Study of Exclusive Radiative B Meson Decays


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We have studied exclusive, radiative $B$ meson decays to charmless mesons in $9.7 \times 10^6$ $B\bar{B}$ decays accumulated with the CLEO detector. We measure $\mathcal{B}(B^0 \to K^{0}(892)\gamma) = (4.55_{-0.72}^{+0.72} \pm 0.34) \times 10^{-3}$ and $\mathcal{B}(B^+ \to K^+(892)\gamma) = (3.76_{-0.83}^{+0.83} \pm 0.28) \times 10^{-3}$. We have searched for CP asymmetry in $B \to K^{*(892)}\gamma$ decays and measure $\mathcal{A}_{CP} = 0.08 \pm 0.13 \pm 0.03$. We report the first observation of $B \to K^*_2(1430)\gamma$ decays with a branching fraction of $(1.66_{-0.53}^{+0.61} \pm 0.13) \times 10^{-5}$. No evidence for the decays $B \to \rho \gamma$ and $B^0 \to \omega \gamma$ is found and we limit $\mathcal{B}(B \to (\rho/\omega)\gamma)/\mathcal{B}(B \to K^{*(892)}\gamma) < 0.32$ at 90\% C.L.

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The radiative decays, $B \to K^{*(892)}\gamma$ and $B \to \rho \gamma$, occur via the quark transition $b \to s, d$ that involves a loop ("penguin") diagram. In the standard model (SM), the loop amplitude is dominated by a virtual intermediate top quark of the $td$ (5284) unitarity triangle effects manifest in the charge asymmetry of amplitudes may result in observable direct non-standard-model (NSM) particles such as a supersymmetric Higgs. The significantly larger dataset now available allows a more precise determination of this branching fraction, the first measurement of charge asymmetries in these decays and the first search for $B \to \rho \gamma$ and $B^0 \to \omega \gamma$ decays. In addition, we report the first observation of $B \to K^*_2(1430)\gamma$ and the first search for the decay $B^0 \to \phi \gamma$ which cannot occur through a radiative penguin transition as the decay $B \to K^+\gamma$. No theoretical prediction exists in the literature for this decay.

The observation of $B \to K^+\gamma$ in 1993 by the CLEO collaboration [7] was the first evidence for $b \to s$ transitions. The data were recorded at the Cornell Electron Storage Ring (CESR) with the CLEO detector [8, 9]. The results in this Letter are based upon an integrated luminosity of 9.2 fb$^{-1}$ of $e^+e^-$ events corresponding to $9.7 \times 10^6$ $B\bar{B}$ meson pairs recorded at the Y(4S) energy and 4.6 fb$^{-1}$ at 60 MeV below the Y(4S) energy ["off-Y(4S)"]. The CLEO detector simulation is based upon GEANT [10]; simulated events are processed in the same manner as the data. The results presented in this Letter supersede the previous CLEO results [7].

Candidates for the decays $B \to K^0_{s}(\bar{q})\gamma$ with the subsequent decays $K^0_{s}(\bar{q}) \to K^+\pi^-\pi^0_{s}, K^0_{s}(\bar{q}) \to K^+\pi^0_{s}, K^0_{s}\pi^+\pi^-$ are selected. We define $K^*(K^0_{s})$ candidates by requiring that the $K\pi$ mass be within $110$ (120) MeV of 890 (1430) MeV. We reconstruct the decays $B \to \rho \gamma$ with $\rho^{0,+} \to \pi^+\pi^-\pi^0$, $B^0 \to \omega \gamma$ with $\omega \to \pi^+\pi^-\pi^0$, and $B^0 \to \phi \gamma$ with $\phi \to K^+K^-$. Reference to the charge conjugate states is implicit unless explicitly stated otherwise. The charged track and $K^0_{s}$ candidates are required to be well reconstructed and to originate near the $e^+e^-$ interaction point (IP). Charged kaons and pions are distinguished using the particle’s measured specific ionization $(dE/dx)$. We require that the $dE/dx$ information, when available, is consistent with the appropriate hypothesis.

