Using $b \to s\gamma$ to Probe Top Quark Couplings

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Abstract

Possible anomalous couplings of the top-quark to on-shell photons and gluons are constrained by the recent results of the CLEO Collaboration on both inclusive and exclusive radiative $B$ decays. We find that the process $b \to s\gamma$ can lead to reasonable bounds on both the anomalous electric and magnetic dipole moments of the top-quark, while essentially no limits are obtained on the corresponding chromoelectric and chromomagnetic moments, which enter the expression for the decay rate only through operator mixing.

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The Standard Model (SM) of electroweak interactions is in very good agreement with present experimental data[1]. Nonetheless, it is believed to leave many questions unanswered, and this belief has resulted in numerous theoretical and experimental attempts to discover a more fundamental underlying theory. Various types of experiments may expose the existence of physics beyond the SM, including the search for direct production of exotic particles at high-energy colliders. A complementary approach in hunting for new physics is to examine its indirect effects in higher order processes. For example, even though the top-quark has yet to be discovered, it has already made its presence known through loop order processes, such as rare decays of the b-quark. Since the top-quark is far more massive than the other SM fermions, its interactions may be quite sensitive to new physics originating at a higher scale. If there are any deviations from SM expectations in the properties of the top-quark, they may indirectly lead to modifications in the anticipated branching fractions for these one-loop induced b-quark decays.

The possibility of having top-quarks with anomalous couplings to various gauge bosons has been discussed in the literature[2, 3]. Strong bounds can be placed on these anomalous couplings at future colliders, such as the SSC/LHC[2] and the next linear $e^+e^-$ linear collider (NLC)[3], which rely on direct production of top-quark pairs. Since the t-quark has yet to appear at the Tevatron, it is clear that any restrictions on these couplings at present can only be obtained indirectly. In this paper we examine the effects of anomalous couplings of the top-quark to on-shell photons and gluons on the process $b \to s\gamma$. If the t-quark has large anomalous couplings, then the resulting prediction of the rate for $b \to s\gamma$ would conflict with experiment. The CLEO collaboration has recently[4] observed the exclusive decay $B \to K^*\gamma$ with a branching fraction of $(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$ and has placed an upper limit on the inclusive quark-level process $b \to s\gamma$ of $B(b \to s\gamma) < 5.4 \times 10^{-4}$ at 95% CL. Using a conservative estimate of the ratio of exclusive to inclusive decay rates[3],
the observation of the exclusive process implies the lower bound $B(b \to s\gamma) > 0.6 \times 10^{-4}$ at 95% CL. These values for the branching fractions are consistent with expectations from the SM[3].

The most general form of the Lagrangian which describes the interactions of top-quarks to on-shell photons, assuming operators of dimension-five or less only, is

$$\mathcal{L} = e\bar{t} \left[ Q_t \gamma_\mu + \frac{1}{2m_t} \sigma_{\mu\nu}(\kappa_\gamma + i\tilde{\kappa}_\gamma \gamma_5)q^\nu \right] tA^\mu, \quad (1)$$

where, for simplicity, we have assumed that the ordinary dimension-four interaction is parity conserving. Here, $Q_t$ is the electric charge of the t-quark, $\kappa_\gamma$ ($\tilde{\kappa}_\gamma$) is the anomalous magnetic (electric) dipole moment, and $m_t$ represents the mass of the top-quark. A similar expression is obtained for the interactions of the t-quark with gluons with obvious substitutions in the above. To simplify our analysis, we will also assume that only one of either the electric or magnetic dipole operators is non-zero. Clearly, if all four operators are non-vanishing, their separate contributions would be quite impossible to disentangle using an analysis of the $b \to s\gamma$ rate alone.

