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Search for $B \to \mu\bar{\nu}_\mu\gamma$ and $B \to e\bar{\nu}_e\gamma$

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Abstract

We have searched for the decays $B \to \mu\bar{\nu}_\mu\gamma$ and $B \to e\bar{\nu}_e\gamma$ in a sample of 2.7 million charged B decays collected with the CLEO II detector. In the muon channel, we observe no candidates in the signal region and set an upper limit on the branching fraction of $\mathcal{B}(B \to \mu\bar{\nu}_\mu\gamma) < 5.2 \times 10^{-5}$ at the 90% confidence level. In the electron channel, we observe 5 candidates in the signal region and set an upper limit on the branching fraction of $\mathcal{B}(B \to e\bar{\nu}_e\gamma) < 2.0 \times 10^{-4}$ at the 90% confidence level.

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In the Standard Model, a measurement of the Cabibbo-Kobayashi-Maskawa mixing angle, V_{ub}, and the $B\overline{B}$ mixing parameter, x_d, can be used to place constraints on the unknown CKM constants of the Wolfenstein parameterization, ρ and η [1] [2]. However, the constraint from $B\overline{B}$ mixing depends on the unmeasured quantity f_B, the B decay constant. Theoretical estimates of f_B vary from 190 MeV by QCD sum rules [3] to around 370 MeV by lattice QCD calculations in the static quark limit [4]. The only direct experimental means to access f_B is through an observation of the purely leptonic decays $B \to \ell\bar{\nu}_\ell$. (Throughout this paper, decays of the type $B \to \ell\bar{\nu}_\ell X$ refer to both $B^- \to \ell^-\bar{\nu}_\ell X$ and $B^+ \to \ell^+\nu_\ell X$.) Both CLEO [5] and ALEPH [6] have published upper limits for $B \to \ell\bar{\nu}_\ell$. However, these limits are are at least an order of magnitude larger than decay rates predicted by the Standard Model, which are low due to the effects of helicity suppression. In this letter, we describe an alternative method of determining f_B through leptonic decays involving hard photon emission.

According to the model of Burdman, Goldman, and Wyler (BGW) [7], the decay rate for $B \to \ell\bar{\nu}_\ell\gamma$ is dominated by Structure Dependent (SD) photon emission. In the SD process, a photon is produced in the transition of a spin-0 B meson to a spin-1 off-shell vector or axial-vector B meson. Because the heavy intermediate state has spin-1, helicity suppression does not occur. Hence, the SD process is suppressed only by the photon coupling. The decay rate depends on the strength of the photon coupling to both the heavy and light quark pieces of the electromagnetic current, the mass difference between the initial and intermediate B meson, and the decay constant of the intermediate B meson. These values are expected to differ for transitions involving vector (B^*) and axial-vector ($B^{'}$) mesons. In the context of Heavy Quark Symmetry (HQS) [8], the axial vector meson has an angular momentum L=1 and may belong to one of two separate spin doublets. These states are labelled j=1/2 and j=3/2, according to the total angular momentum carried by the light degrees of freedom. The B^*-B and $B^{'}$-B mass differences are measured directly [9] [10], and the photon coupling constants (μ^*, $\mu^{'}_j$) are estimated from a combination of charm system measurements and theory [7]. Therefore, to a first approximation, the only uncertain parameters are the decay constants (f^*_B, $\mathrm{f}^{'}_{B_j}$).

Since HQS cannot relate the decay constants of heavy mesons belonging to different spin doublets, it is useful to define the relative strength of the axial-vector and vector processes as:

$$\gamma_j \equiv \frac{\mu^{'}_j \mathrm{f}^{'}_{B_j}}{\mu^* \mathrm{f}^*_B} \quad . \tag{1}$$

If γ_j is small, an observation of $B \to \ell\bar{\nu}_\ell\gamma$ would provide a measurement of f^*_B. Knowledge of f^*_B, together with the HQS relation f^*_B=$\mathrm{m}_B\,\mathrm{f}_B$ [11], would then provide an alternative (albeit model-dependent) means to determine f_B. We might expect γ_j to be small because, according non-relativistic models, $\mathrm{f}^{'}_{B_j}$ is zero. However, relativistic effects can modify these predictions drastically, and allow for values of γ_j between 0 and 1 [12]. Currently, there are no conclusive experimental indications from other hadronic systems of the relative strength of the axial-vector and vector processes. In this paper, we assume $\gamma_j = 0$.