The dominant background comes from continuum ($e^+e^- \to q\bar{q}$ with $q = u, c, s, d$) events with high energy photons originating from initial state radiation or $e^+e^- \to (\pi^0, \eta)X$ with $\pi^0, \eta \to \gamma\gamma$. The $\cos \theta_{\gamma}$ requirement reduces the former background while the latter background is suppressed by rejecting candidate photons that, when combined with an additional photon candidate, have a mass consistent with the $\pi^0$ or $\eta$ mass [5]. The additional selection criteria described below reduce backgrounds from nonradiative $B$ decays to a negligible level. Background from radiative $B$ decays other than the one under study is discussed later.

We suppress the remaining background from nonradiative $B$ decays and continuum by placing requirements on the observables $\theta_T$ (the angle between the thrust axis [11] of the $B$ candidate and the thrust axis of the remainder of the event), $\theta_B$ (the angle between the $B$ candidate direction and the beam axis), $M(R)$ and $\theta_H$ (the mass and helicity angle of the light meson resonance candidate) and $dE/dx$.

Additional background suppression is achieved by requiring the $B$ candidate energy $\Delta E = E(R) + E(\gamma) - E_{beam}$ and the beam-constrained $B$ mass $M^2(B) = E_{beam}^2 - (p(\gamma) + p(R))^2$, where the photon momentum $p(\gamma)$ is rescaled by fixing $E(\gamma) = E_{beam} - E(R)$. The $\Delta E [M(B)]$ resolution of 40 MeV [2.8 MeV] is dominated by the photon energy resolution (beam energy spread). We select signal and sideband candidates by requiring $|\Delta E| < 300$ MeV and...
$5.2 < M(B) < 5.3$ GeV. If two or more candidates in an event pass all selection criteria and share daughter tracks or photons, the candidate with the smallest deviation from the nominal resonance mass is selected. For the $B \rightarrow \rho \gamma$ analysis, the candidate with the smallest $|\cos \theta_B|$ is selected.

We optimize these selection criteria for the $B \rightarrow K^{(2)}_{(s)} \gamma$ analyses to maximize $S^2/(S+B)$, where $S$ is the number of expected signal candidates determined from simulated events assuming $B(B \rightarrow K^{*} \gamma) = 4.2 \times 10^{-5}$ [5] and $B(B \rightarrow K^{(2)}_{(s)} \gamma) = 1.6 \times 10^{-5}$ [12] and $B$ is the number of background candidates determined from off-$Y(4S)$ data. For the other analyses the selection criteria are optimized to yield the smallest upper limit on the branching fraction on average using the method in Ref. [13].

We perform a simultaneous, binned, maximum-likelihood fit to the four $M(B)$ distributions of $B^0 \rightarrow (K^{*} \pi^-) \gamma$, $B^0 \rightarrow (K^0 \pi^0) \gamma$, $B^+ \rightarrow (K^+ \pi^0) \gamma$, and $B^+ \rightarrow (K^0 \pi^+) \gamma$ candidates requiring $|\Delta E| < 100$ MeV. In the fit the signal component is represented by a Gaussian distribution and the background is represented by a threshold function [14]. The fitted total yields for $B^0 \rightarrow K^{*0} \gamma$ and $B^+ \rightarrow K^{*+} \gamma$ are $88.3^{+12.2}_{-11.5}$ and $36.7^{+8.3}_{-7.6}$ (Fig. 1) and correspond to branching fractions of $(4.55^{+0.68}_{-0.34}) \times 10^{-5}$ and $(3.76^{+0.83}_{-0.28}) \times 10^{-5}$, respectively. The fractional systematic uncertainties on the measured branching fractions comprise a common uncertainty of 6.8% dominated by the background shape (5%), the radiative photon detection efficiency (3.3%), and the uncertainties on the reconstruction efficiency of each $K^*$ decay mode that range from 2.6% ($K^0 \pi^+$) to 5.9% ($K^0 \pi^0$).

The reconstruction efficiency for modes with a charged (neutral) pion in the final state is 27% (13%). We assume $B(Y(4S) \rightarrow B^0 B^0) = B(Y(4S) \rightarrow B^+ B^-) = 0.5$ for all branching fractions in this Letter.

