New Physics and Enhanced Gluonic Penguin

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Abstract. We discuss the historical development of the gluonic $B$-penguin, its sensitivity to $H^+$ effects, and $b \to sg \sim 10$–$15\%$ as a possible solution to the $B_{s,l}$ and $B_C$ problems. The latter and the connection of the gluonic penguin to inclusive $B \to \eta' + X_s$ production through the gluon anomaly, with the intriguing prospect of $10\%$ inclusive CP asymmetries, bring us to topics of current interest.

I SM: HISTORICAL BACKDROP

We are here to celebrate the 20th anniversary of the $\Upsilon$ discovery. Because of this historic setting, I will dwell a little more on the historical aspects (from a personal perspective) of gluonic penguins, before I turn to the current.

Shortly after 1977, Bander, Silverman and Soni (BSS) [1] suggested the mechanism of (direct) CP violation in the decay of $b$ quarks. The $B$-penguin was born, as illustrated in Fig. 1 (a). CP violation is possible because all 3 generations run in the loop, while on-shell $u\bar{u}$, $c\bar{c} \to g^* \to q\bar{q}$ rescattering provides the second $i$, an absorptive part. Tony Sanda told me that this work was an inspiration for his mixing dependent CP violation ideas.

![Diagram](attachment:Fig1.png)

**FIGURE 1.** (a) Timelike, (b) lightlike and (c) spacelike gluonic penguin. The cut in (a) corresponds to on-shell $u\bar{u}$ and $c\bar{c}$ pairs, while in general $i = u, c, t$ in the loop.

Perhaps influenced by BSS, Guberina, Peccei and Rückl pointed out [2] in late 1979, using operator language, that $B$-penguin operators “can alter
the ‘natural’ Cabibbo pattern of the Kobayashi–Maskawa model.” Namely, $B \to K\pi > B \to \pi\pi$ is possible, since the penguin is $\propto |V_{cb}| \simeq |V_{ts}|$, while tree level $B \to \pi\pi$ could be suppressed if $V_{ub}$ is very small. This has just turned into fact this year with CLEO’s observation of a few 2-body rare decays [3].

Following the study of $b \to s\gamma$ decay in the early 80’s, Eilam [4] added $b \to sg$ of Fig. 1(b) to the “parton” estimate of the inclusive penguin rate. In 1987, the so-called “large” QCD correction to $b \to s\gamma$ was discovered, leading to the “operator” approach industry. But $b \to sg$ changed only from 0.1% to 0.2% with QCD corrections, much less dramatic than the $b \to s\gamma$ case.

The inclusive gluonic penguin was clarified [5] in 1987 by noting the $q^2$ factor, i.e. $b \to sg^* \equiv b \to sq\bar{q}$, $sg$, and $b\bar{q} \to s\bar{q}$ (timelike, lightlike and spacelike), where the latter, given in Fig. 1(c), is the familiar looking “penguin” from kaon physics. It was found that [5] $b \to sq\bar{q} \sim 1\% \sim b \to u$ while $b\bar{q} \to s\bar{q} < b \to sg$.

However, counter to one’s intuition [6], $b \to sgg \ll b \to sq\bar{q}$. Interestingly, the 3-body $b \to sq\bar{q}$ at $\mathcal{O}(\alpha_s^2)$ dominates over the 2-body $b \to sg$ at $\mathcal{O}(\alpha_s)$, which comes about because of a subtlety of GIM cancellation.

There are two conserved effective $bsg$ couplings; ignoring $V_{ub}$ they are

$$G_F g_s \frac{v_t}{\sqrt{s}} \{\Delta F_1 (q^2 \gamma_{\mu} - q_{\mu} \gamma) L - F_2 i\sigma_{\mu\nu} q^\nu m_b R\} b,$$ \hspace{1cm} (1)

where $\Delta F_1 \equiv F_1^g - F_1^i \simeq 0.25 - (-2/3 \log(m_b^2/M_W^2) - 2/3 \log(m_b^2/M_W^2)) \simeq -1.3 - 2.75$, and $F_2 \simeq F_2^i \simeq 0.2$. $F_1$ contains large logarithms while $F_2$ does not, but suffers from power GIM suppression. However, $F_1$ cannot contribute to $b \to sg$ because of the $q^2$ factor. Thus, the subtle higher order dominance comes about because of having a logarithmic and a power GIM suppressed effective coupling, and only the latter leads to $b \to sg$.

