Search for the decays $B^0 \to e^+ e^- \gamma$ and $B^0 \to \mu^+ \mu^- \gamma$

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We present results of a search for the decays $B^0 \rightarrow \ell^+\ell^-\gamma$ ($\ell = e$ or μ). The search is performed using 320×10^6 $B\bar{B}$ 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: $\mathcal{B}(B^0 \rightarrow e^+e^-\gamma) < 1.2 \times 10^{-7}$ and $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-\gamma) < 1.6 \times 10^{-7}$.

Radiative leptonic decays of neutral *B* mesons, $B^0 \rightarrow \ell^+\ell^-\gamma$ with $\ell = e$ or μ [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 shown in Fig. 1. The largest contributions arise from processes in which a photon is emitted from one of the initial quarks, thus avoiding the helicity suppression of the purely leptonic decays $B^0 \rightarrow \ell^+\ell^-$. A search for the processes $B^0 \rightarrow \ell^+\ell^-$ has been performed by the *BABAR* collaboration and others [2], but there is no previous search for the $B^0 \rightarrow \ell^+\ell^-\gamma$ decays. The expected branching fraction for $B^0 \rightarrow \ell^+\ell^-\gamma$ processes is of order 10^{-10} [3]. A measured branching fraction bigger than this would be evidence for new physics.

The analysis described in this paper uses a sample of 320×10^6 $B\bar{B}$ pairs recorded with the *BABAR* detector at the PEP-II asymmetric energy e^+e^- storage rings. This corresponds to an integrated luminosity of 292 fb^{-1} collected at the $\Upsilon(4S)$ resonance.

A detailed description of the *BABAR* detector can be found elsewhere [4]. Charged-particle trajectories are measured by a five-layer silicon vertex tracker and a 40-layer drift chamber operating in a 1.5 T magnetic field. A detector of internally reflected Cherenkov light is used for charged hadron identification. Surrounding this is an electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals, and the instrumented flux return for the solenoid, which consists of layers of steel interspersed with resistive plate chambers or limited streamer tubes.

A full *BABAR* Monte Carlo (MC) simulation using GEANT4 [5] is used to evaluate signal efficiencies and to identify and study background sources. The signal MC sample is based on a calculation where the $B^0 \rightarrow \ell^+\ell^-\gamma$ transitions depend on three Wilson coefficients C_7, C_9, and C_{10} at leading order [6].

We reconstruct the B^0 signal candidates by combining two oppositely charged leptons and a photon. The B^0 vertex is fitted using a Kalman Filter method [7]. The leptons are required to originate from a common vertex, and the B^0 candidate is required to be consistent with coming from the beam interaction point.

To minimize the number of misidentified particles, the leptons are required to satisfy stringent particle identification criteria [8]. For the electron candidates, bremsstrahlung photons are detected as energy deposits (clusters) in the EMC close to the intersection of their tracks with the EMC and the electron momentum is corrected for this

energy loss. The corrected electron momentum is used in the calculation of the invariant mass of the reconstructed *B* mesons. 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 $m_{ES} = \sqrt{(E^*_{beam})^2 - (\sum_i \mathbf{p}^*_i)^2}$ and $\Delta E = \sum_i \sqrt{m_i^2 + (\mathbf{p}^*_i)^2} - E^*_{beam}$, where E^*_{beam} is the beam energy in the CM frame, $\mathbf{p}^*_i$ and m_i are the momenta in the CM frame, and the masses of the daughter particles i ($i = \ell^+, \ell^-, \gamma$), respectively. E^*_{beam} is used instead of the measured *B* meson energy in the CM frame because E^*_{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 ΔE 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
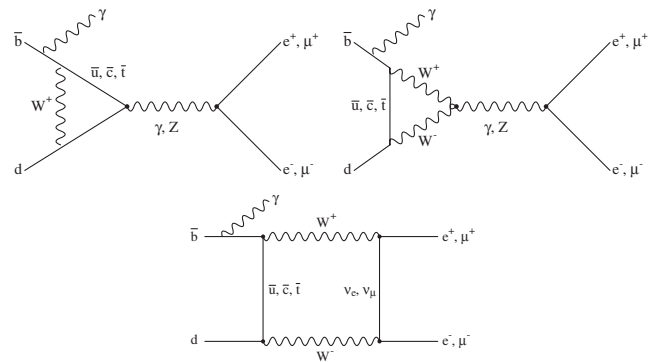