Backgrounds from $B \rightarrow$ charm are negligible and backgrounds from charmless two-body $B$ meson decays are estimated to contribute less than 1.2 and 0.6 events to the $B^0 \rightarrow K^{*0} \gamma$ and $B^+ \rightarrow K^{*+} \gamma$ yields, respectively, based on simulated decays, and are neglected in the evaluation of the branching fractions. We fit the $M(K \pi)$ distribution summed over $K^{*0}$ and $K^{*+}$ within $\pm 150$ MeV of the $K^*$ mass [5] to search for a nonresonant $B \rightarrow K \pi \gamma$ contribution to the calculated $B \rightarrow K^* \gamma$ yields. No significant nonresonant component with a threshold shape $\times [M(K \pi) - M(K) - M(\pi)]^{1/2}$ is found, but allowing for a nonresonant component would contribute an additional relative uncertainty in the fitted yield of 12%. The fitted nonresonant yield is $-16.8 \pm 14.7$ events or less than 23% of the total yield at 90% C.L.

We search for direct CP violation by measuring the partial rate asymmetry $\mathcal{A}_{CP}$.

$$\mathcal{A}_{CP} = \frac{1}{1 - 2\eta} \frac{\mathcal{Y}(B \rightarrow \bar{K}^* \gamma) - \mathcal{Y}(B \rightarrow K^* \gamma)}{\mathcal{Y}(B \rightarrow \bar{K}^* \gamma) + \mathcal{Y}(B \rightarrow K^* \gamma)},$$

where $\mathcal{Y}$ is the fitted yield and $\eta$ is the mistag fraction. We use the $K^*$ decay modes $K^+ \pi^-$, $K^+ \pi^0$, and $K^0 \bar{\pi}^+$ to measure $\mathcal{A}_{CP}$. In these decay modes the charge of the kaon or the $K^*$ contains unambiguous information about the $B$ flavor. Only the $K^+ \pi^-$ decay mode has a mistag rate significantly different from zero, as determined from simulated events. Mistagging in this mode is due to the 100% transverse polarization of the $K^{*0}$, from $B^0 \rightarrow K^{*0} \gamma$ decays, that results in a $\sin^2 \theta_H$ distribution. This distribution favors nearly equal momenta of $\sim 1.2$ GeV/c for the charged kaon and pion from the $K^*$. The kaon and pion cannot be kinematically distinguished when $p_K = p_\pi$, and their expected $dE/dx$ is nearly identical in this momentum range. We exclude these ambiguous $K^{*0}$ candidates from the $\mathcal{A}_{CP}$ measurement by requiring $|p(K) - p(\pi)| > 0.5$ GeV/c. This requirement minimizes the statistical uncertainty on $\mathcal{A}_{CP}$ in the $K^+ \pi^-$ decay mode with $\eta = (3.45 \pm 0.02\%)$ and a relative efficiency of $(62.0 \pm 0.5\%)$ as determined from simulated events.

To measure $\mathcal{A}_{CP}$, we fit the $M(B)$ distributions of $B \rightarrow K^* \gamma$ and $B \rightarrow \bar{K}^* \gamma$ candidates simultaneously for both neutral and charged $B$ meson decays to extract the total yield and asymmetry of both the $B \rightarrow K^* \gamma$ signal and the background in the range $5.2 < M(B) < 5.3$ GeV with a procedure similar to that described for the $B \rightarrow K^* \gamma$ branching fractions. For neutral and charged $B \rightarrow K^* \gamma$ decays, we determine $\mathcal{A}_{CP} = -0.13 \pm 0.17$ and $+0.38^{+0.20}_{-0.19}$, respectively, for the signal and $-0.03 \pm 0.08$ and $+0.06 \pm 0.09$ for the background. The asymmetry for the sum of neutral and charged $B \rightarrow K^* \gamma$ decays

![Figure 1](https://example.com/figure1.png)

