Search for the Decays $B^0 \rightarrow e^+e^-\gamma$ and $B^0 \rightarrow \mu^+\mu^-\gamma$

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We present results of a search for the decays $B^0 \rightarrow \ell^+ \ell^- \gamma \ (\ell = e, \mu)$. The search is performed using $320 \times 10^6 \ BB$ pairs collected at the $\Upsilon(4S)$ resonance with the BABAR detector at the PEP-II $B$ Factory at SLAC. We find no significant signal and set the following branching fraction upper limits at the 90% confidence level: $B(B^0 \rightarrow e^+ e^- \gamma) < 1.2 \times 10^{-7}$ and $B(B^0 \rightarrow \mu^+ \mu^- \gamma) < 1.5 \times 10^{-7}$.

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Radiative leptonic decays of neutral $B$ mesons, $B^0 \rightarrow \ell^+ \ell^- \gamma$ with $\ell = e, \mu$ [1], are flavor-changing neutral-current transitions that are forbidden at the tree level in the standard model (SM). In the SM, such processes are described by penguin and box diagrams to leading order, as coming from the beam interaction point. For photon clusters, the transverse shower shape is expected to be random, and the EMC close to the intersection of their tracks with the EMC. For photon clusters, the transverse shower shape is required to be consistent with an electromagnetic shower. Leptons and photons are required to reside fully in the geometric acceptance of the detector.

Since the signal event contains two neutral $B$ mesons and no additional particles, the total energy of each $B$ meson in the center-of-mass (CM) frame must be equal to half of the total beam energy in the CM frame. We define $m_{ES} = \sqrt{(E^2_{\text{beam}}/c^2 - (\sum_i \vec{p}_i)^2)}$ and $\Delta E = \sum_i m_i^2 + (\vec{p}_i)^2 - E^*_{\text{beam}}$, where $E^*_{\text{beam}}$ is the beam energy in the CM frame. $m_i$ and $E^*_{\text{beam}}$ are the momenta in the CM frame and the masses of the daughter particles, respectively. $E^*_{\text{beam}}$ is used instead of the measured $B$ meson energy in the CM frame because $E^*_{\text{beam}}$ is more precisely known. For correctly reconstructed $B^0$ mesons, the $m_{ES}$ distribution has a maximum at the $B^0$ mass with a standard deviation of about 3 MeV/$c^2$ and the $\Delta E$ distribution has a maximum near zero with a standard deviation of about 30 MeV.

The $B^0 \rightarrow \ell^+ \ell^- \gamma$ candidates are selected by requiring $-0.5 \leq \Delta E \leq 0.5$ GeV and $5.0 \leq m_{ES} \leq 5.3$ GeV/$c^2$. These ranges include both background- and signal-dominated regions. As shown in Fig. 2, five background-dominated regions (sideband areas) are used for the background estimation. To avoid experimenter’s bias, the events in the signal-dominated region (signal box) and in the shaded area covering the signal box are not included in the analysis until the final selection criteria have been optimized and the background estimation has been finalized. The shapes of the $m_{ES}$ and $\Delta E$ distributions of the signal MC are parameterized by the Crystal Ball function [9] to allow for the asymmetric shape of the signal peak due to energy loss in the EMC. The size of the signal box is chosen to be approximately $\pm 3 \times \text{FWHM}$ for $\Delta E$ and $m_{ES}$: $-0.146(-0.112) \leq \Delta E \leq 0.082$ GeV for the $e^+ e^- \gamma$ ($\mu^+ \mu^- \gamma$) mode, and $5.270 \leq m_{ES} \leq 5.289$ GeV/$c^2$ for both modes.

The dominant backgrounds are: 1) unmodeled higher-order QED and hadronic two-photon processes for the $e^+ e^- \gamma$ mode; 2) $B$ decays where the photon comes from a $\pi^0$ decay, or the lepton is from a $J/\psi$ or $\psi(2S)$ decay; and 3) continuum background from $e^+ e^- \rightarrow f \bar{f}$ (where $f = u, d, s, c, or \tau$) processes at the parton level.

