Major new experimental efforts on detecting CP violation in $B$ decays will very soon go on the air. Recent developments suggest that final state interaction phases in exclusive decays of $B$ are unlikely to be small indicating the possibility of observable direct CP asymmetries in these channels. CLEO results on charmless hadronic modes suggest penguin amplitudes are rather big implying that the extraction of $\alpha$ from $B^0-\bar{B}^0$ alone will be difficult, thus necessitating also information from direct CP. Importance of $B(B_s)$ decays to two vectors for model independent tests of electroweak penguins and for extraction of $\alpha(\gamma)$ is emphasized. Inclusive $b \to s g^*$ and related modes, e.g. $B \to \eta' X_s$, are very good probes of CP-odd phase(s) due to beyond the standard model physics. On the other hand, $b \to d g^*$ and related modes, e.g. $B \to \eta' X_d$ are more suitable for CP violation due to the CKM phase. Two body $b$-quark decays: $b \to M q_f$ leading to semi-inclusive, $B$ decays, $B \to M X$ (with $2 \lesssim_E M \lesssim 2.8$ GeV), are very interesting and important. Their theory is relatively clean; partial rate asymmetries may be large in several cases (e.g. $M = K^*, K, \rho, \pi \ldots$) and a few cases provide very good probe of electroweak penguins.

1 Introduction and Summary

Following is the outline of this talk:

I. Introduction and Summary

II. CLEO97: A robust penguin $\Rightarrow B^0-\bar{B}^0$ cannot do it alone.

III. In exclusive $B$-decays, final state rescattering phases are unlikely to be small.

IV. Repercussions of long distance rescattering for direct CP.

V. $B \to V_1 V_2$: Model independent tests for electroweak penguins and extraction of the angles of the unitarity triangle.
VI. Chasing LUCY with beauty: Search for a non-standard-phase via $b \to s g^*$, $B \to \eta' X_s$ and related modes.

VII. $b \to d g^*$, $B \to \eta' X_d$ and related modes for direct CP violation due SM.

VIII. Two body $b$ decays: $b \to q M$ for direct CP studies and for looking for electroweak penguins.

The asymmetric $B$-factories at KEK and SLAC and the symmetric one at CORNELL will begin operation in about six months. There is great degree of expectation that these will soon provide us important new clues with regard to understanding an intriguing mystery of nature—CP violation.

Although the centerpiece of the asymmetric $B$-factories is the study of mixing induced CP via measurements of time dependent asymmetries in $B^0 - \bar{B}^0$ decays, it is becoming increasingly clear that a precise determination of the angles of the unitarity triangle, essential for testing the SM, will require a broader understanding of CP violation i.e. involving extensive studies of direct CP violation dealing with charged as well as neutral $B$ mesons.

The main point is that recent observation of the charmless, hadronic, exclusive modes by CLEO strongly indicate that the size of the penguin amplitudes is appreciable. This renders the extraction of $\alpha$ or $\gamma$ through $B^0 - \bar{B}^0$ observations alone rather difficult. Subtraction of the penguin amplitudes will require study of CP asymmetries in charged $B$ decays as well.

An essential ingredient that drives direct CP violation is the final state (FS) rescattering (CP-even) phase. Reliable calculation of this phase from theory still remains and outstanding and important challenge. Some phenomenological arguments as well as indirect indications suggest that these phases may not be small at the $B$ mass. Thus sizeable direct CP violations in $B$-decays are very likely. Indeed, the FS rescattering phases in exclusive channels originate at least in part due to soft-physics (i.e. non-perturbative effects) and can lead to a different pattern of CP asymmetries than hitherto envisioned to emerge from short distance operators. In exclusive modes (such as $K\pi$) appreciable asymmetries are plausible.

Direct CP measurements in some of the exclusive channels are not entirely in vain insofar as determination of the unitarity angle goes. For example, measurements in the $K\pi$ can be used for quantitatively testing for the presence of electroweak penguins (EWP). If EWP contributions to $K\pi$ are found to be negligible then $B^0, \bar{B}^0, B^\pm \to K\pi$ studies can be used to determine $\alpha$.

$B, B_s$ decays to two vector mesons can be especially useful in this context. Angular distribution of the decay of the vector mesons provide information on polarization of the vector mesons. Model independent tests can be constructed
to monitor the presence of EWP. Modes that show negligible contribution from EWP can then be used to extract $\alpha$ and $\gamma$.

Inclusive $b \to s$ transitions are a very good probe for non-standard CP violation phases. Of particular interest is $b \to sq^*$ since it has $Br \sim 1\%$. However, as such this mode is very difficult to detect. CLEO has recently reported a large signal for $B \to \eta' X_s$. Experimental data, to date, supports the interpretation that an appreciable fraction of the signal comes from $g^* \to g\eta'$ through the anomalous coupling of the $\eta'$ to the two gluons. Consequently $B \to \eta' X_s$ becomes a good search for the non-standard-phase (NSP). It may be useful to extend the search to other expected fragments ($X_g$) of $g^* \to X_g g$. Good examples of $X_g$ (in addition to $\eta'$) are $\eta(1440)$, $f_0(980)$, $f_2(1270)$, $K^+ K^-$, $\pi^+ \pi^-$...

