Desperately Seeking Non-Standard Phases via Direct CP Violation in $b \to sg^*$ Process

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Abstract: Attributing the recent CLEO discovery of $B \to \eta' + X_g$ to originate (primarily) from the fragmentation of an off-shell gluon ($g^*$) via $b \to s + g^*$, $g^* \to g + \eta'$, we emphasize that many such states ($X_g$) should materialize. Indeed the hadronic fragments ($X_g$) of $g^*$ states are closely related to those seen in $\psi \to \gamma(\phi, \omega) + X_g$. A particular final state of considerable interest is $X_g = K^+K^-$. Signals from such states in $B$ decays can be combined to provide a very sensitive search for CP violating phase(s) from non-standard physics. The method should work even if the contribution of these source(s) to the rates is rather small ($\sim 10\%$) to the point that a comparison between theory and experiment may find it extremely difficult to reveal the presence of such a new physics.

Rather compelling theoretical arguments suggest the existence of CP violation phase(s) originating from physics beyond the Standard Model (SM). For one thing it is extremely difficult to understand baryogenesis in the SM whereas it becomes quite plausible in many of its extensions\cite{1}. Of course existence of the three quark families endows the SM its CKM phase\cite{2} and, as a rule, it requires some degree of contrived physics to get rid of this phase.

But, new physics, whether it involves extra Higgs, fermions and/or gauge bosons, rather naturally entails additional CP violating phases. Therefore, on quite general grounds, we should expect non-standard phase(s) in addition to the CKM phase of the SM. It is clearly very important then, to search for these phase(s).

In $B$-physics significant CP violating asymmetries are expected to occur in many processes. In $b \to s$ transitions, however, such asymmetries will
be small as in the standard Wolfenstein representation\[3, 4\] this phase is manifestly small (0(ηλ^2)). Thus looking for CP violation in b → s transitions can be a powerful method to look for CP violation from non-standard phases(s)\[5\]. In particular, since b → sg^* has a rather hefty branching ratio\[6\] (1–2%) it would be very helpful if this class of modes could be used towards that goal. The g^* in this decay carries only a few GeV energy and it is very difficult to perform a completely inclusive search for b → sg^*. Fortunately, recent experiments at CLEO have provided an extremely important clue that enables us now to hunt for fragments of b → sg^*.

Perhaps one of the most important recent development in B-physics is the CLEO discovery\[7\]:

\[
Br(B \rightarrow \eta' + X_s; 2.2 \leq E_{\eta'} \leq 2.7 \text{ GeV}) = (7.5 \pm 1.5 \pm 1.1) \times 10^{-4} \quad (1)
\]

It has been suggested that this finds a natural explanation in the SM as originating from b → sg^* via the fragmentation: g^* → g\eta'\[8\]. Of course, as always, quantitative calculations of purely hadronic modes are extremely uncertain\[9\] but it seems fairly safe to assume that an appreciable fraction of the observed signal has this SM origin. It thus becomes important to ask what other distinctive states can g^* fragment into in an analogous fashion. From an experimental point of view this question is especially significant given the fact that the \eta' detection efficiency is (at least for now) small, only about 5\%\[7\].

Theoretically, on very general grounds, one expects that g^* → gX_g should lead to those states X_g that have the quantum numbers of I(JPC) = 0(0^-), 0(0^+), 0(2^+) etc. In addition to these single particle states, from the experimental perspective there are also interesting continuum of states such as ππ, K\bar{K}, ππK\bar{K}... Indeed there is a close correspondence between these states X_g (expected in g^* → gX_g) and those observed in ψ → γ(φ, w) + X_g.

In ψ decays these states result from fusion of two gluons. Crossing symmetry provides a close link between ψ → γ(w, φ)X_g and g^* → gX_g. Thus in B → X_sX_g the experimentalists should be seeking states X_g that have been seen in ψ → γ(φ, w)X_g. Explicit examples of interesting states are\[10, 11\]:

\[
\begin{align*}
0^{-+} & : \eta(958), \eta(1440), \eta(1295), \eta(1760) \ldots \\
0^{++} & : f_0(980), f_0(1370), f_0(1500) \ldots
\end{align*}
\]
$2^{++} : f_2(1270), f_2'(1525), f_2(2010), f_2(2300), f_2(2340) \ldots$

Continuum : $\pi\pi, K\overline{K}, K\overline{K}\pi, 4\pi, 4K, \pi\pi K\overline{K} \ldots$  \hspace{1cm} (2)