Due to the absence of helicity suppression the decay rate for $B \to \ell\bar{\nu}_\ell\gamma$ is expected to be comparable to or larger than $B \to \ell\bar{\nu}_\ell$ decays. In addition, to first order in $(m_\ell/m_B)^2$, the decay rate is independent of the lepton species. The expected range for the $B \to \ell\bar{\nu}_\ell\gamma$ branching fraction is:

$$1.0 \times 10^{-6} \ < \ \mathcal{B}(B \to \ell \bar{\nu}_\ell \gamma) \ < \ 4.0 \times 10^{-6} \ , \tag{2}$$

where we have used $\tau_{\rm B} = 1.6$ ps, f^*_B= 1.0 GeV^2, and V_{ub}=0.003 as reasonable estimates for these parameters [13] [14] [15]. If we take $\mathcal{B}(B \to \ell \bar{\nu}_\ell \gamma) = 4.0 \times 10^{-6}$, then

$$\mathcal{B}(B \to e \bar{\nu}_e \gamma) \gg \mathcal{B}(B \to e \bar{\nu}_e), \tag{3}$$

$$\mathcal{B}(B \to \mu \bar{\nu}_\mu \gamma) \approx 16 \times \mathcal{B}(B \to \mu \bar{\nu}_\mu), \tag{4}$$

$$\text{and} \quad \mathcal{B}(B \to \tau \bar{\nu}_\tau \gamma) \ll \mathcal{B}(B \to \tau \bar{\nu}_\tau). \tag{5}$$

This letter will focus on a search for $B \to e \bar{\nu}_e \gamma$ and $B \to \mu \bar{\nu}_\mu \gamma$.

We search for events in which there is an energetic lepton-photon pair and the remaining particles are consistent with the decay of a second B. One lepton-photon candidate per event is selected using the most energetic lepton and most energetic photon in the event. According to the BGW model, the lepton energy spectrum for $B \to \ell \bar{\nu}_\ell \gamma$ is slightly more peaked at high energies than would be expected from phase space alone, and has a mean value of 2.0 GeV. The photon energy spectrum has an inverted-parabolic shape with a mean value 1.3 GeV (see Figure 1). The constraints involving particles of the second B are enforced by requiring that the invariant mass and the energy of all detected particles except the lepton-photon pair be consistent with the B mass and beam energy, respectively. We also require that the missing energy and missing momentum of the event be consistent with an undetected neutrino.

The data used in this search were collected with the CLEO II detector operating at the Cornell Electron Storage Ring (CESR). The data consist of approximately 2.7 million $\Upsilon(4S) \to B\bar{B}$ events collected along with 9.6 million continuum events at the $\Upsilon(4S)$ resonance at $\sqrt{s}$ = 10.58 GeV (the "on-resonance" sample). We also use a sample of 5.0 million continuum events collected below resonance at $\sqrt{s} = 10.52$ GeV for background subtraction (the "off-resonance" sample). The on- and off-resonance samples correspond to an integrated luminosity of 2.5 fb^{-1} and 1.3 fb^{-1}, respectively.

The features of the CLEO II detector [16] relevant to this analysis are described here. The trajectories of charged particles are reconstructed using a system of three concentric wire chambers covering 95% of 4π in an axial magnetic field of 1.5 T. A CsI electromagnetic calorimeter covering 98% of 4π detects photons with energies above 30 MeV. Photon candidates are identified by showers in the calorimeter that are not matched to reconstructed tracks in the tracking chamber. Electrons above 1.8 GeV are identified using the momentum-energy balance of tracks matched to showers in the calorimeter and the specific ionization (dE/dx) of tracks in the drift chamber. Muons are required to penetrate at least 7 nuclear absorption lengths of steel surrounding the magnetic coil. This places a lower limit of approximately 2.0 GeV on the muon momentum. Other charged particles are identified through their specific ionization in the main drift chamber. All charged tracks are assigned the pion mass unless they are identified as leptons or their dE/dx is inconsistent with the pion mass hypothesis ($> 2\sigma$) and consistent with either the kaon or proton mass hypothesis ($< 2\sigma$).