The penguin transition $b \to d$ on interference with the tree contribution $b \to u \bar{u} d$ is likely to be a good way to detect direct CP violation from the SM. The modes of interest here are completely analogous to those in the previous paragraph except for the replacement of $X_s \to X_d$.

The last topic to be emphasized in this talk is two body decays of the $b$ quark: $b \to Mq_f$ where $M$ is spin 0 or 1 meson. These decays lead to semi-inclusive $B$ decays. Theory for these should be cleaner than exclusive decays such as $B \to K\pi$, $\rho\pi\ldots$ and their experimental signatures are rather distinctive. Many of the modes could have large partial rate asymmetries (PRA). Two of the modes $B \to \rho^0 X_s$ and $\pi^0 X_s$ are also a good way to look for EWP as the latter dominate over other contributions.

2 CLEO97: A Robust Penguin $\Rightarrow B^0-\bar{B^0}$ Cannot do it Alone

After years of anticipation, in 1997, CLEO reported the first observation of some charmless, hadronic decay modes; both exclusive and inclusive. For our purpose, the most interesting examples of these two categories are

\[ Br(B \to K^+\pi^-) = (1.5 \pm .5 \pm .1) \times 10^{-5} \]  
(1)

\[ Br(B \to \eta' X_s) = (6.2 \pm 1.6(stat) \pm 1.3(syst)_{-0.9}^{+0.0}(bkg)) \times 10^{-4} \]  
(2)

In addition, CLEO has reported lack of a statistically significant signal in the $\pi\pi$ mode:

\[ Br(B \to \pi^+\pi^-) \leq (1.5 \times 10^{-5}) @90\%CL \]  
(3)

A simple way to understand (1) and (3) is to assume that the $\pi\pi$ mode is dominated by tree. Due to the Cabibbo angle, the tree contribution to $K\pi$
must therefore be extremely small compared to (1). Thus $B \to K\pi$ with the stated $Br$ is dominated by the penguin. Also the penguin contribution to $\pi\pi \sim |V_{td}|^2 * 1.5 \times 10^{-5}/|V_{ts}|^2 \sim 10^{-6}$, assuming $|V_{td}/V_{ts}| \sim \lambda \sim .22$, which is quite consistent with the existing constraints. Thus the amplitude ratio of tree vs penguin for $\pi\pi$ is about:

$$P_{\pi\pi}^{T}\pi\pi \gtrsim .25$$ (4)

Therefore, for a precision determination of the unitarity angle $\alpha$, it does not appear safe to ignore the penguin contribution to $\pi\pi$. Assuming EWP contribution is negligible, extraction of $\alpha$ from $B \to \pi\pi$ is still possible but it requires observation of direct CP i.e. partial rate asymmetry (PRA) measurements in the $B^\pm$ will also be needed. In addition, the $Br$ for $\pi^0\pi^0$, likely to be quite small, will also be required.

In fact CLEO measurements (1) and (3) and the resultant $P_{\pi\pi}/T_{\pi\pi}$ also means that the penguin contribution for $B_s \to \rho K_s$ is likely to be very large. Indeed, since the tree is then color suppressed it seems the penguin over tree ratio for $B_s \to \rho K_s$:

$$\frac{P(B_s \to \rho K_s)}{T(B_s \to \rho K_s)} \sim 0(1)$$ (5)

Thus this “text-book example” for extracting $\gamma$ will also become very difficult to implement even when the study of $B_s-\bar{B}_s$ oscillations become an experimental reality.

Thus the first CLEO results on charmless $B$-decays are indicating that studies of $B^0-\bar{B}^0$ for the extraction of angles ($\alpha$ and $\gamma$) of the unitarity triangle are unlikely to suffice; information from direct CP in $B^\pm$ decays is also likely to play an important role. Interestingly there are good reasons to suspect that direct CP asymmetries in many exclusive modes may be appreciably large.

3 In Exclusive $B$-Decays Final State Rescattering Phases are Unlikely to be Small.

From the outset let us emphasize that a reliable methodology for calculating final state phases is not available. So, any conclusions about final state rescattering phases we arrive at will suffer from that drawback. Despite that reservation, it is still perhaps useful to point out that there are several reasons to suspect that final states rescattering phases in exclusive decays of $B$ are unlikely to be negligibly small:

4
1. A long standing problem in $B$-decays is that the measured value of the semi-leptonic branching ratio is a bit (about 10%) less than the number predicted by theory. Most likely this difference between the two numbers originates from the error in the theoretical calculation of the hadronic $B$-width. It is quite possible that value of the total hadronic width calculated by using short distance perturbation theory is missing a contribution due to soft physics or non-perturbative effects.

2. The $B$-baryon lifetime is significantly different from that of $B$-mesons. Short-distance perturbation theory and/or heavy quark effective field theory apparatus is unable to account for such a difference. Most likely this originates from spectator quark interactions which are strongly intertwined with FS interactions.