Fig. 1a shows the SM fragmentation process leading to these states. This SM amplitude (Fig. 1a), as explained above, has a vanishingly small CP-odd (CKM) phase in the Wolfenstein convention. For simplicity, in this work, we will set it to zero. Fig. 1b represents some non-standard physics scenario which contributes to the same final state but has a CP-odd (non-standard) phases $\lambda_F$ in the chromo-electric moment and $\lambda_G$ in the chromo-magnetic moment. Although Fig. 1a does not have a CP-odd phase it does possess a CP-even phase ($\delta_{st}$) originating primarily from the $c\overline{c}$ cut in the Feynman amplitude$^{[12]}$. The crucial point is that to this order in perturbation theory $\delta_{st}$ is only a function of $q^2$ ($q$ is the 4-momentum of $g^*$) and does not depend on the state $X_g$. Thus the same $\delta_{st}$ tends to show up in all the states $X_g$ that result from the fragmentation of $g^*$. Therefore the CP asymmetries can be combined to significantly improve our chances of capturing such a phase 1) due to the vastly improved statistics and 2) due to the fact that many of the states can have improved detection efficiency compared to the 5% of the $\eta'$ $^{[7]}$.

Of course perturbative arguments should be taken with reservation as they are bound to be corrections. But they are some reasons to think that corrections may not be very big. For one thing $\delta_{st}$ is a ratio of the imaginary to the real part of the Feynman amplitude and therefore corrections ought to be less than on each of these amplitudes. Also in QCD, the $0^+ -$ (e.g. $\eta'(958)$) and $0^{++}$ (e.g. $f_0(980)$) $^{[10, 13]}$ states have considerable similarity. In this regard notice in particular that $Br(\psi \rightarrow \phi\eta'(958)) = (3.3 \pm .4) \times 10^{-4}$, $Br(\psi \rightarrow \phi f_0(980)) = (3.2 \pm .9) \times 10^{-4}$; also $Br(\psi \rightarrow \omega\eta'(958)) = (1.67 \pm .25) \times 10^{-4}$, and $Br(\psi \rightarrow w f_0(980)) = (1.4 \pm .5) \times 10^{-4}$. Furthermore, for $\pi\pi$ and $K\overline{K}$, to the extent that SU(3) is a good symmetry, $\delta_{st}$ in $\pi\pi$ must equal $\delta_{st}$ in $K\overline{K}$ for a fixed invariant mass of the pair. Finally, in this regard the most important point is that the theory need not be used to predict the actual magnitudes of the asymmetries. Based purely on the quantum numbers (i.e. CP-odd or CP-even) of the states, theory provides a reliable basis for combining the asymmetries observed in individual channels no matter what the actual magnitudes of the asymmetries might be. Thus theoretical considerations are allowing one to combine the statistics to extend the reach of the experiments without sacrificing the quantitative detail to the
altar of our theoretical inability to accurately predict $\delta_{st}$ via perturbation theory.

The formalism is very simple. We begin with writing a general form for the $bsg$ vertex:\[14\]:

$$\Lambda_{bsg}^{ij} = \frac{V^*_{tb}V_{ts}}{\sqrt{2}} T^a T^{ij} \left[ -i F(q^2)(q^2 \gamma_{\mu} - q_{\mu} q) L + \frac{g_s}{2\pi^2} m_b q_{\mu} \epsilon_{\nu} \sigma^{\mu\nu} G(q^2) R \right] b_j$$ \hspace{1cm} (3)

where $V_{tb} = V^*_{tb} V_{ts}$.

$F(q^2) = e^{i\delta_{st}} F_{SM} + e^{i\lambda_F} F_x$ ; \hspace{1cm} $G(q^2) = G_{SM} + e^{i\lambda_G} G_x$ \hspace{1cm} (4)

and $i, j$ and $a$ are suitable color indices. Here the $F$ and $G$ are chromo-electric and chromo-magnetic\[15, 16\] form factors. The strong phase, $\delta_{st}$ is generated by the imaginary part resulting from the $c\bar{c}$ cut when $q^2 > 4m_c^2$. The subscripts SM indicates a SM origin and $x$ indicates beyond the SM.