We select hadronic events by requiring that there be at least 4 charged tracks and significant visible energy. Other continuum backgrounds (including two photon events) are suppressed by requiring $|\cos\theta_{\rm miss}| < 0.95$, where $\theta_{\rm miss}$ is the angle between the missing momentum and the beam line. This requirement also reduces the number of events containing particles that are lost down the beam pipe. To further suppress continuum decays, we select events that are spherical in shape by requiring that the ratio of the second and zeroth Fox-Wolfram moments [17] (R_2) be less than 0.25.

To identify signal candidates we select one lepton-photon candidate per event using the most energetic lepton and most energetic photon in the event. We then require that the energy, E_2, and the invariant mass, M_2, of all particles in the event except the lepton-photon pair be consistent with coming from a single B decay. In particular, we require 4.8 GeV $< E_2 <$ 5.5 GeV and $M_2 >$ 5.27 GeV. In calculating M_2, we set $E_2 = \mathrm{E_{beam}}$. These requirements suppress events with missing charged tracks, additional neutrinos, and undetected or partially-detected neutral hadrons. After all other cuts, we look for signal events where the missing energy, E_ν, and missing momentum, P_ν, are consistent with an undetected neutrino; in particular, we require $|\mathrm{E}_\nu - \mathrm{P}_\nu| <$ 200 MeV. This constraint is further tightened by substituting $E_2 = \mathrm{E_{beam}}$ and $P_2 =$ 0.320 GeV (the momentum of a B created at the Υ(4S) resonance) in the calculation of $\mathrm{E}_\nu - \mathrm{P}_\nu$.

Backgrounds to $B \to \ell\bar{\nu}_\ell\gamma$ from generic $b \to c\ell\overline{\nu}_\ell$ and $b \to u\ell\overline{\nu}_\ell$ decays frequently occur when the primary lepton is combined with a photon from a π^0 decay. To suppress these backgrounds, we calculate the invariant of mass, $\mathrm{M}_{\gamma\gamma}$, of the candidate photon (the most energetic photon) with respect to all other photons in the event. If any of the $\mathrm{M}_{\gamma\gamma}$ combinations are consistent with the π^0 mass (110 MeV $< \mathrm{M}_{\gamma\gamma} <$ 160 MeV), then the event is discarded. To further suppress $b \to c\ell\overline{\nu}_\ell$ decays, we require that the cosine of the lepton-photon opening angle, $\cos\theta_{\ell\text{-}\gamma}$, be less than 0. This requirement is efficient for signal decays, where the lepton and photon are often produced back-to-back. However, for $b \to c\ell\overline{\nu}_\ell$ events, the decay kinematics and the neutrino mass constraint together favor a small lepton-photon opening angle.

The probability that a $B \to \mu\bar{\nu}_\mu\gamma$ candidate satisfies all selection criteria and lies in the signal region is $(1.93 \pm 0.04)\%$, where the error is statistical only. The corresponding probability for a $B \to e\bar{\nu}_e\gamma$ candidate is $(2.06 \pm 0.14)\%$. These probabilities are determined using a Monte Carlo simulation with the corrections described below.

For the $B \to \mu\bar{\nu}_\mu\gamma$ analysis, the mean number of on(off)-resonance candidates expected from background Monte Carlo to fall into the $\mathrm{E}_\nu - \mathrm{P}_\nu$ sideband, defined by 200 MeV $< \mathrm{E}_\nu - \mathrm{P}_\nu <$ 2 GeV, is $41.3 \pm 3.8(1.0 \pm 0.6)$. Of this yield, 93% come from $b \to c\mu\overline{\nu}_\mu$ decays where the primary muon is the lepton candidate. A much smaller background comes from $q\overline{q}$ events (6%) and $b \to u\mu\overline{\nu}_\mu$ decays (1%). The normalization of the background is determined using the known values for the $B\overline{B}$ and continuum $q\overline{q}$ cross sections. The mean number of background candidates in the signal region is predicted to be 0.5 ± 1.1. The number of on(off)-resonance candidates in the data that fall into the $\mathrm{E}_\nu - \mathrm{P}_\nu$ sideband is $51.0 \pm 7.1(2.0 \pm 1.4)$. A comparison of the Monte Carlo and data $\mathrm{E}_\nu - \mathrm{P}_\nu$ distributions is shown in Figure 2; their agreement helps confirm our understanding of the normalization and composition of the background. No candidates in either the on- or off-resonance sample fall into the signal region. We obtain an upper limit on the signal yield based on zero candidates.

