901: Penguins, charmless $B$ decays and the hunt for CP violation

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1 Introduction

By a multitude of very important observations involving the QCD penguin, CLEO [1] has declared 1997 to be the year of the Strong Penguin. The observed size of the various modes suggest that the penguin is rather robust. The experimental observations have fueled intense theoretical activity some of which we will briefly review here. For convenience, we have divided the theoretical activity into four categories (See Table 1): Exclusive modes, inclusive $\eta'$ modes, the charm deficit and implications for CP violation.

2 The challenge of pure hadronic (exclusive) modes

There are renewed attempts to understand $B$-decays to two-body hadronic modes involving the penguins. Most of the works are centered around modifying factorization. The starting point in these calculations is the next-to-leading-order (NLO) short-distance (SD) Hamiltonian which at the quark level is clearly rather precise with a minimal uncertainty due to scale. However, it is quite unclear as to the advantage of using the NLO apparatus as the calculations of the hadronic matrix elements is highly uncertain. See below.

3 Charming-Penguins

Martinelli et al. [2] have made the interesting observation that graphs containing $c\bar{c}$ loops (the so-called “charming penguins”) could be important for final states involving the light states (such as $K\pi, \pi\pi \cdots$) and therefore should not be ignored as they are commonly done in calculation of matrix elements. The idea of charming penguin is closely related to the eye-graphs which are believed to be important for the emergence of the observed $\Delta I = 1/2$ rule in $K$-decays. Of course, their role in $B$-decays is not known.
Table 1. Sample of Recent Theoretical Works

| Who                          | What                        | Comments                                      |
|------------------------------|-----------------------------|-----------------------------------------------|
| Ciuchini et al. [2]           | 2 Body Modes                | Charming Penguins                            |
| Ali & Greub [3]               | 2 Body Modes                | Improve Factorization, $\eta_c \leftrightarrow \eta'$... |
| Cheng & Tseng [4]             | $\eta'(\eta) + K(K^*, \rho, \pi)$ | Improve Factorization, $\eta_c \leftrightarrow \eta'$... |
| Kagan & Petrov [5]            | $\eta'K$                    | SM Factorization OK·...                       |
| Datta et al. [6]              | $\eta'K(K^*)$               | Factorization and Anomaly                     |
| Shuryak & Zhitnitsky [7]      | $\eta'K$                    | $\eta_c \leftrightarrow \eta'$...            |
| Halperin & Zhitnitsky [8]     | $\eta'K$                    | $\eta_c \leftrightarrow \eta'$...            |
| Halperin & Zhitnitsky [8]     | $\eta'X_s$                  | $\eta_c \leftrightarrow \eta'$...            |
| Hou & Tseng [9]               | $\eta'X_s$                  | New Physics                                  |
| Kagan & Petrov [5]            | $\eta'X_s$                  | New Physics                                  |
| Yuan & Chao [10]              | $\eta'X_s$                  | $(\bar{c}c)_s \rightarrow \eta'X_s$         |
| Datta et al. [6]              | $\eta'X_s$                  | Factorization + Anomaly                      |
| Atwood & S [11]               | $\eta'X_s, \eta X_s$        | QCD Anomaly                                  |
| Dunietz et al. [12]           | Charm Deficit               |                                               |
| Lenz et al. [13]              | Charm Deficit               |                                               |
| Fleischer & Mannel [14]       | $K\pi$                      | $\gamma$                                     |
| London & S [15]               | $\eta'K + \ldots$           | $\beta_{penguin}$                            |
| Dighe et al. [16]             | $\eta'(\eta) + K(\pi)$     | Direct CP                                    |
| Hou & Tseng [9]               | $\eta'X_s$                  | Non-Std-CP                                   |
| Kagan & Petrov [5]            | $\eta'X_s$                  | Non-Std-CP                                   |
| Atwood & S [17]               | $\eta'X_s + \ldots$         | Non-Std-CP                                   |

4  $\eta_c-\eta'$ mixing [18, 3, 4, 7, 8, 10]

Since the decay $b \rightarrow c\bar{c}s$ is accompanied by a hefty CKM factor, $\eta_c \leftrightarrow \eta'$ mixing could possibly become important in $B \rightarrow \eta'$ decays. However, it is quite tricky to isolate this mixing as such. For one thing, some of the glue in the $b \rightarrow s g^*$ originates from $c\bar{c}$ annihilation via $b \rightarrow c\bar{c}s$. So one may equally well think of the $\eta'$ originating from this glue. More specifically mixing with $\eta_c$ and with 2-glue are interrelated. Quite understandably there is an enormous variation in the estimated $\eta_c \leftrightarrow \eta'$ mixing.

Table 2 shows a comparison of some of the recent calculations of exclusive 2-body modes. Notice that $\eta'K^*$ is an excellent discriminator amongst various models. The $\pi^0\pi^0$ mode which is especially important for $\alpha$-extraction appears most difficult to pin down; almost all the models seem to find it below $10^{-6}$ but the predictions are not at all reliable.

