Using $b \to s\gamma$ to probe top quark couplings

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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 (of order a few $\times 10^{-16}$ e cm) on both the anomalous electric and magnetic dipole moments of the top quark. 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 one-loop induced b-quark decays.

The possibility of top quarks possessing anomalous couplings to various gauge bosons has been discussed in the literature [2,3]. Strong bounds can be placed on these effective couplings at future colliders, such as the Superconducting Super Collider (SSC) or CERN Large Hadron Collider (LHC) [2] and the next linear e^+e^- collider (NLC) [3], but they rely on direct production of top-quark pairs. Since the t quark has yet to appear at the Fermilab Tevatron, it is clear that any present restrictions on these couplings 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 in 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% C.L. Using a conservative estimate of the ratio of exclusive to inclusive decay rates [5], the observation of the exclusive process implies the lower bound $B(b \to s\gamma) > 0.65 \times 10^{-4}$ at 95% C.L. These values for the branching fractions are consistent with expectations from the SM [6].

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

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

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, κ_γ ($\tilde{\kappa}_\gamma$) 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 nonzero. Clearly, if all four operators are nonvanishing, their separate contributions would be quite impossible to disentangle using an analysis of the $b \to s\gamma$ rate alone. A nonzero value for the parameter $\tilde{\kappa}_\gamma$ signals the presence of a CP-violating amplitude. It may be difficult, however, to observe any obvious CP-violating effects in this decay since, e.g., the rates for $b \to s\gamma$ and $\bar{b} \to \bar{s}\gamma$ will only differ at the *two*-loop level in the electroweak interactions. (One possibility may be to examine differences in the polarization of the photons in both cases, but this is beyond the scope of this paper.)

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 $b \to Xl\nu$. 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 Cabibbo-Kobayashi-Maskawa (CKM) factors. We use the latest data on the semileptonic branching fraction [7,8], which is given by$B(b \to Xl\nu) = 0.108$, to rescale our result. The semileptonic rate is calculated including both charm and noncharm modes, assuming $|V_{ub}/V_{cb}| = 0.1$, and includes both phase space and QCD corrections [9] with $m_b = 5$ GeV and $m_c = 1.5$ GeV. The calculation of

$\Gamma(b \to s\gamma)$ employs the next-to-leading log evolution equations for the coefficients of the $b \to s$ transition operators in the effective Hamiltonian due to Misiak [10], the gluon bremsstrahlung corrections of Ali and Greub [11], the $m_t = M_W$ corrections of Cho and Grinstein [12], a running $\alpha_{\rm QED}$ evaluated at the b-quark mass scale, and three-loop evolution of the running α_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 also 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 standard and anomalous couplings of the top quark. The extraction of the functions $G_{1,2}$ is relatively straightforward. We insert the couplings presented in Eq. (1) into the two diagrams in which the photon is emitted from the internal top-quark line (those involving the W and charged Goldstone boson in the 't Hooft–Feynman gauge), and extract the pure dipole-like terms after performing the loop integrations. All other potential Lorentz structures are found to vanish as usual due to electromagnetic gauge invariance and the fact that the photon is on shell.

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 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

$$c_7(M_W) = G^7_{\rm SM} + \kappa_\gamma G_1 + i\tilde{\kappa}_\gamma G_2 \,,$$
$$c_8(M_W) = G^8_{\rm SM} + \kappa_g G_1 + i\tilde{\kappa}_g G_2 \,, \tag{2}$$

with

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

$$G_1 = \frac{1}{x-1} - \frac{\ln x}{(x-1)^2} + \frac{\frac{1}{2}x-1}{(x-1)^3}\left[\frac{1}{2}x^2 - 2x + \frac{3}{2} + \ln x\right] - \frac{1}{4}\,,$$
$$G_2 = \frac{-1}{x-1} + \frac{\ln x}{(x-1)^2} + \frac{1}{4}\,,$$

where $x = m_t^2/M_W^2$. Note that this result is completely finite and that we do not have to resort to the use of cutoffs to analyze our results.