FIG. 1. The penguin (top) and box (bottom) Feynman diagrams for $B^0 \rightarrow \ell^+\ell^-\gamma$ ($\ell = e, \mu$) decays. The photon can be emitted from any of the quarks or leptons, but the amplitudes are largest if the photon is emitted from one of the initial quarks.
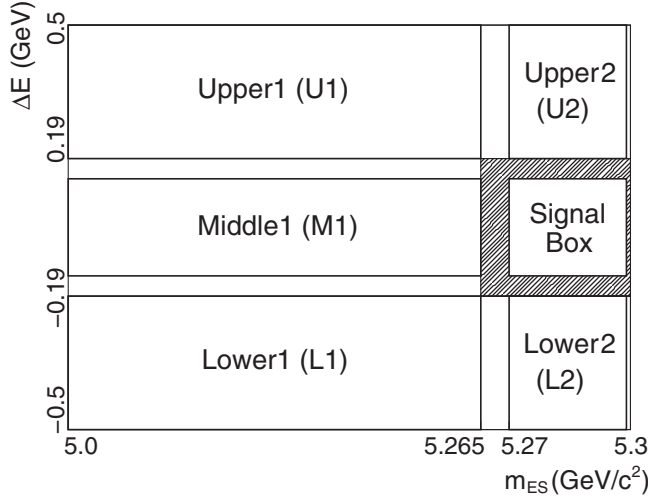
FIG. 2. Definitions of the signal box, blinded area (equal to the sum of the signal box and of the shaded area), and sideband areas in the ΔE vs m_{ES} plot: Upper1 (U1), Upper2 (U2), Lower1 (L1), Lower2 (L2), and Middle1 (M1). The signal box has the same ΔE range as the M1 box (different for each mode), and the same m_{ES} limits as the U2 and L2 boxes. The figure is not drawn to scale.

optimized and the background estimation has been finalized. The size of the signal box is chosen to contain more than 80% of the signal: $-0.146(-0.112) \leq \Delta E \leq 0.082$ 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 asymmetry in ΔE is due to the unrecovered energy losses of the charged leptons and the photon in the detector.

To select particles inside the detector volume, we apply the following fiducial requirements on the polar angles in the laboratory frame: -0.74 (-0.77) $\leq \cos\theta_{e^\pm(\mu^\pm)} \leq 0.93$ (0.92) and $-0.79 \leq \cos\theta_\gamma \leq 0.89$.

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

To suppress higher-order QED processes and hadron production by two-photon annihilation, we tighten the fiducial requirements for electrons and photons and introduce additional selection criteria for the $e^+e^-\gamma$ candidates: we require the cosine of the polar angle of e^- (γ) to be between -0.74 (-0.62) and 0.81 (0.80) in the laboratory frame, the energy of the photon to be ≥ 0.3 GeV also in the laboratory frame, 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) [9], which is calculated with the charged tracks and neutral clusters in the rest of the event (ROE), to be ≤ 0.7.

To reduce the number of events where the photon is from a π^0 decay, we veto photon candidates that can be combined with any other photon in the event to form a π^0 candidate with a mass within 3 standard deviations (~ 20 MeV/c^2) of the nominal π^0 mass.

We veto lepton candidates that form a suitable J/ψ or $\psi(2S)$ using the invariant mass of the lepton pair and ΔE, as described in Ref. [10].

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 dileptons. The neural network rejects 20(36)% of the background while keeping 95(89)% of the signal, for the $e^+e^-\gamma$ $(\mu^+\mu^-\gamma)$ 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 $e^+e^-\gamma$ $(\mu^+\mu^-\gamma)$ 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 $e^+e^-\gamma$ $(\mu^+\mu^-\gamma)$ mode. The $e^+e^-\gamma$ 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 studied, including fitting and counting methods in various m_{ES} and ΔE sideband areas with different conditions. All methods 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_{est}^M 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_{est}^M by the yield in the M1 box. We estimate R_{est}^M as the mean of two ratios R^U and R^L, where $R^{U(L)} = N^{U2(L2)}/N^{U1(L1)}$, and where N^X is the yield in box X. This assumes that the changes in the ratio R^L, R_{est}^M, and R^U are linear in ΔE.

