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

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 $\cal{B}$ of $\cal{B}(B^0 \to \rho^0\gamma) < 1.2 \times 10^{-6}$, $\cal{B}(B^+ \to \rho^+\gamma) < 2.1 \times 10^{-6}$, and $\cal{B}(B^0 \to \omega\gamma) < 1.0 \times 10^{-6}$ 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 $\cal{B}(B \to \rho\gamma) < 1.9 \times 10^{-6}$, corresponding to $\cal{B}(B \to \rho\gamma)/\cal{B}(B \to K^+\gamma) < 0.047$ 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 $\cal{B}(B^+ \to \rho^+\gamma) = (0.9 - 1.5) \times 10^{-6}$.
[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 $B^0 \rightarrow \rho^0 \gamma$, $B^+ \rightarrow \rho^+ \gamma$, and $B^0 \rightarrow \omega \gamma$ are related by the quark model, such that we expect $\Gamma(B^+ \rightarrow \rho^+ \gamma) = 2 \times \Gamma(B^0 \rightarrow \rho^0 \gamma) = 2 \times \Gamma(B^0 \rightarrow \omega \gamma)$. Previous searches [5] have found no evidence for these decays, nor any other $b \rightarrow d\gamma$ 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 (ECM), with photon energy resolution $\sigma_E/E = 0.023(E/\text{GeV})^{-1/4}$ @ 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 $B \rightarrow \rho \gamma$ is reconstructed with $\rho^0 \rightarrow \pi^+\pi^-$ and $\rho^+ \rightarrow \pi^+\pi^0$, while $B^0 \rightarrow \omega \gamma$ is reconstructed with $\omega \rightarrow \pi^+\pi^-\pi^0$. 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 $\pi^0/\eta \rightarrow \gamma\gamma$ 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 $B \rightarrow K^*\gamma$) 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 $b \rightarrow s\gamma$ processes by rejecting charged kaons (e.g., $K^+$ from $B^0 \rightarrow K^{\ast 0}\gamma$). Figure 1(a) shows the particle identification performance measured with a control sample of $D^{\ast +} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ 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 $115 < m_{\gamma\gamma} < 150 \text{MeV}/c^2$, which removes pairs whose invariant mass differs from the true $m_{\pi^0}$ by more than about 3 times the experimental resolution. A kinematic fit with $m_{\gamma\gamma}$ constrained to $m_{\pi^0}$ is used to improve the momentum resolution.
For $B \to \rho \gamma$, the fit uses $m_{ES}$, $\Delta E$, and $m_{\pi\pi}$, whereas for $B^0 \to \omega \gamma$, only $m_{ES}$ and $\Delta E$ are used. The measured variables are largely uncorrelated, even after the $p_{\pi\pi}$ (or $p_{\pi^+\pi^-\pi^0}$) 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 $B^0 \to \rho^0 \gamma$, 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 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 $B \to \rho \gamma$ and $B^0 \to \omega \gamma$ 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
parametrized MC simulations and found to be within the range expected.

We consider three sources of systematic uncertainty in this analysis: the modeling of $B \bar{B}$ backgrounds, the signal reconstruction efficiency, and the fixed parameters of the PDFs used in the fit. The first of these is “additive” in that it could result in background adding to the fitted signal yields. The last two are “multiplicative” in that they affect the way a given signal is interpreted as a branching fraction.

The effect that $B \bar{B}$ backgrounds have on the fitted signal yields is studied with parametrized MC simulations of the $m_{ES}$, $\Delta E'$, and $m_{\pi\pi}$ distributions. Possible correlations in the $m_{ES}$-$\Delta E'$ plane are modeled with two-dimensional distributions. Also, the rates of the dominant background modes are varied within wide ranges. For $b \rightarrow s \gamma$ (including $B \rightarrow K^* \gamma$), the normalization is varied between zero and twice the nominal value to conservatively account for uncertainties in kaon misidentification. For $B^+ \rightarrow \rho^+ \pi^0$ decays the branching fraction is varied between zero and twice the expected rate of $2 \times 10^{-5}$ [16]. Much lower branching fractions are expected for $B^0 \rightarrow \rho^0 \pi^0$ and $B^0 \rightarrow \omega \pi^0$ [16], so these cause negligible backgrounds. The small biases in Table I confirm that the $B \bar{B}$ PDFs are similar to those of continuum background.

All signal-efficiency systematic uncertainties, except those related to the neural network and the $\omega$ mass, which are described above, are estimated in Ref. [8]. The largest uncertainties, which arise from neural net efficiencies, are 5%, 5%, and 10% for $B^0 \rightarrow \rho^0 \gamma$, $B^+ \rightarrow \rho^+ \gamma$, and $B^0 \rightarrow \omega \gamma$, respectively. The $\rho^0$ efficiency also contributes a 5% uncertainty to $B^+ \rightarrow \rho^+ \gamma$ and $B^0 \rightarrow \omega \gamma$.