3. There is a surprising reversal of trend as one goes from $D$ to $B$ decays. For $D$'s one has

$$\Gamma(D^0 \to K\pi)/\Gamma(D^+ \to K\pi) > 1.$$  \hspace{1cm} (6)

In contrast, for the $B$'s one finds

$$\Gamma(B^0 \to D\pi)/\Gamma(B^+ \to D\pi) < 1.$$  \hspace{1cm} (7)

4. Donoghue et al. have recently examined the dependence of the FS rescattering phases on the mass of the decaying $b$-quark; specifically they deal with the case of the $B \to K\pi$ mode. Assuming that the total cross-section for $K\pi$ obeys the same scaling laws as that for the other total hadronic cross sections, and using the optical theorem they show that the effects of elastic rescattering do not diminish as $m_B$ gets larger. In fact Donoghue et al. claim that the effect of inelastic channels is even much bigger than the elastic one leading them to the conclusion that FS rescattering phases are unlikely to disappear at $m_B$.

So, while a compelling theoretical argument is not available, it is quite plausible that final state rescattering phases in exclusive modes are appreciable; final word on the subject will have to come from experiment.

4 Repercussions of Long Distance Rescattering for Direct CP in Exclusive Modes
4.1 Possibility of Large Direct CP in Exclusive Modes such as \( K\pi \)

FS phases due to long distance (LD) rescattering endow direct CP in exclusive modes a rich structure as can be understood by the use of the CPT theorem. Recall that the theorem requires that the total lifetime of \( B \) and \( \bar{B} \) to be exactly equal whereas CP symmetry requires the partial widths of \( B \) and \( \bar{B} \) into conjugate modes to be equal. As a result, when the CP violating partial width difference (PWD) for all the different modes are added up there has to be an exact cancellation to render the equality of the lifetimes. Furthermore, assuming isospin is exactly conserved by the strong interactions, the final states with different isospins cannot participate in the cancellation of PWD.

If multiparticle inelastic channels composed of light quarks make important contributions to the rescattering phases of FS such as \( \pi\pi, K^*\pi \) etc. then the PWD in these FS must cancel against the PWD occurring amongst those multiparticle states responsible for the phase difference, as required by the CPT theorem. In other words, the cancellation of the PWD for FS such as \( \pi\pi, K^*\pi \) etc. need not and will not occur with hadrons containing \( c, \bar{c} \) (i.e. \( D^*\bar{D}, DD\bar{s} \) etc.) in the FS. The latter has to be the case if rescattering phases were all of short distance (SD) origin coming from the penguin operators.

For FS such as \( K\pi, \pi\pi \ldots \) wherein the two mesons each have a non-vanishing isospin an interesting and important possibility for CP violation arises due to the rescattering effects caused by soft physics. For illustration, let us focus on \( K\pi \). Then one way that CPT maintenance can occur in the presence of nonvanishing PRA’s in the channel is for the PWD in the two possible modes of \( B^- (B^0) \) to cancel against each other so that

\[
\delta(K^-\pi^0) = -\delta(K^0\pi^-) = \delta(K^0\pi^0) = -\delta(K^-\pi^+) \tag{8}
\]

where \( \delta \)'s denote the PWDs:

\[
\delta(K^-\pi^0) \equiv \Gamma(B^- \to K^-\pi^0) - \Gamma(B^+ \to K^+\pi^0) \tag{9}
\]

etc. A simple calculation then gives

\[
\delta(K^-\pi^0) = 2\sqrt{2}|V_u||V_c||A||D|\sin\gamma\sin\Phi \tag{10}
\]

where \( V_u = V_{ub}V_{us}^* \), \( V_c = V_{cb}V_{cs}^* \), \( A \) is the \( \Delta I = 1/2 \) penguin amplitude for \( b \to s \), \( D \) is the \( \Delta I = 3/2 \) tree amplitude, \( \Phi \) is the strong rescattering phase, \( \Phi = \arg(DA^*) \) and \( \gamma = \arg(-V_{ub}^* ) \) is the CP-odd weak phase. The corresponding PRAs in these channels become\[\[\text{etc.}\]
\[ PRA(K^-\pi^0) = PRA(\bar{K}^0\pi^0) = -2PRA(\bar{K}^0\pi^-) = -2PRA(K^-\pi^+) = \sqrt{2}r \sin \gamma \sin \Phi \] (11)

where \( r = T_{K\pi}/P_{K\pi} \) for the tree versus penguin amplitudes for \( K\pi \). Setting \( \sin \gamma = \sin \Phi = 1 \) for maximal phases:

\[ PRA(K^-\pi^0)|_{\text{max}} = PRA(\bar{K}^0\pi^0)|_{\text{max}} = -2PRA(\bar{K}^0\pi^-)|_{\text{max}} = -2PRA(K^-\pi^+)|_{\text{max}} = \sqrt{2}r \] (12)

Assuming \( r \sim 3 \), the PRA in \( K^-\pi^0 \) and \( \bar{K}^0\pi^0 \) modes can be \( \sim 42\% \) whereas that in \( \bar{K}^0\pi^- \) and \( K^-\pi^+ \) is \( \sim 21\% \) (with the opposite sign).

We thus see that FS rescattering phases can cause appreciable direct CP violating PRAs in exclusive modes such as \( K\pi \).