All of these theoretical calculations are extremely uncertain and have a huge range. In large part this is a reflection of the fact that scores of assump-
Table 2. Recent studies of exclusive modes; Br’s in units of $10^{-5}$

| Mode       | Sample Studies |
|------------|----------------|
|            | AG [3] | CT [10] | KP [5] | Romans [2] | CLEO [1] |
| $K^+\pi^-$ | 1–3    |         |         |            |          |
| $K^0\pi^+$ |         | 1–2     |         |            |          |
| $\pi^+\pi^-$ | .4–2.4 |         |         |            |          |
| $\pi^0\pi^0$ | .02–.08 |         |         |            |          |
| $\eta'K^\pm$ | 5–6   | 6–7     | 1–12    |            |          |
| $\eta'K^{*\pm}$ | .07–.16 | 1–2    |         |            |          |
| $\eta K^\pm$ | .01–.04 | .2–.5  | .1–.5   | .01–.5     |          |
| $\eta K^{*\pm}$ | .1–.2  | .3–.8  | .1–.4   |            | < 24     |

...and approximations have been made to arrive at these numbers. It is perhaps useful to list some of the assumptions and approximations typically used in these calculations:

1. Effective Wilson coefficients are same for $B \to D\pi$ and $B \to K\pi$.
2. Color suppression works as well for $(\pi\pi, K\pi \cdots)$ as for $(D\pi, D_\ast K \cdots)$.
3. Color suppression works as well for matrix elements of penguin operators as well as it does for matrix elements of tree operators.
4. Factorization works just as well for penguin operators as for tree ones.
5. The eye-graph with the $c$-loop (i.e. the charming penguin) does not contribute to light final states (such as $K\pi, \pi\pi \cdots$) even though lattice studies over the years have suggested that such graphs are important for the emergence of the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decays.
6. Annihilation or exchange contributions are neglected even though these are intimately related to “factorizable contributions” via FSI.
7. Penguin matrix elements are extremely sensitive to the numerical value of current quark mass, $m_s$.

Due to this very long list of assumptions and approximations the calculations for hadronic decays are highly unreliable. Thus deviations of the experimental numbers for the absolute rates from the crude theoretical estimates that are available cannot be used as a reliable hint for the presence of new physics. Search for CP violating asymmetries in some of the modes can be a much more reliable test of new physics.

5 A possible faint silver lining

Despite the morass of dealing with pure hadronic modes there is perhaps sign of a silver lining. The point is that $B$ decays have a multitude of light-light (2-body) final states. The theoretical information that goes into these
calculations is highly correlated. So despite the plethora of assumptions, theoretical models can easily run into trouble. For example, it is difficult to get a hierarchy \( Br(B^+ \to K^0 \pi^+) > Br(B^0 \to K^+ \pi^-) > Br(B^0 \to \pi^+ \pi^-) \). This is especially true for \( K^0 \pi^+ \) versus \( K^+ \pi^- \). So if improved experiments confirm the present trend then it would provide useful constraint on the models. The modes \( wK, \eta'K^*, \eta K, \eta K^* \) can also be very useful tests of models.

6 \( B \to \eta' + X_s \)

Some of the important issues are: SM vs. new physics, the form factor for \( g^* \to \eta'g \), the \( c\bar{c} \) content of the \( \eta' \), direct CP violation etc.

We have made a specific proposal that a large fraction of the inclusive signal \( B \to \eta' + X_s \) originates from the penguin graph through the fragmentation \( g^* \to g\eta' \) via the QCD anomaly [11]. The form factor \([H(q_1^2, q_2^2, m_{\eta'}^2}]\) at the anomalous vertex was estimated by using the measured rate for \( \psi \to \gamma \eta' \) [11]. Explicit calculations indicate that \( \psi \to \gamma \eta' \) is dominated by near “on-shell” gluons, i.e. \( q_1^2 \sim q_2^2 \sim 0 \). Since the gluon in \( b \to sg^* \) is typically with \( q_1^2 \sim 5–10 \) GeV\(^2\), \( q_2^2 \) dependence of \( H \) becomes quite important.

While we are not aware of any theoretical study on the dependence of \( H \) on \( q_1^2 \) for \( g^* \to \eta'g \), the corresponding case of the QED anomaly for \( \pi^0 \to \gamma^* + \gamma \) has received some theoretical attention [19]. Although the details vary there is broad agreement as to how the form factor for \( \pi^0 \to \gamma^* \gamma \) due to the quark loop scales. If one assumes that \( g^* \to \eta'g \) form factor is essentially the same as \( \gamma^* \to \pi^0 \gamma \) then the anomaly contribution to \( B \to \eta'X_s \) would become negligible. However, there are at least two reasons to think that \( g^* \to \eta' - g \) effective form factor is quite different from \( \gamma^* \to \pi^0 - \gamma \).