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 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 in 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 $\pm 10\%$, as recommended by the authors of Ref. [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.

The uncertainty in the branching fraction $\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)$ [11] is taken as systematic uncertainty. We have studied $e^+e^- \to \mu^+\mu^-\gamma$ 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/ψ decays. The uncertainty in the number of $B\bar{B}$ events is 1.1% [12].

The systematic uncertainty related to an imperfect simulation of the ROE is studied using a control sample of $B^0 \to J/\psi K^0_S$ 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 $e^+e^- \to \tau^+\tau^-$ interactions, with one τ 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

TABLE I. Summary of the systematic uncertainties in the signal yields.

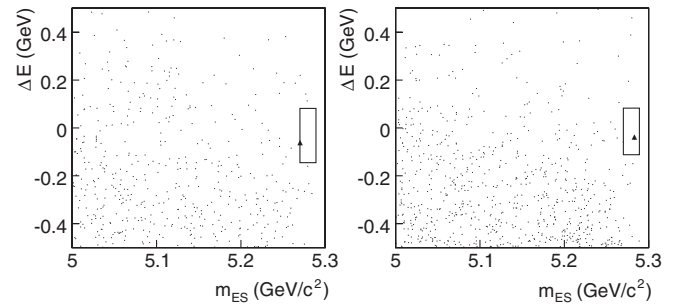|	$e^+e^-\gamma$ (%)	$\mu^+\mu^-\gamma$ (%)
Signal calculation	2.3	3.8
$\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)$	1.6	1.6
Photon reconstruction	1.6	1.6
Lepton identification	0.7	1.3
Number of $B\bar{B}$ pairs	1.1	1.1
Data/MC comparison	1.3	0.4
Tracking efficiency	0.9	0.9
Total	3.8	4.8

FIG. 3. Distribution of events in m_{ES} and ΔE. 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.

TABLE II. Summary of the results where n_{obs} (n^{exp}_{bg}) is the number of observed (expected background) events in the signal box, ϵ_{sig} is the efficiency, N_{UL} is the 90% C.L. upper limit for the signal yield, and $\mathcal{B}_{UL}$ is the upper limit on the branching fraction at the 90% C.L. The stated uncertainties in n^{exp}_{bg} are statistical and systematic, and the uncertainty in ϵ_{sig} is systematic.

Mode	n_{obs}	n^{exp}_{bg}	ϵ_{sig} (%)	N_{UL}	$\mathcal{B}_{UL}$
$e^+e^-\gamma$	1	$1.75 \pm 1.38 \pm 0.36$	7.4 ± 0.3	2.82	1.2×10^{-7}
$\mu^+\mu^-\gamma$	1	$2.66 \pm 1.40 \pm 1.58$	5.2 ± 0.3	2.56	1.6×10^{-7}

$$\mathcal{B}_{UL}(B^0 \to \ell^+\ell^-\gamma) = \frac{N_{UL}}{N_{B^0}} \cdot \epsilon_{sig}, \qquad (1)$$

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_{B^0} is the number of neutral B mesons and ϵ_{sig} is the signal reconstruction efficiency. The systematic uncertainties are included in ϵ_{sig}. We used $\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0) = (49.4 \pm 0.8)\%$ [11]. The 90% C.L. branching fraction upper limits obtained are $\mathcal{B}(B^0 \to e^+e^-\gamma) < 1.2 \times 10^{-7}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-\gamma) < 1.6 \times 10^{-7}$.

In summary, a search for $B^0 \to \ell^+\ell^-\gamma$ ($\ell = e$ or μ) decays has been performed based on 320×10^6 $B\bar{B}$ events. We obtain 90% C.L. upper limits for the branching fractions of $\mathcal{B}(B^0 \to e^+e^-\gamma) < 1.2 \times 10^{-7}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-\gamma) < 1.6 \times 10^{-7}$, which represent the first limits placed on these decay channels. These are well above the SM expectations.

[1] Throughout the paper the charge-conjugate modes are included implicitly.

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