For the $B \to e\bar{\nu}_e\gamma$ analysis, the mean number of on(off)-resonance candidates expected from background Monte Carlo to fall into the $\mathrm{E}_\nu - \mathrm{P}_\nu$ sideband is $79.9 \pm 5.2(1.3 \pm 0.6)$. Of this yield, 97% come from $b \to ce\overline{\nu}_e$ decays where the primary electron is the lepton candidate. The remainder of the background comes from $q\overline{q}$ events (2.4%) and $b \to ue\overline{\nu}_e$ decays (0.6%). The total number of background candidates in the signal region is predicted to be 0.1 ± 0.7.

Only generic $b \to u e \overline{\nu}_e$ candidates contribute to this yield. To obtain an alternative estimate of this yield, we assume a uniform background distribution in the E_2 and M_2 sidebands, and determine the number of candidates in the signal region by extrapolation. Using this method, we obtain an estimate of 1.6 ± 0.1 candidates. This yield is likely an overestimate of the actual background level, since the M_2 background distribution is known to fall sharply above 5.285 GeV [18]. The number of on(off)-resonance candidates in the data that fall into the $\mathrm{E}_\nu - \mathrm{P}_\nu$ sideband is 88.0 ± 9.4 (1.0 ± 1.0). While the data and the Monte Carlo background agree well in the $\mathrm{E}_\nu - \mathrm{P}_\nu$ sideband, they do not agree in the signal region, where we observe 5 on-resonance candidates and 0 off-resonance candidates (see Figure 3).

Each of the 5 candidate signal events was individually examined. None of these events is consistent with a two-photon interaction based on the correlation between the lepton-candidate direction and the beam direction [19]. The candidate events are also not consistent with being beam-gas events, or events containing lepton candidates from photon conversions and $J/\psi \to \mathrm{e}^+\mathrm{e}^-$ decays. Further, it is unlikely that these events are signal events, since the difference in yields between the $B \to \mu\nu\gamma$ and $B \to e\bar{\nu}_e\gamma$ analyses is in disagreement with the lepton-mass independence of the $B \to \ell\bar{\nu}_\ell\gamma$ decay rate in the BGW model. A final possibility is that the candidate events are a product of an upward statistical fluctuation of known backgrounds. If we assume a predicted background of 1.6 candidates, the probability of observing 5 or more candidates is 2.4%. Although it is possible that all five candidates are background, the most conservative upper limit is obtained by assuming that all are signal candidates. We therefore report an upper limit for $B \to e\bar{\nu}_e\gamma$ based on the 5 observed candidates.

The signal detection efficiency is checked with independent data samples and corrected where necessary. In particular, the efficiency for the E_2, M_2, and R_2 requirements is checked using the remaining particles in events in which one of the two B decays has been reconstructed as $B \to D^*\ell\overline{\nu}_\ell$ [20]. A systematic correction on the combined efficiency for the E_2, M_2, and R_2 is estimated by comparing Monte Carlo and data $B \to D^*\ell\overline{\nu}_\ell$ events, and is 0.920 ± 0.134. The uncertainty on this correction is dominated by the statistics of the study. The efficiency for the π^0 veto is checked by calculating $\mathrm{M}_{\gamma\gamma}$ of a signal photon with respect to all other photons in generic $B\overline{B}$ Monte Carlo and data events. The resulting correction factor is 1.007 ± 0.037, where the error is statistical. Other smaller systematic effects related to lepton selection, photon selection, and the electroweak correction to the electron momentum spectrum have been discussed elsewhere [21]. A summary of these systematic studies is given in Table I.