The differential decay rate takes the form:

$$\frac{d\Gamma}{dsdt} = F^2 \Gamma_1 + G^2 \Gamma_2 + 2FG \Gamma_3$$ \hspace{1cm} (5)

The CP-even and CP-odd contribution to the decay rates for $B \to X_s X_g$ and $\bar{B} \to X_s \bar{X}_g$ can be written as

$$\Gamma_s = \frac{1}{2} \frac{d(\Gamma + \bar{\Gamma})}{dsdt} = (F_{SM}^2 + F_x^2 + 2F_{SM} F_x \cos \lambda_F) \Gamma_1 + ((G_{SM}^2 + G_x^2 + 2G_{SM} G_x \cos \lambda_G) \Gamma_2 + 2(F_{SM} G_{SM} + F_x G_{SM} \cos \lambda_F + F_{SM} G_x \cos (\lambda_F - \lambda_G)) \Gamma_3$$

$$\Gamma_A = \frac{1}{2} \frac{d(\Gamma - \bar{\Gamma})}{dsdt} = -2 \sin \delta_{st} F_{SM} (F_x \Gamma_1 \sin \lambda_F + G_s \Gamma_3 \sin \lambda_G)$$ \hspace{1cm} (6)

Here $s = (p_b - p_s)^2$ and $t = (p_s + p_g)^2$; $p_{b,s}$ is the momentum of the $b, s$-quark and $p_g$ the momentum of the gluon.

The important CP violation observable is the partial rate asymmetry (PRA) which in its differential form is obtained by the ratio:

$$A_{PRA}(s,t) = \Gamma_A / \Gamma_s$$ \hspace{1cm} (7)
In these equations $\Gamma_1$, $\Gamma_2$ and $\Gamma_3$ are functions of $s$, $t$ and the masses $m_{X_g}$, $m_b$.

We can then take these expressions for the $b$-quark decay and put them in the $B$-meson system with Fermi-motion and obtain the necessary distributions for the rate and PRA as a function of $m_{\text{rec}}$ where $m_{\text{rec}}^2 = (p_B - p_{X_g})^2$ is the mass recoiling against $X_g$. Fig. 2 shows the $|A_{\text{PRA}}|$ as a function of $m_{\text{rec}}$ where, for concreteness, we have used $\sin \lambda_F = \sin \lambda_G = 1$. Fig. 2a is with the assumption that non-standard physics (NSP) contributes 10\% to the total rate for each channel. Fig. 2b is similar except with the assumption that NSP contributes 50\% to the rate. The PRA tends to scale with the amplitude of NSP so the PRA for the second case is larger by factors of about 2. For simplicity we also show separately the case where the NSP is all due to the chromo-electric (CE) form factor ($F_x$) versus when it is all due to a chromo-magnetic (CM) form factor ($G_x$). Notice that the CE case tends to generate 50-100\% larger asymmetries compared to the CM case. Fig. 2c compares the $|PRA|$ for all the three $J^{PC}$ of interest assuming $G_x = 0$ and the NSP, due to the CE form-factor alone, contributes 10\% to the rate. The PRA shows some dependence on the $J^{PC}$ of the state; the asymmetries for the 2^{++} states are thus somewhat bigger than for the 0^{++} which in turn are bigger than for the 0^{-+}. For a fixed $J^{PC}$ the PRA tends to slowly increase with the mass of the state. The crucial point to note is that the PRA for the 0^{++} and the 2^{++} will, in general, all have the same sign and that for the 0^{-+} will be opposite. The asymmetries in different channels can be combined after taking this sign change into account.

An important background originates from processes such as $B \to D(D_s) + X_g + X$. Most of this background gives $m_{\text{rec}} \geq 2\text{GeV}$ for various $X_g$ states of interest. In the signal region, i.e. $m_{\text{rec}} \leq 2\text{GeV}$, the PRA tends to show only little dependence on $m_{\text{rec}}$ (see fig. 2). For the sake of completion, in Fig.3, we also show the $m_{\text{rec}}$ distribution for the three $J^{PC}$.

We now briefly discuss some of the interesting final states. For $f(980)$ the $\pi\pi$ and $K\overline{K}$ are nice modes with branching ratios $\sim 78\%$ and $\sim 20\%$ respectively\cite{10}. For $f_0(1500)$ the modes of interest include $\eta\eta$ and $4\pi$. $f_2'(1525)$ has a notably large ($\sim 90\%$) branching ratio to $K\overline{K}$ with about 10\% branching ratio to $\eta\eta$\cite{10}. For $0^{-+}$ states (e.g. $\eta(1440)$) the prominent modes include three body modes such as $K\overline{K}\pi$ and $\eta\pi\pi$ as well as $a_0(980)\pi$ and $4\pi$\cite{10,13}. $f_2(2300)$ and $f_2(2340)$ can also decay to $\phi\phi$ states\cite{10}.