4.2 Model Independent Test for EWP and/or New Physics in \( K\pi \)

Many studies of EWP exist by now. However, in their numerical estimates these studies invoke many model dependent assumptions and approximations. Model independent assessment of EWP contributions are essential for possible application of these modes for extraction of the unitarity angles and/or for the search for new physics.

Assuming isospin conservation and making no additional assumptions or approximations allows us to arrive at a sum rule:

\[ 2|m_1|^2 - |m_2|^2 - |m_3|^2 + 2|m_4|^2 = 2|\tilde{m}_1|^2 - |\tilde{m}_2|^2 - |\tilde{m}_3|^2 + 2|\tilde{m}_4|^2 \] (13)

where \( m_1, m_2, m_3, m_4 \) are the amplitudes for \( B \) decays to \( K^+\pi^0, K^0\pi^+, K^+\pi^- \) and \( K^0\pi^0 \) respectively.

A violation of this sum rule will be a model independent test for EWP. If, on the other hand, such a model independent test shows that EWP contribution is negligible, then the direct CP measurements in the \( K\pi \) modes would also become very useful for the extraction of the angle \( \alpha \) via a quadrangle construction involving the four modes of \( (B^+, \bar{B}^0) \) and \( (B^-, B^0) \) each. However, deducing the weak phase \( \alpha \) through this construction also requires, in addition, time dependent oscillation studies of \( (B^0, \bar{B}^0) \) to a self-conjugate final state, i.e. \( K^0\pi^0 \).
4.3 Decays to Two Vectors: Extraction of $\alpha, \gamma$ and search for EWP

The decays $B, B_s \to 2$ vector final states can be especially useful for determining the angles of the unitarity triangle, for model independent tests of EWP and for the search for new physics. For our method to work requires modes in which penguin and the tree are both contributing. Specifically, the final states need satisfy the following two conditions:

1. At least two decay amplitudes related by isospins must be involved.
2. The QCD penguin Hamiltonian must contribute only one isospin amplitude to the FS.

Some illustrative examples are $B \to K^*\omega, K^*\rho, \rho\omega$ and $B_s \to K^*\bar{K}^*$ and $K^*\rho$. The method provides a model independent test (see below) for EWP. Among the $B(B_s)$ modes mentioned above, those that are least affected by EWP can be used for the extraction of $\alpha(\gamma)$.

Once conditions (1) and (2) above are satisfied $B^-, \bar{B}^0$ decays to a given FS can be used to write down a linear combination of the amplitudes that contains only the phase of the tree. As in the previous $K\pi$ case, to extract the weak phase $\alpha$ or $\gamma$, though, time dependent oscillation studies of $B^0, \bar{B}^0$ to the corresponding self conjugate FS are needed.

Another important ingredient in this study is the correlations between the decay distributions of the two vector particles, or equivalently the correlations of their polarizations.

Extraction of the information about the CKM phases proceeds along the following key steps:

1. Following Gronau and London, isolate a linear combination $(c_1u^h_1 + c_2u^h_2)\bar{c}$ which contains only the weak phase of the tree. Here $u^h_1$ and $u^h_2$ are the corresponding amplitudes for $B^-$ and $\bar{B}^0$ decays; the superscript $h = 1, 0, +1$ denotes the helicity of the vector particles. This combination of the amplitude and its CP conjugate will be related as follows:

\[
(c_1u^h_1 + c_2u^h_2)e^{-i\delta_T} = (c_1\bar{u}^h_1 + c_2\bar{u}^h_2)e^{i\delta_T} \tag{14}
\]

where $\delta_T$ is the weak phase of the tree.

2. Angular distributions of the decay products of the two vector particles is used to obtain the magnitudes of the helicity amplitudes and the phases between the pairs of helicity amplitudes.
3. Since the phase differences between different helicities for the same FS can be obtained from the angular distributions, the set of three equations (one for each helicity) can now be regarded as a set of three linear equations for the four remaining undetermined phases, i.e. one phase for each of the two modes and two conjugate modes. If there is no EWP contamination, the equations will have a solution where the phases are unimodular as expected. On the other hand, if such a solution cannot be found, it implies that eqn. (14) fails so EWP contamination or a new physics contribution is present. This test of EWP is completely model independent and is based only on isospin conservation.

4. Finally, as mentioned before, a time-dependent oscillation study of $B^0$-$\bar{B}^0$ to the corresponding self-conjugate FS needs to be done to fix the relative phase between the $B^0$ and the $\bar{B}^0$. This enables the phases between all pairs of amplitudes to become known so that the weak phase of the tree can thus be retrieved.

For $B \to K^*\omega$ the method should work especially well since the color allowed EWP contribution, (resulting in $\gamma$, $Z \to \omega$), carries the same weak phase as the strong penguin. Therefore, the extraction of $\alpha$ is rather clean, suffering only from the contamination of a color-suppressed EWP contribution which will most likely be sub-dominant. In any case, the tests for EWP mentioned above should be able to quantitatively monitor the extent of the contamination.

For $B \to K^*\rho$, since $\bar{B}^0 \to \bar{K}^{*0}\rho^0$ is susceptible to EWP contamination a slightly more involved strategy which uses all four of the $K^*\rho$ modes but does allow a determination of $\alpha$.