II \hspace{1cm} $H^+$ EFFECTS: $F_2^\gamma$ AND $F_2^g$

The above subtlety leads to surprising $H^+$ effects: $F_2^\gamma$ is very sensitive to low $m_{H^+}$. For the Higgs sector of minimal SUSY, the effect is always constructive and does not vanish with $\tan \beta$ (ratio of v.e.v.’s of the two Higgs doublets) [7,8], which holds similarly for $F_2^g$ [8]. Though $b \to sg$ could not be greatly enhanced in this model, both strong enhancement/suppression of $b \to s\gamma$ are possible for a second model, and $b \to sg$ could become very enhanced [8].

At that time the experimental limit was $\mathcal{B}(b \to s\gamma) < 6 \times 10^{-3}$, while $b \to sg$ was practically without bound (except $b \to c$ should be dominant). The curious thing about $b \to sg$ is that it does not lead to any good, tangible signature! By 1992, however, the CLEO limit on $\mathcal{B}(b \to s\gamma)$ improved to $5 \times 10^{-4}$, entering the domain of SM predictions. This had a dramatic implication that $m_{H^+} > 250$ GeV or so [9] in SUSY type models. Unfortunately, because $bsg$ and $bs\gamma$ couplings in Higgs models are highly correlated, the limit and eventual observation of $b \to s\gamma$ by CLEO meant that $b \to sg$ could no longer be strongly enhanced in usual charged Higgs models [10].
III $B_{s,1}$–$n_C$ PROBLEM: ENHANCED $b \to sg$

Some indirect indications for enhanced $b \to sg$ appeared, in fact, in the early 90’s. As $B$ experiments matured, the semileptonic branching ratio ($B_{s,1}$) steadily declined, from $\simeq 12\%$ in 1986, to $10.7\%$ by early 1990. Theory predicted 12–15%, hence it appeared [11,12] that the SM had trouble with the experimental value, with a 10–15% discrepancy. The relevant QCD scale $\mu$ for $B$ decay could be much lower than $m_{b}$[11], or one could have new physics $\Gamma_{\text{New}} \sim 10–15\%$, which drives down $B_{s,1}$ via

$$B_{s,1} = \Gamma(B \to \ell \nu + X)/\left(\Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{New}}\right).$$

(2)

The new process must be relatively well hidden, and low in charm content to accommodate the analogously low charm counting rate [13] (the $n_C$ problem). Two modes were suggested [12], both from $H^+$ effects. The first one, $B \to \tau \nu + X \sim 10\%$, was very quickly ruled out by a superb analysis job of ALEPH, which confirmed SM predictions. The second possibility of $b \to sg \sim 10–15\%$, which is a charmless final state, was very difficult to rule out.

However, by 1994, the possibility of enhanced $b \to sg$ due to $H^+$ effects became implausible because of $b \to s \gamma$ limits/measurements. Subsequently, Kagan [14] suggested that TeV scale physics responsible for quark mass (and mixing) generation might lead to enhanced $b \to sg$. For example, gluonic insertions to $\bar{s}_L b_R$ mass terms could result in effective $s_L b_R g$ couplings. To disentangle $b \to sg$ from $b \to s \gamma$, one must employ more color in the loop. Note that $H^+$ is colorless and does not couple to gluons, hence diagrams for $b \to sg$ are only a subset of $b \to s \gamma$. But gluons could more readily couple to gluinos via SUSY $q_i \tilde{q}_j \tilde{g}$ couplings [14,15] (with flavor violation in squark mass matrix), or to techniscalars [14]. In this way $b \to sg$ could in principle be separated from $b \to s \gamma$ and be strongly enhanced.

The problems of low $B_{s,1}$ and $n_C$ have persisted to this day, despite much theoretical and experimental effort. Two recent analyses [16,17] give $B_{s,1} = 0.105 \pm 0.005$ and $n_C = 1.10 \pm 0.06$, both low by about 10–15%. The problem could still be experimental, and in fact the latest results hint at softening of the problems, but two views are offered on enhanced charmless $b$ decays. Kagan and Rathsman [16] think that $B_{s,1}$, $n_C$ and kaon excess in $B$ decays together hint at $b \to sg \sim 10–15\%$. Using JETSET fragmentation of the $s$ quark, they find the $K$ spectrum to be rather soft, hence $b \to sg$ indeed hides well. On the other hand, Dunietz et al. [17] suggest that half of $b \to sc \bar{c}$ (expected at 20–30% level) has disappeared into light hadrons. The effect has to be nonperturbative to evade the perturbative $b \to sg^* \sim 1\%$ discussed earlier. The proposed mechanism is via a $c \bar{c}g$ hybrid meson, since the $c \bar{c}$ pair is mainly in color octet configuration. The hybrid should [18] be favorably produced in $b \to sc \bar{c}$, should be relatively narrow (long lived) and should have suppressed decays into $D \bar{D} + X$ and usual charmonia. Hence [18], in a sense it is no less exotic than new physics $b \to sg \sim 10–15\%$. 
IV  INCLUSIVE $\eta'$, $b \to sg$, GLUON ANOMALY