In Fig. 1(a) 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 nonzero. For large negative (positive) values of κ_γ, we see that the branching fraction exceeds the inclusive CLEO upper (lower) bound. The constraint on κ_γ from the CLEO upper limit is not sensitive to m_t; however, the restriction on κ_γ from the lower CLEO bound varies

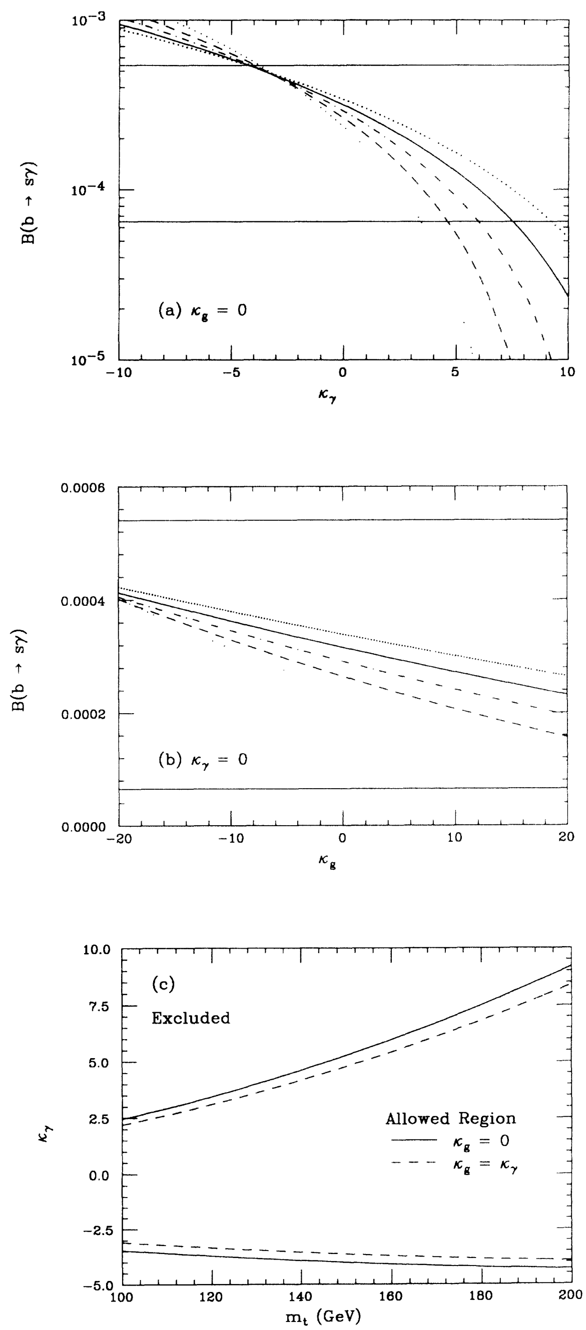

FIG. 1. The branching fraction for $b \to s\gamma$ as a function of (a) κ_γ with $\kappa_g = 0$ or (b) κ_g with $\kappa_\gamma = 0$, assuming $m_t = 120$(140, 160, 180, 200) GeV corresponding to the dotted (dashed, dash-dotted, solid, square-dotted) curve. The solid horizontal lines are the 95% C. L.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

significantly for m_t in the range 120–200 GeV. While the anomalous magnetic dipole moment effects the O_7 operators 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 obtainable on this parameter to be quite weak. We see this explicitly in Fig. 1(b) where we assume that only κ_g is nonzero. It is clear that unless extraordinarily large values of κ_g are realized, the present $b \to s\gamma$ data do not constrain this parameter. If both κ_g and κ_γ are taken to be nonzero, the bounds resulting from Fig. 1(a) on κ_γ are not significantly modified unless enormous values of κ_g are assumed. To demonstrate this we show in Fig. 1(c) the allowed range of κ_γ at the 95% C.L. as a function of m_t, assuming that κ_g is absent (solid curve) or is identical in value to κ_γ (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. For $m_t = 150$ GeV the anomalous magnetic dipole moment is constrained to lie in the range $(-2.6\text{–}3.4)\times 10^{-16}$ e cm, while for other values of m_t, the constraints scale as 6.6×10^{-17} (150 GeV/m_t) e cm multiplied by the bounds on κ_γ given in Fig. 1(c).

In the case of a nonzero 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 semidefinite in our numerical analysis. Since the contribution from these anomalous couplings can only *increase* the prediction of the $b \to s\gamma$ rate over that given by the SM, only the CLEO upper bound will provide a constraint in this case.