Two other vector modes that may be usable for $\alpha$ extraction are $B \to \rho\omega$ and $B \to \rho\phi$. For $B \to \rho\omega$ to work, it will need to be demonstrated that EWP contamination is small as $B^0 \to \rho^0\omega$ receives color allowed EWP contribution from $\gamma$, $Z \to \rho^0\omega$ For $B \to \rho\phi$, EWP contribution is not expected to be a problem; however, its $Br$ is likely to be 0(10$^{-6}$) whereas for $K^*\omega$, $K^*\rho$ and $\rho\omega$ the $Br$’s are likely to be 0(10$^{-5}$).

The method can also be extended to determine $\gamma$ via $B_s \to K^*\rho$ and $K^*K^*$.

5 Chasing LUCY With Beauty: Search for a NSP Via $b \to sg^*$, $B \to \eta'X_s$ and Related Modes.

There are good reasons to think that in addition to the CKM phase of the SM, other CP violation phase(s) exist in nature. For one thing, it appears
difficult to account for baryon asymmetry in the universe with the CKM phase. Besides, extensions of the SM with new scalars, fermions or gauge bosons almost invariably entail new phase(s). [LUCY is a generic name for a non-standard phase (NSP)]. With the advent of $B$-factories it is imperative to ask, how best can $B$-physics be used to search for a NSP.

For a variety of reasons the penguin transition, $b \to s g^*$ (where $g^*$ is an on or off-shell gluon) is a highly suitable probe of LUCY. In inclusive processes the SM-CKM phase is likely to make only a negligible contribution, so non-standard CP violating effects may not get masked that easily. The fairly large $\text{Br} \sim 1-2\%$ can be very helpful. However a completely inclusive search for $b \to s g^*$ is rather difficult.

CLEO experimentalists have recently provided an ingenious clue for harnessing an appreciable fraction of the $b \to s g^*$ signal. We are referring here to an observation of an unexpectedly large inclusive signal of $\eta'$:

$$\text{Br}(B \to \eta' X_s) = [6.2 \pm 1.6(\text{stat}) \pm 1.3(\text{syst})^{+0.0}_{-1.5}(\text{bkg})] \times 10^{-4}$$

(15)

for $2.0 < P_{\eta'} < 2.7$ GeV. The magnitude of this signal is about a factor of 5 bigger than estimates based on the SD Hamiltonian. Of course, since the experimental discovery was first reported a lot of theoretical effort has gone into understanding its origin. An interesting suggestion is that an appreciable fraction of the $\eta'$ signal originates from the coupling of the $\eta'$ to two gluons via the QCD anomaly (see Fig. 1). Recall that this anomalous coupling of the $\eta'$ distinguishes the singlet $\eta'$ from the flavored octet of pseudo-goldstone bosons and renders it heavier than the other members of the octet. The point is that the singlet axial current receives a contribution from the gauge sector:

$$\partial_{\mu} j_{5}^{\mu} = \frac{3\alpha_s}{4\pi} G_{\mu\nu} \tilde{G}^{\mu\nu} + 2i \sum_{q = uds} m_q \gamma^5 q$$

(16)

Needless to say, quantitative estimates of this (or other) contributions to the signal for $\eta' X_s$ is very difficult. To begin with, the mechanism was found to be roughly able to account for the observed signal if one assumes that the $g^* - \eta' - g$ form factor stays approximately constant with $q^2$ over the relevant range, $q^2$ being the 4-momentum of $g^*$. Since then further study by CLEO of the recoil mass distribution seems to give some additional support to the anomaly idea.

It should be emphasized that the $g^* - \eta' - g$ form factor introduces appreciable uncertainty into this calculation; the off-shell gluon ($g^*$) carries a non-vanishing $q^2$, perhaps 0(a few GeV$^2$). There is no good reason to think
that this form factor would be the same as the \( \gamma^* - \pi^0 - \gamma \) one, wherein it goes as \( 4\pi^2 f^2_\pi / q^2 \), with \( f_\pi = 130 \) MeV. For the gluonic-rich \( \eta' \), the analogous form factor may involve a larger dimensionful parameter than \( f_\pi \) e.g. constituent quark mass and/or an effective gluon or glueball mass.

This mechanism (see Fig. 1) is especially significant for searches for CP violation\(^{10,11}\). The key point is that the underlying fragmentation process, \( g^* \to g\eta' \) renders the Feynman amplitude for \( b \to s\eta' g \) for the inclusive \( B \to \eta' X_s \) signal develop an imaginary part at the one loop. This (CP-even) absorptive part is essential in driving observable CP violating asymmetries. This is an interesting and perhaps an important difference between \( b \to s\gamma \) as, in perturbation theory, the latter cannot develop a strong phase at one-loop.

In the SM, though, as already mentioned the \( b \to s\eta' g \) amplitude receives only a negligible CP-odd phase. Therefore detection of a largish CP asymmetry in this channel may be an indication for a non-standard source of CP violation.