To take into account higher-order QED and hadronic two-photon processes, we introduce additional selection criteria for the $e^+ e^- \gamma$ candidates: we require the cosine of the polar angle of $e^- \gamma$ to be between $-0.743 (-0.618)$ and $0.81 (0.8)$, the energy of the photon to be $\geq 0.3$ GeV, the number of charged tracks (EMC clusters) in the event to be $\geq 5 (10)$, and the ratio of the second-to-zeroth order
Fox-Wolfram moments \((R_2)\) [10], which is calculated with the charged tracks and neutral clusters in the rest of the event (ROE), to be \(\leq 0.7\).

To reduce the number of events where the photon is from a \(\pi^0\) decay, we veto photon candidates that can be combined with any other photon in the event to form a \(\pi^0\) candidate with a mass within three standard deviations (\(\sim 20\text{ MeV}/c^2\)) of the nominal \(\pi^0\) mass.

We veto lepton candidates that form a suitable \(J/\psi\) or \(\psi(2S)\), as described in Ref. [11].

To suppress the continuum background, we require \(R_2\), calculated from all charged tracks and neutral clusters, to be less than 0.35, and the absolute value of the cosine of the angle between the thrust axis of the \(B^0\) candidate and that of the ROE to be less than 0.8. These variables are used in a neural network combined with the following variables: 1) the absolute value of the cosine of the angle between the \(B^0\) direction and the beam axis, 2) the absolute value of the cosine of the angle between the thrust axis of the \(B^0\) candidate’s decay products and the beam axis, 3) the ratio of second order to zeroth order Legendre moments of all charged tracks and neutral clusters, and 4) the invariant mass of the dilepton. The neural network rejects 20(36)\% of the background while keeping 95(89)\% of the signal, for the \(e^+e^-\) (\(\mu^+\mu^-\)) mode. All the selection criteria are optimized with MC samples to discriminate signal from background.

After all requirements are applied, there are on average 1.01(1.07) candidates per event for the \(e^+e^-\) (\(\mu^+\mu^-\)) mode. In events with multiple candidates, the one with the highest probability for the vertex fit is retained. The signal efficiency is 7.4(5.2)\% for the \(e^+e^-\) (\(\mu^+\mu^-\)) mode. The \(e^+e^-\) mode has higher efficiency because electrons have higher detection efficiency than muons.

To assess possible background contributions that peak in the signal box, we examined 32 exclusive hadronic and semileptonic \(B\) decays using MC, including events where both \(B\) mesons decay semileptonically, and found no significant contribution.

A variety of methods to estimate the background in the signal box have been tried, including fitting and counting methods in various \(m_{ES}\) and \(\Delta E\) sideband areas with different conditions. All studies yield results that are compatible within uncertainties.

The chosen method is model-independent, is based on data only, and has a small systematic uncertainty. To estimate the background level in the signal box, five different sideband areas are used, as indicated in Fig. 2. The ratio \(R^M_{est}\) is the estimated ratio of the yield in the signal box to the yield in the M1 box. The expected background in the signal box (\(n_{bg}^{exp}\)) is calculated by multiplying \(R^M_{est}\) by the yield in the M1 box. We estimate \(R^M_{est}\) as the mean of two ratios \(R^U\) and \(R^L\), where \(R^U(L) = N^{U(L)}_{\ell\ell}/N^{U(L)}_{U(L)}\), and where \(N^X\) is the yield in the box \(X\). This assumes that the changes in the ratio \(R^L\), \(R^M_{est}\), and \(R^U\) are linear in \(\Delta E\).

