Search for the Radiative Decays $B \to \rho \gamma$ and $B^0 \to \omega \gamma$

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A search of the exclusive radiative decays $B \to \rho(770)\gamma$ and $B^0 \to \omega(782)\gamma$ is performed on a sample of about $84 \times 10^6$ $B\bar{B}$ events collected by the Babar detector at the SLAC PEP-II asymmetric-energy e$^+e^-$ storage ring. No significant signal is seen in any of the channels. We set upper limits on the branching fractions $B$ of $B(B^0 \to \rho^0\gamma) < 1.2 \times 10^{-6}$, $B(B^+ \to \rho^+\gamma) < 2.1 \times 10^{-6}$, and $B(B^0 \to \omega\gamma) < 1.0 \times 10^{-6}$ at 90% confidence level (C.L.). Using the assumption that $\Gamma(B \to \rho\gamma) = \Gamma(B^+ \to \rho^+\gamma) = 2 \times \Gamma(B^0 \to \rho^0\gamma)$, we find the combined limit $B(B \to \rho\gamma) < 1.9 \times 10^{-6}$, corresponding to $B(B \to \rho\gamma)/B(B \to K^*\gamma) < 0.047$ at 90% C.L.

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Within the standard model (SM), the decays $B \to \rho\gamma$ and $B^0 \to \omega\gamma$ proceed primarily through an underlying $b \to d\gamma$ electromagnetic “penguin” diagram that contains a top quark in the loop [1]. These processes are analogous to the $B \to K^*\gamma$ process mediated by the $b \to s\gamma$ transition, but with the final-state $s$ quark replaced by a $d$ quark, and the relevant element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix changed from $V_{ts}$ to $V_{td}$. There may also be contributions resulting from physics beyond the SM, such as supersymmetry [2]. Recent calculations of the branching fraction in the SM indicate a range $B(B^+ \to \rho^+\gamma) = (0.9 - 1.5) \times 10^{-6}$.
[3,4]. The range is due both to uncertainties in the value of $V_{ud}$ and to uncertainties in the calculation of the relevant hadronic form factors. The rates for $B^0 \to \rho^0 \gamma$, $B^+ \to \rho^+ \gamma$, and $B^0 \to \omega \gamma$ are related by the quark model, such that we expect $\Gamma(B^+ \to \rho^+ \gamma) = 2 \times \Gamma(B^0 \to \rho^0 \gamma) = 2 \times \Gamma(B^0 \to \omega \gamma)$. Previous searches [5] have found no evidence for these decays, nor any other $b \to d \gamma$ processes.

The analysis uses data collected by the BABAR detector [6] at the SLAC PEP-II asymmetric-energy $e^+e^-$ storage ring [7]. The data sample consists of $(84.4 \pm 0.9) \times 10^6$ $B\bar{B}$ events corresponding to 78 fb$^{-1}$ on the Y(4S) resonance (“on resonance”), and 9.6 fb$^{-1}$ recorded 40 MeV below the Y(4S) resonance (“off resonance”).

The BABAR detector consists of five subdetectors. Charged-particle trajectories are measured in both a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) in a 1.5-T solenoidal magnetic field. Photons and electrons are detected in a CsI(Tl) electromagnetic calorimeter (EMC), with photon energy resolution $\sigma_{\gamma}/E = 0.023(E/\text{GeV})^{-1/4} \cdot 0.019$. A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. The magnetic flux return is instrumented with resistive plate chambers to identify muons.

The decay $B \to \rho \gamma$ is reconstructed with $\rho^0 \to \pi^+ \pi^-$ and $\rho^+ \to \pi^+ \pi^0$, while $B^0 \to \omega \gamma$ is reconstructed with $\omega \to \pi^+ \pi^- \pi^0$. Charge-conjugate channels are implied throughout this Letter. Background high-energy photons are produced primarily in continuum $u, d, s,$ and $c$ quark-antiquark events through $\pi^0/\eta \to \gamma \gamma$ decays or via initial-state radiation. The reconstruction uses quantities both in the laboratory and Y(4S) center-of-mass frames, where the latter are denoted by an asterisk.