For simplicity, we assume that the CKM phase in \( b \to s \) penguin amplitude is negligible. The \( b \to sg^* \) effective vertex can be parameterized as\(^{10,14}\) (see. Fig. 2)

\[
\Lambda_{bsg}^{\mu} = (c_t G_F / \sqrt{2}) \bar{s}_i T_{ij}^{\alpha} [-i F(q^2) (q^2 q_\mu - q_\mu q) L]
\]
Figure 2: The contributions of non-standard physics to $b \rightarrow s g^*$ followed by $g^* \rightarrow g + \eta'$, $f_0$, $f_2$ or other such states. The non-standard process is indicated by the hexagon.

$$+(g_s/2\pi^2)m_bq_\mu\sigma^{\mu\nu}G(q^2)R[j]$$

Here

$$F(q^2) = e^{i\delta_{st}}F_{SM} + e^{i\lambda_F} F_x$$
$$G(q^2) = G_{SM} + e^{i\lambda_G} G_x$$

where $\delta_{st}$ is the strong phase generated by the absorptive part resulting form the $c\bar{c}$ cut for $q^2 > 4m_c^2$. To keep the discussion completely general we have introduced $\lambda_F$ and $\lambda_G$ as the CP-odd non-standard phases in the chromo-electric and chromo-magnetic form factors.

Although the inclusive $\eta'$ signal is rather large, it is only about 5% of the total $b \rightarrow s g^*$. Besides, the $\eta'$ detection efficiency is very low; at CLEO it is only about 5% for the inclusive signal. It is, therefore, useful to ask, if the fragmentation reaction, $g^* \rightarrow gg'$ can lead to some other particle(s) in addition to the $\eta'$, an appreciable fraction of the time.

Clearly the possible states that couple to two gluons have to have $J^{PC} = 0^{-+}$, $0^{++}$ and $2^{++}$. Some interesting examples are:

$$0^{-+} : \eta(958), \eta'(1440) \ldots$$
$$0^{++} : f_0(980), f_0(1370) \ldots$$
$$2^{++} : f_2(1270), f_2(1525) \ldots$$

Continuum : $\pi\pi, K\bar{K}, K\bar{K}\pi \ldots$
One can also arrive at these candidate states by looking at final states in radiative decays of the $\psi$.

There are a couple of additional points worth keeping in mind:

1. At least in the case of $\psi$ decays there appears to be a close similarity between the states $(0^{-}+)$ coupling to $G \cdot \tilde{G}$ versus those $(0^{++})$ coupling to $G \cdot G$:

   \begin{align*}
   Br(\psi \to \phi \eta'(958)) &= (3.3 \pm .4) \times 10^{-4} \\
   Br(\psi \to \phi f_0(980)) &= (3.2 \pm .9) \times 10^{-4} \\
   Br(\psi \to \omega \eta') &= (1.67 \pm .25) \times 10^{-4} \\
   Br(\psi \to \omega f_0) &= (1.4 \pm .5) \times 10^{-4}
   \end{align*}

2. Inspection of $\psi$ decays also seems to show that the signal for the $\eta(1440)$ may be comparable to that for the $\eta'$.

3. A particularly interesting continuum of states is $K \bar{K}$ as it leads to the overall signal of $B \to K \bar{K} + X_s$ (or $B \to K \bar{K} + X_d$) which may be quite distinctive. Once again, inspection of $\psi$ decays suggests that the ratio of $Br$'s: $(g^* \to K \bar{K} + g)/(g^* \to \eta' + g)$ could be around one or even somewhat bigger.

Calculation of the PRA proceeds along well known lines. Fig. 3(a) and 3(b) show the PRA as a function of the recoil mass ($m_{rec}$) for states of different $J^{PC}$. Fig. 3(a) is the case when beyond the SM (BSM) physics contributes only 10% to the production rate and Fig. 3(b) is assuming that 50% of the rate is due to new physics. In both figures we have set the CP-odd NSP to be maximal (i.e. $\lambda_F, \lambda_G = \pi/2$). These figures also show separately the cases when the chromoelectric form factor dominates (and the chromomagnetic is zero) and vice-versa. We see that PRA tend to be bigger (by 50–100%) for the case when chromoelectric dominates. Notice that the asymmetries are $\sim 12–34\%$ in Fig. 3(b) and in Fig. 3(a), which is for the case when NSP is contributing only 10% to the rate, the asymmetries are still appreciable $\sim 8–17\%$. This is quite remarkable as it would be virtually impossible to detect the presence of the new physics, if BSM physics contributes only 10% to the rate, by comparison of the measured rate with theoretical expectation as the rate calculations are extremely unreliable. Search for CP violation can clearly be extremely worthwhile and decisive.
Figure 3: (a) $|\text{PRA}|$ versus $m_{\text{rec}}$ assuming non-standard physics (NSP) contributes $\sim 10\%$ to the rate for each state. Also, $\sin \lambda_F = \sin \lambda_G = 1$ is used. The black shading shows the $|\text{PRA}|$ for $b \to s + g + 0^{-+}$ assuming that $F_x = 0$ and taking $m_{0^{-+}}$ to vary from 958 MeV to 1725 MeV. The horizontal striped region is the $|\text{PRA}|$ for the same $0^{-+}$ states, now assuming that $G_x = 0$. Note that the region indicated by the diagonal stripes shows the $|\text{PRA}|$ for $b \to s + g + 0^{++}$ assuming that $F_x = 0$ with $m_{0^{++}}$ ranging from 980 MeV to 1710 MeV; the dotted region is the $|\text{PRA}|$ for the $0^{++}$ assuming that $G_x = 0$. (b) $|\text{PRA}|$ versus $m_{\text{rec}}$ assuming NSP contributes $\sim 50\%$ to the rate for each state. The black shading ($F_x = 0$) and the horizontal striped ($G_x = 0$) are for $0^{-+}$ states as in Fig. 3(a). Diagonal striped ($F_x = 0$) and the dotted ($G_x = 0$) regions are now for $b \to s + g + 2^{++}$ with $m_{2^{++}}$ from 1270 to 2300 MeV. See also caption to Fig. 3(a).
6  \( b \rightarrow dg^* \), \( B \rightarrow \eta'X_d \) and Related Modes for Direct CP violation due SM