**FIG. 1.** Beam-constrained $B$ mass distributions for (a) $B^0 \rightarrow K^{*0}(892) \gamma$, (b) $B^+ \rightarrow K^{*+}(892) \gamma$, and (c) $B \rightarrow K^*_2(1430) \gamma$. The data (solid circles) are overlaid with the fit to a Gaussian and background shape [14] (solid line). The fitted background is indicated by the dashed line.
is \( +0.08 \pm 0.13 \) \((+0.01 \pm 0.06)\) for the signal (background). Systematic searches for detector- or reconstruction-induced charge asymmetries for charged pions and kaons revealed no significant bias \((|\Delta A_{CP}| < 1.5\%\)). In addition, studies of simulated \( B \to K^*\gamma \) decays indicate that cross-feed between different \( K^* \) modes is \(<1\%.\) Our conservative estimate of the systematic uncertainty on \( A_{CP} \) is 2.5\%.

Radiative \( B \) meson decays to the \( K_2^* \) and the nearby \( K^{*}(1410) \) can be distinguished by the helicity angle distributions \((\propto \cos^2 \theta_H - \cos \theta_H \sin \phi_H, \propto \sin^2 \theta_H, \) respectively) as well as the resonance widths of \( \sim 100 \) and \( \sim 230 \) MeV [5]. We fit the \( M(B) \) distributions of candidates that pass (fail) the requirement \(|\cos \theta_H| < \mathcal{H}| \) designed to enhance (deplete) \( B \to K_2^*\gamma \) decays, where \( \mathcal{H} \) ranges from 0.20 to 0.30 depending on the \( K_2^* \) decay mode. The overall efficiency for passing [failing] the helicity angle requirements is \((10.1 \pm 0.3\%) \,(1.09 \pm 0.08\%\) and \((0.80 \pm 0.13\%)\, (0.59 \pm 0.10\%\) for simulated \( B \to K_2^*\gamma \) and \( B \to K^{*}(1410)\gamma \) decays, respectively, where the quoted efficiency includes \( \mathcal{B}(K_2^* \to K\pi) = (49.9 \pm 1.2\%) \) and \( \mathcal{B}(K^{*}(1410) \to K\pi) = (6.6 \pm 1.3\%\) [5]. The simultaneous determination of \( \mathcal{B}(B \to K_2^*\gamma) \) and \( \mathcal{B}(B \to K^{*}(1410)\gamma) \) from the two fitted yields and the quoted efficiencies shows that \( \mathcal{B}(B \to K_2^*\gamma) \) is significant at over \( 3\sigma \) for the most probable value of \( \mathcal{B}(B \to K^{*}(1410)\gamma) \) while \( \mathcal{B}(B \to K^{*}(1410)\gamma) \) is less than \( 1\sigma \) significant for the most probable value of \( \mathcal{B}(B \to K_2^*\gamma) \). We therefore interpret the signal as being due to \( B \to K_2^*\gamma \) only and determine \( \mathcal{B}(B \to K^{*}(1410)\gamma) < 12.7 \times 10^{-5} \) at 90\% C.L. The \( M(B) \) distribution of \( B \to K_2^*\gamma \) candidates passing the \(|\cos \theta_H| \) requirements is shown in Fig. 1(c), summed over the charged and neutral \( K_2^* \) meson decays. The fitted yield of \( 15.9^{+5.7}_{-3.1} \) events is significant at \( 4.3\sigma \) \((3.3\sigma)\) before (after) inclusion of systematic uncertainties. Assuming equal decay rates to charged and neutral \( K_2^* \), the yield corresponds to a branching fraction of \((1.66^{+0.59}_{-0.53} \pm 0.13) \times 10^{-5}, \) where the systematic uncertainties are evaluated as described for the \( B \to K^*\gamma \) branching fractions.

The branching fractions of \( B \to K^*\gamma \) and \( B \to K_2^*\gamma \) have been predicted by two groups [12,15] and differ in the treatment of long-distance effects on the form factors. The minimal uncertainty is achieved by the ratio \( \mathcal{B}(B \to K_2^*\gamma)/\mathcal{B}(B \to K^*\gamma) = 0.39^{+0.15}_{-0.13} \) that compares favorably with the prediction of Veseli and Olsson of 0.37 \pm 0.10 [12,16] and disagrees with the Ali, Ohl, and Mennel range of \( 3.0-4.9 \) [15].