1997 will be remembered as the year of the strong penguin. Since the Aspen Winter Conference, CLEO has reported the first observations of a host of two-body rare $B$ decays. $K\pi \sim 10^{-5}$ is observed, while $\pi\pi$ is not, confirming the GPR suggestion [2]. The $\omega h^\pm$ mode is larger than expected, while $\eta'K \sim 10^{-4}$ is huge, but $\eta'K$ is not seen! All in all, we see that penguins are large.

What is even more astounding is the observation of [3]

$$B(B \to \eta' + K + X) = (75 \pm 15 \pm 11) \times 10^{-5} \quad (2.0 < p_{\eta'} < 2.7 \text{ GeV})$$ (3)

where $X = 0-4\pi \ (\leq 1\pi^0)$. While a cut on $p_{\eta'}$ is in part to suppress background, it is astonishing to see so many events in this rather unusual channel. If one extrapolates from Eq. (3), one could easily saturate $b \to sg^* \sim 1%$.

The most prominent feature is that the $\eta'$ is fast! Since $\eta'$ is the heaviest and “stickiest” (glue rich) of the lowest lying mesons, it would have been last on the list of possible fast, leading particles in $B$ decay searches. There is one thing unique to $\eta'$, however, namely its connection to the gluon anomaly. $\eta'\eta'$ mixing is said to be related to the axial U(1) problem, and the symmetry is broken by the $GG$ gluon anomaly. Indeed, in the chiral limit of $m_q \to 0$ (assuming $N_F = 3$ of light flavors), one has $\langle 0|\partial_{\mu}J_{\rho\delta}|\eta'\rangle = \langle 0|(2N_F\alpha_s/4\pi)\text{tr}(G^\dagger G)|\eta'\rangle$, and it is this large, topological glue content of $\eta'$ that makes it so heavy. So, is the $\eta'$ production linked to $b \to sg$?

A  $\eta'$-$g$-$g$ Coupling and Need for $b \to sg \sim 10\%$

Atwood and Soni [19] (AS) have indeed made such a connection, linking $b \to sg^*$ to inclusive $\eta'$ via the $\eta'$-$g$-$g$ gluon anomaly. Defining the phenomenological coupling

$$H(q^2, k^2, m_{\eta'}^2)\varepsilon_{\mu\nu\alpha\beta}q^\mu k^\nu\varepsilon^\alpha(q)\varepsilon^\beta(k)$$

they extract $H(0, 0, m_{\eta'}^2) \simeq 1.8 \text{ GeV}^{-1}$ from $J/\psi \to \eta'\gamma$ decay. Assuming that $H(q^2, 0, m_{\eta'}^2) \approx H(0, 0, m_{\eta'}^2)$ is constant, they find that the SM $b \to sg^* \sim sg\eta'$ could account for Eq. (3). However, they seem to have mistaken $d\Gamma/dq$ for $d\Gamma/dm$, where $m = m_{X_s} \equiv m_{\text{recoil}}$. They hence have a false sensitivity to Fermi motion. Furthermore, the assumption of constant $H(q^2, k^2, m_{\eta'}^2)$ is definitely too strong.

The $q^2$ ranges from 0 to $m_{\eta'}^2$, way beyond the QCD scale that determines $m_{\eta'}$. We shall assume that form factor effects do not set in, which in itself is already a big assumption. But even then, for such a broad range of $q^2$, one does not expect couplings to stay constant. This is especially so since one finds that $d\Gamma/dq$ peaks at large $q > 3 \text{ GeV}$ (Fig. 2(b)).