The penguin \( b \rightarrow d \) transition interfering with the tree \( b \rightarrow u\bar{u}d \) can be a rich source of direct CP violation due to the SM-CKM phase. Specifically it is important to try to use \( b \rightarrow dg^* \). Once again \( g^* \rightarrow g\eta' \) and other fragments discussed in the preceding section can be used. While the \( Br \) for \( B \rightarrow \eta'X_d \) is expected to be somewhat smaller (\( \sim 7 \times 10^{-5} \)) than \( B \rightarrow \eta'X_s \), the PRA driven by the CKM phase are expected to be appreciably bigger for the \( B \rightarrow \eta'X_d \) case compared to that for \( B \rightarrow \eta'X_s \). For values of the CKM matrix which match current constraints, PRA \( \sim O(12\%) \) for \( B \rightarrow \eta'X_d \). The asymmetries for \( B \rightarrow \eta(1440) \pm X_d \), \( f_0(980) + X_d \), and \( f_2(1270) + X_d \) are quite similar but somewhat bigger.

7  Two Body Decays: \( b \rightarrow qM \) for Direct CP Studies and for Looking for EWP

The importance of the two body decays of the \( b \)-quark is due to the fact that their theory is relatively simpler and many of them have relatively clean experimental signatures. To the extent that the spectator approximation works, these 2-body decays at the quark level end up materializing in quasi-two-body (QS2B) decays of the \( B \)-meson. Indeed, a famous recent example is \( B \rightarrow \eta'X_s \) although from the point of view of the theory, the \( \eta' \) case is somewhat of a special one due to the unique relation of the \( \eta' \) to the QCD anomaly. As far as experimental detection goes, the inclusive \( \eta' \) does serve an excellent example for the semi-inclusive decays \( B \rightarrow MX \) that are under discussion in this section. As in the case for the \( \eta' \), the meson \( M \) originating from the 2-body decay \( b \rightarrow Mg_f \) tends to obey two body kinematics and therefore has \( E_M \sim 2.5 \pm 0.3 \) GeV. The quark \( g_f \) leads to the debris of mesons with (1) relatively low average multiplicity \( \sim 3 \), (2) total energy \( \sim 2 \pm 0.3 \) GeV and (3) with negligible total transverse momentum (to \( \vec{p}_M \) in the rest frame of \( B \)).

Theoretical calculation for the QS2B decays are simpler than the traditional exclusive mode such as \( B \rightarrow K\pi, \rho\pi \ldots \) A key difference is that the latter reactions require knowledge of exclusive form factors, e.g. \( \langle B|J_1^0|\rho \rangle \) or \( \langle B|J_2^0|K \rangle \ldots \) where \( J \)'s are the appropriate quark level currents. The QS2B reactions bypass the need for these form factors as they represent a sum over the exclusive channels. Indeed, as a rule, the \( Br \) for the QS2B tends to be bigger compared to the exclusive two body modes, in some cases by factors of \( \sim 5-10 \). In instances where the formation of \( M \) via the QS2B reactions is color suppressed whereas \( M \) can be made in a color allowed manner with the participation of the spectator for the corresponding exclusive two body mesons
reactions, then the latter can have a bigger $Br$ compared to the QS2B. This may well, for example, be the case for $B^\pm \to \omega \rho^\pm$ versus $b \to \omega d$.

For these QS2B decays the CP-even FS interaction phase needed for generating the CP violating PRAs arises from the penguin Hamiltonian. Indeed since these are semi-inclusive reactions the calculations of the FS phase originating from the absorptive part of the penguin graph is close in spirit to the original quark level calculation\footnote{23}. It is quite likely that the FS rescattering effects due to LD or soft (non-perturbative) physics are much smaller in these inclusive processes than in the corresponding exclusive channels\footnote{5}.

A quick look at the Table shows that the PRA may be quite large in several channels\footnote{15, 29}, e.g. $M = K^*, K, \rho, \pi \ldots$ Also given in the Table is $N_B^{3\sigma}$, the number of $B$ mesons needed to obtain a $3 - \sigma$ signal for the PRA, as well as an estimate of the EWP contribution. While it would be interesting and important to search for these PRA it would be very worthwhile even if the $Br$’s of some of these channels are measured. The resulting input from experiment could be valuable in fine tuning the calculational parameters of this whole class of reactions. In this context, it is also worth noticing that the recoil spectrum (see Fig. 4) for these reactions can be calculated in much the same way as for the $B \to \gamma X$\footnote{30} (or $B \to \eta X$\footnote{14}). This means that the input parameters for the recoil spectrum can be refined by using data from all of these reactions.