In order to limit \( |V_{ud}/V_{ub}| \), we searched for the decays \( B \to \rho \gamma \) and \( B^0 \to \omega \gamma \). The \( \rho \gamma \) final states suffer from background both from continuum and from \( B \to K^*\gamma \) when a charged kaon is misidentified as a pion. Continuum is the only significant background to \( B \to \omega \gamma \). The \( \Delta E \) vs \( M(\pi\pi) \) distributions for \( B^0 \to \rho^0\gamma \) and \( B^+ \to \rho^+\gamma \) candidates are shown in Fig. 2 after a requirement of \( 5274 < M(B) < 5286 \) MeV. The \( K^* \) background peaks in the lower left-hand corner of each distribution while the signal peaks near the center, and the continuum background is constant. Twenty-four [ten] candidates survive the final selection criterion. The dotted line distinguishes events that would contain 90\% of the \( B \to \rho \gamma \) \((B \to K^*\gamma)\) candidates.
distribution. This corresponds to the ground to be shown in Fig. 3(b). We estimate the combinatorial background at 90% C.L.

$\epsilon_i$ is the reconstruction efficiency, and $\mathcal{B}_{ij}$ is the daughter branching fraction. Similarly, we form $\mathcal{L}(|V_{td}/V_{ts}|)$ by using the relationship $|V_{td}/V_{ts}|^2 = R/\xi$, where $\xi$ is the ratio of the $B \to \rho \gamma$ and $B \to K^* \gamma$ form factors. The upper limit of $R < 0.32$ (0.36) corresponds to $|V_{td}/V_{ts}| < 0.72 (0.76)$ at 90% (95%) C.L. for $\xi = 0.58 [1]$. Other estimates of $\xi$ are 0.77 [17] and 0.81 ± 0.09 [18]. Our evaluation of $a |V_{td}/V_{ts}|$ limit assumes that these decays proceed via top-quark-dominated electromagnetic penguin transitions and neglects possible contributions from final state interactions [19], $W$ exchange [20], or $W$ annihilation [21].

We observe one $B^0 \to \phi \gamma$ candidate in the signal region $|\Delta E| < 100$ MeV and 5274 < $M(B) < 5286$ MeV shown in Fig. 3(b). We estimate the combinatorial background to be 1.2 ± 0.1 events from the fit to the $M(B)$ distribution. This corresponds to $\mathcal{B}(B^0 \to \phi \gamma) < 0.33 \times 10^{-5}$ at 90% C.L. with the reconstruction efficiency of (23.0 ± 0.6)%.

In summary, the $B \to K^*(892)\gamma$ branching fractions have been measured with improved precision. A new radiative decay mode $B \to K^*_2(1430)\gamma$ has been observed and found to agree with one of two theoretical predictions. The partial rate asymmetries in $B \to K^*(892)\gamma$ decays are measured with a precision of better than 20% and found to be consistent with standard model expectations. We find no evidence for the process $b \to d \gamma$ and determine a limit on the ratio of $\mathcal{B}(B \to \rho \gamma)/\mathcal{B}(B \to K^*(892)\gamma) < 0.32$ at 90% C.L. Using a model-dependent derivation of the ratio of the $B \to \rho \gamma$ and $B \to K^*(892)\gamma$ form factors, the ratio of branching fractions implies that $|V_{td}/V_{ts}| < 0.72$ at 90% C.L.

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[2] We refer to $K^*(892)$ as $K^*$, and $K^*_2(1430)$ as $K^*_{20}$.
[14] $f(x) \propto x^{\kappa-1} - x^{\kappa} \exp[\kappa(1 - x^2)]$, where $x = M(B)/E_{\text{beam}}$. The parameter $\kappa$ is determined by the fit. H. Albrecht et al., Phys. Lett. B 241, 278 (1990); 254, 288 (1991).
[16] The uncertainty on the ratio of branching fractions is dominated by the additional fractional uncertainty in $\mathcal{B}(B \to K^*_2 \gamma)$ M.G. Olsson (private communication).