Uncertainties on the signal detection efficiency also arise from an incomplete knowledge of γ_j in the BGW model. In particular, large values of γ_j imply a greater admixture of axial-vector meson decays which results in a harder photon energy spectrum and softer lepton spectrum. Since both high energy leptons *and* photons are favored by the event selection criteria, larger values of γ_j simultaneously increase the photon selection efficiency and decrease the lepton selection efficiency. To study the net systematic effect on the signal detection efficiency, we use a signal Monte Carlo with an inordinately high value for the relative axial vector strength, γ_j=1, and find a net increase in the signal detection efficiency by a factor 1.039 ± 0.040. Since we are measuring upper limits for $B \to \mu\nu\gamma$ and $B \to e\nu\gamma$, the choice γ_j=0 in our BGW signal Monte Carlo leads to a conservative estimate of the efficiency.

The total uncertainty on the signal detection efficiency is obtained by adding the systematic uncertainty ($\pm 14.8\%$) and statistical uncertainty ($\pm 1.9\%$ for $B \to \mu\bar{\nu}_\mu\gamma$ and $\pm 6.7\%$ for $B \to e\bar{\nu}_e\gamma$) in quadrature. In addition, there is an uncertainty of $\pm 1.8\%$ in the number of B^+B^- events in our data sample.

To calculate an upper limit on the number of signal candidates observed, we use Poisson statistics [22]. If we regard all on-resonance candidates that pass the event selection criteria as signal candidates, we obtain an upper limit on the signal yield for $B \to \mu\bar{\nu}_\mu\gamma$ and $B \to e\bar{\nu}_e\gamma$ of 2.3 and 9.3, respectively, at the 90% confidence level. To calculate an upper limit on the branching fraction, the estimated signal detection efficiency is reduced by one standard deviation. This, combined with the total number of charged B decays in the data sample (about 2.7 million), gives:

$$\mathcal{B}(B \to \mu\bar{\nu}_\mu\gamma) < 5.2 \times 10^{-5} \quad (90\%\ \mathrm{CL}), \tag{6}$$

$$\mathcal{B}(B \to e\bar{\nu}_e\gamma) < 2.0 \times 10^{-4} \quad (90\%\ \mathrm{CL}). \tag{7}$$

Using the upper limit on $\mathcal{B}(B \to \mu\bar{\nu}_\mu\gamma)$, the assumption γ_j=0, and the allowed range of μ^*, we extract a range of limits on f^*_B. Given the lower(upper) limit for μ^*, we obtain $\mathrm{f}^*_B <$ 7.25(3.62) GeV^2 at the 90% confidence level. Using the HQS relation $\mathrm{f}^*_B = \mathrm{m}_B\,\mathrm{f}_B$, we obtain $\mathrm{f}_B <$ 1.37(0.69) GeV at the 90% confidence level. For comparison, the constraint obtained from the upper limit on $B \to \tau\bar{\nu}_\tau$ [5] is $\mathrm{f}_B <$ 1.23 GeV at the 90% confidence level.

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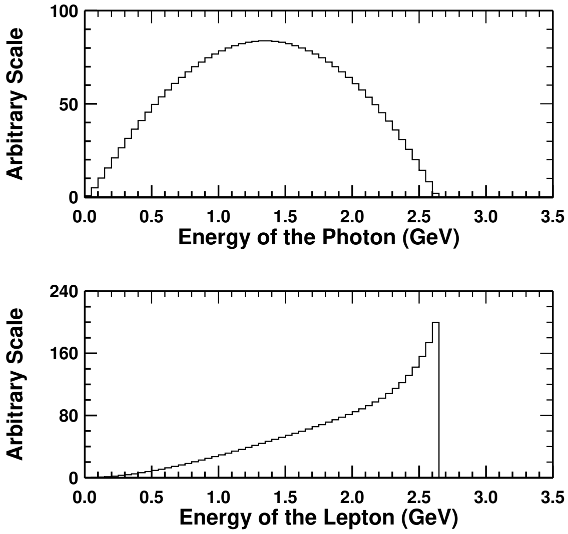

FIG. 1. The lepton and photon spectra of $B \to \ell \bar{\nu}_\ell \gamma$ decays in the B rest frame (BGW model).