To test our assumption of this linearity, we use MC samples and calculate the ratio \(R^M\) by dividing the yield in the signal box by the yield in the M1 box. The relative difference between \(R^M\) and \(R^M_{est}\) in MC samples is assigned as a systematic uncertainty. The estimated background is \(1.75 \pm 1.38 \pm 0.36 (2.66 \pm 1.40 \pm 1.58)\) events

![FIG. 1: The penguin (left and middle) and box (right) Feynman diagrams for \(B^0 \rightarrow \ell^+\ell^-\gamma (\ell = e, \mu)\) decays. The photon can be emitted from any of the quarks or leptons, but the amplitudes are largest if the photon is emitted from one of the initial quarks.](image1)

![FIG. 2: Definitions of the signal box, blinded area (equal to the sum of the signal box and of the shaded area), and sideband areas in the \(\Delta E\) vs. \(m_{ES}\) plot: Upper1 (U1), Upper2 (U2), Lower1 (L1), Lower2 (L2), Middle1 (M1). The signal box has the same \(\Delta E\) range as the M1 box (different for each mode), and the same \(m_{ES}\) limits as the U2 and L2 boxes. The figure is not drawn to scale.](image2)
for the $e^+e^-\gamma (\mu^+\mu^-\gamma)$ mode, where the stated errors represent the statistical and systematic uncertainties, respectively.

The dominant source of systematic uncertainty on the signal yield is the calculation used for the signal MC [6]. The three theoretical input parameters, the Wilson coefficients $C_7, C_9,$ and $C_{10},$ used in the calculation are varied by $\pm10\%,$ as recommended by the authors of [6]. This variation changes the kinematics of the signal events and can thereby impact the detection efficiency. The largest relative change in signal efficiency by this variation is assigned as a systematic uncertainty.

We have studied $e^+e^-\rightarrow \mu^+\mu^-\gamma$ decays in data to assess the systematic uncertainty in photon reconstruction.

The systematic uncertainty from the lepton identification has been determined using an independent control sample of $J/\psi$ decays. The uncertainty on the number of $B\bar{B}$ events is $1.1\%$ [12].

The systematic uncertainty related to an imperfect detector simulation is studied using a control sample of $B^0 \rightarrow J/\psi K^0_S$ events. The same continuum background suppression requirements are applied on this sample and the signal efficiency is calculated. The relative difference in the signal efficiencies between data and MC samples is assigned as a systematic uncertainty.

The systematic uncertainty related to the tracking efficiency is determined from $e^+e^- \rightarrow \tau^+\tau^-$ interactions, with one $\tau$ decaying leptonically and the other to three charged hadrons. All the contributions to the systematic uncertainties are added in quadrature and summarized in Table I.

After applying the selection criteria we find one event in the signal box for each mode, as shown in Fig. 3 and Table II. These numbers are compatible with the expected background for both modes.

An upper limit on the branching fraction is computed from

$$B_{UL}(B^0 \rightarrow \ell^+\ell^-\gamma) = \frac{N_{UL}}{N_{BG} \cdot \epsilon_{sig}},$$

where $N_{UL}$ is the 90% confidence level (C.L.) upper limit for the signal yield, determined by taking into account

the one observed event in the signal box and the estimated background, using the frequentist method described in Ref. [13] including both statistical and systematic uncertainties, $N_{BG}$ is the number of neutral $B$ mesons and $\epsilon_{sig}$ is the signal reconstruction efficiency. The systematic uncertainties are included in $\epsilon_{sig}$. It is assumed that $B(T(4S) \rightarrow B^0\bar{B}^0) = B(T(4S) \rightarrow B^+B^-)$, and so $N_{BG}$ is equal to the number of $B\bar{B}$ events. The 90% C.L. branching fraction upper limits obtained are $B(B^0 \rightarrow e^+e^-\gamma) < 1.2 \times 10^{-7}$ and $B(B^0 \rightarrow \mu^+\mu^-\gamma) < 1.5 \times 10^{-7}$.