Figure 2(a) displays the $b \to s\gamma$ branching fraction as a function of $\tilde{\kappa}_\gamma$ for several different top-quark masses assuming all other effective 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 $m_t \gtrsim 125$ 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 $b \to s\gamma$ decay rate through operator mixing. Figure 2(b) 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. 2(c) we present the m_t dependence of the 95% C.L. upper bound on $\tilde{\kappa}_\gamma$ both when all other effective 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 $b \to s\gamma$ to the chromoelectric moment of the top quark. As pointed out above, the bound on $\tilde{\kappa}_\gamma$ strengthens with increasing m_t for values in excess of 125 GeV. However, we see that the constraints also become stronger as the value of m_t decreases from 125 GeV. The weak limits near $m_t = 125$ GeV are due to a cancellation between the various terms in G_2. For $m_t = 150$ GeV, the anomalous electric dipole moment is restricted to be $< 5.1\times 10^{-16}$ e cm.

How will the constraints we have obtained be improved in the future? From $b \to s\gamma$ 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 in-

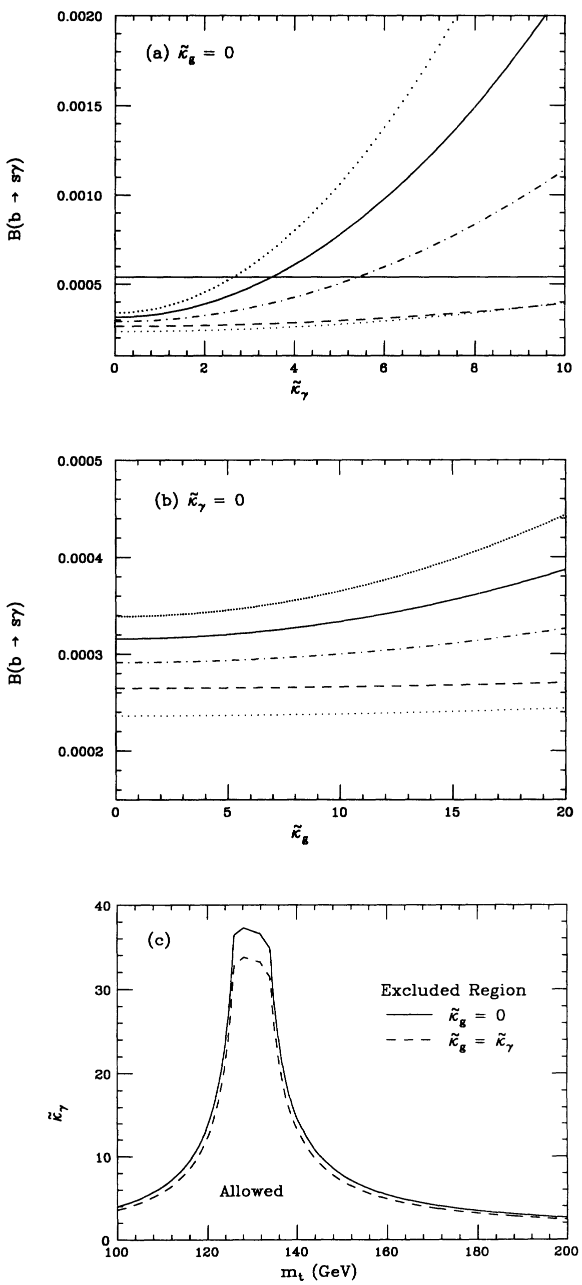

FIG. 2. Same as Fig. 1, but for the couplings $\tilde{\kappa}_g$ and $\tilde{\kappa}_\gamma$.

vestigated. 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 effective couplings that can be examined at these colliders will be for *on-shell* top quarks with *off-shell* photons and gluons, e.g., the situation opposite to that which we examine here. Peskin and Schmidt, Djouadi, and Berneuther [3] have studied in detail the capabilities of the NLC in constraining anomalous couplings of the top quark by the use of polarized beams and the top decay distribution. For integrated luminosities in the 10 fb^{-1} range, all these groups find comparable results, i.e., that both κ_γ and $\tilde{\kappa}_\gamma$ would be restricted to the range $<$ a few $\times 10^{-18}$ e cm. (Of course, such analyses will have to disentangle possible photon and Z anomalous interactions.) If higher luminosities and/or center of mass energies are obtainable, these limits might be improved by another order of magnitude. Although such bounds are far weaker than those already known to exist for more conventional particles, such as the electron, they improve the indirect limits that we have obtained above by more than two orders of magnitude. A similar situation is found to hold in the case of anomalous top couplings to gluons [2] except for the well-known difficulties involving strong interactions and the complexities of the hadron supercollider environment.

In summary, we have shown that the new CLEO results on radiative B decays place strong constraints on the anomalous electric and maganetic 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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