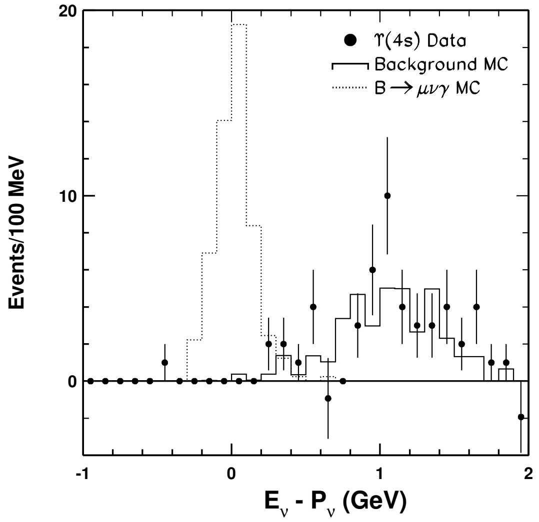

FIG. 2. The $E_\nu - P_\nu$ distribution for $B \to \mu\bar{\nu}_\mu\gamma$ event candidates. The signal region is defined by $-200\,\mathrm{MeV} < E_\nu - P_\nu < 200\,\mathrm{MeV}$. An overlay is shown of on-$\Upsilon(4S)$ resonance minus scaled off-$\Upsilon(4S)$ resonance data (filled circles), the Monte Carlo background prediction (solid line), and the Monte Carlo signal prediction for a branching fraction of $\mathcal{B}(B \to \mu\bar{\nu}_\mu\gamma) = 1.1 \times 10^{-3}$ (dotted line).

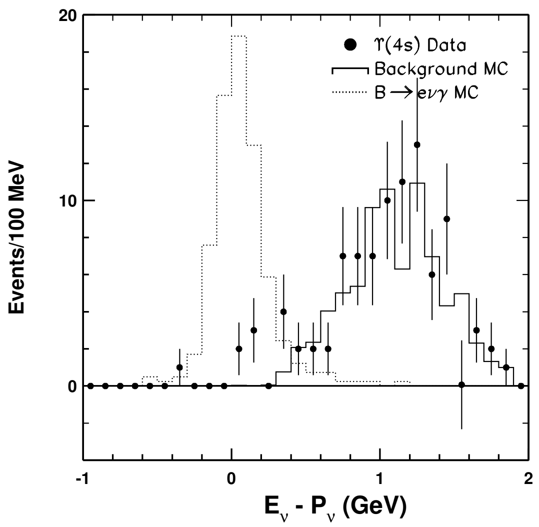

FIG. 3. The $\mathrm{E}_\nu - \mathrm{P}_\nu$ distribution for $B \to e\bar{\nu}_e\gamma$ event candidates. The signal region is defined by $-200\,\mathrm{MeV} < \mathrm{E}_\nu - \mathrm{P}_\nu < 200\,\mathrm{MeV}$. An overlay is shown of on-$\Upsilon(4S)$ resonance minus scaled off-$\Upsilon(4S)$ resonance data (filled circles), the Monte Carlo background prediction (solid line), and the Monte Carlo signal prediction for a branching fraction $\mathcal{B}(B \to e\bar{\nu}_e\gamma) = 1.3 \times 10^{-3}$ (dotted line).

TABLE I. Efficiency Corrections and Systematic Uncertainties on the Signal Detection Efficiency. The corrections are percentage changes to the efficiency.

Requirement	Efficiency Correction	Systematic Uncertainty
Lepton Selection		
Muon ID	–	$\pm5.0\%$
Electron ID	–	$\pm5.0\%$
Photon Selection	$+0.7\%$	$\pm0.4\%$
$R_2 \cup E_2 \cup M_2$	-8.0%	$\pm13.4\%$
π^0 veto	$+0.7\%$	$\pm3.7\%$
$P_e > 1.8$ GeV	-2.5%	$\pm0.01\%$
$B \to \mu\bar{\nu}_\mu\gamma$	-6.7%	$\pm14.8\%$
$B \to e\bar{\nu}_e\gamma$	-9.0%	$\pm14.8\%$