The primary photon in the $B$ decay is identified as an energy deposition in the EMC. The deposition must meet a number of criteria (described in detail in our Letter [8] on $B \to K^+\gamma$) that reduce background from charged particles, hadronic showers, and $\pi^0$ and $\eta$ decays.

As in Ref. [8], the charged tracks used in identifying the $\rho/\omega$ meson are well-measured tracks with a momentum transverse to the beam direction greater than 0.1 GeV/$c$. A charged pion selection based on $dE/dx$ measurements in the SVT and DCH and on Cherenkov photons reconstructed in the DIRC is used to reduce backgrounds from the $b \to s \gamma$ processes by rejecting charged kaons (e.g., $K^+$ from $B^0 \to K^{*0}\gamma$). Figure 1(a) shows the particle identification performance measured with a control sample of $D^{++} \to D^0(\to K^-\pi^+)\pi^+$ decays.

Neutral pion candidates are identified using two photon candidates reconstructed in the calorimeter, each with energy greater than 50 MeV. The invariant mass of the pair is required to satisfy $115 < m_{\psi} < 150$ MeV/$c^2$, which removes pairs whose invariant mass differs from the true $m_{\psi}$ by more than about 3 times the experimental resolution. A kinematic fit with $m_{\pi \psi}$ constrained to $m_{\psi}$ is used to improve the momentum resolution.

A $\rho^0$ candidate is reconstructed by selecting two identified pions that have opposite charge and a common vertex. The $\rho^+$ candidates are obtained by pairing $\pi^0$ candidates with an identified charged pion. We select $\rho$ candidates with invariant mass $m_{\pi\pi}$ within 250 MeV/$c^2$ of $m_{\pi} = 770$ MeV/$c^2$ [9] and momentum $2.3 < p_{\pi\pi} < 2.85$ GeV/$c$. The $\omega$ candidates are reconstructed from combinations of oppositely charged identified pions with a common vertex and $\pi^0$ candidates with invariant mass $m_{\pi\pi\pi\pi}$ within 23 MeV/$c^2$ of $m_{\omega} = 783$ MeV/$c^2$ [9] and momentum $2.4 < p_{\pi\pi\pi\pi} < 2.8$ GeV/$c$. The $m_{\pi\pi\pi\pi}$ resolution is slightly poorer in data than in Monte Carlo (MC) simulation. The resulting change in signal efficiency of the $m_{\pi\pi\pi\pi}$ selection is accounted for as a systematic error in the signal efficiency.

A charged pion selection based on $dE/dx$ is used to improve the momentum resolution.
in the $\omega$ rest frame. We also calculate several additional discriminating variables. The energy flow of the event excluding the $B$-meson daughters in $10^\circ$ cones centered on the photon-candidate momentum provides discrimination between the jetlike continuum background and the more spherical signal events. For suppression of the initial-state radiation background, we consider $R_2$, the ratio of second- to zeroth-order Fox-Wolfram moments [10] in the frame recoiling from the photon momentum. We define the net flavor content as
\[ \sum |N_i - N_i^*|, \]
where $N_i$ are the number of $e^\pm, \mu^\pm, K^\pm$, and slow pions of each sign identified in the event [11]. On average, $BB$ events have larger net flavor than continuum events. In the $B^0 \rightarrow \rho^0\gamma$ and $B^0 \rightarrow \omega\gamma$ analyses, we use the separation along the beam axis of the $B$-meson candidate vertex and that of the rest of the event. This variable is useful due to the finite $B$ lifetime. In the $B^0 \rightarrow \omega\gamma$ analysis, we use the $\omega$ Dalitz angle $\theta_\omega$, which is defined as the angle between the $\pi^0$ and the $\pi^+$ in the $\pi^+\pi^-\pi^0$ rest frame [12]; $\cos\theta_\omega$ follows a $\sin^2\theta_\omega$ distribution for true $\omega$ decays, as opposed to the uniform distribution of combinatorial background.

The background-suppression variables are combined into one discriminating variable via a neural network, which responds nonlinearly to the input variables and exploits correlations between the variables [13]. A separate neural network is trained for each mode.