Recall that the overall signature for these modes (i.e. $B \to X_s + X_g$) is
that the $X_s$ must hadronize as a $K + n\pi$. Application of CP tests require that $B$ and $\bar{B}$ be distinguished. A number of strategies can be used here. For one thing, the "other $B$" can be tagged e.g. through its semi-leptonic decay modes. Typically this can have a tagging efficiency of about 20% (including both $e^\pm$ and $\mu^\pm$ final states). Also "self-tagging" can be used. This means that to a high degree of accuracy the net charge carried by the kaons will distinguish $b$ from $\bar{b}$. Since the $s$ (or $\bar{s}$) quarks in the $b \to s$ or $\bar{b} \to \bar{s}$ transition will give a $K^-$ (or $K^+$) about half the time, this method will have an efficiency of about 50%. Thus the total tagging efficiency will be about 60%.

We want to emphasize that non-resonant, continuum originating from the fragmentation of the $g^*$ can also be very useful. Perhaps the best example here is the case of $K\bar{K}$. First of all notice from $\psi$ decays that $Br(\psi \to \phi K\bar{K})/Br(\psi \to \phi \eta') \sim 4$. Thus the $K\bar{K}$ final state could well appear in appreciable fraction as $X_g$ (i.e. $g^* \to gK\bar{K}$) in $B$ decays as well. Such a final state should be rather distinctive as it will have three kaons in the final state.

Since a $K\bar{K}$ final state cannot be in a CP-odd configuration, resonant or non-resonant, it will only be in one of the CP-even states with “natural” $J^{PC}$, i.e. $0^{++}$, $1^{--}$, $2^{++}$ etc. Thus statistics for the PRA in $K\bar{K}$ states, whether produced through a resonance or the continuum, may be combined. Since the PRA varies little with the invariant mass or the total spin of the $K\bar{K}$ system (see fig. 2), the breakdown of the total $K\bar{K}$ sample into various resonance and continuum states will not greatly effect the resultant PRA. In the continuum state the invariant mass of the $K\bar{K}$ will play the role of $m_{X_g}$. Clearly similar comments apply to $\pi\pi$ states.

Let us now try to estimate the reach of the proposed experiments. For this purpose we will take the new physics to contribute $\sim 10\%$ to the rate for each of these states. Due to its distinctiveness let us first consider $X_g = K^+K^-$. The expected PRA (see fig. 2a) ranges between 13% and 18%; we will take it to be 15%. We further estimate the detection ($\epsilon_d$) and tagging ($\epsilon_b$) efficiencies to be 60% each. Although $\psi$ decays suggest that $g^* \to gK^+K^-$ could even be appreciably bigger than than $g^* \to g\eta'$, for our illustrative purpose we assume they are the same. Thus the number ($N^{3\sigma}$) of $B$ (i.e. $N^{3\sigma}$ is the total number of $B$ plus the total number of $\bar{B}$) mesons needed to see a signal
with 3σ significance in the $K^+K^-X_s$ channel is:

$$N^{3\sigma} = \frac{9}{\text{Br}A_{\text{PRA}}^2 \epsilon_d \epsilon_b} \approx 1.5 \times 10^6$$

(8)

This means that the existing data sample at CLEO ($\sim 2 \times 10^6$) may already be able to provide a useful indication for non-standard physics.

To gain a second perspective let us consider now the case of various individual resonances, in particular those with $J^{PC} = 0^{-+}, 0^{++}$ and $2^{++}$. The PRA in each channel can be $8 - 18\%$ (see fig. 2a); for concreteness we take PRA $\sim 10\%$. For the purpose of making an estimate let us further assume that by combining many of the modes listed above the effective Br is roughly three times that of the $\eta'$. Also in this example we take the effective detection efficiency ($\epsilon_d$) to be 20% and the tagging efficiency ($\epsilon_b$) to be 60%. The required number of $B(\bar{B})$ to see a $3 - \sigma$ signal is then given by

$$N^{3\sigma} = \frac{9}{\text{Br}_{\text{eff}}A_{\text{PRA}}^2 \epsilon_d \epsilon_b} \approx 4 \times 10^6$$

(9)

Thus, from eqs. (8–9), we see that with a sample of several million $B\bar{B}$ pairs the presence of a CP violating phase from physics beyond the SM could be detected even if the contribution to the overall rate from such sources is rather small ($\sim 10\%$). This is especially significant since the calculation for the absolute rate of such purely hadronic decays are notoriously difficult and it would be virtually impossible to reliably compare the predictions of the SM with experiment with regard to rates to such a high degree of accuracy.

