

|          | BaBar       | Belle       | BBNS       | CP       |
|----------|-------------|-------------|------------|----------|
| $A_{CP}$ | $-0.102 \pm 0.05$ | $-0.07 \pm 0.06$ | $0.08$     | $0.00$   |
| $K^+\pi^-$ | $-0.09 \pm 0.09$ | $0.23 \pm 0.11$ | $0.14$     | $0.06$   |
| $K^+\pi^0$ | $-0.17 \pm 0.10$ | $0.07 \pm 0.09$ | $0.01$     | $0.11$   |
| $K^0\pi^+$ | $-0.03 \pm 0.18$ | $-0.14 \pm 0.24$ | $0.0$      | $0.0$    |
| $\pi^+\pi^0$ | $-0.22 \pm 0.08$ | - | $-0.04$ | $0.25$   |
| $\rho^+\pi^-$ | $0.28 \pm 0.17$ | - | $-0.16$ | $-0.47$ |
| $C_{\pi\pi}$ | $-0.30 \pm 0.25$ | $-0.77 \pm 0.27$ | $0.17$     | $-0.03$  |
| $S_{\pi\pi}$ | $+0.02 \pm 0.34$ | $-1.23 \pm 0.41$ | $0.10$     | $0.03$   |
| $C_{\rho\pi}$ | $+0.36 \pm 0.15$ | - | $0.02$ | $-0.27$ |
| $S_{\rho\pi}$ | $+0.19 \pm 0.24$ | - | $0.32$ | $0.27$   |
| $\Delta C_{\rho\pi}$ | $+0.28 \pm 0.19$ | - | $0.17$ | $0.33$   |
| $\Delta S_{\rho\pi}$ | $+0.15 \pm 0.25$ | - | $0.0$ | $0.05$   |
| $C_{\phi K^0}$ | $-0.80 \pm 0.38$ | $0.56 \pm 0.41$ | $-0.02$ | $-0.21$ |
| $S_{\phi K^0}$ | $-0.18 \pm 0.51$ | $-0.73 \pm 0.64$ | $0.76$ | $0.74$ |

Figure 1: Result for the Unitarity Triangle fit for BBNS (left) and charming penguins (right). The shaded area shows the $3\sigma$ allowed region for the apex of the Unitarity triangle. The data point shows the fit result from the Unitarity Triangle fit from other measurements taken from CKMjitter$^9$.

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