The fixed parameters of the signal PDFs are studied in fits to data for the topologically and kinematically similar, but much more common, $B \rightarrow K^* \gamma$ decays: $B^0 \rightarrow K^{*0} \gamma$, $K^{*0} \rightarrow K^- \pi^+$ for $B^0 \rightarrow \rho^0 \gamma$ and $B^+ \rightarrow K^{*+} \gamma$, $K^{*+} \rightarrow K^+ \pi^0$ for $B^+ \rightarrow \rho^+ \gamma$ and $B^0 \rightarrow \omega \gamma$. In these fits, the signal PDF parameters are allowed to float. The signal event yields are compared to those expected from the branching fractions measured in Ref. [8] and found to agree.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield (Events)</th>
<th>Bias (Events)</th>
<th>Upper限 (Events) (%)</th>
<th>$\varepsilon$</th>
<th>$B$ (10^{-6})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \rho^0 \gamma$</td>
<td>4.8$^{+0.7}_{-0.4}$</td>
<td>$[-0.5, 0.8]$</td>
<td>12.4</td>
<td>12.3</td>
<td>0.4$^{+0.6}_{-0.5}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^+ \gamma$</td>
<td>6.2$^{+0.7}_{-0.6}$</td>
<td>$[-0.1, 2.0]$</td>
<td>15.4</td>
<td>9.2</td>
<td>0.7$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \omega \gamma$</td>
<td>0.1$^{+0.3}_{-0.2}$</td>
<td>$[-0.3, 0.5]$</td>
<td>3.6</td>
<td>4.6</td>
<td>0.0$^{+0.7}_{-0.5}$</td>
</tr>
</tbody>
</table>

The statistical uncertainties of the PDF parameters, one of which is the background $m_{\pi\pi}$ resonant fraction, are used as ranges within which we vary the parameters of the $B \rightarrow (\rho/\omega)\gamma$ fits. The resulting variations in the fitted signal yield, which amount to 5% for $B^0 \rightarrow \rho^0 \gamma$ and $B^0 \rightarrow \omega \gamma$ and 10% for $B^+ \rightarrow \rho^+ \gamma$, are taken as systematic uncertainties. The total multiplicative systematic error, including the signal-efficiency uncertainty, is 8% for $B^0 \rightarrow \rho^0 \gamma$ and 13% for $B^+ \rightarrow \rho^+ \gamma$ and $B^0 \rightarrow \omega \gamma$.

We assume $B(\Upsilon(4S) \rightarrow B^0(B^+) \rho(\omega)) = B(\Upsilon(4S) \rightarrow B^+ \bar{B}^0) = 0.5$. In calculating upper limits, we correct for bias from $B \bar{B}$ backgrounds by subtracting the smallest observed bias, which is found to be negative for all three modes, from the signal yield. We include the effects of the multiplicative systematic uncertainties by using an extension [17] of the method described in Ref. [18], wherein the systematic and statistical errors are convolved. The resulting 90% confidence level (C.L.) upper limits for the branching fractions are $B(\rho^0(\omega)\gamma) < 1.2 \times 10^{-6}$, $B(B^+ \rightarrow \rho^+ \gamma) < 2.1 \times 10^{-6}$, and $B(B^0 \rightarrow \omega \gamma) < 1.0 \times 10^{-6}$. 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 $B \rightarrow \rho \gamma$ by assuming $\Gamma(B \rightarrow \rho \gamma) = \Gamma(B^+ \rightarrow \rho^+ \gamma) = 2 \times \Gamma(B^0 \rightarrow \rho^0 \gamma)$ and using the lifetime ratio $\tau_{B^0}/\tau_{B^+} = 1.083 \pm 0.017$ [9]. The resulting 90% C.L. upper limit is $B(B \rightarrow \rho \gamma) < 1.9 \times 10^{-6}$. Using the measured value of $\mathcal{B}(B \rightarrow K^* \gamma)$ [8], this corresponds to a limit of $\mathcal{B}(B \rightarrow \rho \gamma)/\mathcal{B}(B \rightarrow K^* \gamma) < 0.047$.

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

$$\frac{\mathcal{B}(B \rightarrow \rho \gamma)}{\mathcal{B}(B \rightarrow K^* \gamma)} = \frac{|V_{td}/V_{ts}|}{2} \left(1 - \frac{m_{l}^2}{M_B^2} - \frac{m_{s}^2}{M_B^2}\right)^3 \zeta^2[1 + \Delta R].$$

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 $\sigma$ and find the limit $|V_{td}/V_{ts}| < 0.34$ at 90% C.L.

In conclusion, we have found no evidence for the exclusive $b \rightarrow d \gamma$ transitions $B \rightarrow \rho \gamma$ and $B^0 \rightarrow \omega \gamma$ in $(8.4 \pm 0.9) \times 10^6 \ B \bar{B}$ 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: $f_{CB} = \exp(-\frac{10-\mu}{2\sigma})$ for $\frac{10-\mu}{\sigma} \geq \alpha$ and $A \times [B - \frac{10-\mu}{\sigma}]^{-n}$ for $\frac{10-\mu}{\sigma} < \alpha$, where $A = \frac{\alpha^2}{m_E^2}$ exp($-\frac{1}{2} \alpha^2$) and $B = \frac{\alpha^2}{m_E^2} - |\alpha|$ are defined such as to maintain continuity of the function and its first derivative.
[15] We use the distribution $x \sqrt{1-x^2} \times \exp[\xi(1-x^2)]$, where $x = m_{ES}/E_{beam}$, to describe the background $m_{ES}$ distribution. H. Albrecht et al., Z. Phys. C 48, 543 (1990).