### Table I: Summary of the systematic uncertainties on the signal yields.

| Mode          | $e^+e^-$ (%) | $\mu^+\mu^-$ (%) |
|---------------|-------------|------------------|
| Signal Calculation | 2.3         | 3.8              |
| Photon Reconstruction | 1.6         | 1.6              |
| Lepton Identification | 0.7         | 1.3              |
| Number of $B\bar{B}$ Pairs | 1.1         | 1.1              |
| Data/MC comparison | 1.3         | 0.4              |
| Tracking Efficiency | 0.9         | 0.9              |
| Total         | 3.5         | 4.6              |

In summary, a search for $B^0 \rightarrow \ell^+\ell^-\gamma$ ($\ell = e$ or $\mu$) decays has been performed based on $320 \times 10^6 B\bar{B}$ events. We obtain 90% C.L. upper limits for the branching fractions of $B(B^0 \rightarrow e^+e^-\gamma) < 1.2 \times 10^{-7}$ and $B(B^0 \rightarrow \mu^+\mu^-\gamma) < 1.5 \times 10^{-7}$, which represent the first limits placed on these decay channels. These are well above the SM expectations.

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![Figure 3: Distribution of events in $m_{ES}$ and $\Delta E$. The left plot is for the $e^+e^-\gamma$ mode and the right plot is for the $\mu^+\mu^-\gamma$ mode. The dots are the events outside the signal box (rectangular region), and the triangles are the events inside the signal box.](image-url)
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[1] Throughout the Letter the charge-conjugate modes are included implicitly.
[2] G. Eliam et al., Phys. Lett. B 391, 461 (1997); T.M. Aliev et al., Phys. Rev. D 55, 7059 (1997).
[3] B. Aubert et al., [BABAR Collaboration], Phys. Rev. Lett. 94, 221803 (2005); M.-C. Chang et al., [Belle Collaboration], Phys. Rev. D 68, 111101 (2003); T. Bergfeld et al., [CLEO Collaboration], Phys. Rev. D 62, 091102 (2000).
[4] B. Aubert et al., [BABAR Collaboration], Nucl. Instr. Meth. A 479, 1 (2002).
[5] S. Agostinelli et al., Nucl. Instr. Meth. A 506, 250 (2003).
[6] Y. Dincer and L. M. Sehgal et al., Phys. Lett. B 521, 7 (2001).
[7] P. Billoir, Nucl. Instr. Meth. A 225, 225 (1984); D.N. Brown, E.A. Charles, D.A. Roberts, The BABAR track fitting algorithm, Proceedings of CHEP 2000, Padova, Italy, 2000.
[8] See for instance B. Aubert et al., [BABAR Collaboration], Phys. Rev. D 66, 032003 (2002).
[9] M.J. Oreglia, Ph.D Thesis, SLAC-236(1980), Appendix D; J.E. Gaiser, Ph.D Thesis, SLAC-255(1982), Appendix F; T. Skwarnicki, Ph.D Thesis, DESY F31-86-02(1986), Appendix E.

The Crystal Ball function can be written as:

\[
CB(m) = \begin{cases} 
\exp \left( -\frac{(m-\mu)^2}{\alpha^2} \right) & m > \mu - \alpha \sigma \\
\frac{(n/\alpha)^n \exp(-\alpha^2/2)}{(n/\alpha)^n \exp(-\alpha^2/2)} & m < \mu - \alpha \sigma,
\end{cases}
\]

where \(\mu\) is the mean value, \(\sigma\) is a measure of the width, and \(n\) and \(\alpha\) are parameters describing the tail.
[10] G. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978).
[11] B. Aubert et al., [BABAR Collaboration], Phys. Rev. D 73, 092001 (2006).
[12] B. Aubert et al., [BABAR Collaboration], Phys. Rev. D 67, 032002 (2003).
[13] R. Barlow, Comput. Phys. Commun. 149, 97 (2002).