Our investigation of this process proceeds as follows. To obtain the $b \to s\gamma$ branching fraction, the inclusive $b \to s\gamma$ rate is scaled to that of the semileptonic decay $b \to X\ell\nu$. This removes major uncertainties in the calculation associated with (i) an overall factor of $m_b^5$ which appears in both expressions and (ii) the imprecisely known Cabbibo-Kobayashi-Maskawa (CKM) factors. We use the latest data on the semileptonic branching fraction[7, 8], which is given by $B(b \to X\ell\nu) = 0.108$, to rescale our result. The semileptonic rate is calculated including both charm and non-charm modes, assuming $|V_{ub}/V_{cb}| = 0.1$, and includes both phase space and QCD corrections with $m_b = 5$ GeV and $m_c = 1.5$ GeV[9]. The calculation of $\Gamma(b \to s\gamma)$ employs the next-to-leading log evolution equations for the coefficients of the operators in the effective Hamiltonian due to Misiak[10], the gluon bremsstrahlung
corrections of Ali and Greub[11], the $m_{top} \neq M_W$ corrections of Cho and Grinstein [12], a running $\alpha_{QED}$ evaluated at the b-quark mass scale, and 3-loop evolution of the running $\alpha_s$ matched to the value obtained at the $Z$ scale via a global analysis[13] of all data. Phase space corrections for the strange quark mass in the final state are included and the ratio of CKM mixing matrix elements in the scaled decay rate, $|V_{tb}V_{ts}/V_{cb}|$, is taken to be unity. The details of this procedure are presented elsewhere[14]. To complete the calculation we use the one-loop matching conditions for the various operators[10] in a form that includes contributions from both the SM and the top-quark anomalous couplings.

In practice, only the coefficients of the dipole $b \to s$ transition operators, traditionally denoted as $O_7$ and $O_8$, are modified by the presence of the anomalous couplings. At the $W$ scale, $O_7$ is the only operator which mediates the decay $b \to s\gamma$, however, mixing occurs between the various $b \to s$ transition operators during the evolution of the coefficient of $O_7$ to the b-quark mass scale, so that in principle all the operators can contribute at the scale $m_b$. We can write the coefficients of $O_7$ and $O_8$ at the $W$ scale as, e.g.

$$c_7(M_W) = G^7_{SM} + \kappa_\gamma G_1 + i\tilde{\kappa}_\gamma G_2,$$

$$c_8(M_W) = G^8_{SM} + \kappa_g G_1 + i\tilde{\kappa}_g G_2,$$

with

$$G^7_{SM} = -\frac{1}{2} \left[ -\frac{3x^3 + 2x^2}{2(1-x)^4} \ln x - \frac{8x^3 + 5x^2 - 7x}{12(1-x)^3} \right],$$

$$G^8_{SM} = -\frac{1}{2} \left[ \frac{3x^2 \ln x}{2(x-1)^4} + \frac{x^3 - 5x^2 - 2x}{4(x-1)^3} \right],$$

$$G_1 = \frac{1}{x-1} - \frac{\ln x}{(x-1)^2} + \frac{1}{2} \frac{x-1}{(x-1)^3} \left[ \frac{1}{2} x^2 - 2x + \frac{3}{2} + \ln x \right] - \frac{1}{4},$$

$$G_2 = \frac{1}{x-1} - \frac{\ln x}{(x-1)^2} - \frac{1}{4}.$$
where $x = m_t^2/M_W^2$. Note that this result is completely finite and that we do not have to resort to any use of cut-offs to analyze our results.

In Fig. 1a we show the predicted $b \to s\gamma$ branching fraction for several different top-quark masses assuming only the anomalous magnetic dipole moment of the top is non-zero. For large negative(positive) values of $\kappa_\gamma$, we see that the branching fraction exceeds the inclusive CLEO upper(lower) bound. While the constraint on $\kappa_\gamma$ from the CLEO upper limit does not appear to be sensitive to $m_t$, the restriction on $\kappa_\gamma$ from the lower CLEO bound varies significantly for $m_t$ in the range $120 - 200$ GeV. While the anomalous magnetic dipole moment effects the $O_7$ operator directly, the anomalous chromomagnetic dipole moment only contributes to the rate for $b \to s\gamma$ indirectly through operator mixing. Thus we would naively expect that the resultant bounds that are obtainable on this parameter to be quite weak. We see this quite explicitly in Fig. 1b where we assume that only $\kappa_g$ is non-zero. It is clear that unless extraordinarily large values of $\kappa_g$ are realized, the present $b \to s\gamma$ data does not constrain this parameter. If both $\kappa_g$ and $\kappa_\gamma$ are taken to be non-zero, the bounds obtainable from Fig. 1a on $\kappa_\gamma$ will not be significantly modified unless huge values of $\kappa_g$ are assumed. To demonstrate this we show in Fig. 1c the allowed range of $\kappa_\gamma$ at the 95% CL as a function of $m_t$, assuming that $\kappa_g$ is absent (solid curve) or is identical in value to $\kappa_\gamma$ (dashed curve). We see that both sets of constraints are remarkably similar. The general weakening of the limits with increasing $m_t$ should be noted.