So, let us try [18] to understand the $\eta'$-$g$-$g$ coupling better. The $\eta'$ problem in QCD is in itself an active field of research. The anomaly coupling comes from the Wess-Zumino term, without assuming PCAC and soft pions,

$$-ia_g cp \eta' \varepsilon_{\mu\alpha\beta} \varepsilon^\alpha(q)\varepsilon^\beta(k)q^\mu k^\beta,$$ (4)
where \( a_g(\mu^2) = \sqrt{N_c} \alpha_s(\mu^2)/\pi f_{\eta'} \equiv H(q^2, k^2, m_{\eta'}^2) \) of AS. The explicit \( \alpha_s \) factor strongly suggests that one should use running coupling. In the case at hand, since \( k^2 \to 0 \) and \( q^2 > m_{\eta'}^2 \) is the dominant scale, we expect \( \mu^2 = q^2 \). As a cross check, we find that \( a_g(m_{\eta'}^2) \equiv H(0, 0, m_{\eta'}^2) \) of AS, but for larger \( q^2 \), this would suppress the SM \( b \to sg^* \) effect, since the strong coupling changes by a factor of 2 from \( m_{\eta'} \sim 1 \) GeV to \( m_b \) scale. We find [18] a factor of 1/3 suppression of SM \( b \to sg^* \to sg\eta' \), hence \( b \to sg \approx 10\% \) is precisely what is called for. It is interesting that both \(|F_{1}^{\text{SM}}| \sim 5\) and \(|F_{2}^{\text{New}}| \sim 2\) effects are needed. Furthermore, because in the SM the \( F_{1} - F_{2} \) interference effect is destructive, the sign of \( F_{2}^{\text{New}} \) should be opposite to that in the SM, which is precisely what is found in the SUSY example of \( b \to sg \approx 10\% \) [15]!

![Graph](attachment:graph.png)

**FIGURE 2.** (a) \( dB/dm \) and (b) \( dB/dq \) for \( b \to \eta' sg \) (solid) and \( \bar{b} \to \eta' \bar{sg} \) (dashed). The \( \bar{c}c \) threshold is evident in (b), while the CP asymmetry is due to new phase \( \sigma \) in \( F_{2} \).

**B BONUS: Potential for New \( a_{\text{CP}} \sim 10\% \)**

For inclusive \( b \to s \) transitions, it is known that [20] \( a_{\text{CP}} \lesssim 1\% \), due to the smallness of \( v_u \equiv V_{us}^{\ast} V_{ub} \sim \lambda^5 \) and unitarity constraints. However, because of the appearance of the \( b_R \) field in Eq. (1), the \( F_{2}^{\text{New}} \) dipole coupling probes new phases that are independent of CKM phase. At the same time, the \( F_{1}^{\text{SM}} \) coupling, which is needed also to account for the rate, provides the necessary rescattering phase, from the \( \bar{c}c \) cut in Fig. 1(a). The differential BR’s \( dB/dm \) and \( dB/dq \) are shown in Fig. 2, assuming phase difference \( \sigma = 90^\circ \) between \( F_{1} \) and \( F_{2} \). Note that, thanks to the anomaly \( \eta' - g - g \) coupling, although \( q^2 \) is not a physical variable, \( m^2 \) directly corresponds to the physical recoil mass against \( \eta' \). Furthermore, large \( q^2 \) (hence fast \( \eta' \)) is favored by the anomaly coupling! The upshot is that we can account for the huge branching ratios that are already observed, while the asymmetry \( a_{\text{CP}} \sim 10\% \) in \( B \to \eta' + K^\pm + X \).

In principle, CLEO could probe this asymmetry very soon.
V CONCLUSION

The SM expectation that $b \rightarrow sq\bar{q} \sim 1\%$ and $b \rightarrow sg \sim 0.2\%$ is quite firm. However, persistent $B_{s\ell}$ and $n_L$ problems hint at the possibility of $b \rightarrow sg \sim 10\%$ from new physics. The recent observation of spectacularly large semi-inclusive $B \rightarrow \eta' + X_s \sim 0.75 \times 10^{-3}$ where $p_{\eta'} > 2$ GeV poses an additional challenge to the SM. It is proposed that large $b \rightarrow sg$ leads to large $B \rightarrow \eta' + X_s$ through the gluon anomaly. We find that, with running $\alpha_s$ in the $g^* - g - \eta'$ coupling, both SM $b \rightarrow sg^* \sim 1\%$ and new physics $b \rightarrow sg \sim 10\%$ are needed, to feed down to $B \rightarrow \eta' + X_s$. The anomaly coupling preferentially leads to fast $\eta'$ mesons. Since the new physics color dipole transition involves right-handed couplings to the $b$ quark, one probes a new CP violating phase that is independent of CKM.

The $B \rightarrow \eta' + X_s$ mode is already observed at 0.1\% level. With 10\% $a_{CP}$ possible because of the interplay of SM and new physics, perhaps CP violation could be observed before 1999, the year that B Factories turn on.

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