Interactions of \( \eta' \) with a gluon are likely to be significantly different from that of the \( \pi^0 \) with \( \gamma \). Specifically, for the former case the interaction does not have to proceed through a \( \bar{q}q \) loop. Given that the \( \eta' \) owes its existence to the gluons, the \( \eta' \) wave function should contain \( G \bar{G} \). The important dimensionful parameter for the \( g^*\eta'g \) form factor may not be \( f_\pi \) (or \( f_{\eta'} \sim f_\pi \)) but rather the effective gluon mass, \( m^e_{\eta'} \). Lattice calculations as well as phenomenological arguments suggest \( m^e_{\eta'} \sim 500–700 \) MeV. Since \( (m^e_{\eta'} / f_\pi)^2 \sim 16–25 \) the anomaly contribution to \( B \to \eta' + X_s \) will be significantly more than estimated by the use of the pionic form factor.

Furthermore, the \( g^*\eta'^-g \) form factor may also be greatly influenced by the presence of nearby gluonia or states rich in gluonic content. The gluon from the penguin can combine with a soft glue to make such a state which subsequently decays to \( \eta' + \) light hadrons. These states can be searched by the resonant structure in \( \eta' + \pi\pi, \eta' + K\bar{K} \cdots \) amongst the \( \eta' + X_s \) events.

6.1 \textbf{Enhanced} \( b \to sg \) \textit{via new physics}

Hou and Tseng and Kagan and Petrov suggest that the large \( B \to \eta'X_s \) signal is due to a very large branching ratio for \( b \to sg \) due to new physics:
i.e. about 100 times the SM value. It is difficult to see how such a major perturbation from new physics would not affect $B \to X_s \gamma$; after all gluon emission enters this calculation in important ways [20].

Also Ref.[5] argues that the exclusive $B \to \eta'K$ signal is OK for the SM and the inclusive is problematic. Since the inclusive/exclusive ratio is about $8 \pm 2$ and is in the same ball-park as for $(B \to \gamma X_s)/(B \to \gamma K^*) \sim$ it is difficult to appreciate their concern.

6.2 Enhanced $b \to sg^*$ in the SM

An important point to note is that $b \to sg^*$ may be significantly enhanced over the expectation of perturbation theory due especially to the possibility of enhanced FSI in the dominant decay, $b \to c\bar{c}s$.

7 Correspondence with $\psi$ decays

Examination of $\psi$ decays reveals several interesting final states which presumably result from fusion of two gluons. In general one expects these states to have $J^{PC} = 0^{++}, 0^{-+}, 2^{++} \ldots$ etc. Many of these states appear in radiative $\psi$ decays with branching ratios comparable to $\psi \to \gamma \eta'$. In particular, there appears to be a close correspondence between $G \cdot \bar{G}$ (i.e. $0^{-+}$) and $G \cdot G$ (i.e. $0^{++}$) [17]. So we should expect $f_0$, with appreciable BR’s as well.

8 Non-Standard CP

As is well known in $b \to s$ transitions, CP violation effect due to the SM are expected to be suppressed as the relevant CKM phase $\sim 0(\eta \lambda^2)$. Due to their big rates they can be powerful in searching for non-standard CP phase.

For simplicity we can assume that $b \to s$ penguin has no SM CP-odd phase, but due to the $u\bar{u}, c\bar{c}$ threshold the SM contribution possesses a CP-conserving strong phase. Non-SM interactions possessing a CP-odd phase may contribute another amplitude. Interference between the two leads to direct CP which can cause partial rate asymmetry in e.g. $B \to \eta' X_s$.

Three recent studies have examined such asymmetries. In the HT [9] and KP [5] works, the non-standard phase is assumed to be in the chromomagnetic form factor for $b \to sg$. Also, as mentioned before, they assume that the rate for $b \to sg$ is enhanced over the SM by about two orders of magnitude. In our work [17] we allow the non-standard CP-odd phase to reside in the chromo-electric or chromo-magnetic form factor. In fact the chromo-electric form factor is found to lead to larger asymmetries. Our study also showed that appreciable asymmetry (8–18%) can arise even if Non-Standard-Physics contributes only 10% to the production rate. This is especially significant as comparison of the rate between experiment and theory is extremely unlikely.
to show the presence of such a source of new physics and yet CP search can prove to be a viable thermometer. We also emphasize that there are many final states with similar asymmetries. A specially interesting mode is \( B \rightarrow K\bar{K}X \), i.e. with three kaons [17].

9 Summary

CLEO has seen signals of a rather robust QCD penguin in several exclusive channels providing new impetus for improved theoretical understanding. The observed modes so far do not seem to require (a large) intervention by new physics. Many of them are useful to search for a non-standard CP phase. Page limits forced many omissions, e.g. \( \gamma[14] \).

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