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SEARCH FOR RADIATIVE PENGUIN DECAYS $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, AND $B^0 \to \omega\gamma$

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A search for the decays $B \to \rho(770)\gamma$ and $B^0 \to \omega(782)\gamma$ is performed on a sample of 211 million $\Upsilon(4S) \to B\overline{B}$ events collected by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring. No evidence for the decays is seen. We set the following limits on the individual branching fractions $\mathcal{B}(B^+ \to \rho^+\gamma) < 1.8 \times 10^{-6}$, $\mathcal{B}(B^0 \to \rho^0\gamma) < 0.4 \times 10^{-6}$, and $\mathcal{B}(B^0 \to \omega\gamma) < 1.0 \times 10^{-6}$ at the 90% confidence level (C.L.). We use the quark model to limit the combined branching fraction $\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma] < 1.2 \times 10^{-6}$ and constrain $|V_{td}|/|V_{ts}|$.

Keywords: *BABAR*; PEP-II; radiative penguin; $|V_{td}|/|V_{ts}|$.

1. Physics Motivation

Within the Standard Model (SM), the decays $B \to \rho\gamma$ and $B^0 \to \omega\gamma$ proceed primarily through a $b \to d\gamma$ electromagnetic penguin process that contains a top quark within the loop[1]. The rates for $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, and $B^0 \to \omega\gamma$[2] are related by the spectator-quark model, and we define the average branching fraction[3], $\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma] = \frac{1}{2}\left\{\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}[\mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma)]\right\}$, where $\frac{\tau_{B^+}}{\tau_{B^0}}$ is the ratio of B-meson lifetimes[4]. Recent calculations of $\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]$ in the SM[5,3] indicate a range of $(0.9 - 1.8) \times 10^{-6}$. There may also be contributions resulting from physics beyond the SM[6]. The ratio between the branching fractions for $B \to (\rho/\omega)\gamma$ and $B \to K^*\gamma$ is related in the SM to the ratio of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{td}|/|V_{ts}|$[7,3]. Previous searches by *BABAR* [8] and CLEO[9] have found no evidence for $B \to (\rho/\omega)\gamma$ decays.

2. Analysis Overview

We search for $B \to \rho\gamma$ and $B^0 \to \omega\gamma$ decays in a data sample containing 211 ± 2 $\Upsilon(4S) \to B\overline{B}$ decays, collected by the *BABAR* detector [10] at the PEP-II asymmetric-

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energy e^+e^- storage ring.

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 $\omega \to \pi^+\pi^-\pi^0$. Background comes primarily from $e^+e^- \to q\bar{q}$ continuum events, where $q = u, d, s, c$, in which a high-energy photon is produced through $\pi^0/\eta \to \gamma\gamma$ decays or via initial-state radiation. There are also significant $B\overline{B}$ backgrounds: $B \to K^*\gamma$, $K^* \to K\pi$, where a $K^\pm$ is misidentified as a $\pi^\pm$; $B \to (\rho/\omega)\pi^0$ and $B \to (\rho/\omega)\eta$, where a high-energy photon comes from the π^0 or η decay; and combinatorial background, mostly from $b \to s\gamma$ decays.

The details of the event selection criteria and the background suppression are described elsewhere[11]. Several variables are derived to distinguish $B\overline{B}$ decay events from continuum events; these exploit the event shape and physics processes in the rest of the event, which is defined to be all candidates not used to reconstruct the B candidate. These variables are combined together using a neural network[12] (NN) to give a single output $\mathcal{N}$, which discriminates between signal and background events. To further suppress background, a number of signal-decay variables are combined into a Fisher discriminant[13] ($\mathcal{F}$).

The signal yield is extracted using an unbinned maximum likelihood fit over 4 variables: $\mathcal{N}$,$\mathcal{F}$, and two kinematic variables: $\Delta E^* \equiv E^*_B - E^*_{\text{beam}}$ and $m_{ES} \equiv \sqrt{E^{*2}_{\text{beam}} - \mathrm{p}^{*2}_B}$, where E^*_{beam} is the center of mass (c.m.) beam energy and E^*_B (p^*_B) is the c.m. energy (3-momentum) of the reconstructed B candidate. Five event hypotheses (signal, continuum background, $B \to (\rho/\omega)\pi^0$ (and $B \to (\rho/\omega)\eta$) background, $B \to K^*\gamma$ background and combinatoric B background) are considered for each decay mode with the exception that in $B^0 \to \omega\gamma$ decay mode only the first three are considered. The fit to the data determines the shape parameters of the continuum background m_{ES} and ΔE^* PDFs, as well as the signal, continuum background and combinatorial $B\overline{B}$ background yields. All other parameters are fixed from Monte Carlo samples or sideband data, including the peaking $B\overline{B}$ background yields.