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[9] As emphasized in Ref.[8] the data suggests that the $g^* - g - \eta'$ vertex is being influenced by the presence of near-by resonances, as it should become even more apparent in this Letter. Thus the form-factor tends to stay fairly constant even for rather large $q^2$. After that key assumption is made, which requires non-perturbative physics to modify a power-like $q^2$ dependence, perturbative effects (such as running of $\alpha_s$, which can only have a logarithmic dependence on $q^2$) cannot be applied reliably. Thus in Ref.[8], QCD corrections were not taken into account seriously for the chromo-electric form factor, rather they were primarily considered to include their effects only on the chromo-magnetic form-factor (which is non-leading anyway) as it is rather sensitive to radiative effects.

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[14] We are assuming here that non-standard physics only modifies the form-factors (F and G) and not the chirality (L and R) to enable the new physics to interfere with the SM without entailing a $m_s/m_b$ suppression.

[15] We note that A. Kagan (Phys. Rev. D51, 6196(1995)) postulates a specific class of non-standard physics scenario to significantly enhance the on-shell glue decay, $b \to s + g$ (i.e. only the chromo-magnetic form-factor) over that of the SM. This is done, at least in part, in an attempt to explain the “problems” in $B$-decays of the semi-leptonic $Br$ and that of the charm-deficit.

[16] W.-S. Hou and B. Tseng [hep-ph/9705304] argue that the SM cannot account for the $\eta'$ rate (i.e. eqn. (1)). They invoke new physics of the same type as [15] to enhance on-shell glue in $b \to s + g$ such that $Br(b \to s + g) = 10\%$ (recall that in the SM this $Br$ is only about 0.1% [17]) to account for the observed $\eta'$ rate as well as the other “problems” in $B$-decays (see the previous reference). They also calculate PRA for $B \to \eta' + X_s$ due to a CP-odd phase in such a non-standard modification restricted to the chromo-magnetic form-factor only. See also Ref.[18].

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[19] The $\eta (1440)$ deserves special experimental attention. Inspection of $\psi$ decays into final states containing $\eta'(958)$ or $\eta(1440)$ suggests that the $Br(\bar{B} \to X_s \eta(1440))$ is likely to be in the same ball-park as $Br(\bar{B} \to X_s \eta'(958))$.

[20] Although, in perturbation theory, one expects the production of $1^{--}$ states through our fragmentation mechanism to be suppressed as they
require an extra gluon, some of the vector states may well be more readily accessible experimentally to offset such a suppression. Notice, in particular, $\phi$ which has a distinctive signature ($\phi \to K\bar{K}$) falls into this class of interesting examples of $X_g$. 

Figure Captions

Figure 1: (a) The penguin diagram giving rise to $b \rightarrow sg^*$ followed by $g^* \rightarrow g + \eta', f_0, f_2$ or other such states. (b) Contributions to this process from non-standard physics (NSP) is indicated by the hexagon.

Figure 2: (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 $b \rightarrow g + 0^{--}$ assuming that $F_x = 0$ and taking $m_{0--}^0$ 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 $b \rightarrow g + 0^{++}$ assuming that $F_x = 0$ with $m_{0^{++}}^0$ ranging from $980 MeV$ to $1710 MeV$; the dotted region is the $|\text{PRA}|$ for the $0^{++}$ assuming that $G_x = 0$. Note that the PRA for all the $0^{++}(2^{++})$ states will have an opposite sign to that of the $0^{--}$ states.

(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. 2a. Diagonal striped ($F_x = 0$) and the dotted ($G_x = 0$) regions are now for $b \rightarrow g + 2^{++}$ with $m_{2^{++}}$ from 1270 to 2300 MeV. See also caption to fig. 2a.

(c) $|\text{PRA}|$ versus $m_{\text{rec}}$ assuming NSP contributes $\sim 10\%$ to the rate and $G_x = 0$. Now the dotted region is for $0^{--}$, striped for $0^{++}$ and solid for $2^{++}$. See also caption to Fig. 2a.

Figure 3: The distribution $d\Gamma/(\Gamma dm_{\text{rec}})$ in the standard model. The solid line is for $J^{PC} = 0^{--}$, the dashed line is for $J^{PC} = 0^{++}$, and the dotted line is for $J^{PC} = 2^{++}$. 

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Figure 2b
Figure 2c