The output for the neural network trained for $B^0 \rightarrow \rho^0\gamma$ is shown in Fig. 1(b), where the MC simulation of the continuum background is compared with the off-resonance data, and the output for MC-simulated $B^0 \rightarrow D^-\pi^+$ decays is compared with $B^0 \rightarrow D^-\pi^+$ decays reconstructed in the on-resonance data. The latter comparison provides a cross-check of those input variables that depend on the properties of the other $B$ meson in the event. This includes all of the variables except for $\theta_{h'}$ and $\theta_D$, which, for this check, are modeled using the signal distributions.

To suppress the continuum background, we make a selection on the neural-network output that is optimized for minimum statistical error as determined using MC samples of signal and background. The efficiency of this selection for the $B \rightarrow D\pi$ control sample differs slightly between the data and MC simulation. We account for this difference as a systematic error in the signal efficiency. For $B^+ \rightarrow \rho^+\gamma$, we also require $|\cos\theta_H| < 0.6$ to reject $B^+ \rightarrow \rho^+\pi^0$ events, which have a $\cos^2\theta_H$ distribution, as opposed to the expected $\sin^2\theta_H$ distribution of the signal process.

After applying the neural network, $\cos\theta_H$, and fit-region selection to the on-resonance data, 449 events remain in the $B^0 \rightarrow \rho^0\gamma$ data, 480 events for $B^+ \rightarrow \rho^+\gamma$, and 54 events for $B^0 \rightarrow \omega\gamma$. MC studies indicate that about 90% of the background in these samples comes from continuum events, and only about 10% from $B\bar{B}$.

For the signal extraction, we perform an unbinned extended maximum likelihood fit to the selected events. For $B \rightarrow \rho\gamma$, the fit uses $m_{ES}, \Delta E^*$, and $m_{\pi\pi}$, whereas for $B^0 \rightarrow \omega\gamma$, only $m_{ES}$ and $\Delta E^*$ are used. The measured variables are largely uncorrelated, even after the $p_{\pi\pi}$ (or $p_{\pi\pi\pi}$) cut, allowing the probability density function (PDF) to be constructed as a product of independent distributions for each variable. Since the $B\bar{B}$ backgrounds have PDFs that largely resemble continuum but are much smaller, the signal extraction uses only a continuum component to describe the background. Biases due to $B\bar{B}$ backgrounds are considered below. The signal $m_{ES}$ and $\Delta E^*$ distributions are described by the “crystal ball” shape [14], with the exception of the $m_{ES}$ distribution for $B^0 \rightarrow \rho^0\gamma$, where the Gaussian distribution is used. The relativistic Breit-Wigner line shape is used for the signal $m_{\pi\pi}$ distribution. The signal PDF parameters are obtained from MC simulation. The background $m_{ES}$ and $\Delta E^*$ distributions are described by the ARGUS threshold function [15] and a second-order polynomial, respectively. The background $m_{\pi\pi}$ function is a sum of a Breit-Wigner component and a combinatorial component described by a first order polynomial. The background PDF parameters are determined in the fit, with the exception of the $m_{\pi\pi}$ resonant fraction, which is fixed to the value measured in off-resonance data.

The $\Delta E^*$ vs $m_{ES}$ distributions of the selected $B \rightarrow \rho\gamma$ and $B^0 \rightarrow \omega\gamma$ candidates are shown in Fig. 2 and the fitted signal yields are shown in Table I. No significant signal is seen in any mode. The quality of the fit is checked by comparing the overall likelihood of the fit with values obtained from an ensemble of...