In the case of a non-zero anomalous electric or chromoelectric dipole moment, a somewhat different situation occurs due to the relative phase between these and the conventional SM contributions to $c_{7,8}(M_W)$. When evolved down to the b-quark scale, these contributions do not interfere with those of the SM and thus can only appear quadratically in the modified expression for the $b \to s\gamma$ rate. Thus, we will assume both $\tilde{\kappa}_\gamma$ and $\tilde{\kappa}_g$ to be positive semi-definite in our numerical analysis. Since the contribution from these anomalous couplings
can only \textit{increase} the prediction to the $b \rightarrow s\gamma$ rate over that given by the SM, we anticipate that only the CLEO upper bound will provide a constraint. This expectation is borne out by our explicit calculations.

Fig. 2a displays the $b \rightarrow s\gamma$ branching fraction as a function of $\tilde{\kappa}_\gamma$ for several different top-quark masses assuming all other anomalous couplings are zero. Given the set of top-quark masses we consider, the bound on this parameter apparently strengthens as the value of $m_t$ increases. This conclusion is quite valid provided $m_t \gtrsim 130$ GeV, however, as we will see below, it is not quite correct for smaller values of $m_t$. As in the case of the chromomagnetic dipole moment, any constraints on the chromoelectric dipole moment are expected to be quite poor as it only enters into the expression for the $b \rightarrow s\gamma$ decay rate through operator mixing. Fig. 2b shows this is indeed the case, as there is apparently very little sensitivity to $\tilde{\kappa}_g$ alone even for very large values of this anomalous coupling. In Fig. 2c we present the $m_t$ dependence of the 95\% CL upper bound on $\tilde{\kappa}_\gamma$ both when all other anomalous couplings are absent (solid) as well as when $\tilde{\kappa}_g = \tilde{\kappa}_\gamma$ (dashed). Again, very little difference is seen between the two cases, demonstrating the lack of sensitivity of $b \rightarrow s\gamma$ to the chromoelectric moment of the top. As pointed out above, the bound on $\tilde{\kappa}_\gamma$ strengthens with increasing $m_t$ for values in excess of 130 GeV. However, we see that for smaller values of $m_t$ below 130 GeV the limits also become stronger. This is due to a cancellation between the various terms in $G_2$ near $m_t = 130$ GeV.

How will the constraints we have obtained be improved in the future? From $b \rightarrow s\gamma$ itself, we see that any imaginable improvement in the data will not qualitatively alter the allowed ranges we have obtained unless the top-quark mass is known. Even in this case, the other calculational uncertainties render it unlikely that drastic improvements are possible from this process alone. Of course, input from other processes involving top-quark loops may be of some help and should be aggressively investigated. Clearly, the next major step
forward will be the examination of the top-quark production process itself after the t-quark is found. Both the SSC/LHC and the NLC will be able to probe anomalous couplings which are two to three orders of magnitude smaller than those discussed here. We remind the reader, however, that the anomalous couplings that can be examined at these colliders will be for \textit{on-shell} top-quarks with \textit{off-shell} photons and gluons, \textit{e.g.}, the situation opposite to that which we examine here.

In summary, we have shown that the new CLEO results on radiative $B$ decays place strong constraints on the anomalous electric and magnetic dipole moment couplings of the top-quark even though it has not yet been directly observed at the Tevatron. The corresponding limits we obtain on the chromoelectric and chromomagnetic dipole moments are quite weak as they enter our calculation only via operator mixing. Clearly other low energy processes might also lead to constraints on such anomalous couplings and should be examined. It is most likely, however, that we will have to wait for detailed studies of top-quark production at future colliders before more restrictive bounds can be obtained.

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Figure Captions

Figure 1. The branching fraction for $b \rightarrow s\gamma$ as a function of (a) $\kappa_\gamma$ with $\kappa_g = 0$ or (b) $\kappa_g$ with $\kappa_\gamma = 0$, assuming $m_t = 120(140, 160, 180, 200)$ GeV corresponding to the dotted (dashed, dash-dotted, solid, square-dotted) curve. The solid horizontal lines are the 95% CL upper and lower bounds from CLEO. (c) The allowed range of $\kappa_\gamma$ as a function of $m_t$ assuming $\kappa_g = 0$ (solid curve) or $\kappa_g = \kappa_\gamma$ (dashed curve).

Figure 2. Same as Fig. 1 but for the couplings $\tilde{\kappa}_g$ and $\tilde{\kappa}_\gamma$. 

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