Figure 4: The normalized recoil spectra for the quasi-twobody decays, $b \to \pi^- u$ (solid), $K^*- u$ (dashed) and $D^- c$ (dotted) are shown.
Table 1: Some modes of interest; $Br$, PRA and $N_{B}^{3σ}$ along with EWP contributions (to color allowed channels only) are shown. Note $γ ≡ \arg(-V_{ub}^{*}V_{ud}/V_{cb}^{*}V_{cd})$. Note that the $Br$ column does not include contributions from EWP.

| Mode  | $Br$  | $|\text{PRA}|/\sin γ (%)$ | $N_{B}^{3σ} \sin^2 \gamma \xi_{eff}/10^6 \text{ Br due to EWP}$ |
|-------|-------|---------------------------|--------------------------------------------------|
| $\pi^- u$ | $1.3 \times 10^{-4}$ | 8 | 12 | 4.7 $\times 10^{-8}$ |
| $\rho^- u$ | $3.5 \times 10^{-4}$ | 8 | 4 | 7.0 $\times 10^{-9}$ |
| $\pi^0 d$ | $2.4 \times 10^{-6}$ | 36 | 28 | 7.0 $\times 10^{-9}$ |
| $\rho^0 d$ | $5.9 \times 10^{-6}$ | 38 | 10 | 7.0 $\times 10^{-9}$ |
| $ω d$ | $5.8 \times 10^{-6}$ | 39 | 10 | 7.0 $\times 10^{-9}$ |
| φd | $2.3 \times 10^{-7}$ | 0 | 4 | 7.0 $\times 10^{-9}$ |
| $K^0 s$ | $2.5 \times 10^{-6}$ | 5 | 1200 | 4.7 $\times 10^{-8}$ |
| $K^0 s$ | $2.9 \times 10^{-6}$ | 16 | 120 | 7.0 $\times 10^{-9}$ |
| $D^- c$ | $1.7 \times 10^{-3}$ | 2 | 17 | 4.7 $\times 10^{-7}$ |
| $D^*^- c$ | $2.2 \times 10^{-3}$ | 2 | 13 | 4.7 $\times 10^{-7}$ |
| $K^- u$ | $2.9 \times 10^{-5}$ | 33 | 3 | 4.7 $\times 10^{-7}$ |
| $K^*- u$ | $5.1 \times 10^{-5}$ | 51 | 1 | 4.7 $\times 10^{-7}$ |
| $K^0 d$ | $2.0 \times 10^{-5}$ | 1 | 3000 | 4.7 $\times 10^{-7}$ |
| $K^0 d$ | $2.6 \times 10^{-5}$ | 3 | 540 | 1.6 $\times 10^{-6}$ |
| $\pi^0 s$ | $9.8 \times 10^{-8}$ | 0 | | 4.7 $\times 10^{-7}$ |
| $\rho^0 s$ | $2.5 \times 10^{-7}$ | 0 | | 4.7 $\times 10^{-7}$ |
| $ω s$ | $1.3 \times 10^{-6}$ | 0 | | 1.6 $\times 10^{-6}$ |
| φs | $6.3 \times 10^{-5}$ | 0 | 4.7 $\times 10^{-7}$ | 4.7 $\times 10^{-7}$ |
| $D^- c$ | $4.2 \times 10^{-2}$ | 0.1 | 300 | 4.7 $\times 10^{-7}$ |
| $D^*_-- c$ | $5.3 \times 10^{-2}$ | 0 | | 1.6 $\times 10^{-6}$ |

Finally, we draw attention to the fact that $B^0 \rightarrow \rho^0 X_s$ and $B^0 \rightarrow π^0 X_s$ appear highly suited for searching for EWP. This can be qualitatively understood as the EWP contributions are color allowed whereas the others are color suppressed. The EWP contribution from the tree graph is also CKM suppressed. The EWP appears to be the dominant contributor with $Br(B^0 \rightarrow ρ^0 X_s) \sim 4 \times 10^{-6}$ and $Br(B^0 \rightarrow π^0 X_s) \sim 2 \times 10^{-6}$. The same comments may also be true for the related reactions, $B^+ \rightarrow ρ^0 X_s$, $B^+ \rightarrow π^0 X_s$, except that in this case there is a possible background from the tree process $\bar{b} \rightarrow \bar{u} \bar{u} \bar{s}$ wherein the $\bar{u}$ can combine with the spectator to form the $ρ^0$ or $π^0$ in a color allowed manner. Although most of the background from the tree process would be expected to give rise to lower momentum $ρ^0$ or $π^0$, one can estimate that the high momentum component of the $ρ^0$ or $π^0$ energy spectrum can produce a
signal comparable to the EWP contribution.

Acknowledgements

We are grateful to the organizers of the International Workshop, and especially to George Hou, for the very warm and gracious hospitality. This research was supported in part by US DOE Contract Nos. DE-FG01-94ER40817 (ISU) and DE-AC02-98CH10886 (BNL).

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