3. Physics Results

The fitted signal yield, n_{sig}, and the signal efficiency, ϵ, for each decay mode are shown in Table 1. The branching fraction is then calculated assuming $\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0) = \mathcal{B}(\Upsilon(4S) \to B^+B^-) = 0.5$. The significance of each result is determined as $\sqrt{2\Delta \log \mathcal{L}}$ where $\Delta \log \mathcal{L}$ is the log likelihood difference between the best fit and the null-signal hypothesis. No evidence for the signal decays is seen. The 90% C.L. is taken as the largest value of the efficiency-corrected signal yield, $n_{eff} = n_{sig}/\epsilon$, at which $2\Delta \log \mathcal{L} = 1.28^2$. We include systematic uncertainties by increasing n_{eff} by 1.28 times its systematic uncertainty.

A combined fit is performed relating the modes using the definition of $\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]$ to determine an effective yield ($\overline{n}_{\text{eff}}$) assuming $n_{sig}(B^+ \to \rho^+\gamma) = \overline{n}_{\text{eff}} \cdot \epsilon(B^+ \to \rho^+\gamma)$ and $n_{sig}(B^0 \to \rho^0/\omega\gamma) = \frac{1}{2}\frac{\tau_{B^0}}{\tau_{B^+}}\overline{n}_{\text{eff}} \cdot \epsilon(B^0 \to \omega\gamma)$. The combined result is shown in Table 1; there is no significant evidence for $b \to d\gamma$ transitions.

Table 1. The signal yield (n_{sig}), significance in standard deviations σ, efficiency (ϵ), and branching fraction ($\mathcal{B}$) central value and upper limit at the 90% C.L for each mode. The results of the combined fit are shown in the bottom row where n_{sig} is equal to $\overline{n}_{\mathrm{eff}}$, which is described in the text. When two errors are quoted, the first is statistical and the second is systematic.

Mode	n_{sig}	$\epsilon(\%)$	Significance (σ)	$\mathcal{B}(10^{-6})$	$\mathcal{B}(10^{-6})$ 90% C.L.
$B^+ \to \rho^+\gamma$	26^{+15+2}_{-14-2}	13.2 ± 1.4	1.9	$0.9^{+0.6}_{-0.5} \pm 0.1$	< 1.8
$B^0 \to \rho^0\gamma$	$0.3^{+7.2+1.7}_{-5.4-1.6}$	15.8 ± 1.9	0.0	$0.0 \pm 0.2 \pm 0.1$	< 0.4
$B^0 \to \omega\gamma$	$8.3^{+5.7+1.3}_{-4.5-1.9}$	8.6 ± 0.9	1.6	$0.5 \pm 0.3 \pm 0.1$	< 1.0
Combined	$269^{+126+40}_{-120-45}$	—	2.1	$0.6 \pm 0.3 \pm 0.1$	< 1.2

We set an upper limit of 1.2×10^{-6} at 90% C.L. for $\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]$.

Using the measured value of $\mathcal{B}(B \to K^*\gamma)$[14], we calculate a limit of $\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]/\mathcal{B}(B \to K^*\gamma) < 0.029$ at 90% C.L. This limit is used to constrain the ratio of CKM elements $|V_{td}/V_{ts}|$ by means of the equation[3,7]:

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

where ζ describes the flavor-SU(3) breaking between ρ/ω and K^*, and ΔR accounts for annihilation diagrams. Following Ref. 3, we choose the values $\zeta = 0.85 \pm 0.10$, and $\Delta R = 0.10 \pm 0.10$, to find the limit $|V_{td}|/|V_{ts}| < 0.19$ at 90% C.L, ignoring the theoretical uncertainties. Varying the values of ζ and ΔR within their uncertainties leads to changes in the limits by ±0.03 for $|V_{td}|/|V_{ts}|$.

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