![FIG. 2. $\Delta E^*$ vs $m_{ES}$ fit regions for (a) $B^0 \rightarrow \rho^0\gamma$, (b) $B^+ \rightarrow \rho^+\gamma$, and (c) $B^0 \rightarrow \omega\gamma$ candidates. The boxes indicate the regions where signal events would appear: $0.2 < \Delta E^* < 0.1$ GeV and $5.27 < m_{ES} < 5.29$ GeV/c$^2$. Assuming $\mathcal{B}(B^0 \rightarrow \rho^0\gamma) = \frac{1}{2}\mathcal{B}(B^+ \rightarrow \rho^+\gamma) = \mathcal{B}(B^0 \rightarrow \omega\gamma) = 10^{-6}$, we expect 9.9, 12.1, and 3.4 signal events in these regions, respectively.](image-url)
The last two are "multiplicative" in that they could result in background adding to the fitted signal. The small biases in Table I confirm the uncertainties, which arise from the neural net efficiencies, are described above, are estimated in Ref. [8]. The largest 90% C.L. upper limits for the branching fractions are $B(B^0 \to \rho^0 \gamma) < 1.2 \times 10^{-6}$, $B(B^+ \to \rho^+ \gamma) < 2.1 \times 10^{-6}$, and $B(B^0 \to \omega \gamma) < 1.0 \times 10^{-6}$. Although no significant signals are seen, Table I shows the measured $B$ for each mode. For this calculation, we subtract a bias corresponding to the center of the allowed range, treat the half-width of the range as the systematic error, and add systematic and statistical errors in quadrature.

We also calculate a combined limit for the generic process $B \to \rho \gamma$ by assuming $\Gamma(B \to \rho \gamma) = \Gamma(B^0 \to \rho^0 \gamma) = 2 \times \Gamma(B^0 \to \rho^0 \gamma)$ and using the lifetime ratio $\tau_B^0/\tau_{B^0} = 1.083 \pm 0.017$ [9]. The resulting 90% C.L. upper limit is $B(B \to \rho \gamma) < 1.9 \times 10^{-6}$. Using the measured value of $B(B \to K^* \gamma)$ [8], this corresponds to a limit of $B(B \to \rho \gamma)/B(B \to K^* \gamma) < 0.047$.

This limit may be used to constrain the ratio of CKM elements $|V_{td}/V_{ts}|$ by means of the equation [4]:

$$\frac{B(B \to \rho \gamma)}{B(B \to K^* \gamma)} = |V_{td}/V_{ts}|^2 \left( \frac{1}{1 - m^2_\rho/M^2_B} \right)^3 \frac{1}{1 - m^2_K/M^2_B} \zeta^2[1 + \Delta R],$$

where $\zeta$ describes the flavor-SU(3) breaking between $\rho$ and $K^*$, and $\Delta R$ accounts for annihilation diagrams. $\Delta R$ is different for $\rho^0$ and $\rho^+$, but we do not take this into account here. Both $\zeta$ and $\Delta R$ must be taken from theory and there are several different [4,19] values published. As an example, we choose the values $\zeta = 0.76 \pm 0.10$ and $\Delta R = 0.0 \pm 0.2$. We adjust both parameters down by one standard deviation and find the limit $|V_{td}/V_{ts}| < 0.34$ at 90% C.L.

In conclusion, we have found no evidence for the exclusive $b \to d \gamma$ transitions $B \to \rho \gamma$ and $B^0 \to \omega \gamma$ in $(84.4 \pm 0.9) \times 10^6$ $B \bar{B}$ decays studied with the BaBar detector. The 90% C.L. upper limits on the branching fractions are significantly lower than previous values and start to restrict the range indicated by SM predictions [3,4].

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[13] We use the Stuttgart Neural-Network Simulator (http://www-ra.informatik.uni-tuebingen.de/SNNS) to train a neural net with one hidden layer of ten nodes.
[14] The crystal ball (CB) line shape is a modified Gaussian distribution with a transition to a tail function on the low side: 

\[ \frac{1}{\sigma} \exp \left( -\frac{x^2}{2\sigma^2} \right) \text{ for } \frac{x^2}{2\sigma^2} < \alpha \quad \text{and} \quad A \times \left[ B - \left( \frac{x^2}{2\sigma^2} \right) \right]^{-n} \text{ for } \frac{x^2}{2\sigma^2} > \alpha, \]

where \( A = \frac{\sigma}{\sqrt{2\pi}} \exp(\frac{1}{2} \alpha^2) \) and \( B = \frac{\alpha}{\sqrt{2\pi}} \). \( \sigma \) and \( \alpha \) are defined such as to maintain continuity of the function and its first derivative.
[15] We use the distribution \( x \sqrt{1 - x^2} \times \exp(\frac{1}{2} \alpha^2) \), to describe the background distribution. H. Albrecht *et al.*, Z. Phys. C 48, 543 (1990).